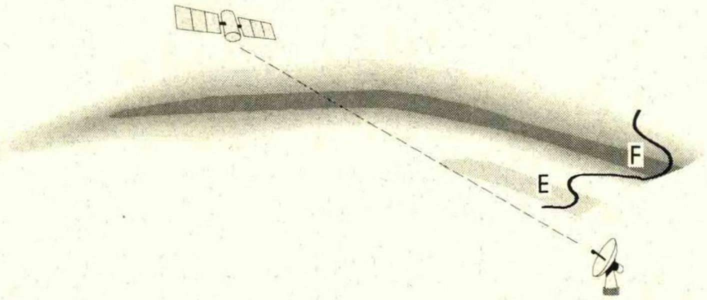
Proceedings



Space Weather Effects on Propagation of Navigation & Communication Signals

22-24 October 1997, COMSAT Corp, Bethesda, Maryland

Sponsored by
National Science Foundation (NSF) and
National Oceanic & Atmospheric Administration (NOAA)

in Cooperation with
Air Force Research Laboratory (AFRL) and
Office of Naval Research (ONR)

Organized by
NorthWest Research Associates (NWRA)

Workshop Proceedings

Space Weather Effects on Propagation of Navigation & Communication Signals

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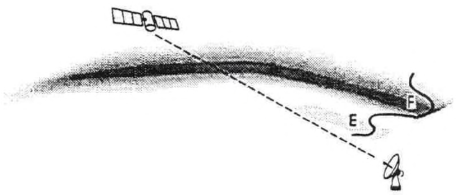
Photo by Vic Hessler



Preface

If this focused workshop ultimately proves successful, it will be by means of (a) followup to the recommendations reached by consensus of its participants and (b) continued dialogue between the research and applications communities. I feel invigorated by the initial dialogue we achieved in two and a half days, and I owe thanks for that to many people.

First, I extend the appreciation of all participants to our host organization and to numerous COMSAT employees for their assistance and their forbearance. We owe a special thanks to the facilities, security, and cafeteria staffs. Through their efforts, a technical workplace served us as if its primary function was that of a conference center.

The Program Committee, listed near the end of these Proceedings, cooperated ably and unselfishly in guiding the contents of the workshop and in critiquing my summary and reporting of the plenary discussions. Sustained yeoman duty was put forth by our Program and Arrangements Coordinators, also named there. Thanks to all the speakers and poster authors, and to our engaging after-dinner speaker, for sharing their experience and knowledge with a disparate audience.

I particularly appreciate the vigor and stamina of our three facilitators and six recorders. Even (or, perhaps, especially) discussion groups vitally interested in the topic at hand can flounder without guidance that is both clear-headed and flexible, and recording even the most productive discussion challenges one's attentiveness and perseverance.

Finally, thanks to all participants, especially those from the applications community, who by-and-large entered an unfamiliar arena and provided much-needed guidance to us practitioners of ionospheric research.

Edward J. Fremouw

TABLE OF CONTENTS

Erratum:

In the Table of Contents, page numbers 231 and larger should be decreased by 2.

Space Weather Effects on Propagation of Navigation & Communication Signals

1 Summary of the Workshop

E.J. Fremouw
Northwest Research Associates

1.1 Overview

Natural phenomena taking place on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere can affect a variety of human-made systems. Collectively termed "space weather," these phenomena produce effects ranging from spacecraft charging and radiation damage to disruptive currents induced geomagnetically in terrestrial power grids. A National Space Weather Program (NSWP) has been formulated and is being implemented by the Office of the Federal Coordinator for Meteorological Services and Supporting Research, under guidance provided by the National Space Weather Program Council. The Council includes senior representatives from the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) and from the Departments of Commerce, Defense, Energy, and the Interior. It is assisted by the Interagency Committee for Space Weather, which has members from the same federal agencies.

A subset of space-weather phenomena, either generated in direct response to solar occurrences or due to on-going atmospheric dynamics (ultimately solar-driven, as well), takes place in the ionosphere. The ionospheric phenomena can affect navigation and communication signals due to interaction of the radio waves carrying the signals with the ionospheric plasma through which they must propagate. The National Science Foundation and the National Oceanic and Atmospheric Administration (NOAA), in collaboration with the Air Force Research Laboratory (AFRL) and the Office of Naval Research, sponsored a workshop focused on the radiowave-propagation aspects of space weather on 22-24 October 1997. Held at the facilities of COMSAT Corp. in Bethesda MD and organized by Northwest Research Associates (NWRA), the workshop was attended by 133 individuals from industry, military and civilian agencies, government laboratories, research institutes, and universities. The agenda included 13 review talks from the research and applications communities, followed by extensive specialized discussion periods, and posters displaying 28 sets of user-oriented research results and space-weather products.

With the fundamental objective of promoting a two-way flow of information between researchers and applications practitioners, the workshop was structured to facilitate participant interaction. The first morning and early afternoon (Wednesday) were devoted to invited talks designed to review (1) the state of ionospheric knowledge and (2) the major types of navigation and communication systems whose signals propagate via or through the ionosphere. With all attendees participating, the workshop goals then were refined in open session. Thereafter, the assembled participants divided into two groups to begin interactive consideration of space-weather issues confronting (a) communication systems and (b) navigation systems. Following these initial one-and-a-half-hour "breakout" sessions, participants were introduced to the poster displays by their authors.

An evocative after-dinner address Wednesday evening by E.W. (Joe) Friday helped to set the context for development of effective space-weather services. As Assistant Administrator of NOAA for Oceanic and Atmospheric Research and former Director of the National Weather Service (NWS), Dr. Friday provided an historical sketch of weather forecasting in the United States. That history includes the disquieting fact that public impetus for advancing the infrastructure needed for improved forecasting often arose only in response to weather-caused disasters. As a precedent for space-weather forecasting, the NWS experience can provide important guidelines for transitioning space-weather research results into practical tools of economic and human value. Hopefully, on-going dialogue between developers/operators of space systems and the space-weather research and forecasting communities can pre-empt the disaster-based experience.

The second morning (Thursday) was devoted to reports on existing space-weather services and identified needs for space-weather information. It was followed by the core activity of the workshop, in-depth discussions by the breakout groups. The meeting facilities graciously provided by COMSAT proved to be very well suited for such discussions. Its flexibility was most evident when the utility of a third breakout group – one devoted to commercial delivery of space-weather services – became evident. The facility was reconfigured smoothly into separate rooms for several hours of deliberation by the three breakout groups. Thereafter, the groups rejoined one another for refreshments and informal discussions amidst the posters.

The final session of the workshop (Friday morning) brought together all participants for plenary discussion and development of consensus. The resulting workshop recommendations are enumerated in Section 1.3 of these proceedings.

1.2 Oral Presentations and Posters

Following an overview of *The National Space Weather Program* by Richard Behnke (NSF), Michael Kelley (Cornell) presented *An Introduction to Space Weather in the Ionosphere*. Prof. Kelley sketched the tenuous-plasma nature of the ionosphere, its relation to neutral-atmospheric dynamics at middle and low latitudes, and the dominant influence of the solar wind and magnetosphere at high latitudes. He employed a variety of visual aids to impart an appreciation for structuring of the ionospheric plasma through several decades of scale size. Structured plasma is responsible for many of the radiowave-propagation effects addressed at the workshop. Specific ionospheric effects were reviewed by Anthony Mannucci (Jet Propulsion Lab), who described *Group Delay and Phase Advance due to Ionospheric Total Electron Content* (TEC), and by Edward Fremouw (NWRA) and Santimay Basu (AFRL), who characterized *The Signal Statistics* and *Climatology*, respectively, *of Transionospheric Scintillation*.

Comparable to Prof. Kelley's review of ionospheric physics was a description of *Communication Satellite Systems and the Ionosphere* by John Evans (COMSAT). Concentrating on systems whose performance could be degraded by ionospheric effects, Dr. Evans described imminent and envisioned "Little LEO" systems intended to provide data-messaging services to small terminals at VHF/UHF and "Big LEO" systems for mobile telephony via handheld radios, most of which will operate at L Band. The effects of greatest concern are those produced by intensity and phase scintillation. Much attention was given at the workshop to the Global Positioning System (GPS), following *An Overview of GPS* by Keith McDonald (Sat Tech Systems) and a description of its *Wide Area Augmentation System* (WAAS) by Richard Domikis (Federal Aviation Administration).

Descriptions of space-environment requirements and services in the Department of Defense were given by Gretchen Lindsay (Aerospace Corp.) for Russell Kutzman (Air Force Space Command, AFSPC), Gus Lott (Naval Postgraduate School), Michael Christie (AFSPC), and David Anderson (AFRL). Services and issues in the civilian sector were described, respectively, by Joseph Kunches (NOAA Space Environment Center) and Thomas Tascione (Sterling Software).

Summaries of the oral presentations appear in Section 2 of these proceedings. Summaries of presentations displayed in the poster session, organized by James Secan (NWRA), appear in Section 3.

1.3 Recommendations

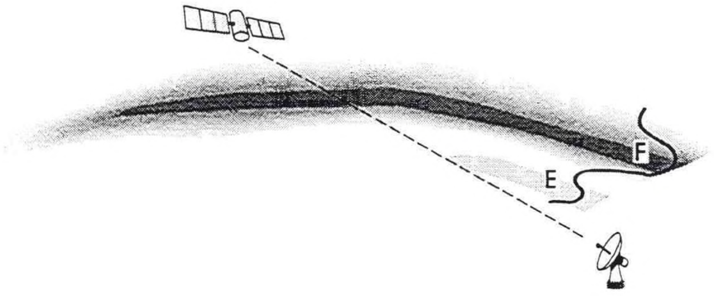
Each discussion group was served by a facilitator and two recorders, who reported back to the re-assembled participants on the last morning of the workshop. Based on those reports, the participants reached consensus on the following key conclusions:

1. Validation of space-weather measurements, models, and products and development of metrics for quantifying their accuracy and reliability are crucial.
2. GPS users want scintillation to be characterized in terms of
   - the duration and recurrence rate of fades as functions of their depth;
   - the rate-of-change and acceleration of phase; and
   - the spatial extent of scintillation patches (number of GPS satellites affected).
3. Development of a test bed and standards for testing the response of GPS receivers to scintillation is to be encouraged.
4. The ability of WAAS' 5°-by-5° grid to capture operationally relevant TEC gradients needs to be assessed.
5. Ionospheric monitoring systems should be operated through solar maximum as inputs to nowcast and forecast models. Examples identified included
   - continued transmission of phase-coherent VHF/UHF signals from the Transit satellites of the Navy Ionospheric Monitoring System;
   - ground-based sensors such as chains of Transit receivers for TEC tomography and latitudinal mapping of scintillation, networks of GPS receivers for TEC measurement, and ionosondes for ionospheric profiling;
   - a low-inclination satellite orbiting modestly above the F-layer peak and carrying a suite of instruments for monitoring the electrodynamics and plasma structuring of the equatorial ionosphere, such as that proposed by AFRL to the Air Force Space Test Program (STP); and
   - a UV instrument in geostationary orbit capable of imaging night-time TEC with sufficient resolution to detect and track scintillation-prone regions, such as that proposed by the Navy to the Air Force STP.
6. Continued operation of the Advanced Composition Explorer satellite at the Earth-sun libration point throughout its five-year design lifetime (presently

assured for only two years) would represent an extremely cost-effective means to provide data that are crucial for detecting space-weather events nearing Earth.

7. Creation of a Rapid Prototyping Center for space-weather products, such as that envisioned for NOAA's Space Environment Center, is needed to foster development of a space-weather industry in the private sector.

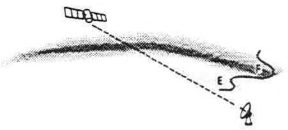
The foregoing workshop recommendations will be referred to the Interagency Committee for Space Weather for consideration in advising the National Space Weather Program Council on NSWP priorities.



2 Summaries of Invited Talks

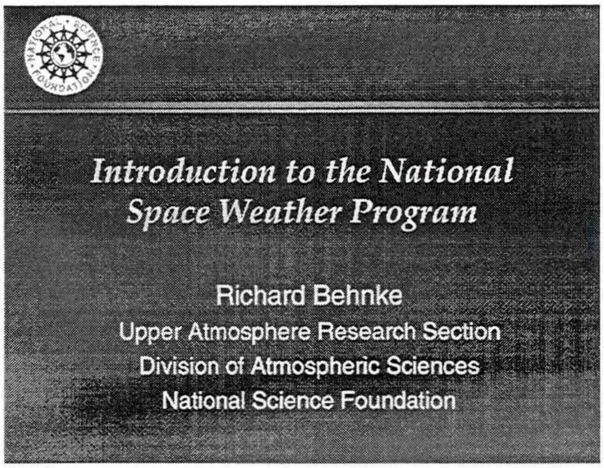
2.1 The National Space-Weather Program (NSWP)

Richard A. Behnke



THE NATIONAL SPACE WEATHER PROGRAM (NSWP)

Richard Behnke
NSF



Introduction to the National Space Weather Program

Richard Behnke
Upper Atmosphere Research Section
Division of Atmospheric Sciences
National Science Foundation

“Space Weather” refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a broad range of socio-economic losses.

The overarching goal of the National Space Weather Program is to provide timely, accurate, and reliable space environment observations, specifications, and forecasts. The NSWP will build on existing capabilities and establish an aggressive, coordinated process to set national priorities, focus agency efforts, and leverage resources.

The Program includes contributions from the user community, operational forecasters, researchers, modelers, and experts in instruments, communications, and data processing and analysis. It is a multi-agency partnership between academia, industry, and government.

Today, space weather forecasting is in a situation similar to that of weather forecasting half a century ago. Even with the present and planned instruments, the data are sometimes too sparse, and some critical data, such as in-situ solar wind parameters, are not available at all. The gaps in our ground-based observations are particularly acute at very high latitudes, where the magnetic field maps out to the distant regions of the magnetosphere. New ground- and space-based instruments, coupled with quantitative modeling, will provide an enormous improvement in space weather specification and forecasting quality.

The NSWP has several key elements and goals. Principal among these are:

- Improve accuracy, reliability, and timeliness of forecasts and specification
- Support basic research on physical processes of the coupled sun-earth system
- Ensure that critical ground- and space-based observations are available
- Develop end-to-end, physics-based models with predictive capabilities and user-friendly interfaces
- Focus educational efforts toward forecasters, engineers, students, customers, and the general public
- Ensure technology transition and integration of research and models into operation systems.

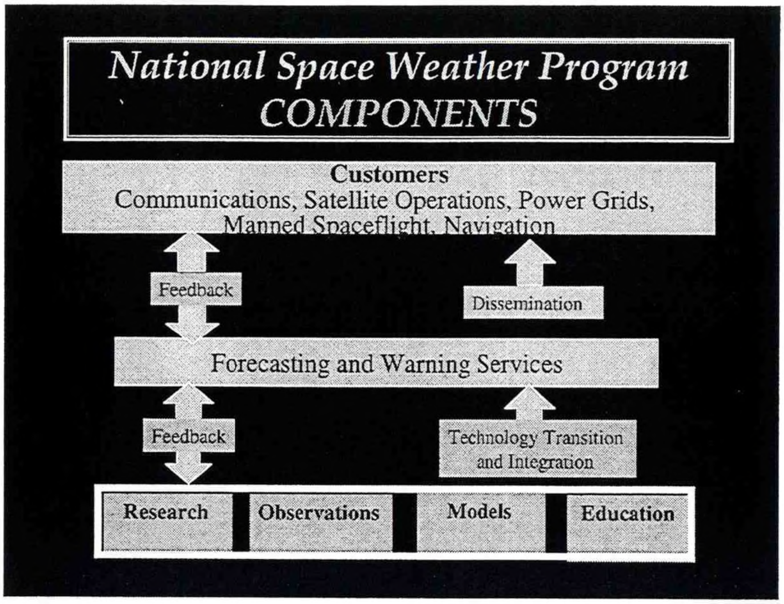
Presently, the nation's capabilities to provide adequate warnings, nowcasts, or forecasts do not meet the needs in any of the domains of interest. This is shown dramatically by the following table. In this table, red means no capability, orange means limited capability, yellow signifies requirements can occasionally be met and green indicates that the capability is adequate.

Table 2-1. Current Capabilities Based on Requirements

	Warning	**Nowcast**	**Forecast**	**Post-Analysis**
Solar/interplanetary	Yellow/red	Yellow/red	Yellow/red	Yellow
Magnetosphere	Red	Yellow/red	Red	Yellow/red
Ionosphere	Red	Yellow/red	Red	Yellow
Neutral atmosphere	Red	Yellow/red	Red	Yellow/red

As can be seen there is no green! There is no area of space weather where the capabilities are adequate. It is the job of the NSWP to turn this table to green.

To accomplish this, the NSWP is organized around four pillars: research, observations, models and education. These pillars then feed into providing improved forecasting and warning sevices, which are ultimately tailored and disseminated to customers for their specific purpose. The customers then provide feedback to the forecasting and warning providers (NOAA's SEC and the USAF 55th Space Weather Squadron) who help fine tune and focus basic research. It is an interactive system that is continually striving to improve.



National Space Weather Program COMPONENTS

Customers
Communications, Satellite Operations, Power Grids, Manned Spaceflight, Navigation

Feedback

Dissemination

Forecasting and Warning Services

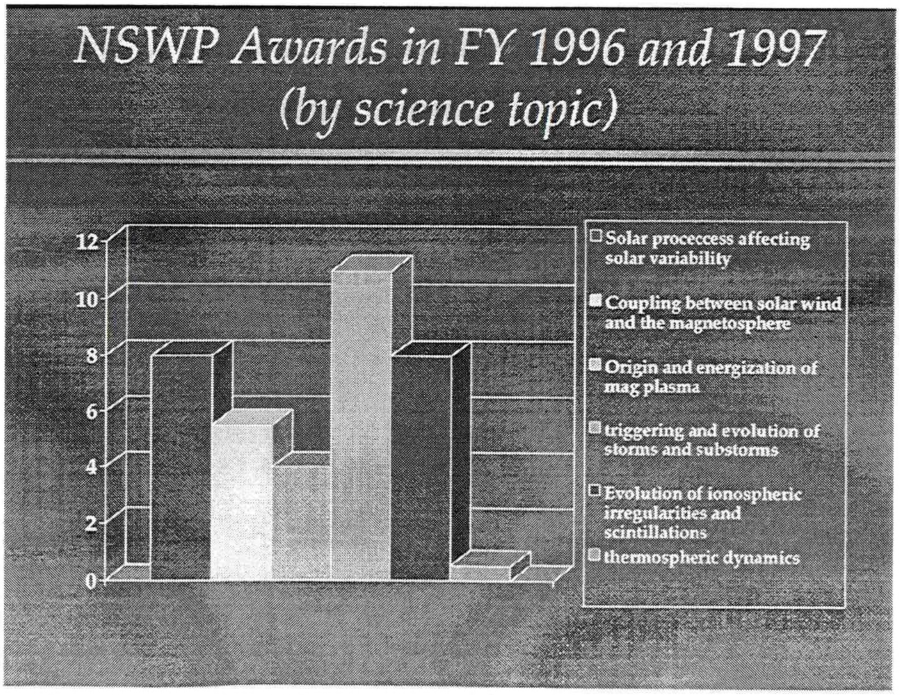
Feedback

Technology Transition and Integration

Research | **Observations** | **Models** | **Education**

One central issue in the process is providing for the transition of basic research into operations. The USAF does this via, for example, Phillips Lab and NOAA's SEC is charged with this task on the civilian side. Tight budgets have made this transitioning of results a real issue. It is perhaps the single biggest choke point of the NSWP and one that has not been fully addressed to date.

In the area of basic research the NSWP has been very active. In FY 1996 and 1997, the National Space Weather Program has made approximately 35 basic research awards aimed at improving key area of space weather. The distribution of these awards is shown below:



NSWP Awards in FY 1996 and 1997 (by science topic)

A recent area of emphasis is to understand the metrics of space weather. We must be able to demonstrate quantitative improvement. Metrics are needed to tell us

- What are the quantitative goals against which progress can be measured.
- What are the parameters and events to be predicted?
- Where are we in terms of model and measurement capabilities?
- What level of prediction accuracy, timeliness, etc. is required?

To end, I have put together a short list of recent highlights of the National Space Weather Program:

- 17 new awards, $1.0M
- Space Weather: Research to Operations meeting in Boulder
- NOAA CRADA to implement and operate numerical models
- NSF award to establish interface to satellite industry
- Space Weather Effects on Navigation and Communication Systems workshop at COMSAT
- White paper on Metrics prepared; special fall AGU session on Metrics
- NSF award to develop Space Weather outreach material
- Meeting at IAGA to discuss international Space Weather efforts
- USAF NASA Space Environment Meeting to discuss expanded cooperation in Space Weather
- National Academy (Committee for Solar Terrestrial Research) agrees to review annually the NSWP Implementation Plan

The NSWP has been very successful. It has brought government agencies together, created a high priority National program resulting in increased visibility and funding at several agencies, defined a focus for meetings and workshops such as this one, motivated recent media attention and inspired new scientific studies and collaborations.

2.2 On the Origins of Weather in the Ionosphere

Michael C. Kelley

ON THE ORIGINS OF WEATHER IN THE IONOSPHERE

M. C. Kelley
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ABSTRACT

The ionosphere is characterized by highly structured density and velocity fields. Here we concentrate on planetary and mesoscale features of ionospheric space weather. At low to middle latitudes the dominant planetary structure is the day-night asymmetry in lower ionospheric content and electrical conductivity. The tropical ionospheric anomaly and the pre-reversal enhancement of the zonal electric field are also important planetary scale ionospheric structures that play a role in space weather. In the mesoscale, internal waves from the lower atmosphere organize the ionospheric plasma in large undulations at the same wavelength. In addition, in some cases the undulations become unstable to plasma instabilities, which nonlinearly create vast regions of turbulent plasma. This is the ionospheric equivalent of a thunderstorm. At the planetary scale in the high latitude zone, the convection electric field and the associated flow pattern of the ionosphere are determined by the geometry of the interplanetary magnetic field as it is swept by the earth in the solar wind. The size, orientation and multiplicity of the flow vortices imposed upon the high-latitude plasma varies on a minute-by-minute basis, creating an extremely dynamical flow. This flow pattern mixes and stretches the density field, which itself varies on a planetary scale due to the combined action of solar production, recombination losses, and impact ionization by precipitating particles. In the mesoscale, local mixing by turbulent eddies in the flow, local production by particle precipitation, and localized loss processes due to enhanced or long-lived recombination effects create structure. The mean flow convects these features for vast distances. Auroral arcs and their associated local turbulent electric field mix the plasma further. In addition, the generalized **ExB** instability creates structure on unstable gradients.

I. INTRODUCTION

From the earliest days of space research using ionosondes, it has been clear that considerable "weather" exists there. The literature is very rich, as are the variety of experimental techniques and theoretical tools applied to the study of ionospheric phenomena. Each instrument is sensitive to a restricted range of wavelength as well as to some small region of space and time. One of the challenges is to reconcile the results of very diverse measurement methods with each other and with theory.

The ionosphere is characterized by the number of electrons per cubic centimeter as a function of altitude, whereas the earth's atmosphere is better organized by its temperature. The typical profiles are shown in Figure 1, along with the various names we use.

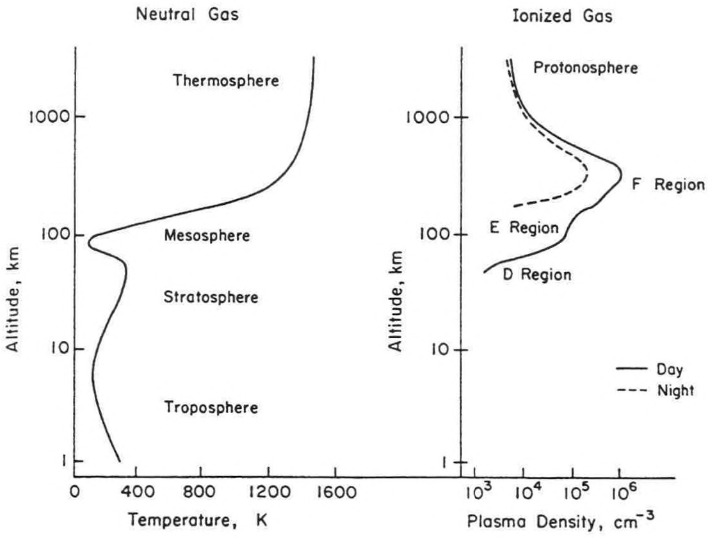

Figure 1.

We will concentrate on the F region of the ionosphere in this work since it contains the bulk of the plasma and hence has the most effect on communication systems. For more information on the other altitude zones, the reader is also referred to articles [1-2] (which considerably overlap the present work), and a textbook dealing in much more detail with the plasma physics and electrodynamics in the Earth's ionosphere [3].

At low to middle latitudes the plasma source is the high-energy portion of the sun's spectrum, which ionizes the upper atmosphere. The flux of such high-energy photons is solar-cycle dependent and at any given location, depends on season and latitude. If these were the only important factors, ionospheric weather would be quite boring. But just as in meteorology, dynamical factors are very important at all latitudes and the resulting weather is very complex. To further complicate matters, additional sources of plasma exist at high latitudes due to ionizing effects of energetic electrons and ions in the aurora.

In this work we concentrate primarily on ionospheric weather caused by dynamical factors.

II. SOURCES OF IONOSPHERIC DYNAMICS

A. Low- and Midlatitude Dynamics

The ionosphere is somewhat of a battleground between the earth's neutral atmosphere from below and the earth's magnetosphere and the sun's atmosphere from above. Below a certain latitude, the neutral atmosphere plays a dominant dynamical role, and is the source of the electric field (**E**), which controls many aspects of ionospheric plasma processes. The geometry of the earth's magnetic field (**B**) controls the manner by which the neutrals control the plasma. Parallel to **B**, the neutral wind (**U**) easily pushes plasma hither and yon, but how does it affect plasma motion across the magnetic field? Although the plasma bulk motion cannot directly follow the neutral across the magnetic field, there is a small current generated in that plane, which is given by

$$\mathbf{J} = \sigma \cdot (\mathbf{UxB}) \tag{1}$$

where σ is the conductivity sensor. In a steady state the charge continuity equation dictates that $\nabla \cdot \mathbf{J} = 0$, so if either σ or **U** vary in space, an electric field must build up such that

$$\mathbf{J} = \sigma \cdot (\mathbf{E} + \mathbf{UxB}) \tag{2}$$

is divergence free. The electric field that results can cause plasma motion across the magnetic field via the so-called **ExB** drift,

$$0 = \mathbf{E} + \mathbf{UxB} \tag{3}$$

Thus, irregular horizontal flow is equivalent to horizontal variations in the electric field, and taken along with the neutral wind component along **B**, the dynamics can be described.

Now σ and **U** both display variations on scales ranging from planetary down to sub-kilometer wavelengths, and it is no surprise then that electric fields also exhibit such variations. Atmospheric tides and gravity waves propagate upward from the stratosphere and troposphere, growing as they progress through the exponentially decreasing atmospheric density. The finite vertical and horizontal wave number of these waves is associated with non-divergent current and electric fields on the same scale. In turn, more structure in the ionosphere is created by the wind and electric field patterns. In some regions these winds and electric field patterns create or seed conditions for plasma instabilities, which create electric fields and then in turn create smaller scale structure.

Such processes dominate the low-latitude region and contribute as well to high-latitude dynamics. However, two major factors limit the importance of the neutral atmosphere in this latter region. First, **B** is nearly vertical. This means that the divergence of the current in Equation 1 is associated with horizontal **k** values that tend to be smaller than the vertical wave number. More importantly, the neutrals begin to lose control of the electrodynamics. To understand where this transition occurs we must realize that to zeroeth order the neutral gas rotates with the earth. Ignoring all other dynamical effects for now, if the ionosphere did not also corotate, a large current would flow which, through **JxB** forcing, would eventually create a force-free state and a co-rotating ionosphere in which **J**=0. The electric field, which builds up to create the **J**=0 condition, may be determined as follows. Since **J** and **B** are independent of reference frame for small velocities, we can investigate the non-rotating, sun-fixed coordinate system in which $\mathbf{U}=\mathbf{U}_E$, the rotation velocity of the earth. In that frame, **J**=0 implies

$$\frac{\mathbf{ExB}}{B^2} = \left(\mathbf{U}_E\right)_\perp \qquad (4)$$

In this frame, then, the plasma moves in the plane perpendicular to **B** with a velocity $\mathbf{ExB}/\mathrm{B}^2 = (\mathbf{U}_e)_\perp$. Now since the magnetosphere is full of plasma, this electric field maps along the magnetic field and causes the entire inner magnetosphere to corotate as well.

The transition between control of the ionosphere by the rotation of the atmosphere and control by external processes occurs when the electric field in a sun-fixed coordinate system is larger than the corotation electric field due to magnetospheric and solar wind effects. The magnitude of the electric field in this coordinate system, after projection to the equatorial plane, is plotted in Figure 2 [4].

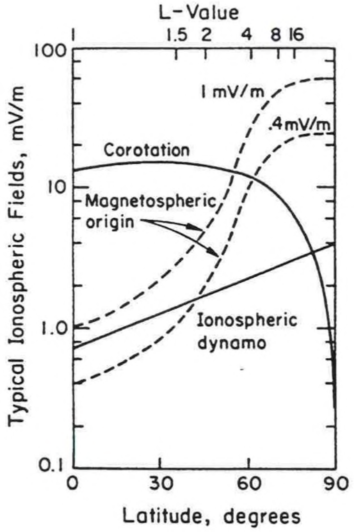

Figure 2.

The transition between high- and low-latitude zones occurs where this corotation field becomes smaller than the field impressed upon the magnetosphere from "outside", that is, from the solar wind. On average, this occurs at a latitude of 60°. In a dipole magnetic field, the field lines at 60° cross the equatorial plane at a distance of 4 earth radii (R_e) from the center of the earth. So, within 4 R_e, the plasma in the inner magnetosphere to first order rotates with the earth. Figure 3 shows a cut-away view of the earth's magnetosphere, illustrating the corotating portion of the system as a torus-like feature near the earth.

A given magnetic flux tube in this inner zone thus has both feet in the ionosphere and is filled during the daytime with plasma from the photoionization source in the ionosphere. Above this latitude the flux tubes have much more complex trajectories, trajectories determined by "weather" in the magnetosphere and the solar wind. There are discernible patterns in the high-latitude flow, just as there are discernible patterns in a rushing mountain stream, but the variability is much more pronounced than it is at low latitude.

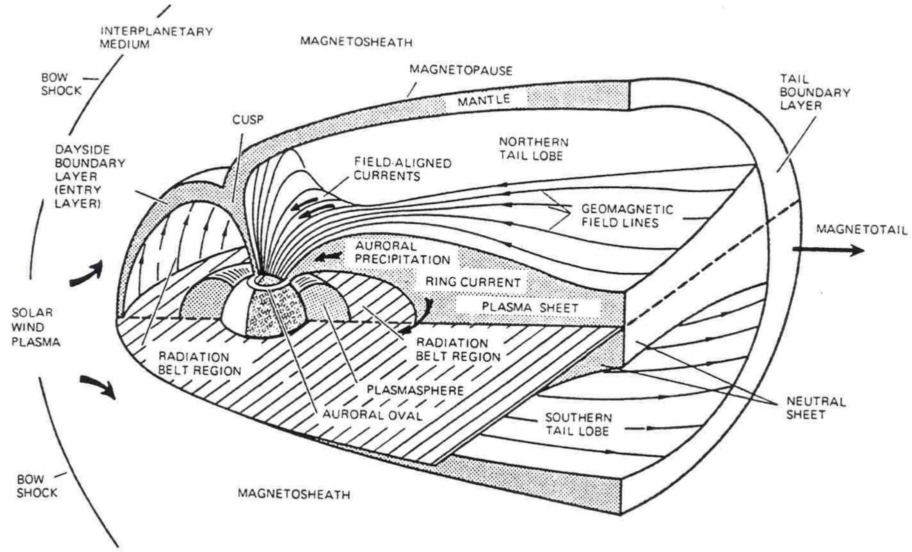

Figure 3.

Our purpose here is an attempt to make some order out of the chaos in ionospheric structure. The study is organized by scale size. These are made up purely at the whim of the author and are subject to legitimate debate. Their main purpose is to give a framework about which to organize the problem.

III. WEATHER AT PLANETARY SCALES ($\lambda > 600$ km)

Low Latitude Phenomena. The major feature on a planetary scale affecting this latitude zone is the solar terminator. Data showing this effect of sunset and sunrise on the ionosphere are shown in Figure 4 [5]. Here the plasma density is shown as a function of height over the Arecibo Observatory from just before sunset until just after sunrise. The dominant feature is that the lower portion of the ionosphere disappears rapidly after sunset, but the main F layer lasts all night. Since most of the ionospheric conductivity is in this lower portion of the plasma profile, the electrodynamics change drastically between day and night. In fact, the control over the electric field shifts from the winds and tides in the daytime E region to a combination of E- and F-region dynamos.

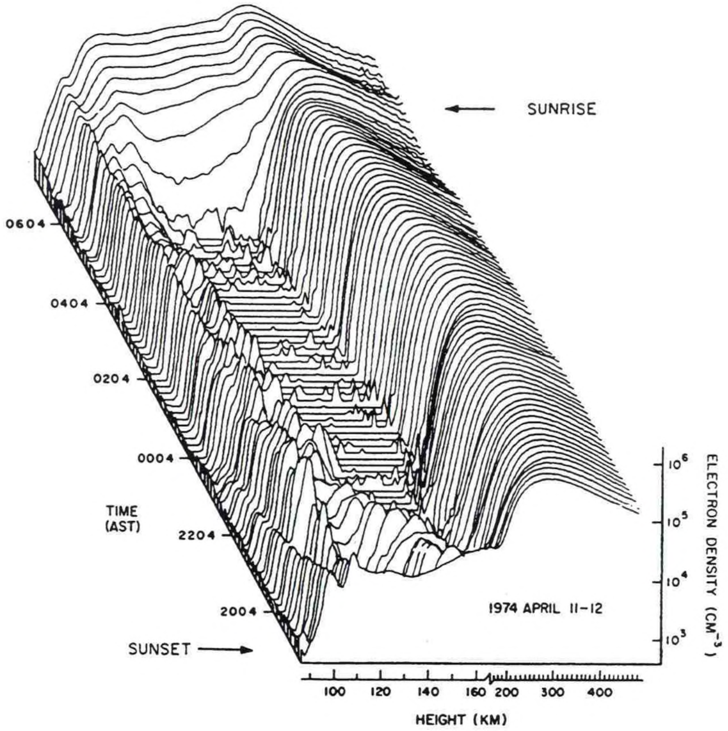

Figure 4.

Another large-scale feature is illustrated in Figure 5 (courtesy of J.D. Craven, L.A. Frank, and R.L. Rairden), a view of the earth using airglow emissions. On either side of the magnetic equator two bands of light are seen that are due to two roughly symmetrical regions of high electron density caused by the equatorial fountain effect. In this process, plasma is lifted high above the magnetic equator by the electric field, which is eastward (upward **ExB** drift) during the day. The fountain effect is illustrated in Figure 6 (courtesy of E. Weber). The largest total electron content (TEC) encountered by trans-ionospheric radio signals occurs in this portion of the planet. Likewise, when severe mesoscale weather erupts here (see below), the largest signal scintillation also occurs in this zone. Even gigahertz frequency systems suffer over 20-db signal fades in such events.

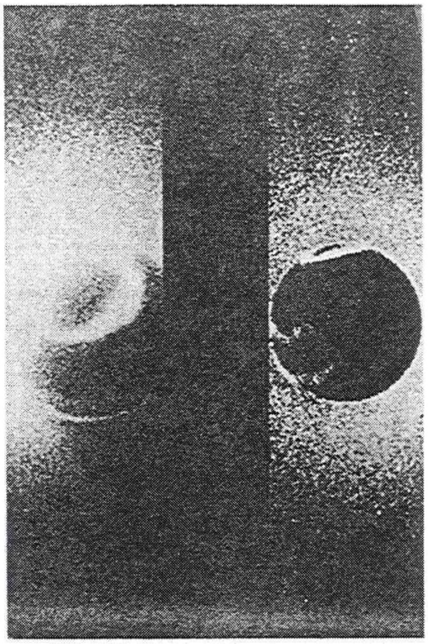

Figure 5.

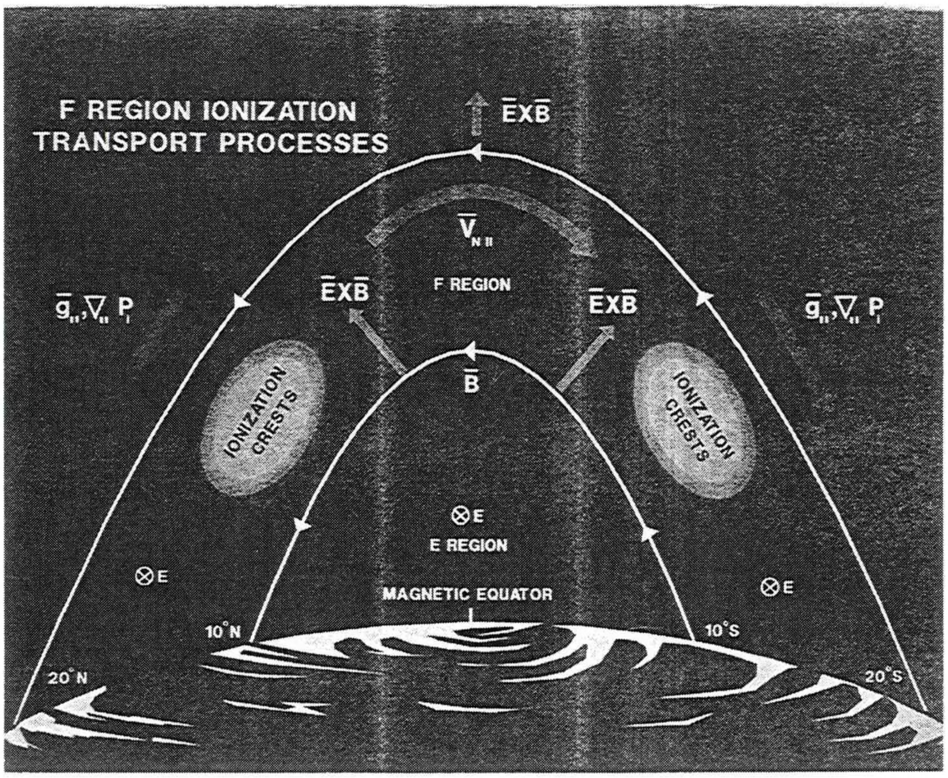

Figure 6.

Another planetary scale feature is caused by the pre-reversal enhancement of the eastward electric field near the dusk terminator. This feature is roughly one hour in duration and, since it rotates with the planet, is about 1500 km in size. Its importance stems from the fact that it throws the main ionosphere to extremely high altitudes at the exact time when sunset removes the E-region conductivity. All of a sudden the "conducting end plates" of this plasma machine in the sky are removed. With the end plates no longer present to short out perturbation electric fields, the plasma instabilities discussed below can erupt.

As can be seen by the previous discussion, a huge factor in the day-to-day variability of low-latitude space weather is the character of the eastward electric field during the day and just at the terminator. The variability of this component can be seen in Figure 7, which is a multi-day plot of this parameter as measured at the Jicamarca (Peru) Radio Observatory. The magnitude and duration of the bump in the eastward electric field (vertical plasma drift) each vary by a factor of 2 or more, giving more than a factor of 4 in the ionospheric uplift. The single most important dynamical measurement needed to allow for prediction of space weather in this zone is the zonal electric field, which could be provided by a small number of low-altitude satellites with appropriate instrumentation.

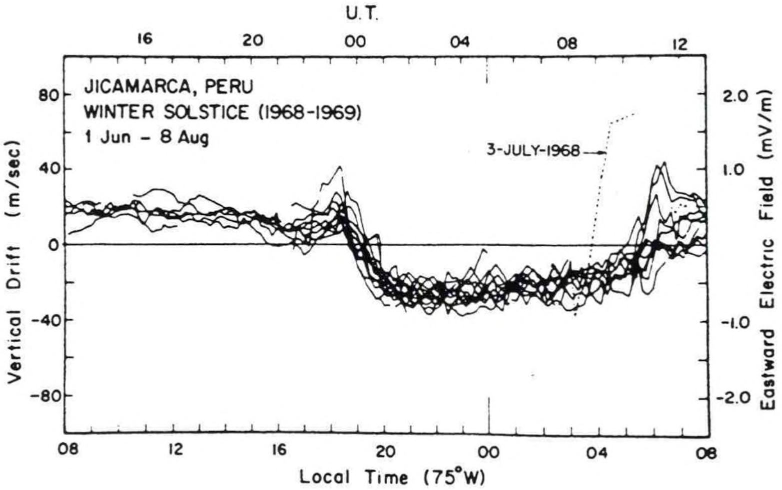

Figure 7.

Notice also the anomalous reversal of the westward electric field on July 3, 1968. This type of event is associated with the transient penetration of high-latitude electric fields during rapid changes in the latter [6,7]. The most spectacular event of this type ever seen is illustrated in Figure

8. Here the entire ionosphere from Peru to India to Alaska oscillated with a one-hour period driven by similar fluctuations in the interplanetary magnetic field! This is not just planetary scale, but solar-system scale variability. When an uplift occurs after midnight (such as happened on July 3, 1968), severe weather can occur, as it often does in the post-sunset region. Even though most of the low- to mid-latitude weather is independent of high-latitude phenomena, there is the occasional event triggered by the penetrating electric fields described above. Occasionally, high-latitude thermospheric heating can be so extreme during magnetic storms and substorms that the entire global wind pattern is changed. Disturbance dynamo electric fields then occur and naturally affect the evolution of the entire ionosphere on a global scale.

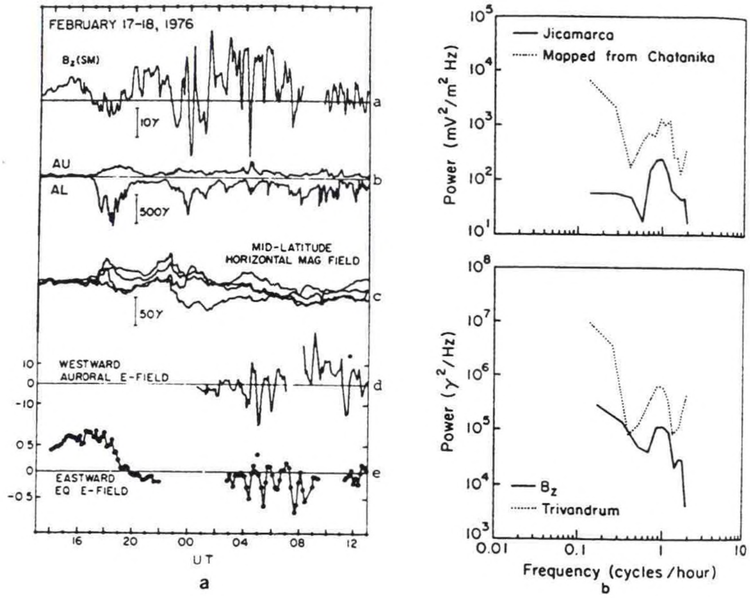

Figure 8.

High Latitude Phenomena. The velocity field applied to the ionosphere from the solar wind-magnetosphere interaction has a number of discernible patterns at planetary scales. However, which of these patterns applies at a given time is highly dependent upon conditions in the interplanetary medium. The most crucial parameter is the sign of the north-south component (B_z) of the interplanetary magnetic field (IMF). When the IMF is southward for any extended time (e.g., tens of minutes), the classic two-celled convection pattern is imposed upon the ionosphere. Figure 9 (courtesy of R.A. Heelis and W.B. Hanson) shows measurements of the ionospheric drift velocity in the northern hemisphere for two satellite passes when the IMF was southward.

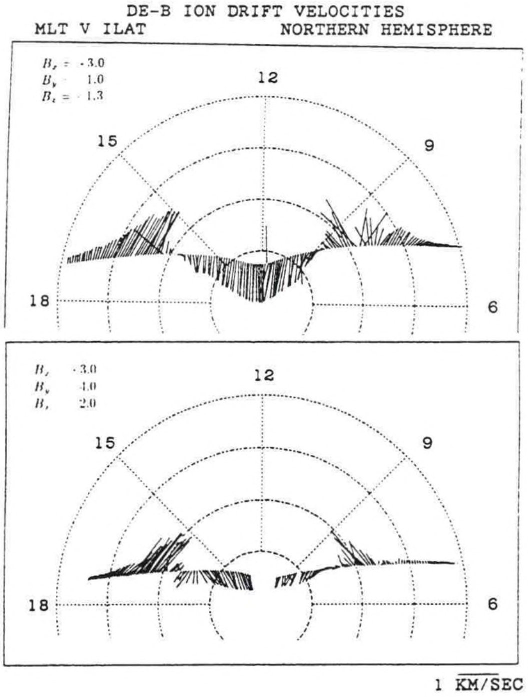

Figure 9.

The flow often exceeds 1 km/s, which is about the sound speed in the thermosphere. The pattern is fixed with respect to the sun and the earth rotates underneath it. To first order, the flow is antisunward in the polar cap and sunward in the auroral zone. The polar cap component of this flow can be understood from the cartoon in Figure 10. Here the polar cap magnetic field lines are shown connected to the IMF. Like conducting wires, the interplanetary electric field is then impressed upon the ionosphere in the dawn-to-dusk direction for a southward IMF. Up to several-hundred kilovolts can be tapped in this manner. The system is something of a half-wave rectifier, though, since when the IMF is northward the magnetic field connection cannot occur and the entire solar wind ionospheric interaction decreases and shrinks in scale on the planet. This solar wind control of the ionospheric flow pattern and the space weather it generates is the primary variability factor, which we need to measure for predictive capability. Measurements of the solar wind parameters well out in front of the earth are needed as, of course, are optical observations of the solar disk and corona.

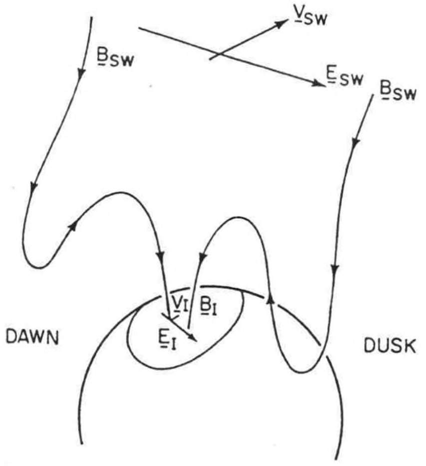

Figure 10.

For steady B_z south, the two-cell ionospheric flow pattern is more or less fixed with respect to the sun-earth line. The earth and its neutral atmosphere rotate under this plasma flow pattern once a day (ignoring acceleration of the neutrals by the plasma!). This creates a planetary scale, diurnally varying plasma flow field in the ionosphere. Now even with B_z held south, the classic symmetric two-cell flow shifts with respect to the sun-earth line as other components of the IMF vary (particularly the component parallel to the earth's orbit, B_y). This shifting of the flow field can occur within one or two Alfvén travel times from ionospheric altitudes to the generator. Likewise as B_z and the velocity of the solar wind change, the rate of energy transfer to the magnetosphere varies from minute to minute and a flow field that is highly variable in space and time results.

When B_z changes sign to northward the major source of energy transfer ceases, but other effects take over. A viscous interaction seems to create a small two-cell pattern, and the connection of field lines to the IMF in regions of the magnetosphere far from the ecliptic plane also creates multiple cells with planetary scales, although much reduced in size.

To gauge the effect of these complex flow fields on plasma content, we first need to discuss the processes that create and destroy plasma on planetary scales. The most important source is photoionization by sunlight. In a nonrotating frame this region is bounded by the terminator, which moves across the polar region on a seasonal basis. On the dark side of this line, recombination rapidly destroys plasma below 200 km, but only erodes the F-peak region very slowly. The time constant is roughly one hour at 300 km.

Now when the planetary scale flow is imposed on this source and loss pattern, it is clear that solar plasma can be transported for vast distances into and clear through regions of total darkness before recombination can play much of a role. In this way planetary scale structuring of the plasma occurs that is much more complex and interesting than the simple terminator effect would have been. Large-scale plasma bergs break off the dayside and are convected across the polar cap, creating conditions for severe scintillations much like those in the low-latitude anomaly zone.

A more subtle process can create planetary scale depletions of plasma as well [8]. Since the dipole magnetic axis of the earth is offset by 11° from the rotation axis and the plasma flow is organized by the magnetic geometry, in the winter time some convection patterns have flux tubes that are never illuminated by sunlight. Then very deep plasma depletions can occur due to recombination, yielding peak plasma densities as low as 10^2 cm^{-3} with He^+ the dominant ion.

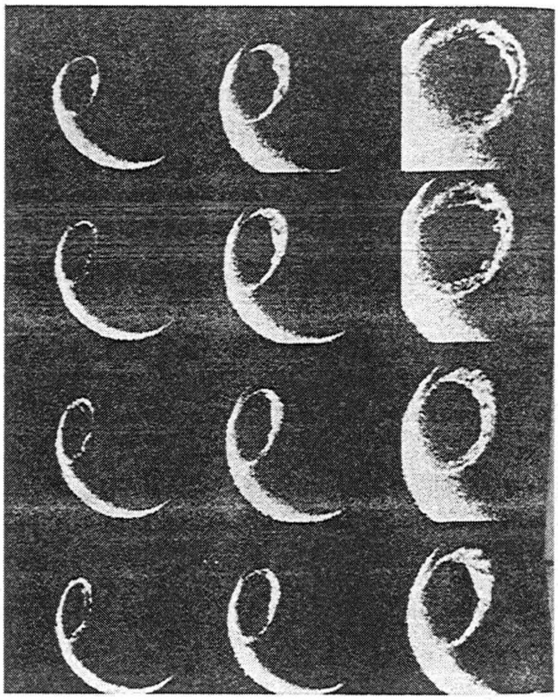

Figure 11.

The two-cell convection pattern is associated with another planetary scale plasma source: impact ionization by particle precipitation in the auroral oval. A view from high above the earth, reproduced in Figure 11 (courtesy of L.A. Frank, J.D. Craven, and R.L. Rairden), shows some of this complexity. From a visual perspective this band of light around the polar region expands and thickens with increasing B_z south and shrinks when B_z is northward. Much of the plasma in this oval is created so low in the atmosphere (≤ 200 km) that it is short-lived. Nonetheless, the lowest energy-precipitating particles produce plasma high enough in altitude to create an important F-layer plasma source, particularly in winter.

Figure 12.

When the oval shrinks during northward IMF a remarkable auroral feature sometimes splits the oval with a sun-aligned auroral arc as shown in Figure 12 (courtesy of L.A. Frank, J.D. Craven, and R.L. Rairden). From space the resulting emissions look like a theta, a theta aurora. This and other sub-visual sun-aligned auroral arcs create F-layer plasma in the winter ionosphere as well. The plasma content near such an arc is very complex. In rocket overflights of a sun-aligned arc, the plasma density and electric fields are seen to change drastically on either side of the arc [9]. The plasma had clearly come from two very different sources on either side of the arc.

B. Mesoscale Weather (1 km $\leq \lambda \leq$ 600 km)

Low-Latitude Phenomena. A composite spectrum assembled from satellite measurements during the most severe low-latitude space weather is presented in Figure 13 [10]. At even smaller scales, rocket data show that the spectrum drops off dramatically for $\lambda \leq 50$ m. This phenomenon is termed equatorial spread F from its appearance on ionograms in the 1930s and the name has stuck. The field spectrum covers 5^+ orders of magnitude in scale and many more orders of magnitude in spectral density. A peak occurs in the several-hundred kilometer range with monotonically decreasing spectral density at smaller scales. The integral over this spectrum is the order of 90% so it truly represents severe weather. The plasma density can drop, for example, by three orders of magnitude in a few kilometers across the satellite track. Such depletions, when detected between sunset and midnight, are almost always accompanied by rapid upward convection and turbulence just like a thunderstorm. Indeed, the case can be made that this type of space weather is an ionospheric thunderstorm. Potentials as high as several kilovolts accompany the events, but no lightning is observed!

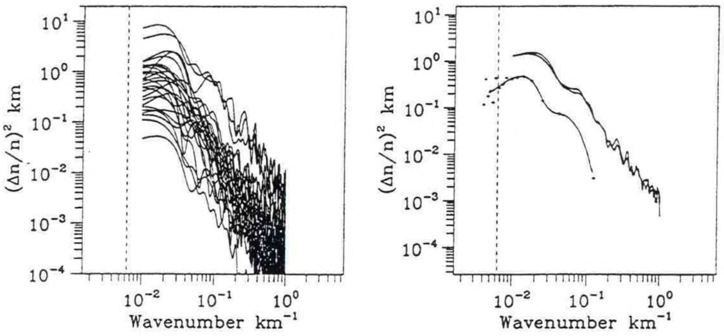

Figure 13.

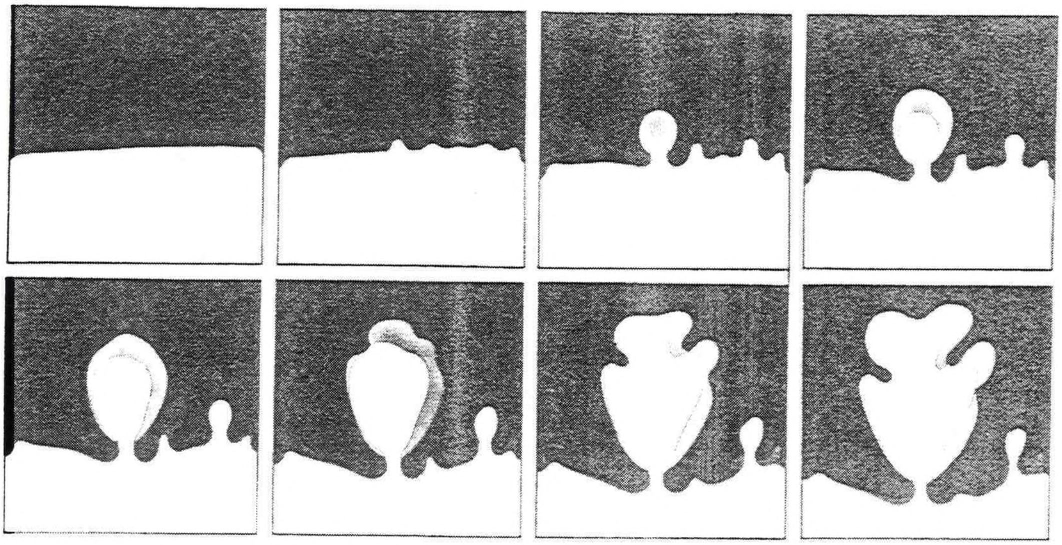

Figure 14a.

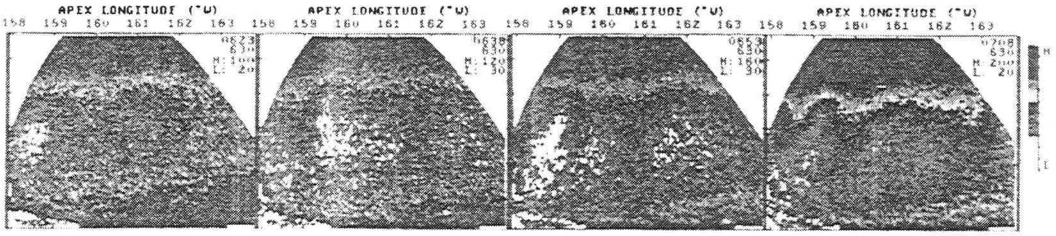

Figure 14b.

Figures 14a,b illustrate how these ionospheric thunderstorms occur. The former shows sequential photographs of a child's toy that uses the hydrodynamical Rayleigh-Taylor instability. When the device is flipped over, the heavy fluid is suddenly on top and in an unstable equilibrium. Small perturbations soon develop and grow into large ones, which cause the two fluids to interchange. The other photo is an edge on view of the equatorial ionosphere taken from Hawaii [11]. Very analogously, the bottom of the F layer is seen to start rippling as the gravitational energy of the levitated ionosphere is released.

Once the Rayleigh-Taylor process begins it has a high growth rate over a vast range of scales. This is one reason the spectrum shown above extends for such a range of scales. But there are also nonlinear phenomena that link energy between scales just as occurs in neutral turbulence. Fortunately, the structure extends even to the meter scale, allowing us to detect the phenomenon with backscatter radars. One of the more spectacular events captured over Peru by the Jicamarca Radar (50 MHz) is presented in Figure 15 (courtesy of B. Tinsley). Here not only the large-scale undulation is seen, but finer-scale periodic oscillations with a vertical wavelength of about 50 km are seen.

The horizontal oscillations are several-hundred kilometers across and one is forced to wonder how they begin, to wonder what the source is of the initial ripple that grows into a towering plume, sometimes exceeding a thousand kilometers in altitude. Of course, plasma instabilities like the Rayleigh-Taylor process can grow from thermal noise, but many people think that the geophysical noise is larger than the thermal noise at such scales and dominates the initial phase. A candidate for this geophysical noise comes from the atmospheric waves bombarding the ionosphere from below.

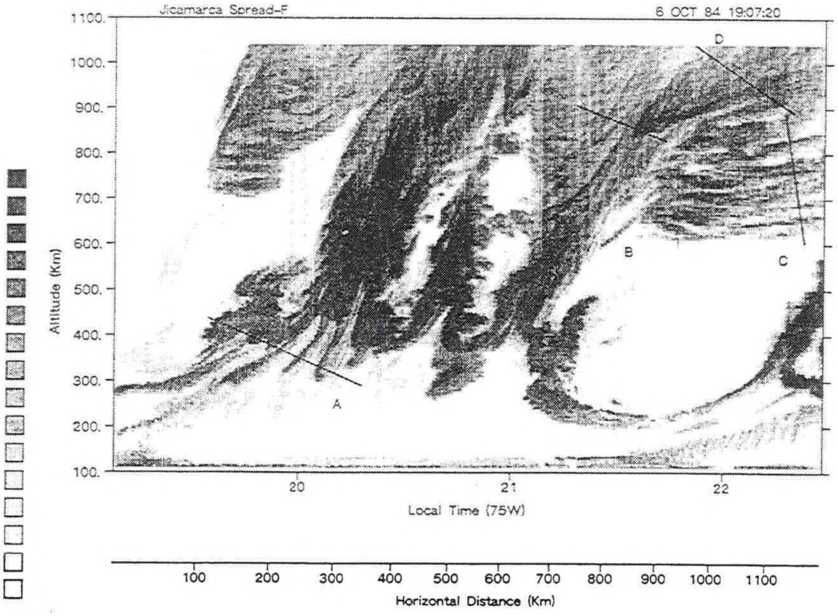

Figure 15.

Hines [12] provided a mathematical framework for the study of these waves by considering small changes in five quantities: pressure (p), temperature (T), density (ρ), horizontal velocity (v), and vertical velocity (w). Solving this problem thus requires five equations, which he accomplished by using two components of the momentum equation, the energy equation, the continuation, and the equation of state for the gas. The first four equations correspond, respectively, to the principles of momentum, energy, and mass conservation. Hines searched for solutions corresponding to a plane wave solution. Among the many interesting properties, two stand out:

1. The amplitudes of the pressure, density, temperature and velocity all increase with altitude (just as the observational evidence in Figure 16 suggests). But since the kinetic energy per unit volume is $(1/2)\rho_o(v^2 + w^2)$, how can the solution satisfy conservation of energy if v and w are increasing drastically with height? The answer to this riddle is that the kinetic energy of the wave is more precisely $(1/2)\rho_o(z)[v^2(z) + w^2(z)]$, that is, as ρ_o decreases exponentially with height in a planetary atmosphere, $(v^2 + w^2)$ must *increase* in order to conserve energy. So rather than defying this law, the increasing wave amplitude is necessary to satisfy it. In fact, all the perturbation quantities vary as

$$\sim e^{+z/2H}$$

where H is the scale height of the atmosphere (H ~ 7 to 156 km below about 200 km and grows to 50 km at the top of the thermosphere). Thus, as the background density decreases by a factor of about 3, every scale height (v^2 + w^2) must increase by a factor of 3 just to compensate.

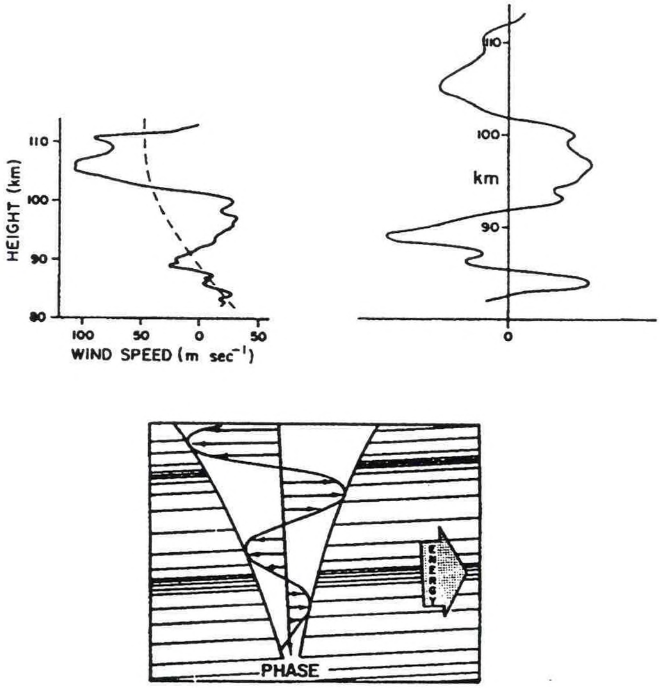

Figure 16.

2. Another curious property of these waves is that as the energy propagates upward, the crests and troughs of the waves move downward (see Figure 17). Again, this was observed in the data and provided clear support of Hines' theory. For example, electrons and ions in the ionosphere can be pushed around easily by the wind. They all slosh back and forth like sand and small organisms in the surge of an ocean wave along the sea floor. This organization of the electrons makes the waves observable by radar as shown in the Arecibo data in Figure 17. The downward slant of the oscillations is unmistakable [13]. The waves only seem to be coming down, since the energy is going upward just as Hines predicted.

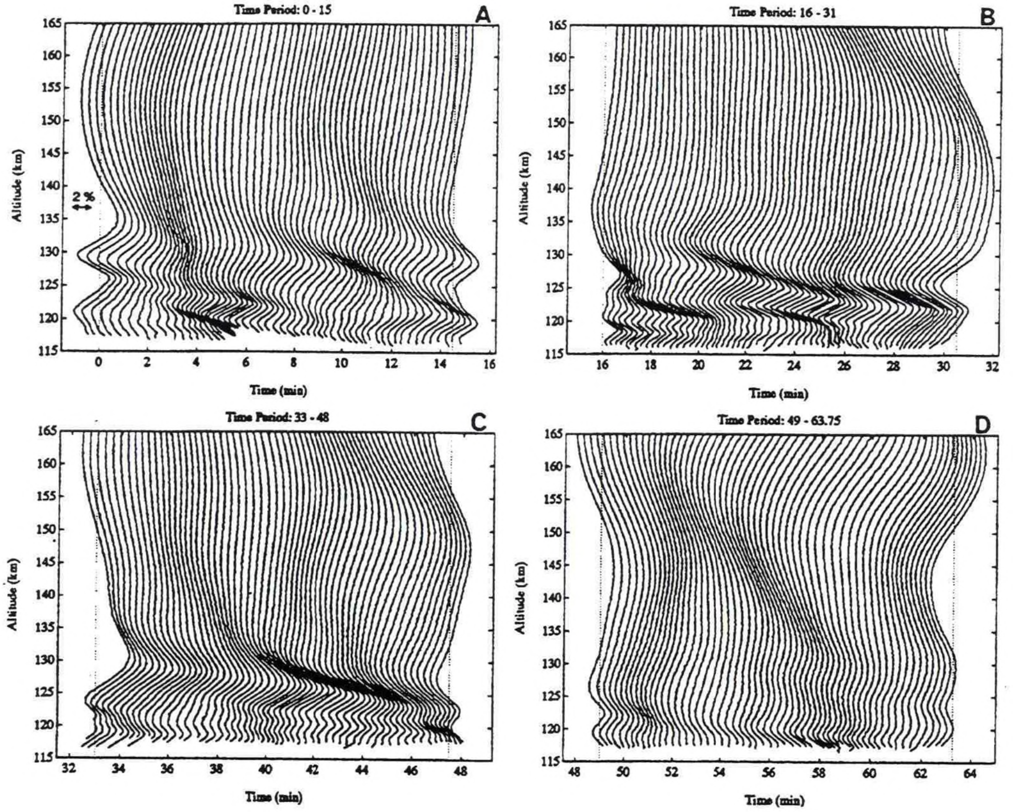

Figure 17.

A computer simulation showing how a gravity wave-induced neutral wind could create the periodic convection storms is presented in Figure 18a [14]. Here we see periodic structures at both the original scale and a smaller scale on just one side of the original perturbation. Such features are observed in nature as shown in Figure 18b.

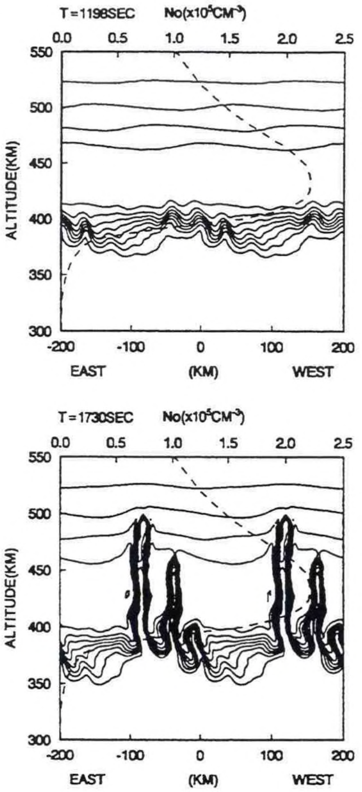

Figure 18a.

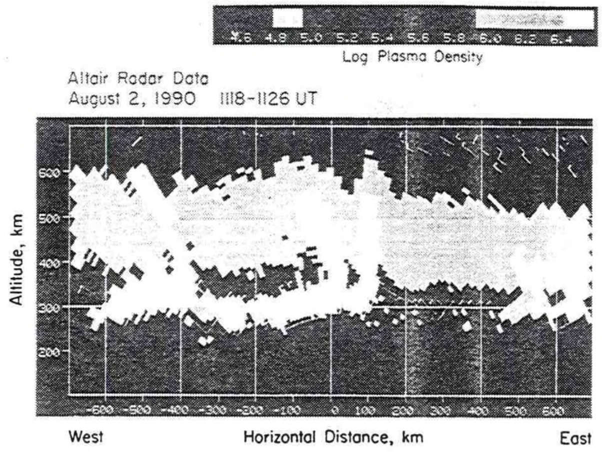

Figure 18b.

Recent measurements at Arecibo and Jicamarca have revealed for the first time the periodic electric fields associated with gravity waves in the ionosphere, both at equatorial latitudes and in the tropical zone. In the latter case these electric fields are thought to seed the so-called Perkins

Instability, which operates in regions with a finite magnetic dip angle. Figure 18 above (18b courtesy of Roland Tsunoda) shows how the nighttime ionosphere can undulate with a few-hour period typical of internal waves. Shorter period waves can be observed with modern CCD cameras using the 630 nm emission. An example from January of this year over Arecibo is presented in Figure 19 and shows a packet of undulations moving across the field of view with a phase velocity of 58 m/s and a horizontal wavelength of 105 km. This corresponds to a period in the earth frame of about 30 minutes.

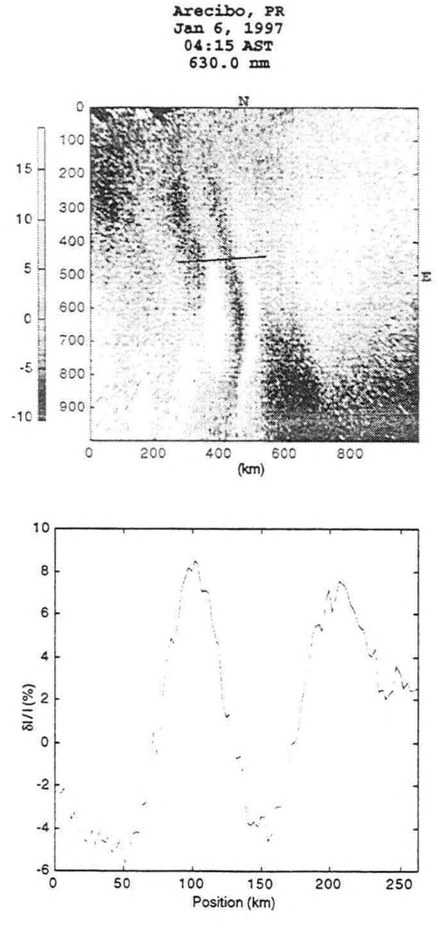

Figure 19.

These mid-latitude structures apparently become quite violent at times, but by far the most important space weather effect, even in the tropics, is the equatorial process. This holds since as the towering plumes extend to high altitudes, the magnetic field lines link to higher and higher latitudes. Thus, vast wedges of rapidly moving turbulent plasma are present, even in the anomaly zone at times where the plasma density is the highest. When satellite-based signals traverse this region the total electron content fluctuations are the most extreme on the planet.

High Latitude Phenomena. At these scales, diffusion of plasma across **B** is extremely slow, so if a structure forms it can be transported for vast distances by the flow field. Now both solar and particle precipitation sources on planetary scales (see Figure 11) are subject to a flow field that is highly variable in space and time due to the influence of weather on the solar wind, the sporadic nature of substorm activity in the inner magnetosphere, and even to "quiet" auroral arcs (which are only "quiet" when compared to a break-up aurora). (A substorm is an explosive release of energy stored in the non-dipolar configuration of the distorted magnetosphere, which often appears to "break up" existing quiet auroral arcs.) An example of the distortion of an initially circular plasma blob by even a steady flow field is given in Figure 20 [15]. If time variations are added, the distortion will just get worse.

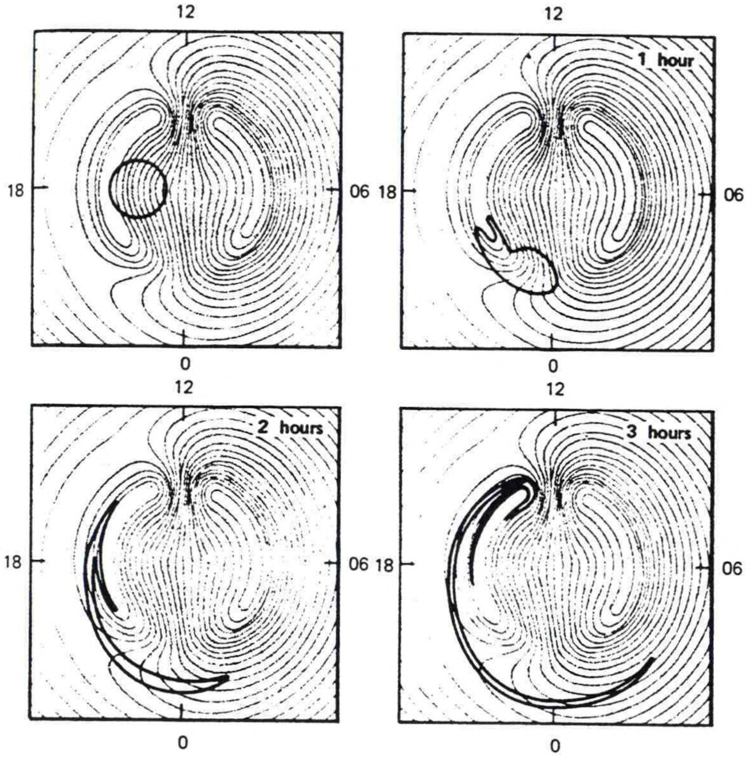

Figure 20.

Figure 21.

To first order, the velocity field at scales below "planetary" displays a power law, spatial spectrum with an index between -1.5 and -2.5. Structure thus exists at all scales, which mixes any gradient in the plasma density and creates a mirror image in the plasma structure. A view of the aurora from above in Figure 21 [3] shows just how dynamical the light patterns are, patterns that mirror both the production of plasma and the velocity fields around the precipitation zones. The irregular plasma is then swept along with the mean flow. A classic example occurs in the polar cap where, for B_z south, large patches (500-1000 km) break off the dayside solar-produced, high-latitude plasma and, like icebergs, drift across the polar sky [16]. Similarly, in the midnight sector (as shown in Figure 22), large blobs of plasma are seen to move through the field-of-view of an incoherent scatter radar, particularly, it seems, near solar maximum. These blobs may be due to soft (low-energy) electron precipitation [17].

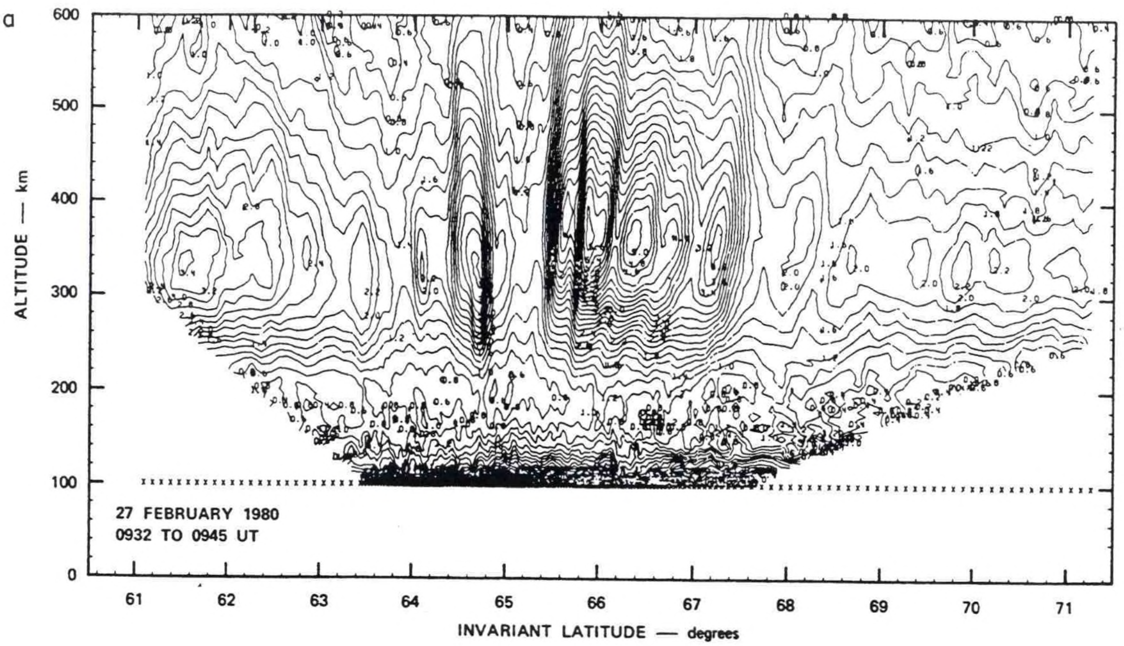

Figure 22.

In addition to turbulent mixing at large scales, there are boundary phenomena at both edges of the auroral oval, creating large-scale undulations and patches of auroral light visible from space. Observers [18] have reported a variety of undulations and cusp-like features on the equatorward side of the auroral oval with scale sizes in the 400 km range. A magnetospheric Kelven-Helmholtz instability has been suggested [19], citing numerous satellite observations of large velocity shears in that region, including several within an hour or so of DMSP photographs of undulations.

The aforementioned radar/optical study also experimentally showed a strong anti-correlation between F-region plasma density and very strong electric fields at the equatorward edge of the diffuse aurora. Even during relatively quiet periods, such a depletion or plasma trough occurs for reasons similar to the polar hole discussed above. Since the earth rotates eastward in the sun-flexed frame, any plasma driven westward in the earth-fixed frame at the same velocity (≈ 217 m/s at 60° latitude) will be stationary in solar coordinates. Low-latitude electrodynamics are such that plasma flows eastward in the dusk-to-midnight period while high-latitude electrodynamics dictate a westward flow. So, at some latitude the magic velocity must exist and the plasma will be stationary and hence always in darkness [20]. In such a case, recombination proceeds at will and a trough develops. An example of the evolution of the plasma density in time and space near the edge of the auroral oval is given in Figure 23 [21]. The trough is seen as a density depletion at a range of -100 on the plot (seen most clearly in the bottom left-hand panel). It persists even after the aurorally produced plasma at about 100 km withdraws to the north.

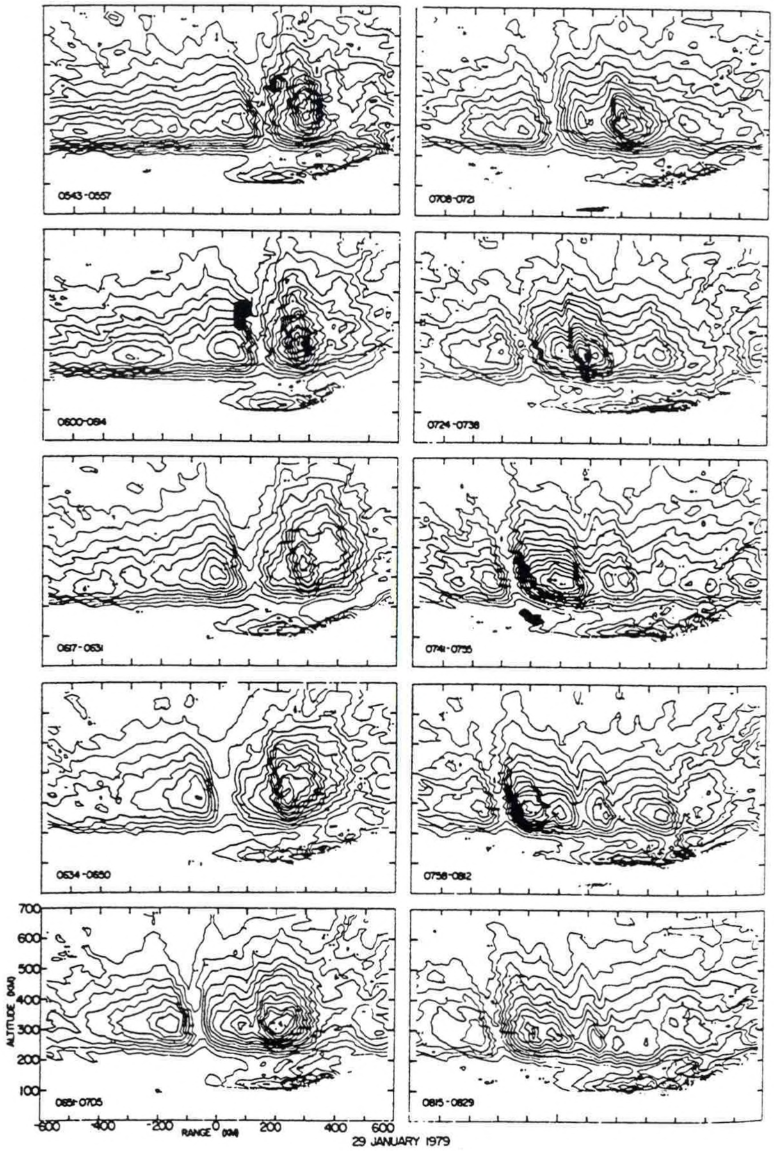

Figure 23.

During magnetic storms, however, another effect enhances trough development when very large ionospheric electric fields develop at the edge of the diffuse aurora [22]. Then recombination is greatly enhanced due to the large differential velocity between the plasma and the neutral gas since the ion chemical reaction is highly velocity dependent [23]. A remarkable anticorrelation exists between the flow velocity and the plasma density. The depletion rate reported in the latter reference is even higher than the present theory predicts. This region still has many secrets to pursue due to the competing influences of the magnetosphere, ionosphere, and atmosphere.

Such localized regions of low-plasma density, of course, are just as important as plasma enhancements in the structuring of high latitudes at large scales. Since large localized electric fields certainly occur at high latitudes, depletion regions must be present, not only in the trough, but elsewhere as well.

Another important high-latitude effect is the structured precipitation of soft electrons. It has long been thought that in the F region, horizontal structuring was not likely caused by this source due to the low altitude of the peak in production rate, even for soft particles. However, rocket experiments in the dayside oval seem to have settled the matter on the side of particle precipitation as a valid F-region source [24]. In the dayside oval at least, the rocket data indicate enhancements in the range of 20 - 50 km and must be associated with precipitation sources that are steady and co-moving with the ionospheric plasma for several minutes.

The horizontal gradients in plasma density associated with particle precipitation discussed above will have Fourier components at much smaller scales. In fact, since a steep edge has a k spectrum with a power law with negative index equal to 2, these structures *could* be responsible for the common observations of such power laws using rocket and satellite density probes.

The fact of the matter is that auroral arcs are inextricably intertwined with structured electric fields. At the altitude of the auroral acceleration zone (≈ 3-5000 km) in fact, the electric field is turbulent in a much larger region than that of the electron beams themselves. The acceleration zone is embedded in this turbulent plasma, which only partially extends to ionospheric heights [25]. It seems clear that any ionospheric plasma gradient *must* be mixed by those applied turbulent electric fields.

The reader may have noticed that not a single *ionospheric* plasma instability has yet been mentioned. Local plasma instabilities of the interchange type (e.g., the **ExB** process) do occur in the high latitude sector and striking examples have been presented [26]. The key to identifying these events is to show cases when only one side of a plasma blob is unstable since that is the production of the theory. Indeed, such cases have been found that are very similar in appearance to rocket data during equatorial spread F (if one turns his or her head sidewise, that is).

One cannot conclude from such examples, however, that the **ExB** instability controls high-latitude ionospheric irregularity production since numerous examples of structuring on all manner of gradient directions exist in the literature. The vertical magnetic field reduces the importance of ionospheric interchange instabilities. Due to diffusion and gravity, the F-layer plasma is not very extended along **B**. This means that the field line-integrated Pedersen conductivity is not very large. At the magnetic equator, the field lines are nearly horizontal, very long, and characterized by very large conductivities. This feature is also true of large artificial plasma clouds. Both of these latter plasmas therefore have a low internal resistance, low enough at night to support electrostatic interchange instabilities against "end plate shorting" of electric field perturbations by the E region.

C. Conclusion

Space weather is alive and well in the earth's ionosphere and its full explanation will keep researchers busy for years to come. Nonetheless, we now have the basic ideas worked out. Our next tasks are (1) to apply computational methods in beginning to test predictive models and (2) to validate/test these models with targeted experimental approaches.

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2.3 An Overview of GPS

Keith McDonald

An Overview of GPS

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National Science Foundation
National Oceanic and Atmospheric Administration
Air Force Phillips Laboratory
Office of Naval Research

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Abstract

OVERVIEW OF GPS

Keith D. McDonald
Sat Tech Systems
Alexandria, VA

This presentation addresses the basic elements of the Global Positioning System (GPS), including its orbital configuration, the ground control segment, the user equipment, and the signal structure. A brief introduction is given of the military and civil performance capabilities of GPS with an indication of the current status and future growth projections for the system. The receiver processing of the GPS signals is described including a perspective of the position, velocity, and time solutions obtained by processing the pseudorandom noise (PRN) coded signals. Techniques are also addressed for obtaining increased precision by the use of both differential measurements of the code and similar measurements of the relative phase of the received carrier. The errors affecting GPS are briefly described, especially the propagation errors associated with the troposphere and the ionosphere. The performance and applications of GPS are reviewed showing the extensive range of capabilities inherent in the system.

An Overview of GPS

Outline

Basic Elements of GPS
- Space Segment
- Control Segment
- User Segment

GPS Signals and Solutions
- Signasl and signal structure
- Pseudoranging, correlation processing
- Navigation solution
- Velocity solution

GPS Operational Modes
- Autonomous
- Differential code
- Differential carrier phase

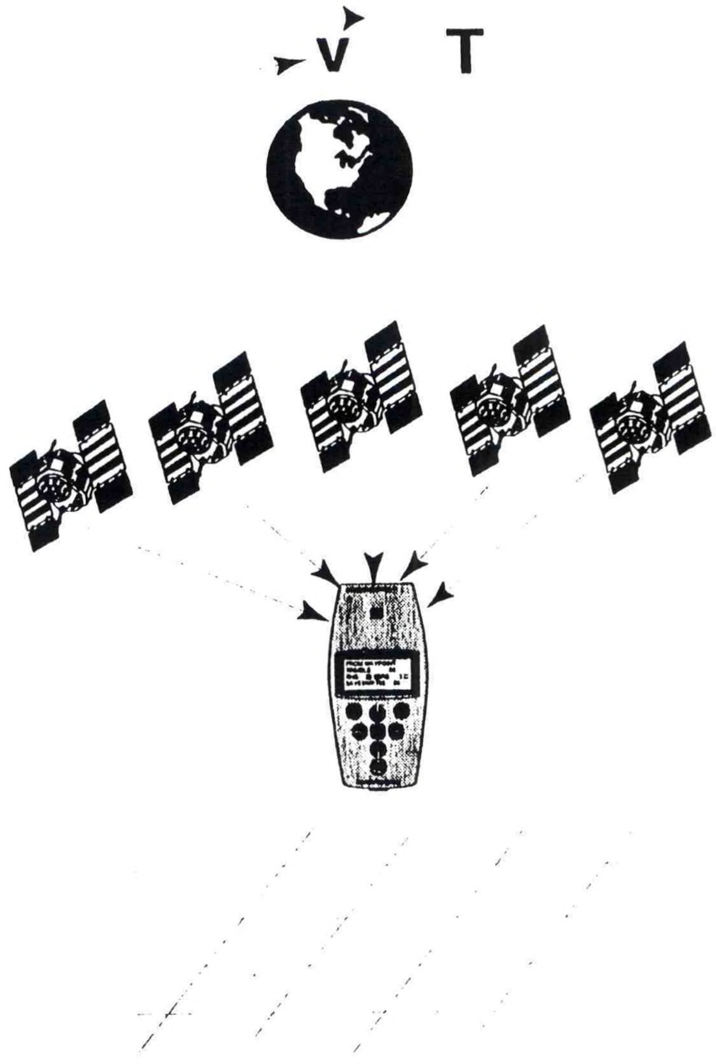
GPS Performance and Applications
- Typical error budget
- Performance
- Applications

Future
- Growth
- GPS modernization

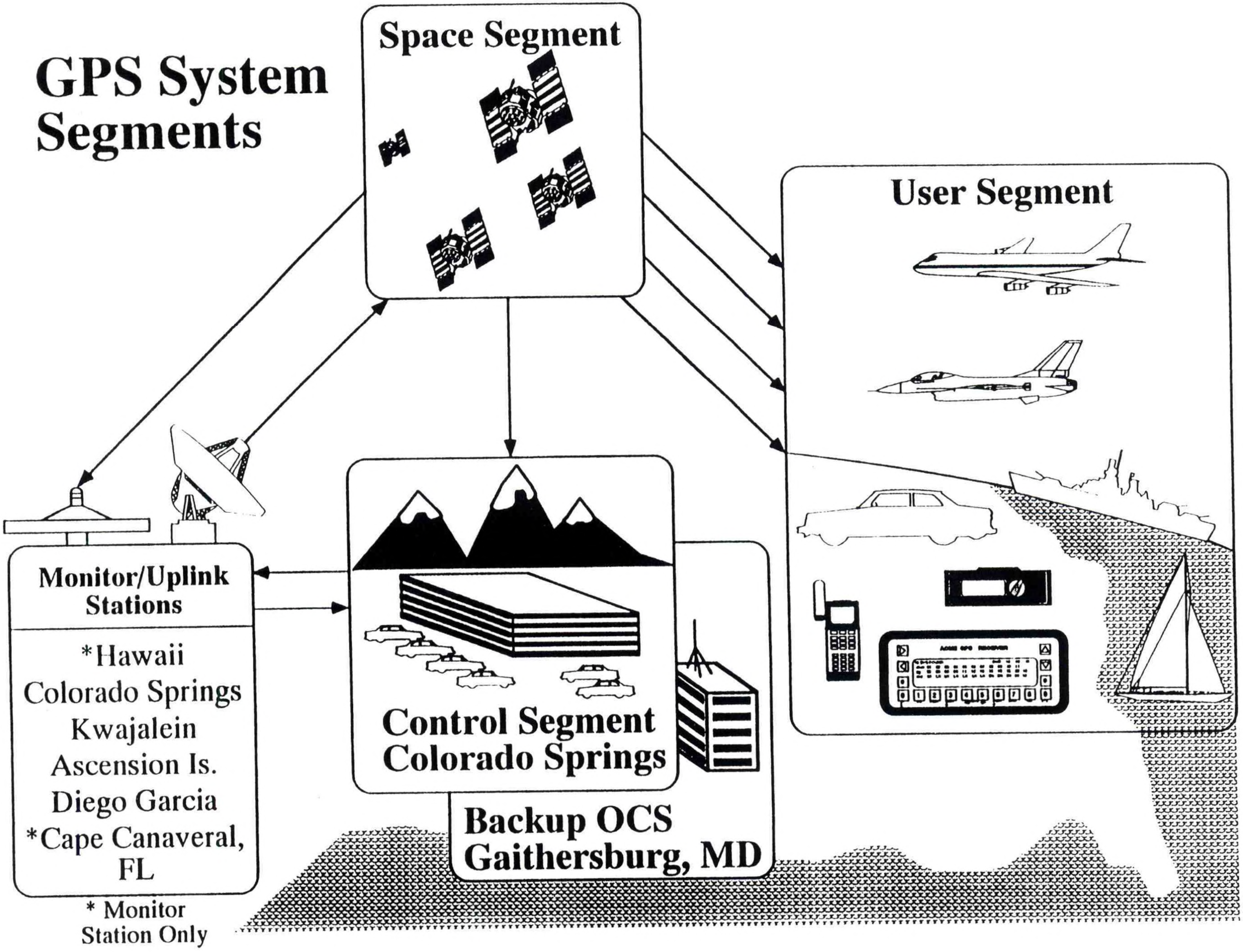
GPS Unique Capabilities

- High accuracy **3D position**
- **Velocity vector** and **time**
- **Global coverage**
- **Continuous** availability
- **Passive** service
- **Unlimited** number of users
- Resistant to **interference and jamming**
- Allows **common grid reference**

- **(x, y, z)**



GPS System Segments



Space Segment

User Segment

Control Segment
Colorado Springs

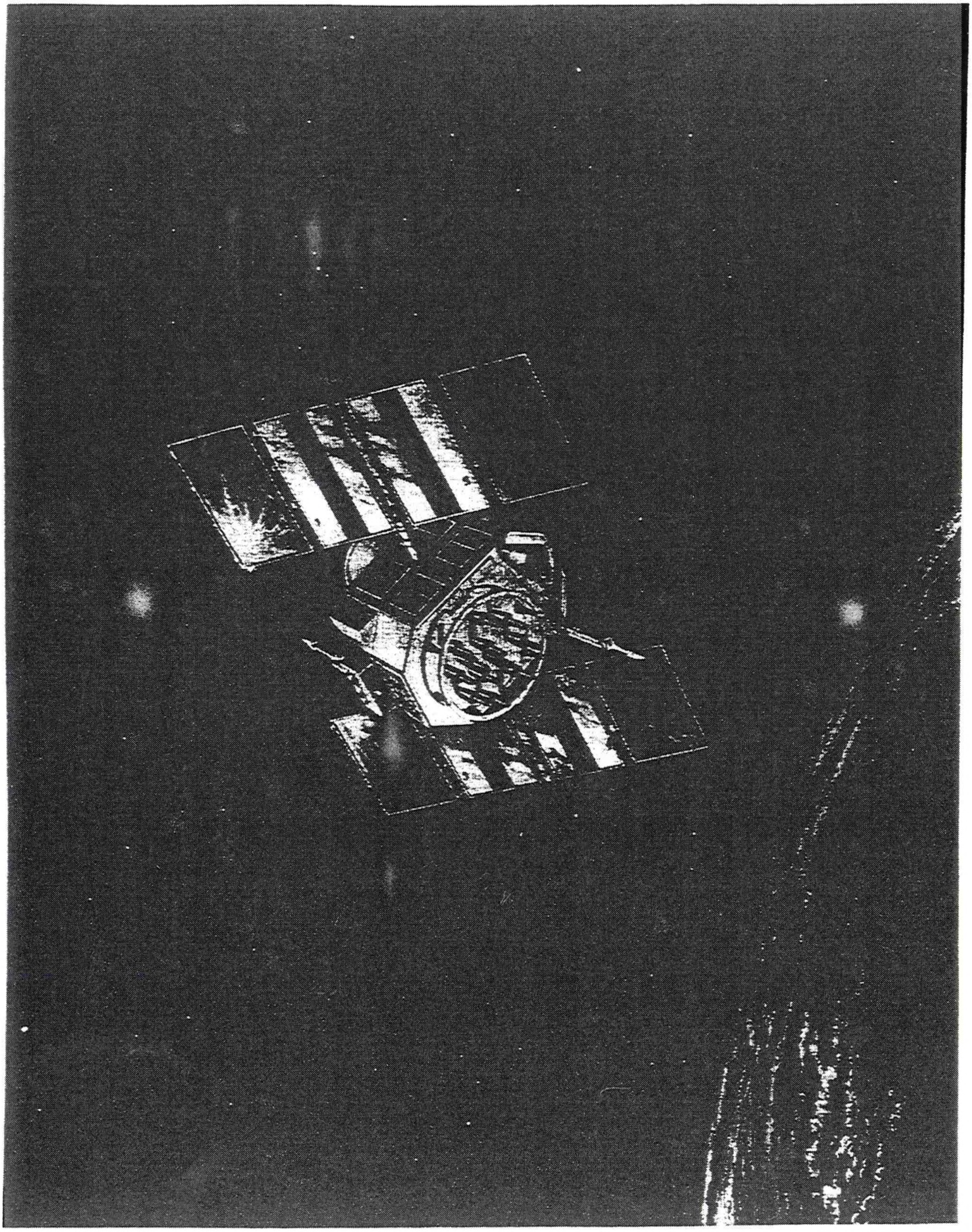
Backup OCS
Gaithersburg, MD

Monitor/Uplink Stations

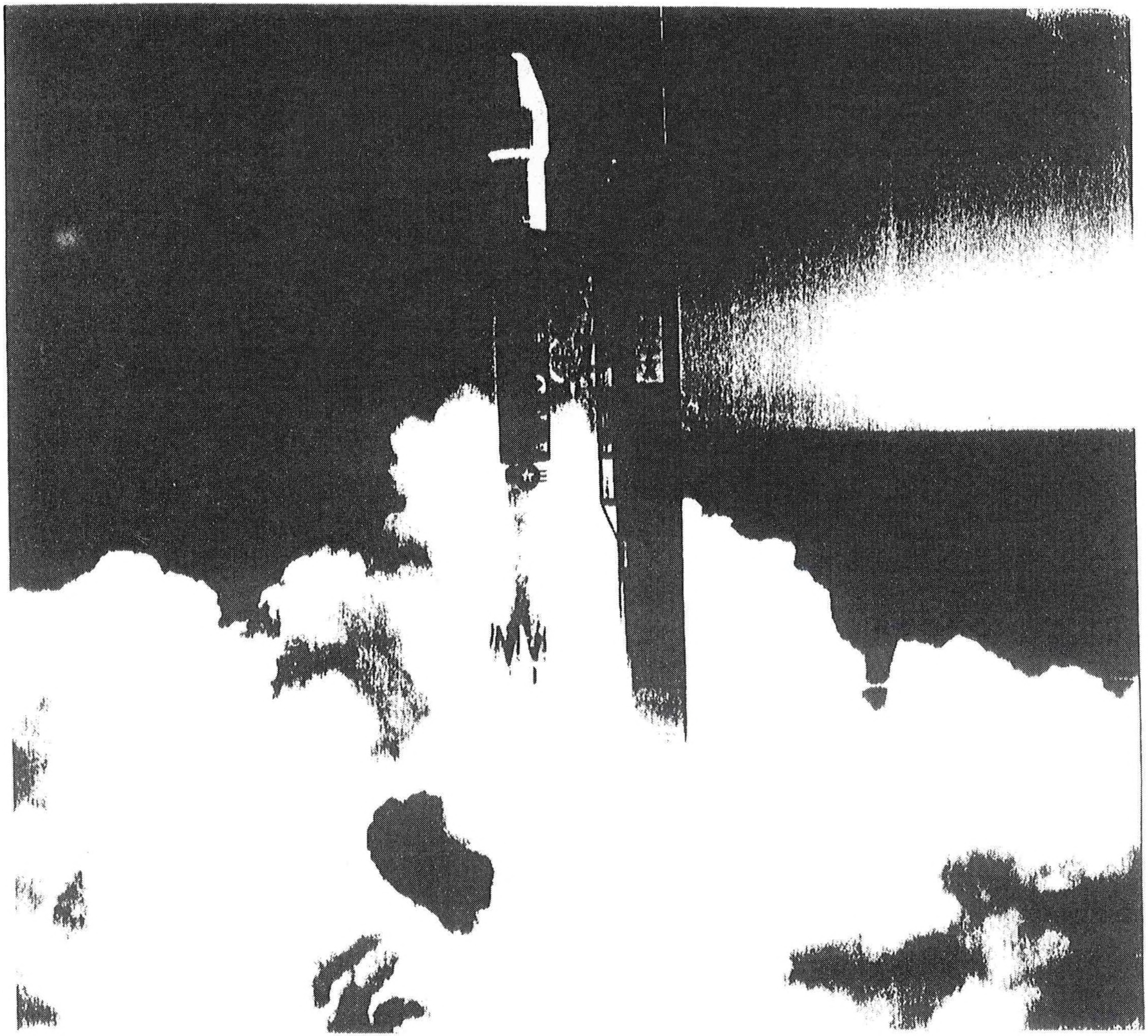
*Hawaii
Colorado Springs
Kwajalein
Ascension Is.
Diego Garcia
*Cape Canaveral, FL

* Monitor Station Only

SS042

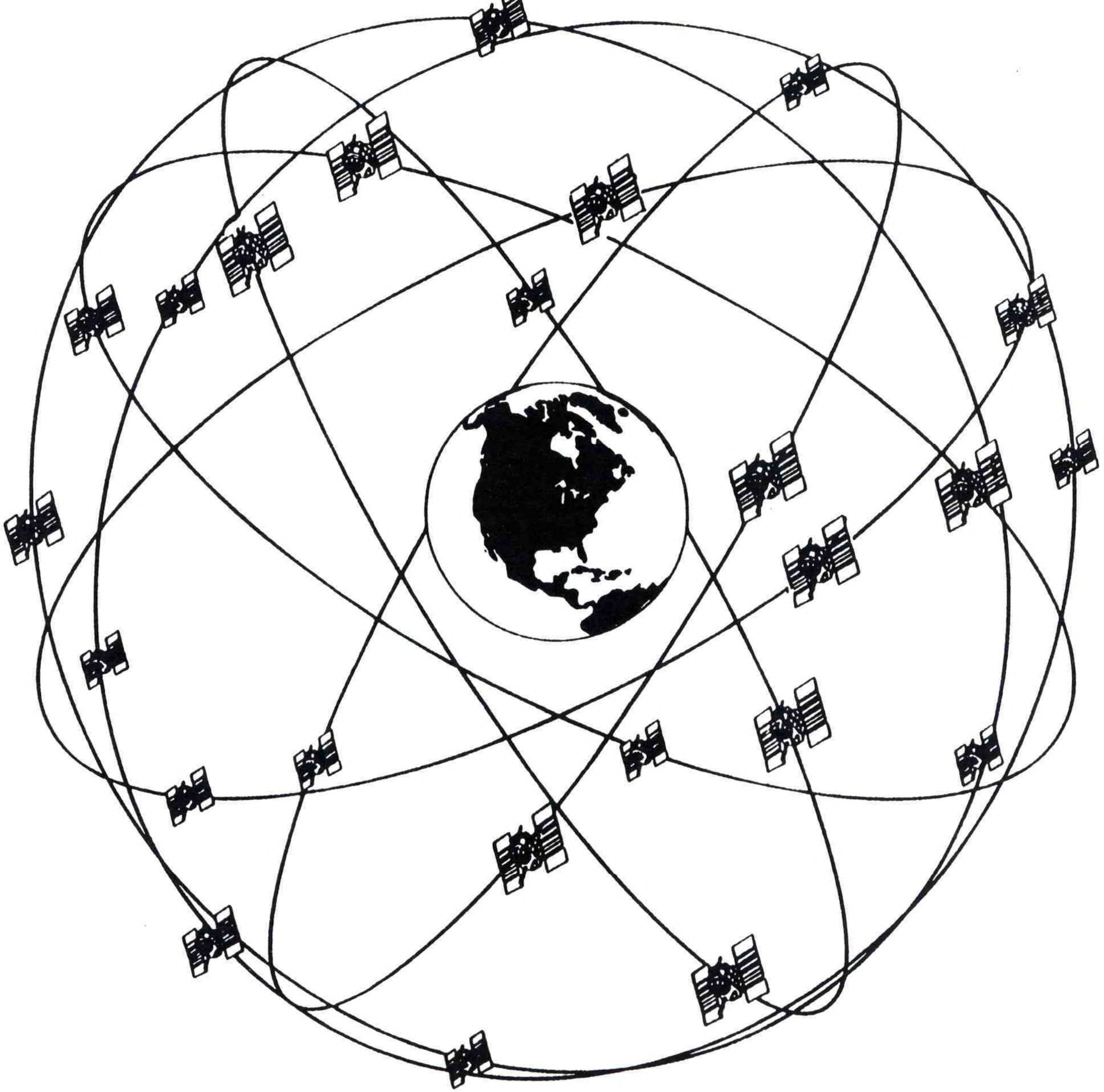


Launch of the Delta II



The Navstar GPS Operational Constellation

(24 Satellites, Including 3 Active Spares)



GPS Space Segment

Operational - Block II

- Final constellation normally provides **24 satellites** for worldwide coverage
- **6 to 11 satellites** are always in view
- Orbit period is **12 hours** (approximate)
- Orbit altitude is **10,900 n.mi. or 20,200 km.**
- GPS satellites launched by **expendable launch vehicles** (ELV's)
- **$1.2 billion** contract for **28 Block II** spacecraft (S/C)
- **Delta II ELV's** have been built and delivered.
- **IOC** (Initial Operational Capability) declared by **DoD on 8 Dec 93**
- **FOC (Full Operational Capability) declared by DoD on 27 April 95**

Navtech Seminars, Inc.
703-931-0500

GPS On-Orbit Satellite Status

As of: Jan. 97

GPS Operational Constellation Status

Slot

Orbit Plane	1	2	3	4	5*
A	SVN 39/PRN 9 II-21 26 JUN 93 20 JUL 93	SVN 25/PRN 25 II-12 23 FEB 92 24 MAR 92	SVN 27/PRN27 II-15 9 SEP 92 30 SEP 92	SVN 19/PRN 19 II-4 21 OCT 89 23 NOV 98	
B	SVN 22/PRN 22 II-18 3 FEB 93 4 APR 93	SVN 30/PRN 30 II-27 12 SEP 96 1 OCT 96	SVN 31/PRN 2 II-2 10 JUN 89 10 AUG 89	SVN 35/PRN 5 II-22 30 AUG 93 28 SEP 93	
C	SVN 36/PRN 6 II-24 10 MAR 94 28 MAR 94	SVN 33/PRN 3 II-25 28 MAR 96 9 APR 96	SVN 31/PRN 31 II-19 30 MAR 93 13 APR 93	SVN 37/PRN 7 II-20 13 MAY 93 12 JUN 93	SVN 28/PRN 28 II-13 10 APR 92 27 APR 92
D	SVN 24/PRN 24 II-11 4 JUL 91 30 AUG 91	SVN 15/PRN 15 II-9 1 OCT 90 15 OCT 90	SVN 17/PRN 17 II-5 11 DEC 89 5 JAN 90	SVN 30/PRN 30 II-23 26 OCT 93 29 NOV 93	
E	SVN 14/PRN 14 II-1 14 FEB 89 15 APR 89	SVN 21/PRN 21 II-8 2 AUG 90 22 AUG 90	SVN 40/PRN 10 II-26 16 July 96 15 Aug 96	SVN 23/PRN 23 II-10 26 NOV 90 10 DEC 90	SVN 16/PRN 16 II-3 18 AUG 89 18 OCT 89
F	SVN 32/PRN 1 II-16 22 NOV 92 11 DEC 92	SVN 26/PRN 26 II-14 7 JUL 92 23 JUL 92	SVN 18/PRN 18 II-6 24 JAN 90 15 FEB 90	SVN 29/PRN 29 II-17 18 DEC 92 5 JAN 93	

* undefined

Key

SVN/PRN NUMBER
MISSION NUMBER
LAUNCH DATE
SET USABLE DATE

▨ Marginal

☐ Useable

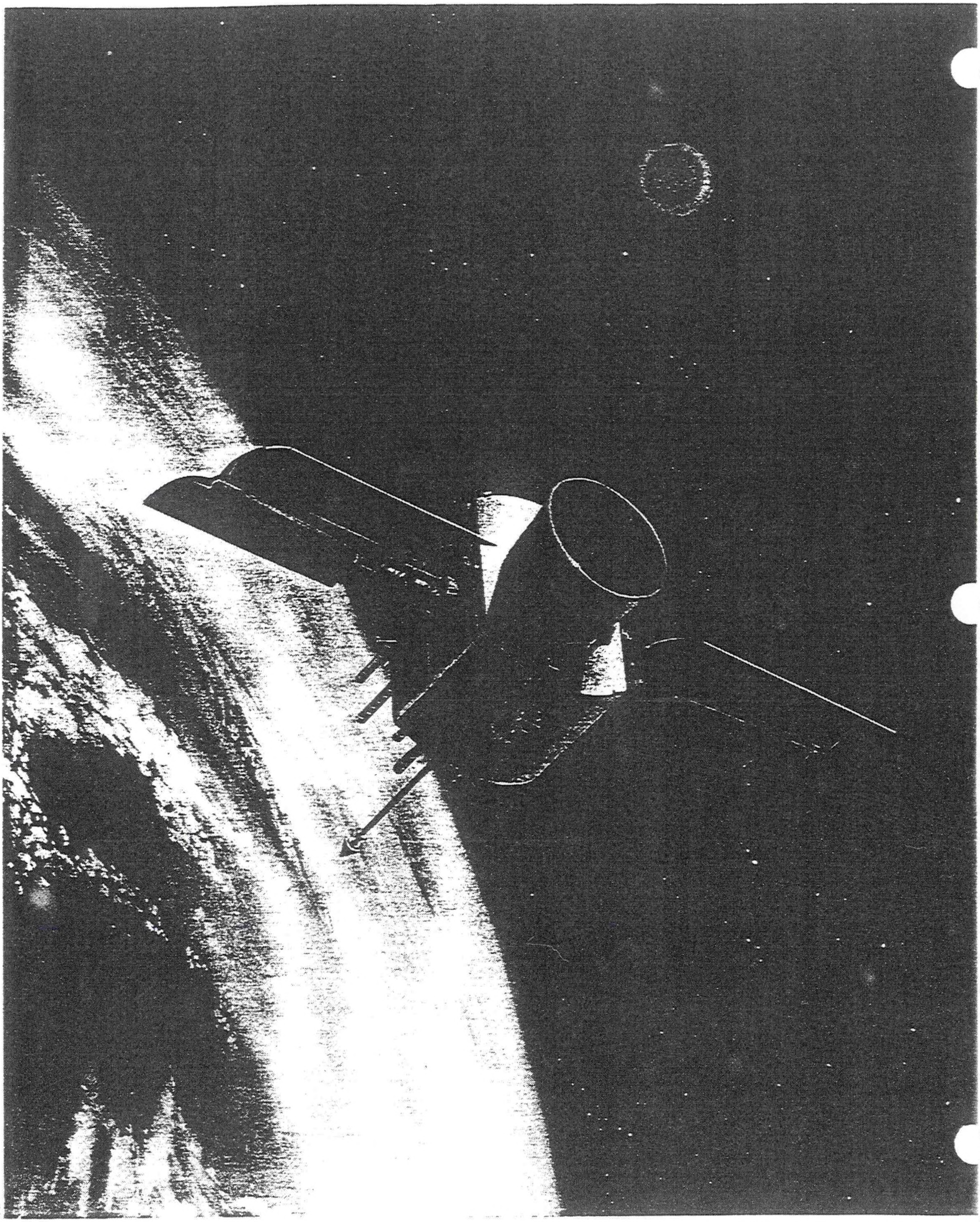
Navtech data from
USCG GPS Info Center and
other sources

SS1002qT

Navstar GPS Satellites

Acquisitions

Block I (1978-1985) (all launched)	• **Developmental** satellites • Contractor: Rockwell Space Division • 11 launched - 1 failure (SV-7) • Navstar - 12 (config. S/C) not launched
Block II, IIA (1989-1996) (launches)	• **Operational** satellites • Contractor: Rockwell Space Division • 28 satellites acquired • Supports 24 satellite constellation
Block IIR (1997-200X)	• **Operational Replenishment** satellites • Contractor: Lockheed Martin Astro Space • 21 satellites in production or completed • First IIR launch on Jan. 17, 1997 had Delta II LV failure; satellite destroyed
Block IIF (2001-2015+)	• **Operational Follow-on** satellites • Contractor: Boeing Space • 32 satellites in procurement • First IIF launch planned for 2001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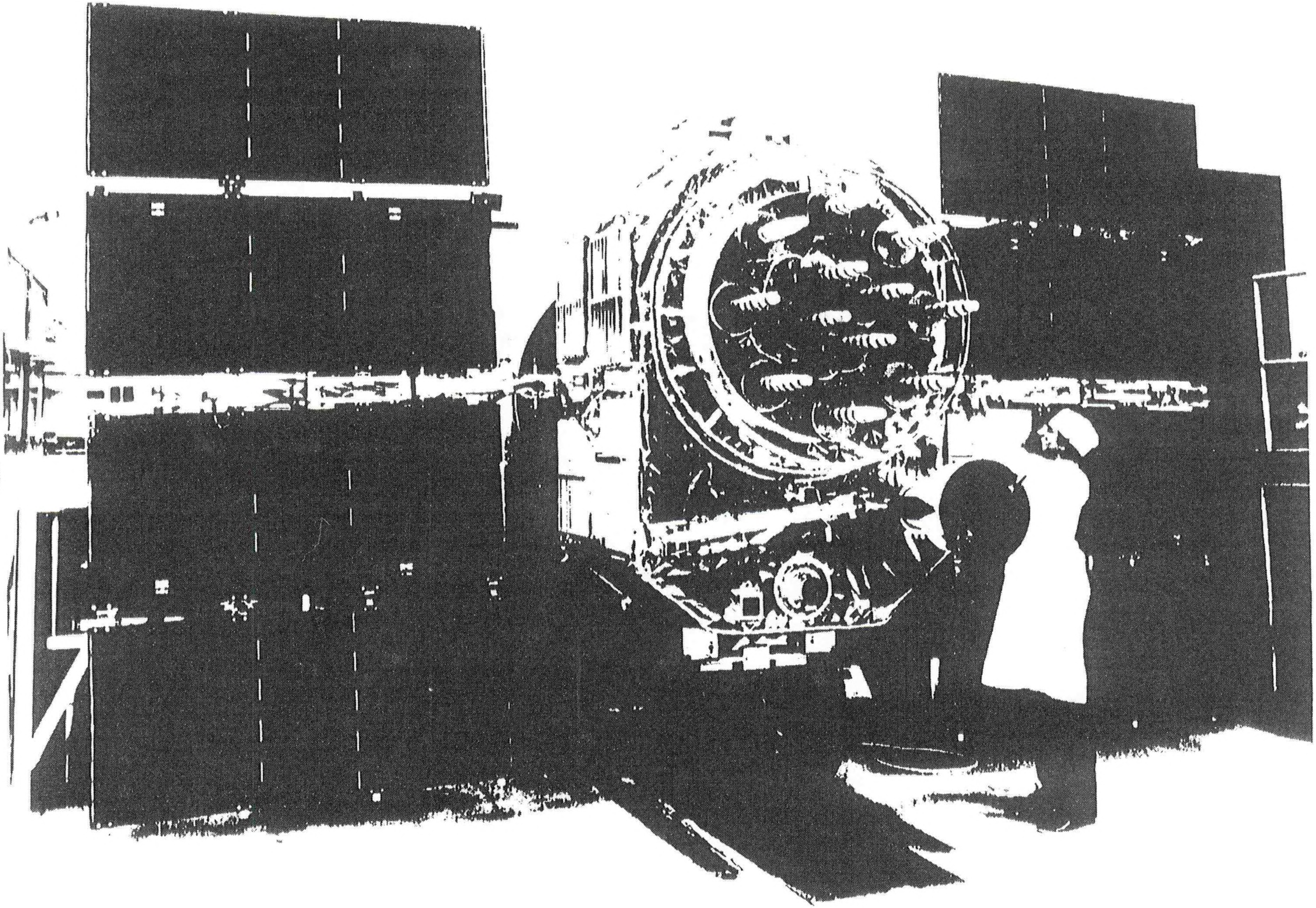

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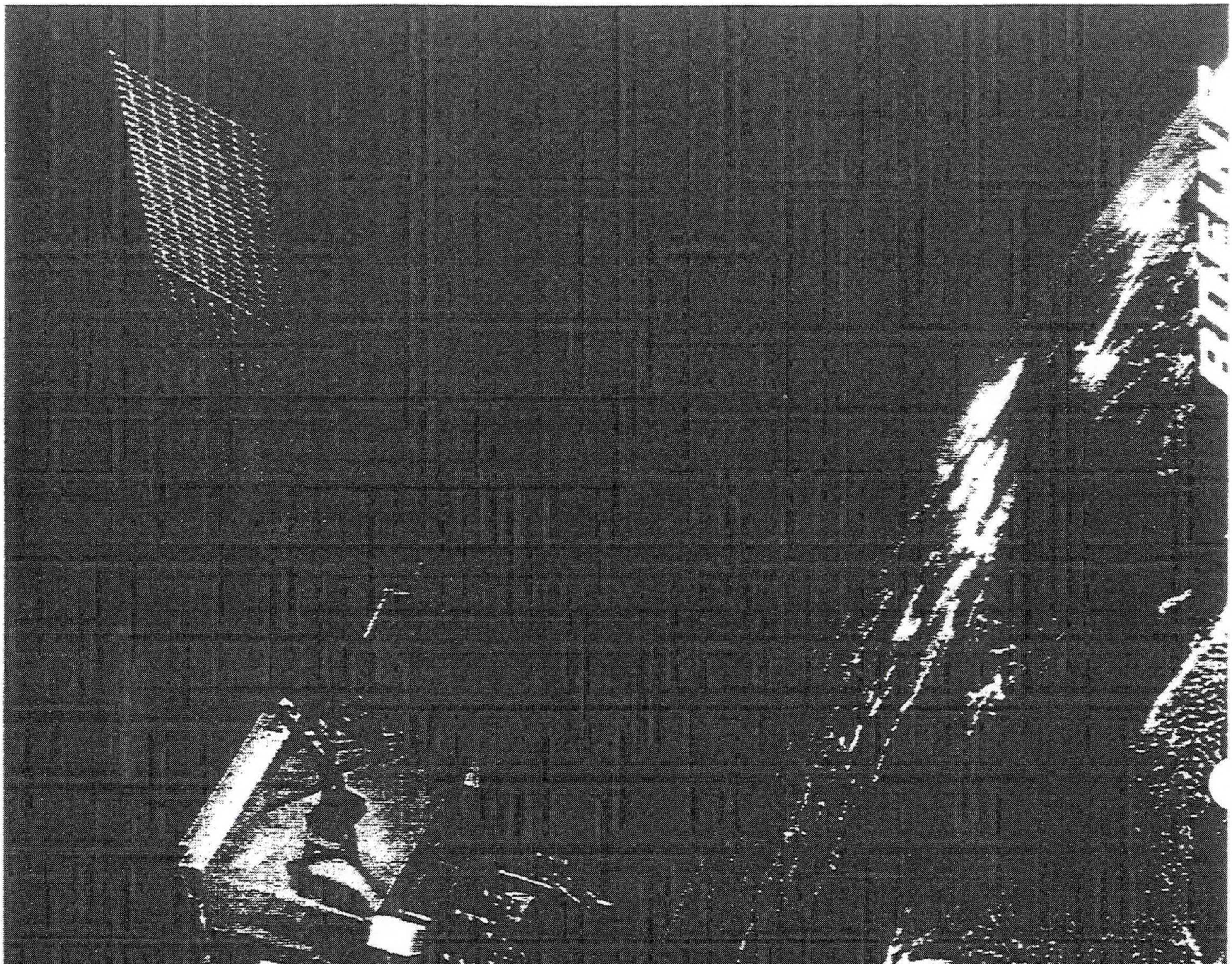
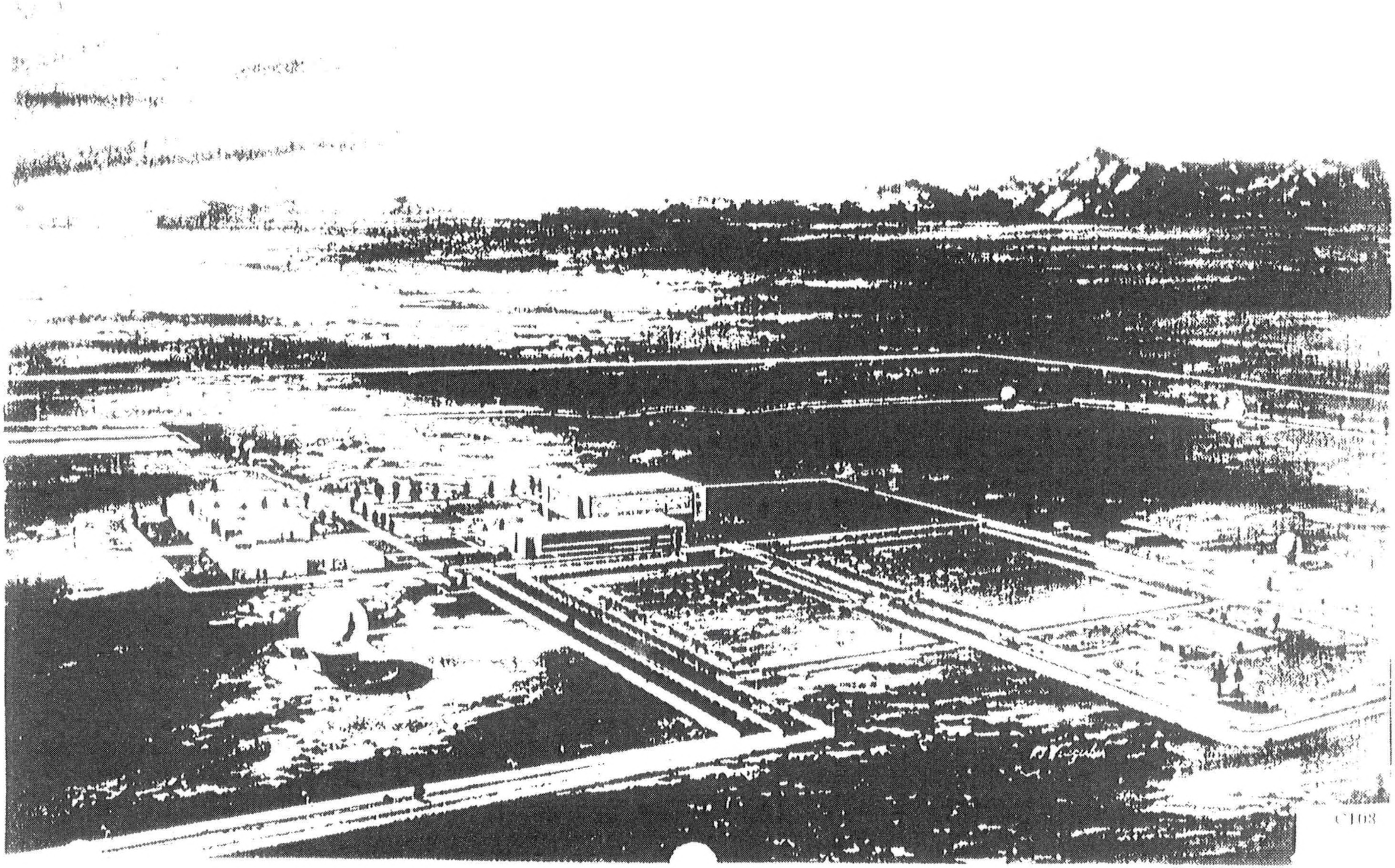


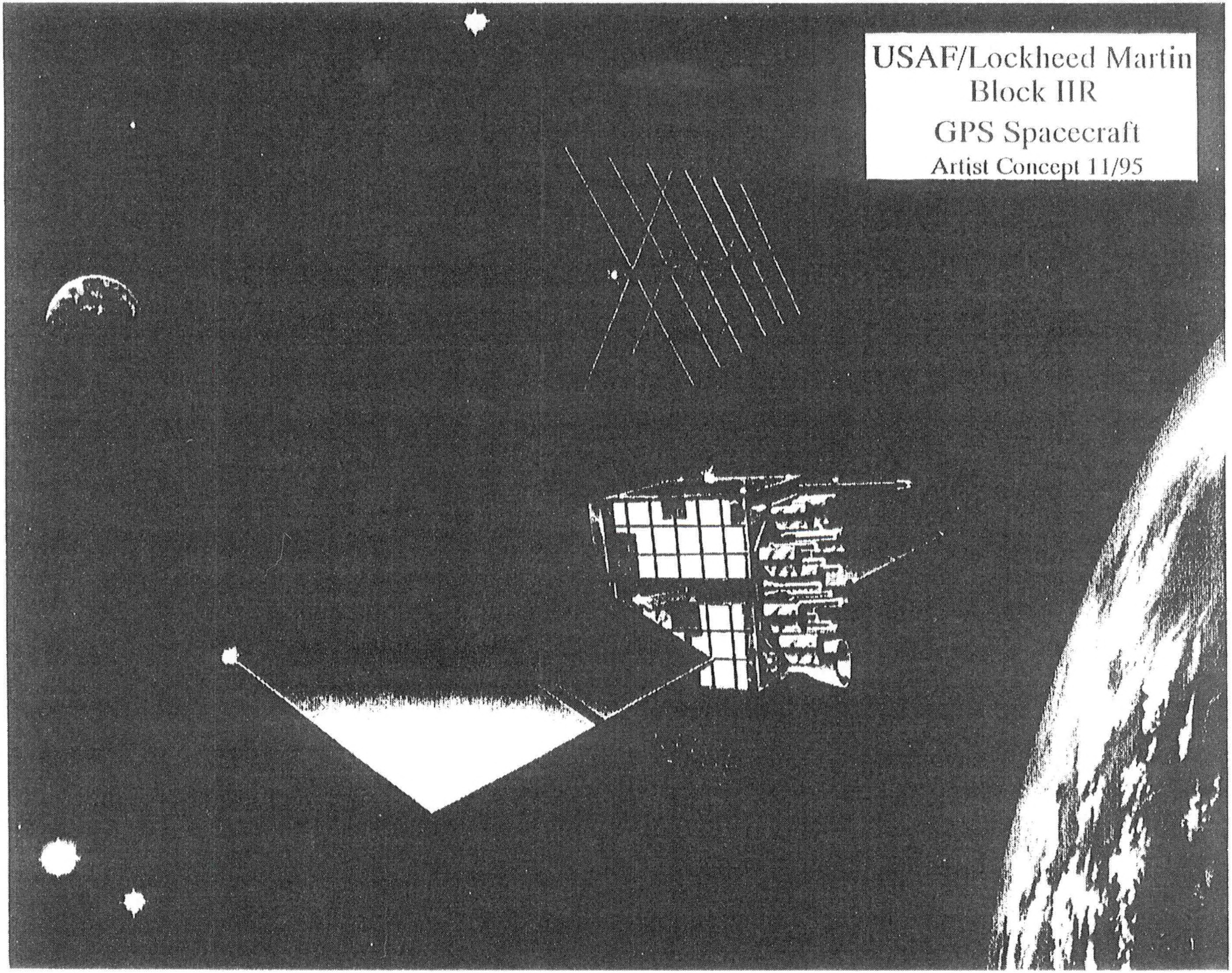
GPS Orbital Elements and Ephemeris Parameters

$\sqrt{A}$	Square root of semi-major axis (convenience)
e	Eccentricity of orbit
t_{OE}	Ephemeris reference time
i_0	Inclination at reference time
Ω_0	Right ascension at reference time
ω	Argument of perigee
$\dot{i}$	Rate of change of inclination
$\dot{\Omega}$	Rate of change of right ascension
M_0	Mean anomoly at reference time (angle)
Δn	Change in mean motion (time change in angle)
C_{uc}, C_{us}	Corrections to argument of latitude
C_{rc}, C_{rs}	Corrections to orbital radius
C_{ic}, C_{is}	Corrections to inclination

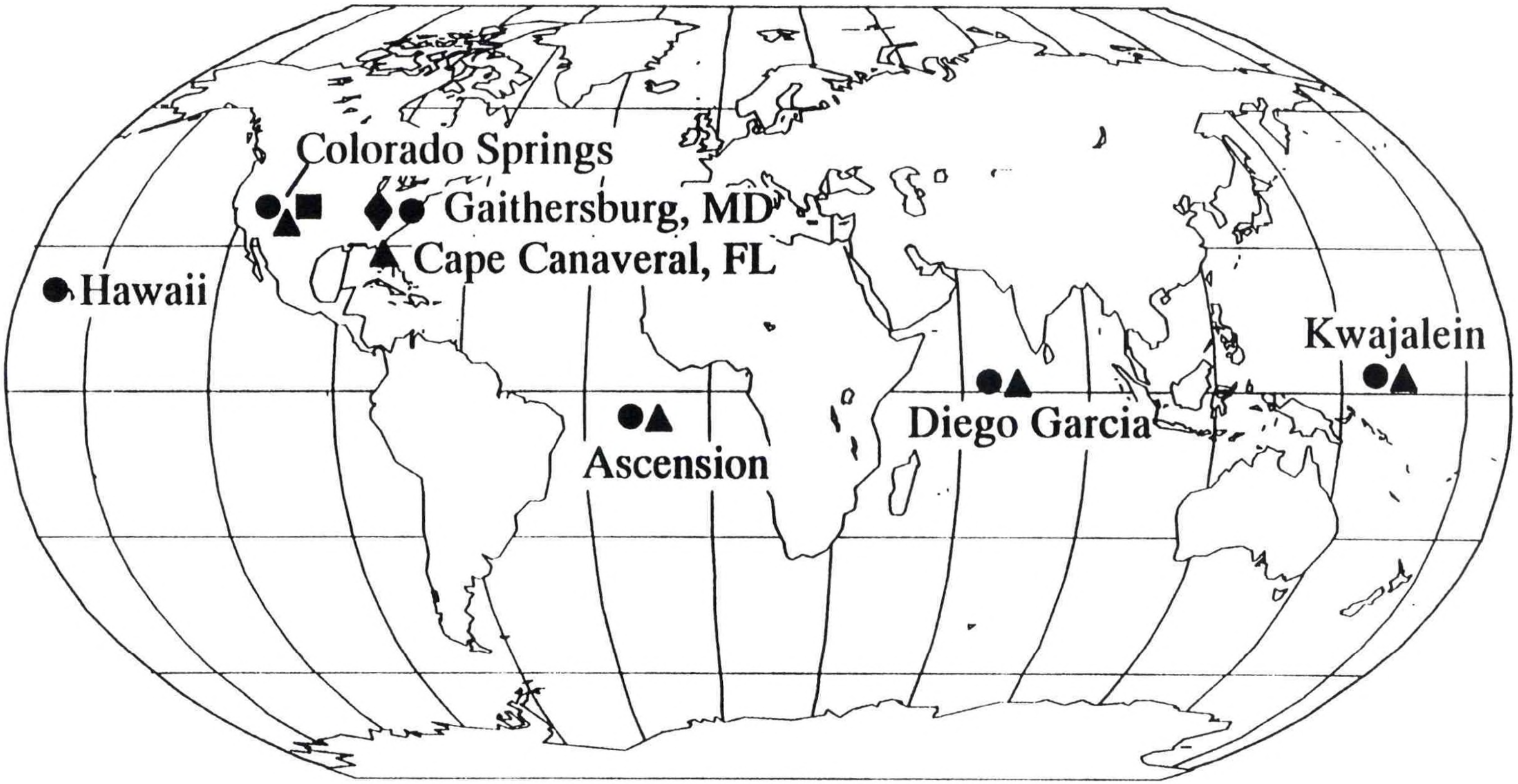
USAF Consolidated Space Operations Center

(CSOC, Falcon Air Force Base, Colorado Springs)



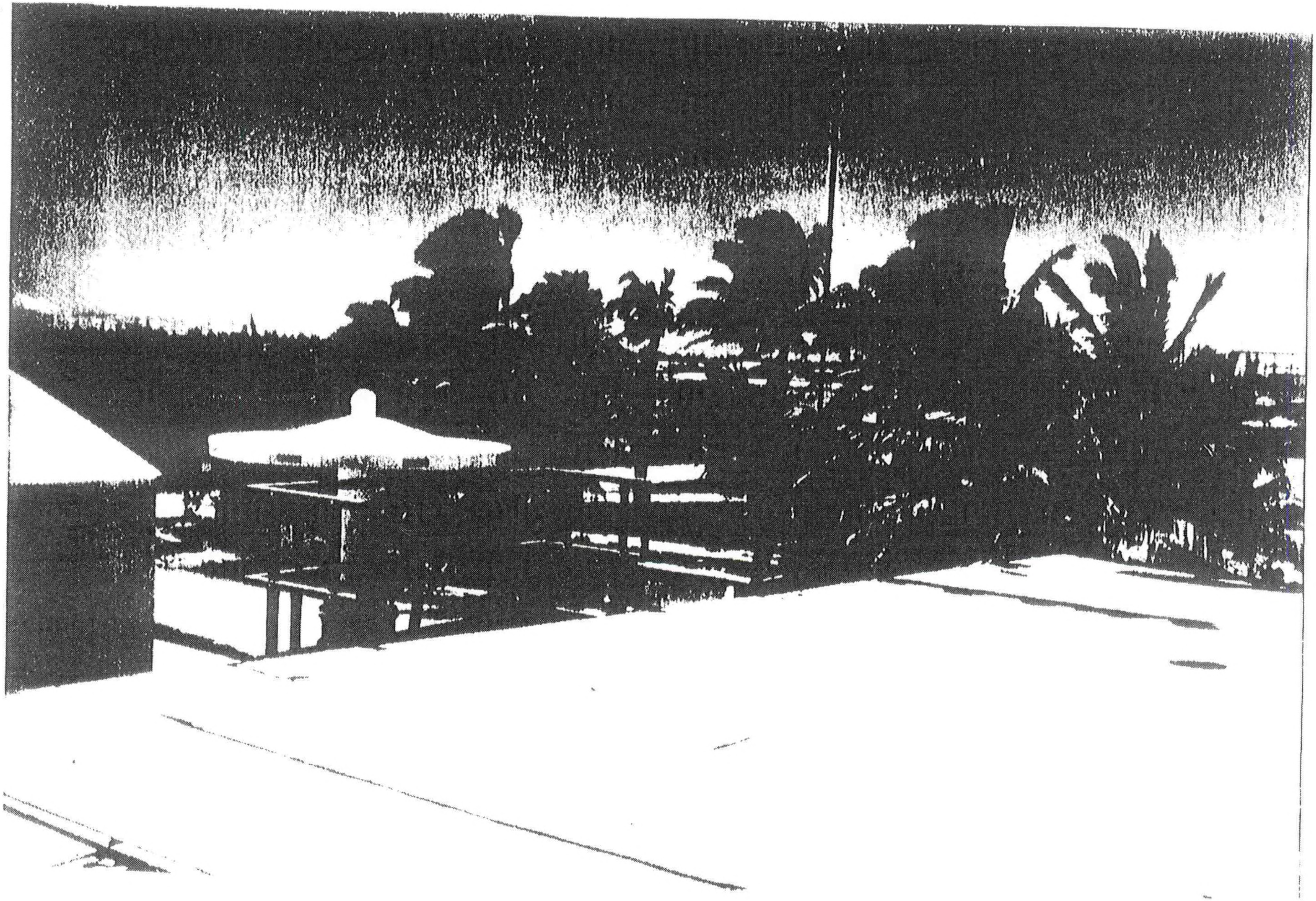

USAF/Lockheed Martin
Block IIR
GPS Spacecraft
Artist Concept 11/95

GPS Operational Control System



- ■ Master Control Station
- ● Monitor Station
- ▲ Upload Capability
- ◆ Backup Control Station

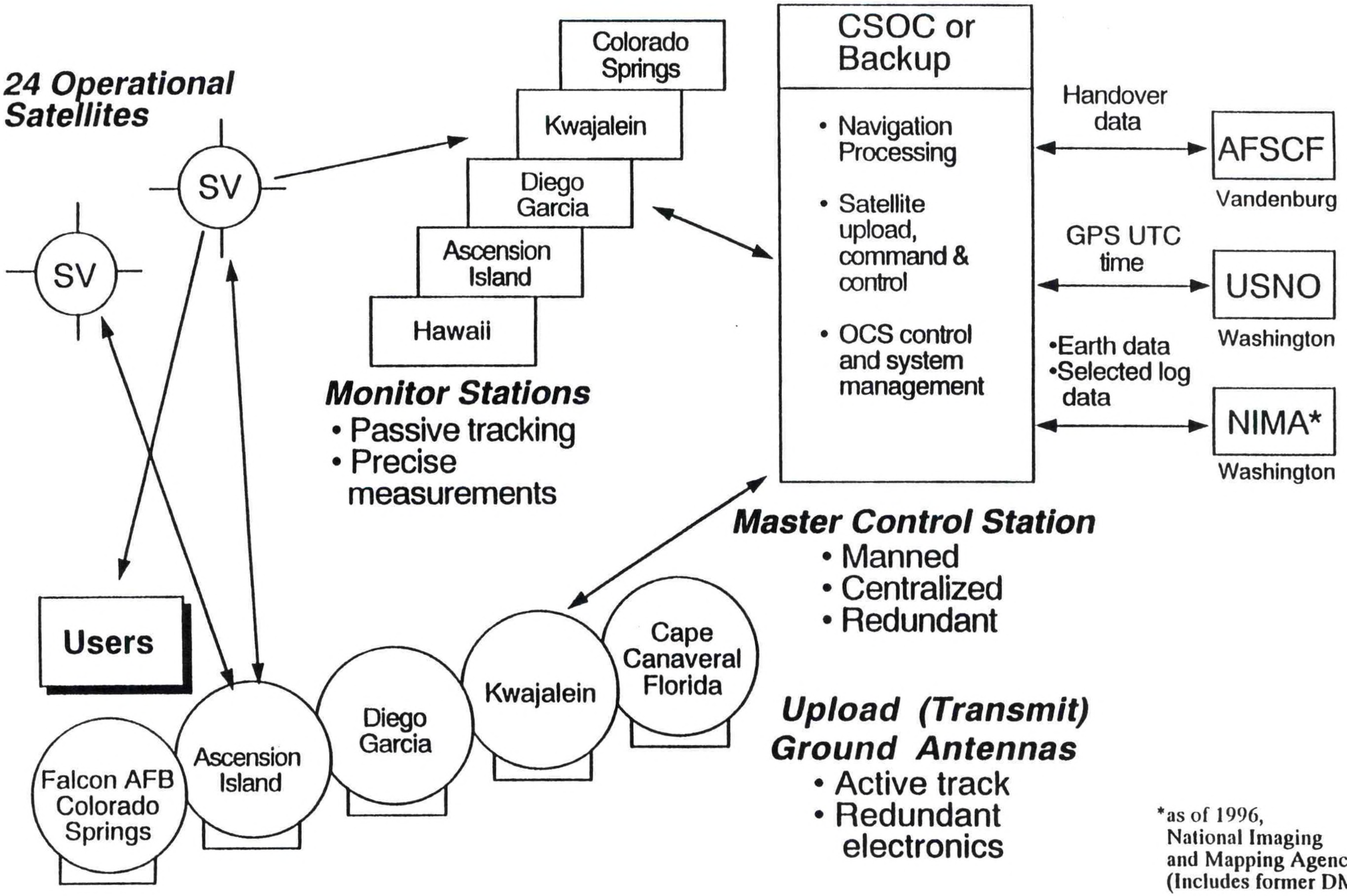
C021h



Kwajalein GPS Control Station

C020a

Operational Control Segment Configuration



24 Operational Satellites

SV

SV

Colorado Springs

Kwajalein

Diego Garcia

Ascension Island

Hawaii

Monitor Stations
- Passive tracking
- Precise measurements

CSOC or Backup

- Navigation Processing
- Satellite upload, command & control
- OCS control and system management

Master Control Station
- Manned
- Centralized
- Redundant

Handover data

AFSCF

Vandenburg

GPS UTC time

USNO

Washington

- Earth data
- Selected log data

NIMA*

Washington

Users

Falcon AFB Colorado Springs

Ascension Island

Diego Garcia

Kwajalein

Cape Canaveral Florida

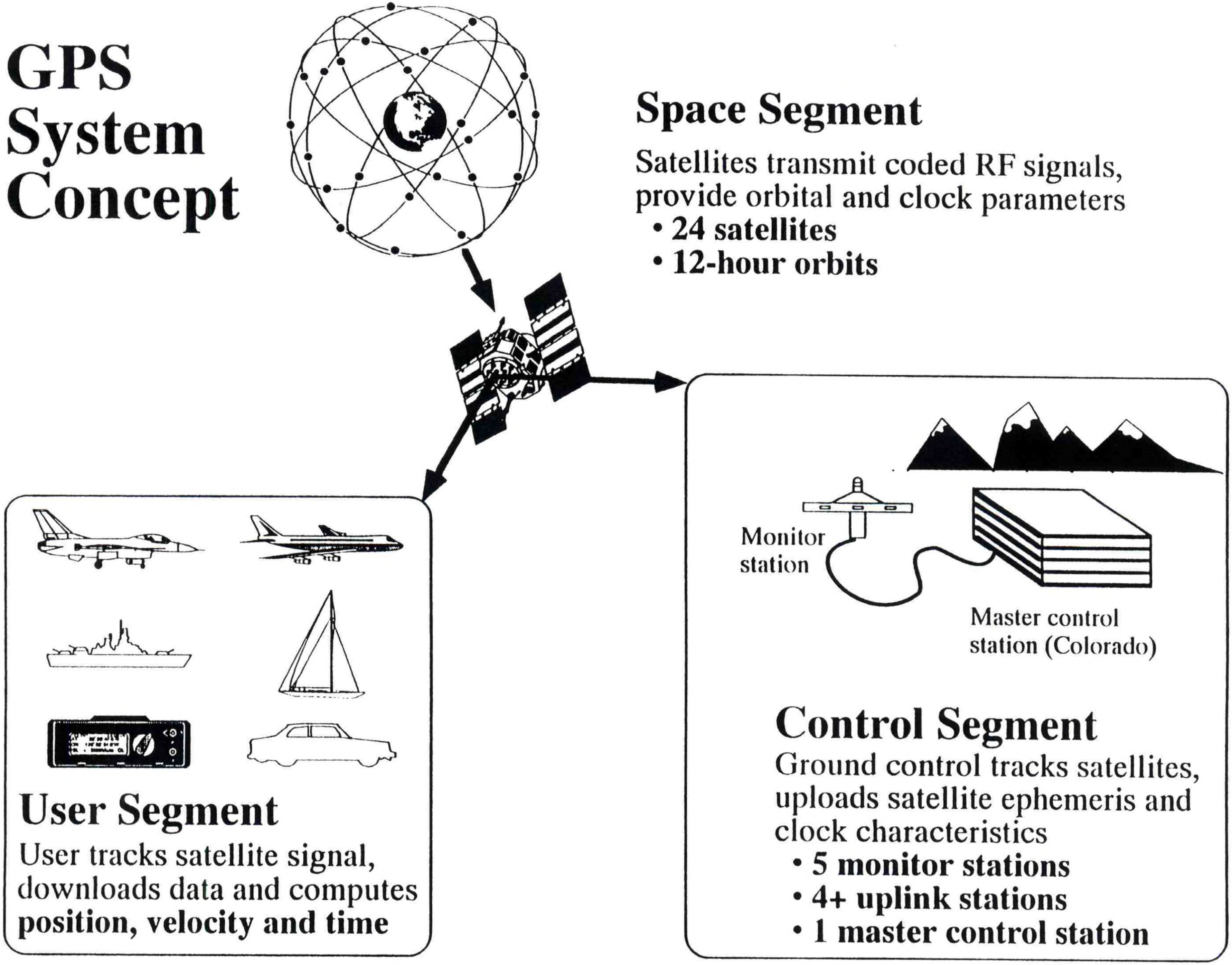
Upload (Transmit) Ground Antennas
- Active track
- Redundant electronics

*as of 1996,
National Imaging
and Mapping Agency
(Includes former DMA)

C010k

66

GPS System Concept



Space Segment

Satellites transmit coded RF signals, provide orbital and clock parameters

- **24 satellites**
- **12-hour orbits**

User Segment

User tracks satellite signal, downloads data and computes **position, velocity and time**

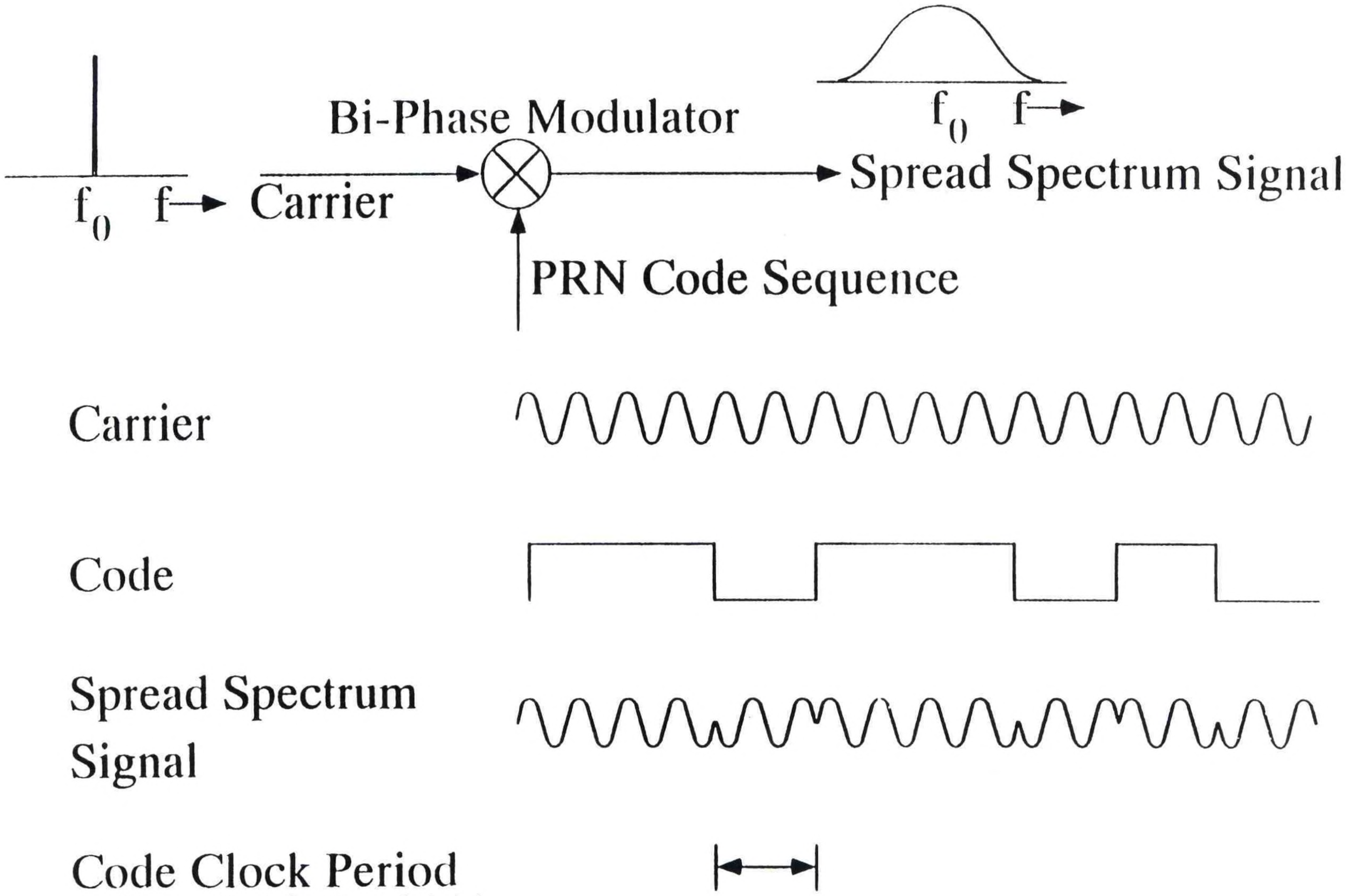
Control Segment

Ground control tracks satellites, uploads satellite ephemeris and clock characteristics

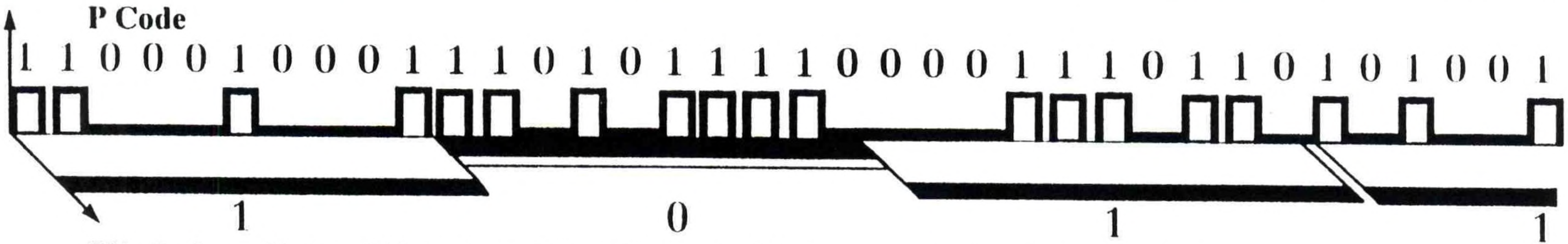
- **5 monitor stations**
- **4+ uplink stations**
- **1 master control station**

GPS Code Modulation

from the GPS Spacecraft



GPS PSEUDORANDOM CODES

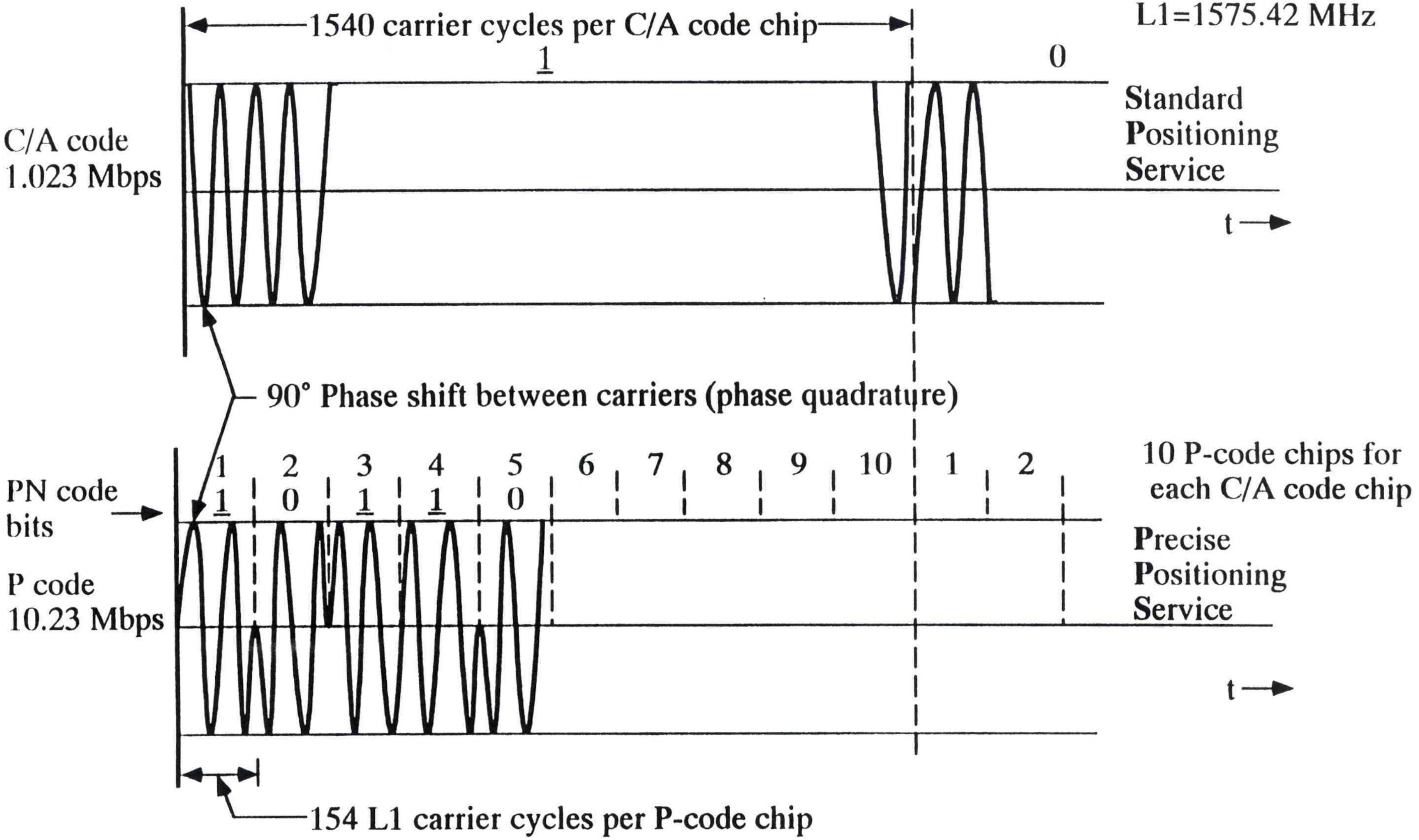


Note: C/A code and P code transmitted on carrier in phase quadrature

Parameter	C/A Code	P Code	Data
CHIPPING RATE	$1.023 \text{ X } 10^6$ bits/sec	$10.23 \text{ X } 10^6$ bits/sec	50 bits/sec
SPATIAL LENGTH (PER BIT)	290m (960 ft)	29m (96 ft)	6000km (3235 n. m.)
REPETITION INTERVAL	0.001 sec	7 days	Not applicable
CODE TYPE	Gold code	267 day pseudo random code	Not applicable
TOTAL NO. OF CODES	36 unique Gold codes	37 seven-day sections	Not applicable
SPECIAL PROPERTIES	Easy to acquire	Slightly more accurate. Resistant to jamming and spoofing. Rejection of multipath.	Provides handover from C/A to P code, ephemeris data and clock correction.

GPS Signal Waveform

Showing PN code transitions affecting L1 carrier



1540 carrier cycles per C/A code chip

L1=1575.42 MHz

C/A code
1.023 Mbps

Standard
Positioning
Service

90° Phase shift between carriers (phase quadrature)

10 P-code chips for
each C/A code chip

PN code bits

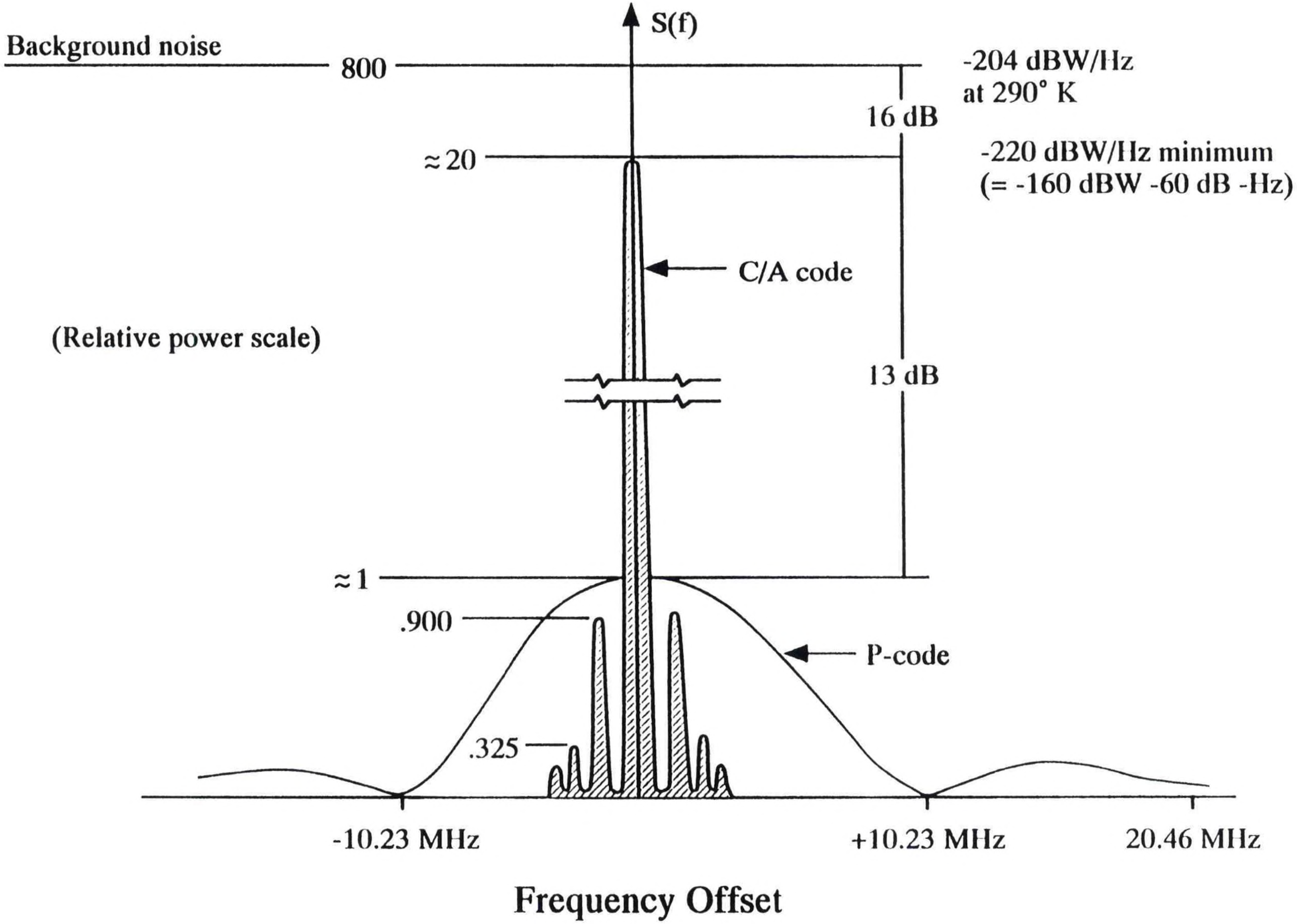
P code
10.23 Mbps

Precise
Positioning
Service

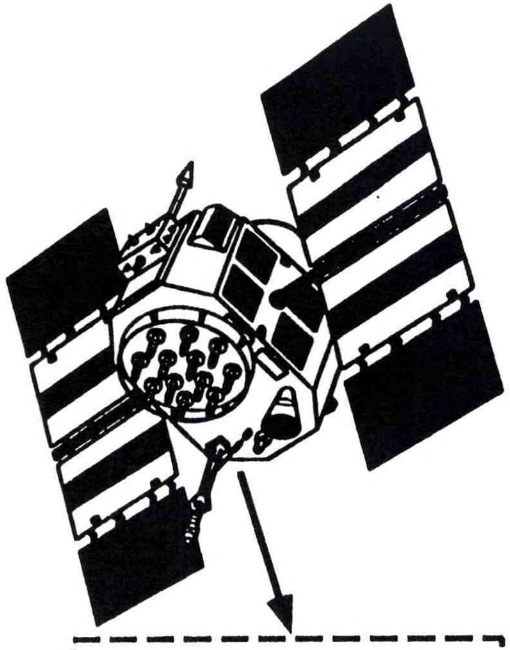
154 L1 carrier cycles per P-code chip

The GPS Signal Structure

Spectrum of Combined Waveform

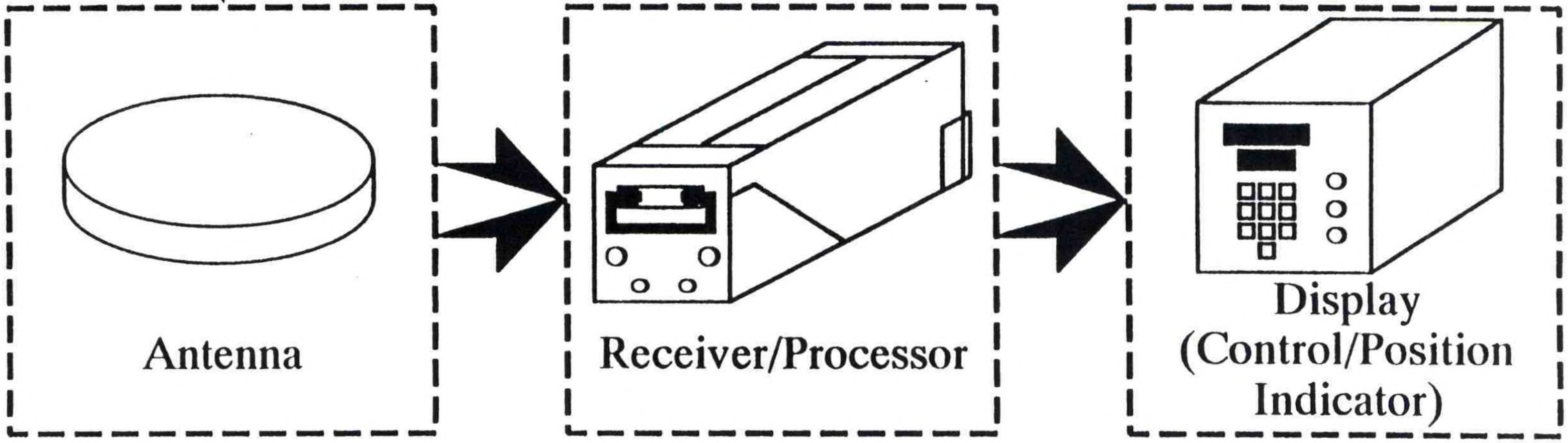


User Set Functions

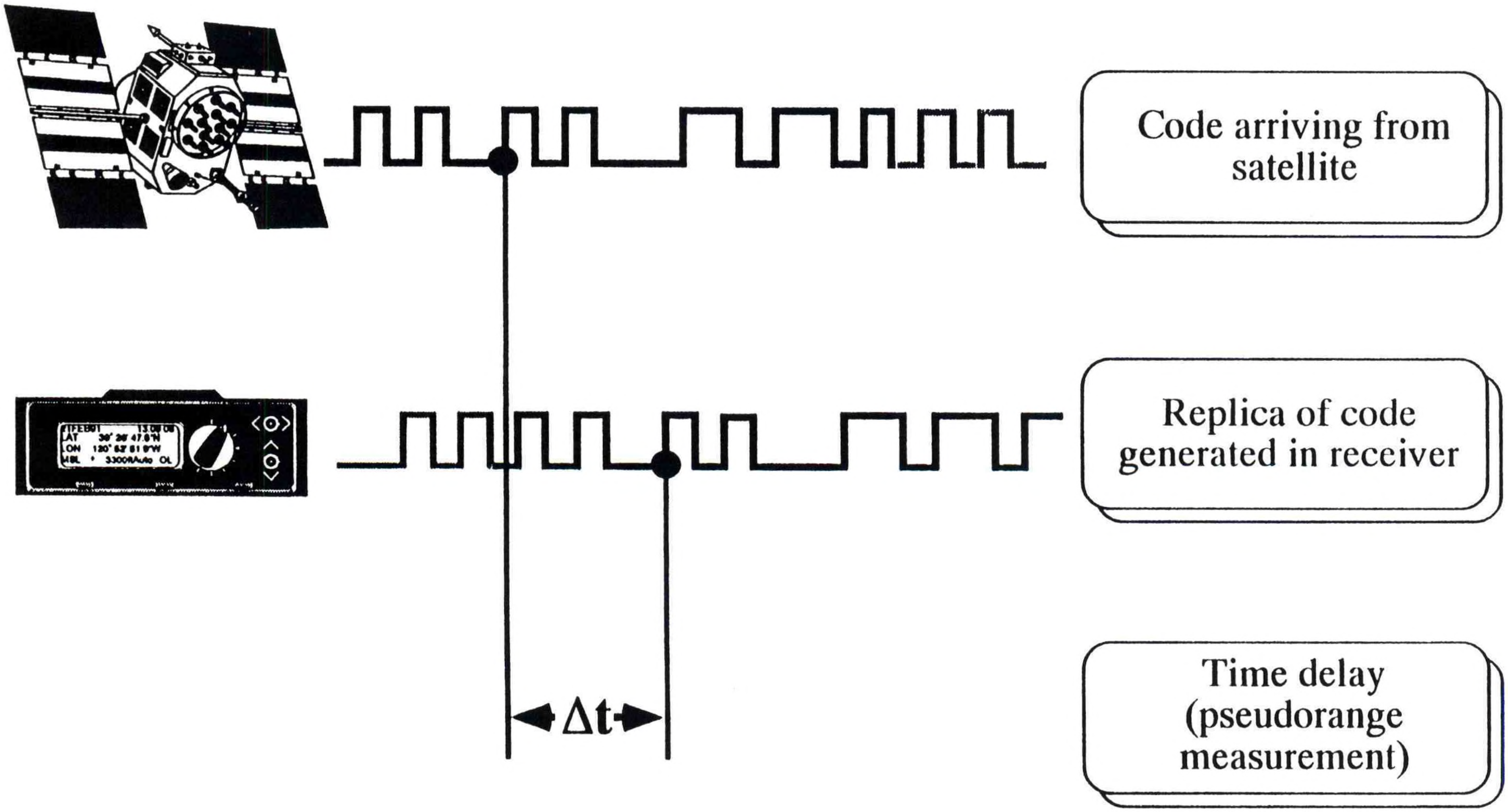


Processes the time and position information from four or more satellites to obtain accurate position, velocity and timing measurements

User Set Major Components



GPS Single Pseudorange Measurement



Code arriving from satellite

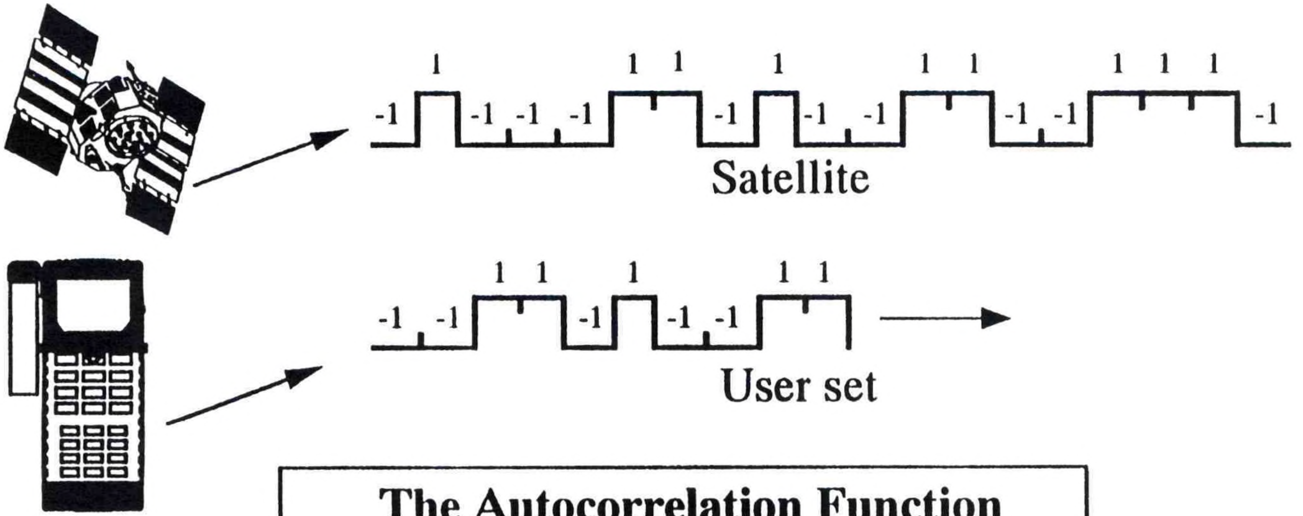
Replica of code generated in receiver

Time delay (pseudorange measurement)

Δt is a measure of the propagation time
(and therefore range) between S/C and receiver

The Correlation Process

Matching the received code sequence with the user set replica



The Autocorrelation Function

$$\frac{1}{T}\int_0^T X(t) * X(t\text{-}\tau)dt = \frac{1}{N}\sum_{i=1}^{N} X_i * X_{i\text{-}j}$$

In the case above:

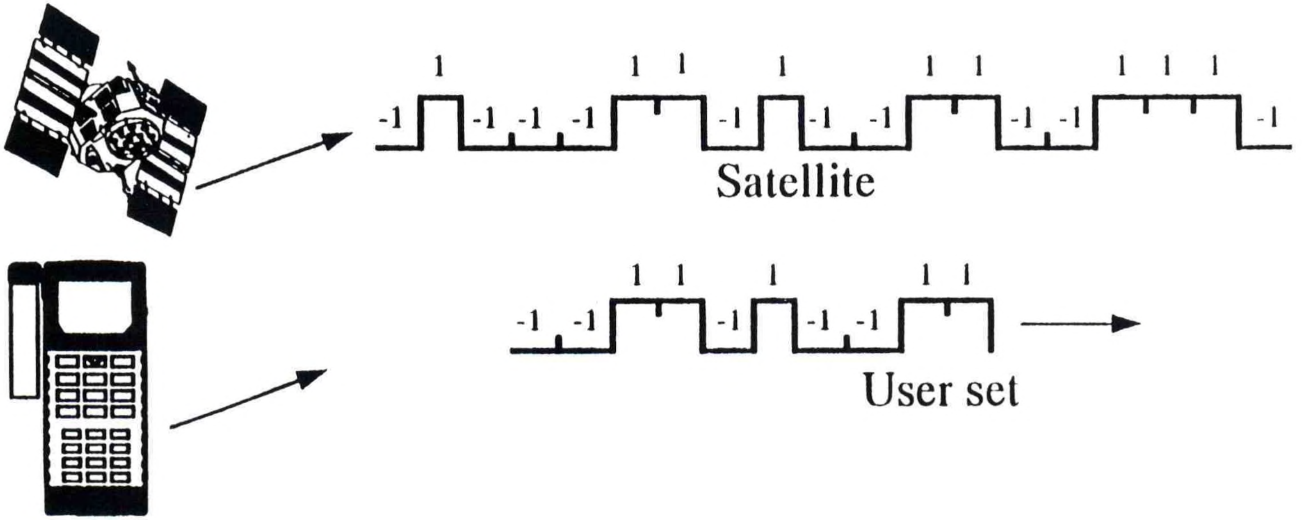
$$\frac{1}{10}\sum_{i=1}^{10} X_i * X_{i-3} = \frac{1}{10}\{(-1)(-1)+(1)(-1)+(-1)(1)+(-1)(1)+(-1)(-1)+(1)(1)+(1)(-1)+(-1)(-1)+(1)(1)+(-1)(1)\}$$

$$= \frac{1}{10}\{+1-1-1-1+1+1-1+1+1-1\} = 0$$

The Correlation Process

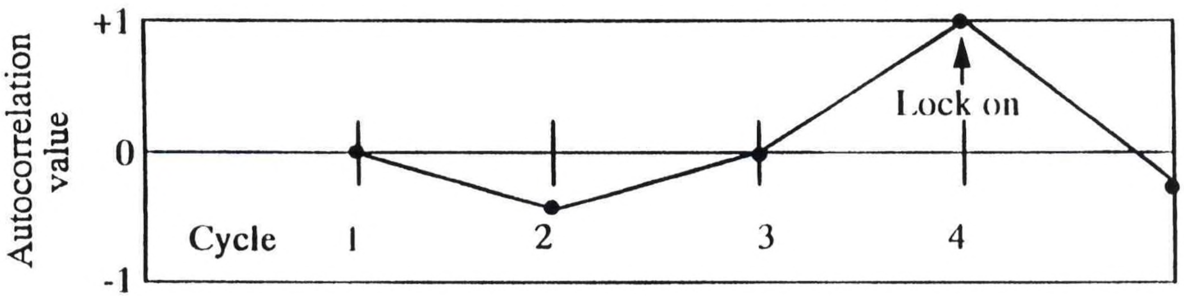
(Continued)

Shifting user code three places to the right - keeping track of the shift (Δt):



$$\frac{1}{10}\sum_{i=1}^{10} X_i * X_i = \frac{1}{10}\{(-1)(-1)+(-1)(-1)+(1)(1)+(1)(1)+(-1)(-1)+(1)(1)+(-1)(-1)+(-1)(-1)+(1)(1)+(1)(1)\}$$

$$= \frac{1}{10}\{1+1+1+1+1+1+1+1+1+1\} = 1$$



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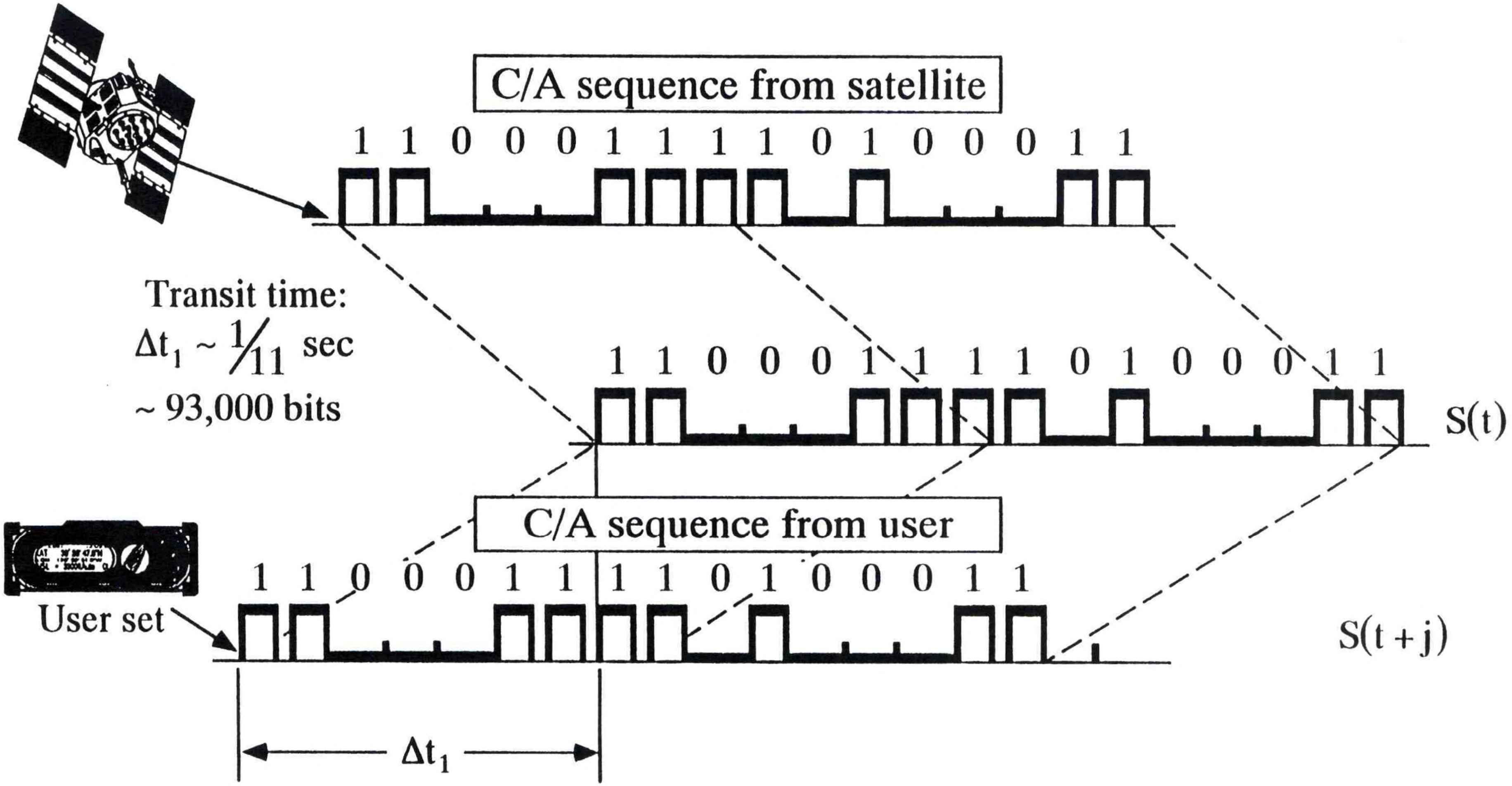
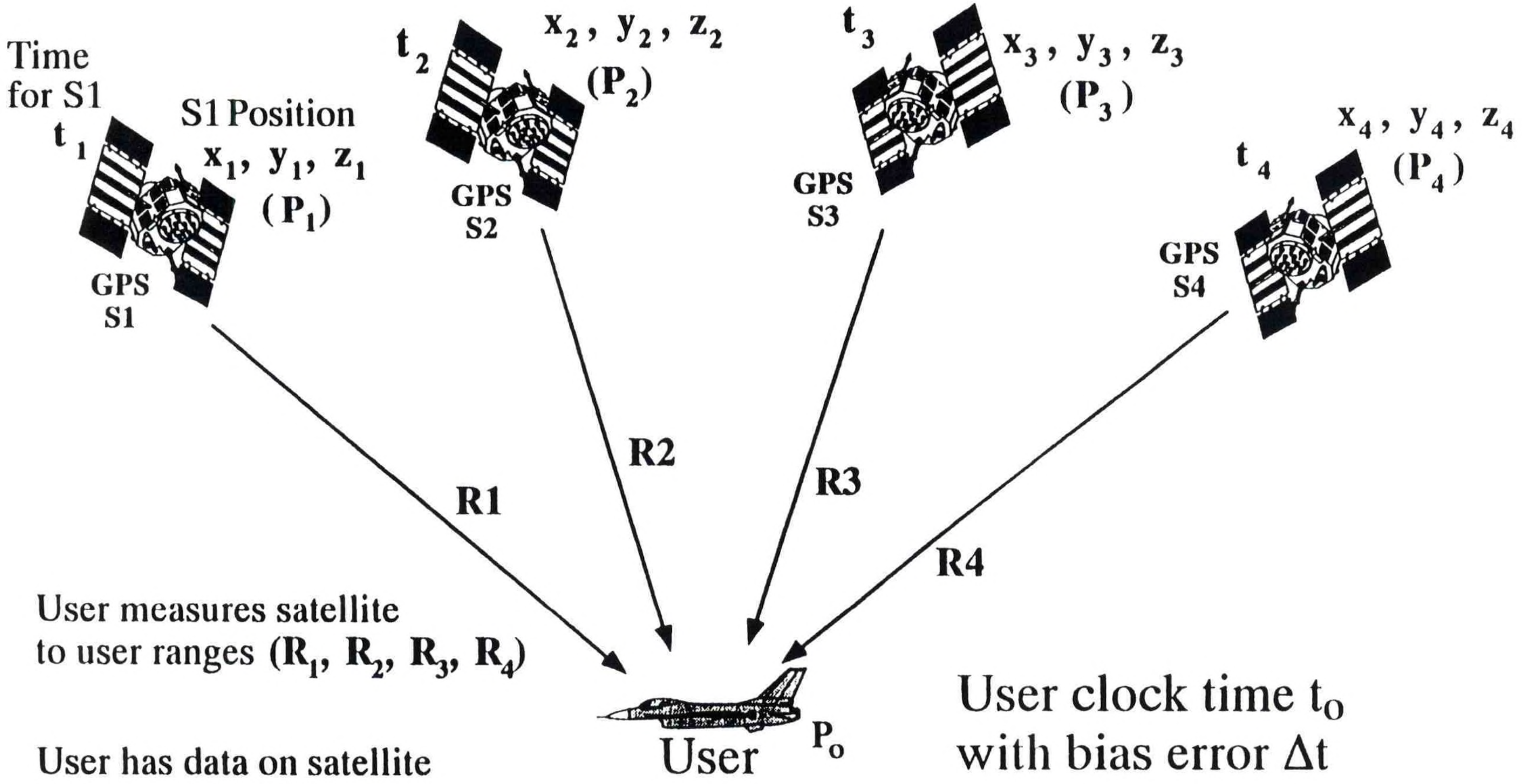
Acquisition of the GPS C/A Signal



Transit time:
$\Delta t_1 \sim 1/11$ sec
~ 93,000 bits

GPS Position Determination Technique

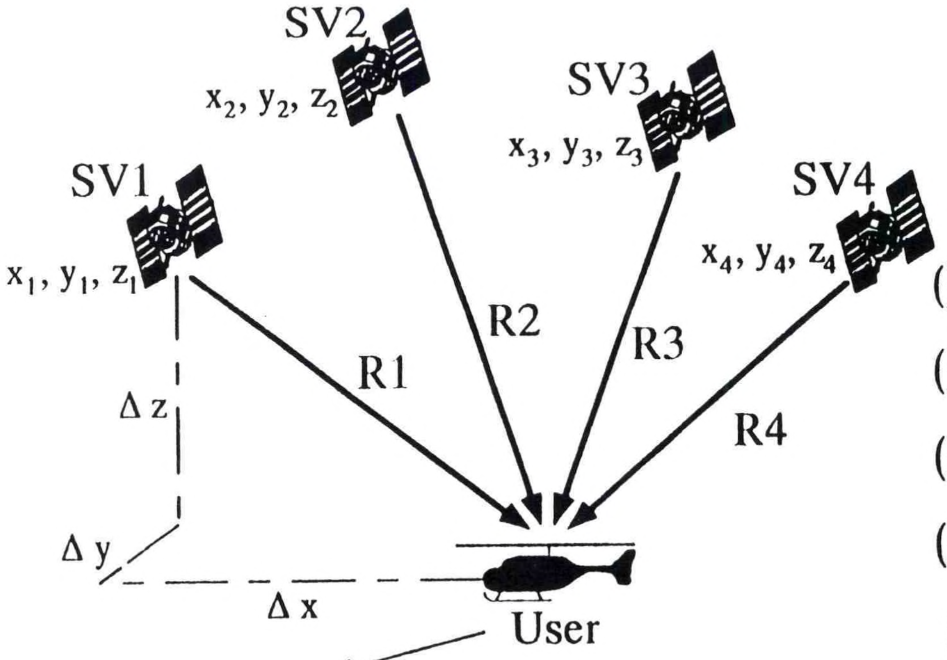


User measures satellite
to user ranges **(R_1, R_2, R_3, R_4)**

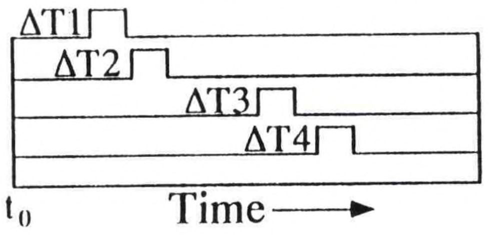
User has data on satellite
location **(P_1, P_2, P_3, P_4)**

User clock time t_o
with bias error Δt

GPS Navigation Solution



Measures four pseudo range ($\tilde{R}_i$) values



Signals transmitted by satellite

$\tilde{R}_1 = c\Delta T_1$

$\tilde{R}_2 = c\Delta T_2$

$\tilde{R}_3 = c\Delta T_3$

$\tilde{R}_4 = c\Delta T_4$

R_i = true range

$\tilde{R}_i$ = pseudorange

$R_i = \tilde{R}_i - c\Delta T_3$

Compute position coordinates
(Four equations with four unknowns)

$$(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (\tilde{R}_1 - c\Delta T_B)^2$$

$$(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (\tilde{R}_2 - c\Delta T_B)^2$$

$$(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (\tilde{R}_3 - c\Delta T_B)^2$$

$$(X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (\tilde{R}_4 - c\Delta T_B)^2$$

Solve for user's position coordinates
(U_x, U_y, U_z) and clock bias (ΔT_B)

Clock bias ranging error = $c\Delta T_B$

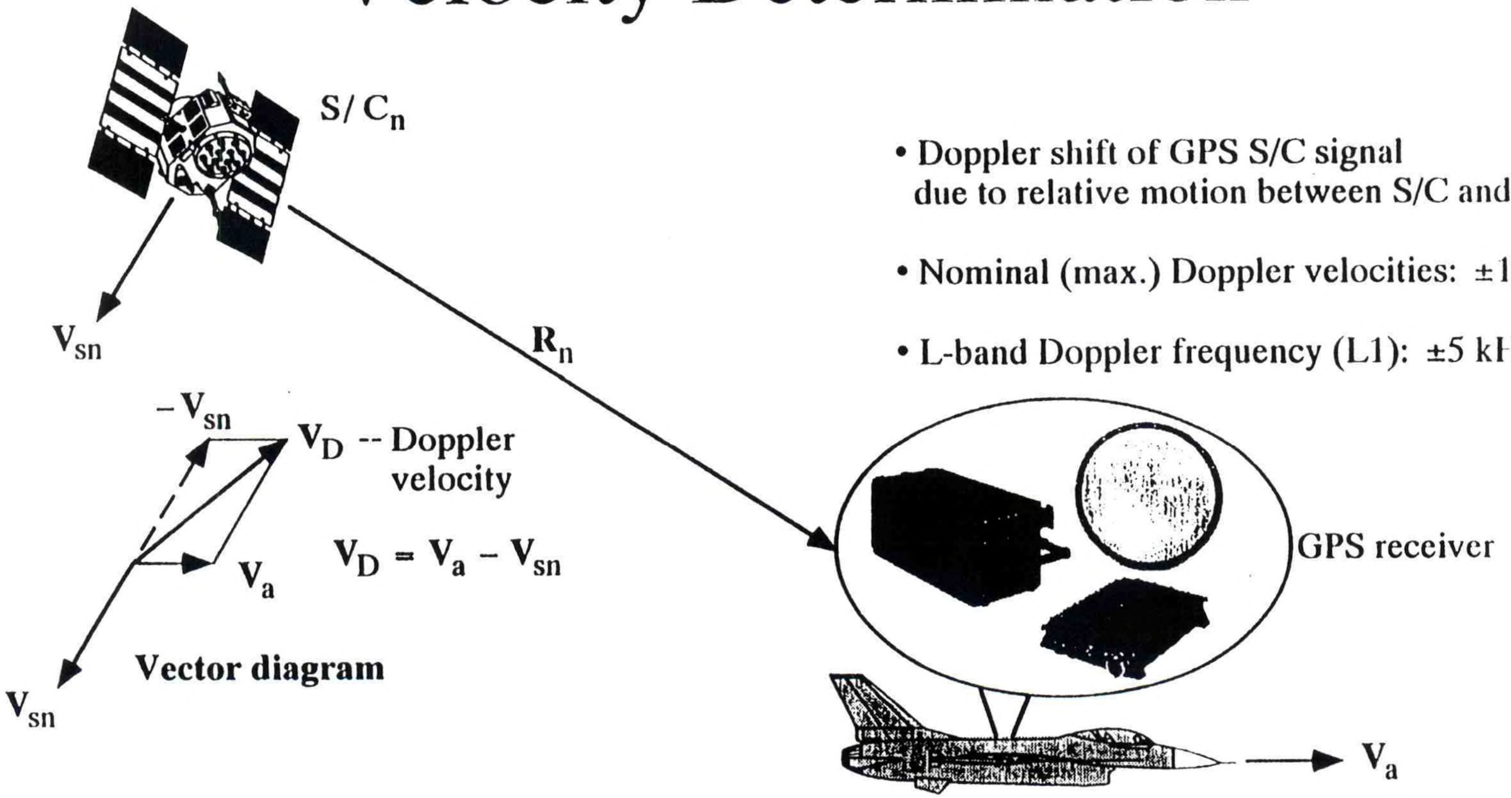
ΔT_B = user clock bias or timing error

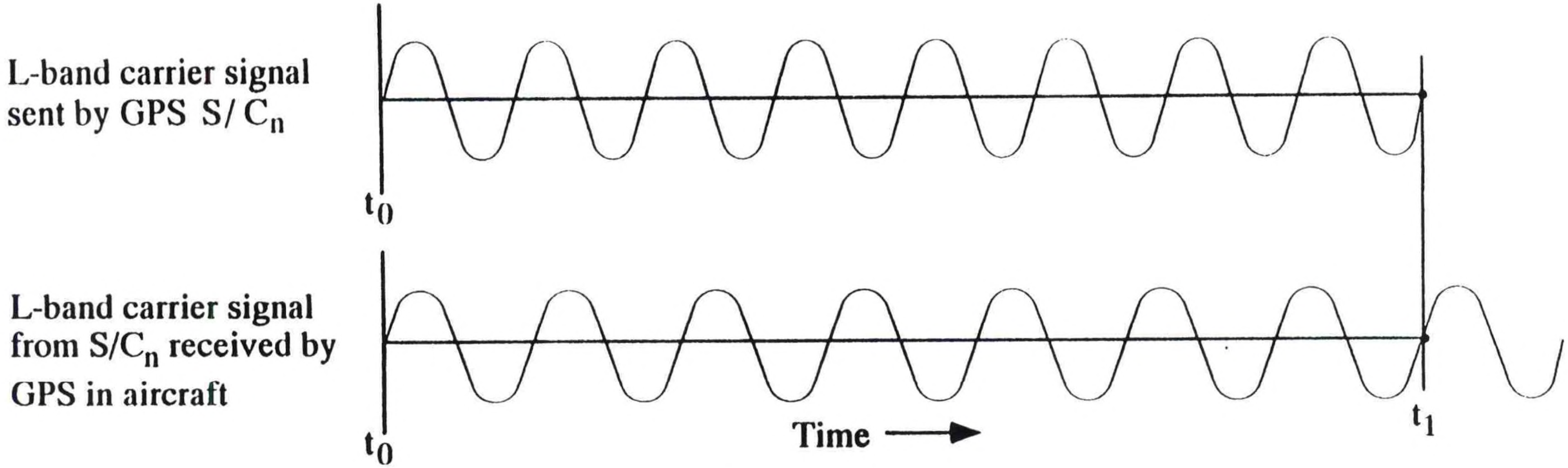
c = speed of light

Measured ΔT_n's include the user receiver clock (time) bias error (ΔT_B)

Velocity Determination

- Doppler shift of GPS S/C signal due to relative motion between S/C and A/C
- Nominal (max.) Doppler velocities: ±1000 mps
- L-band Doppler frequency (L1): ±5 kHz





Velocity Determination (cont'd)

Navigation Solution:

$$(x_i - u_x)^2 + (y_i - u_y)^2 + (z_i - u_z)^2 = (\tilde{R}_i - c\,B)^2 \quad ;$$

for i'th satellite, where i=1, 2, 3, 4

B is receiver clock bias (Δt), and $c\,B << R_i$

$\dot{B}$ is receiver clock drift (dB/dt)

Differentiating nav. solution with respect to time:

$$(x_i - u_x)(\dot{x}_i - \dot{u}_x) + (y_i - u_y)(\dot{y}_i - \dot{u}_y) + (z_i - u_z)(\dot{z}_i - \dot{u}_z) = R_i(\dot{R}_i - c\,\dot{B}) \; ; \qquad f_D = \dot{R}/\lambda ,$$

Doppler measurement

To obtain the 4 satellite velocity solution; and simplifying, by substituting for the pseudorange components $p_{xi} = x_i - u_x, \cdots$

$$p_{x1}(\dot{x}_1 - \dot{u}_x) + p_{y1}(\dot{y}_1 - \dot{u}_y) + p_{z1}(\dot{z}_1 - \dot{u}_z) = R_1(\tilde{R}_1 - c\dot{B})$$

$$p_{x2}(\dot{x}_2 - \dot{u}_x) + p_{y2}(\dot{y}_2 - \dot{u}_y) + p_{z2}(\dot{z}_2 - \dot{u}_z) = R_2(\tilde{R}_2 - c\dot{B})$$

$$p_{x3}(\dot{x}_3 - \dot{u}_x) + p_{y3}(\dot{y}_3 - \dot{u}_y) + p_{z3}(\dot{z}_z - \dot{u}_z) = R_3(\tilde{R}_3 - c\dot{B})$$

$$p_{x4}(\dot{x}_4 - \dot{u}_x) + p_{y4}(\dot{y}_4 - \dot{u}_y) + p_{z4}(\dot{z}_4 - \dot{u}_z) = R_4(\tilde{R}_4 - c\dot{B})$$

User velocity components

S/C$_n$ velocity components

Pseudorange components $x_i - u_x$

Measured pseudoranges (from navigation solution)

Measured pseudorange rates (Dopplers)

GPS Navigation Services

Precise Positioning Service (PPS)

- Military use GPS service (primarily)
- Higher precision capabilities than SPS
- High rate PN sequence used (P or Y code at 10.23 Mbps)
- Dual frequency (L1 and L2) operation with P/Y-codes available
- Full system accuracy available to authorized users (DoD and some others):

16 meters	(X, Y, Z) SEP	3D position (original GPS spec.)
22 meters	(X, Y) 2drms	2D position (horiz)*
29 meters	(Z) 2σ or 95%	Altitude*
90 nsec	(t) 95%	Time*
0.1 m/s	(v) 95%	Velocity vector (3D)

- Other characteristics of PPS:
  - Anti-jam capabilities (spread spectrum signal)
  - Selective availability (SA) degradation (on C/A and P/Y code)
  - Anti-spoof (A-S) encryption (onY code)
- Requires decryption techniques to access full performance capabilities (to decrypt Y-code and remove SA degradation)

* *1992 Federal Radionavigation Plan*, DoD/DoT, p. A-38 and A-39. Text values on p. A-39 are 22m for horizontal, 27.7 meters for vertical and 90 n sec. for time. This time accuracy is used in lieu of 200 nsec value in table on A-38. PPS accuracies are not given in 94 FRP.

GPS Navigation Services

Standard Positioning Service (SPS)

- Civil use system capability
- Dual frequency (L1 and L2 "carrier phase") operation
- Low rate PN sequence used (C/A-code at 1.023 Mbps) on L1
- Degraded accuracy for non-DoD users (selective availability, or SA). Accuracy of C/A-code on L1 is degraded.

100 meters	2 drms (x,y)	Horizontal (2D) position (95%)
150 meters	2 σ (z)	Vertical position
350 nsec	2 σ (t)	Time
0.3 m/s	2 σ (v)	Velocity vector (3D)

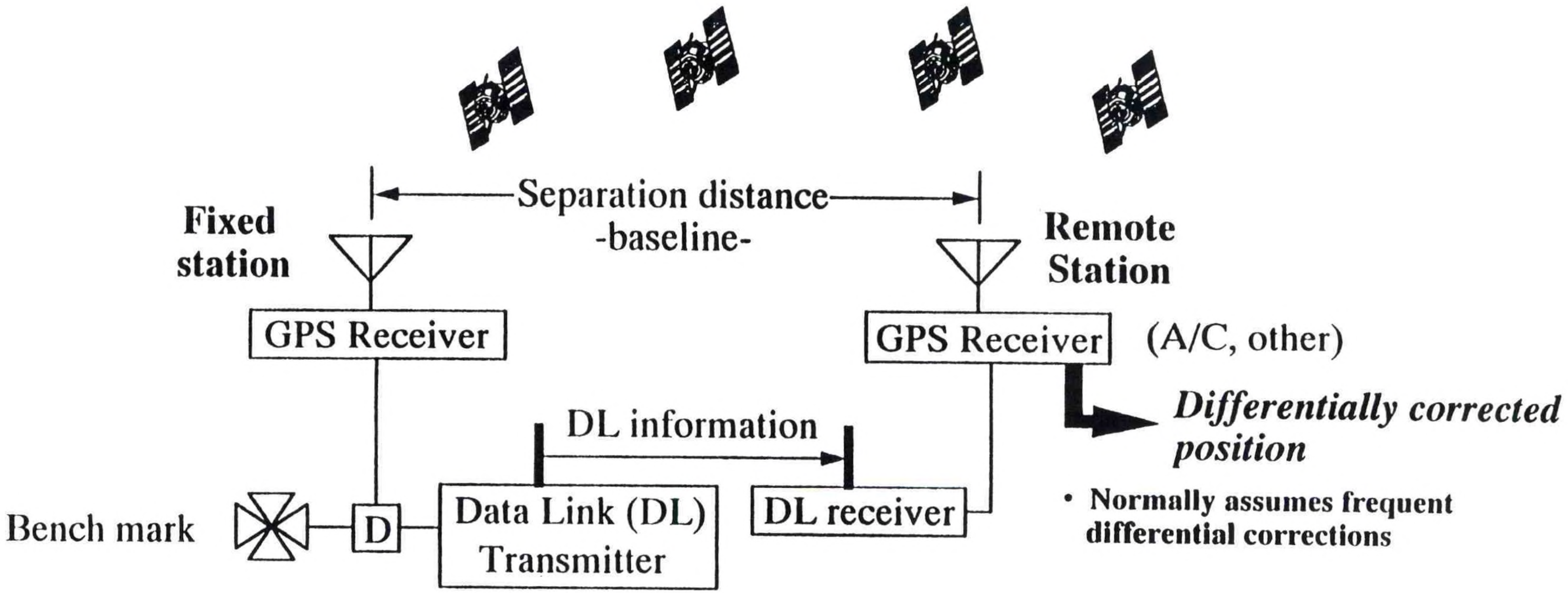
- Undegraded accuracy for authorized users (DoD and some others) 10 - 30m. (2drms)
- Civil accuracy degradable (further) when national policy dictates

GPS and GLONASS Representative System Error Budget for User Range Error

SPS Receiver (C/A Code)

Segment	Error Source	Error Budget (meters, 2σ)	RSS Calculation
Space	Clock stability	**3.3**	*10.9*
	Predictability of SV perturbations	**1.0**	*1.0*
	Other	**0.5**	*0.25*
Control	Ephemeris prediction	**4.3**	*18.5*
	Other	**0.5**	*0.25*
User	Ionospheric delay from model	**7.5**	*56.25*
	Tropospheric delay from model	**2.0**	*4.0*
	Receiver noise	**2.0**	*4.0*
	Multipath	**2.0**	*4.0*
	Other	**0.5**	*0.25*
	2σ UERE	**10.0m**	$\sqrt{99.4}$

Differential GPS Principle of Operation (Simplified - ECEF Technique)



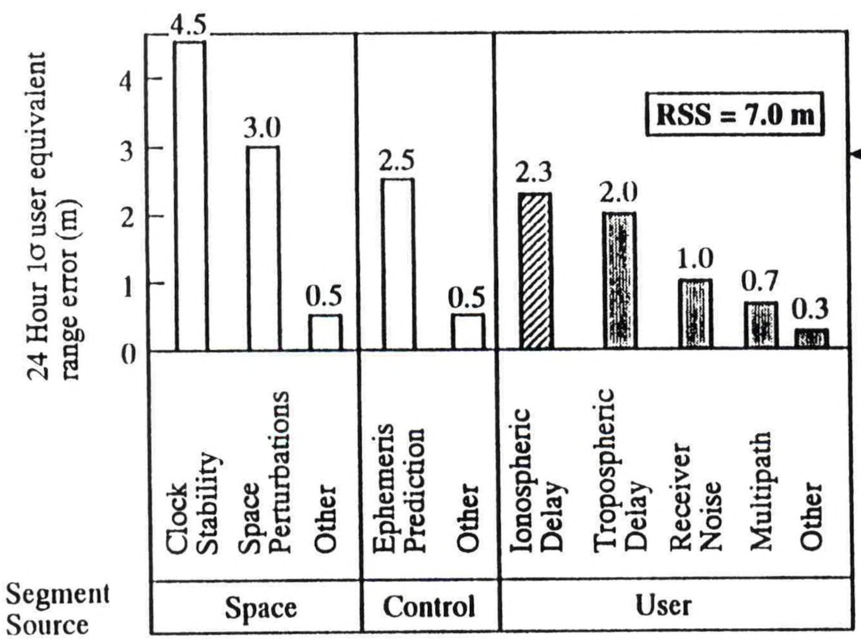
- **Normally assumes frequent differential corrections**

Navigation Accuracy Calculations

Precise Positioning Service (PPS)
P or Y Code

Normal Operation

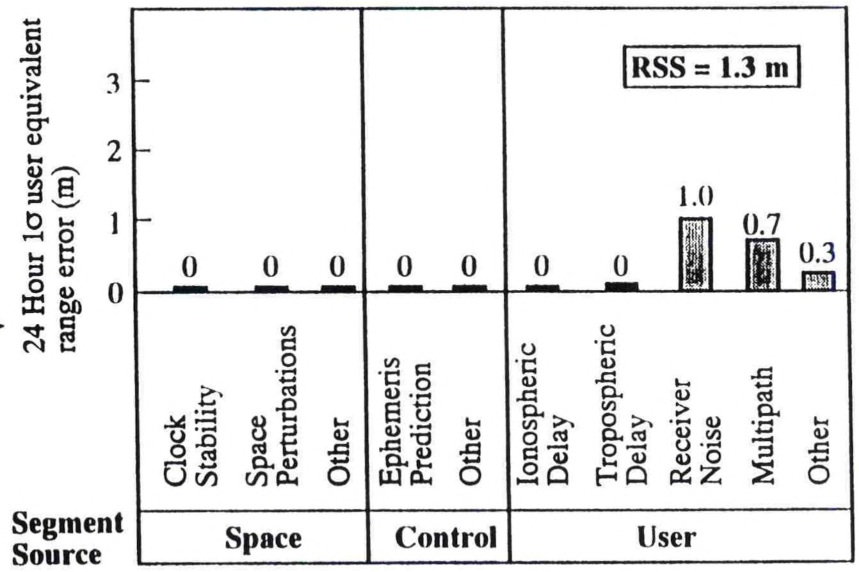
Error Components



Nav Accuracy ~ GDOP x UERE
~ 2.3 x 7.0 m
~ 16 m

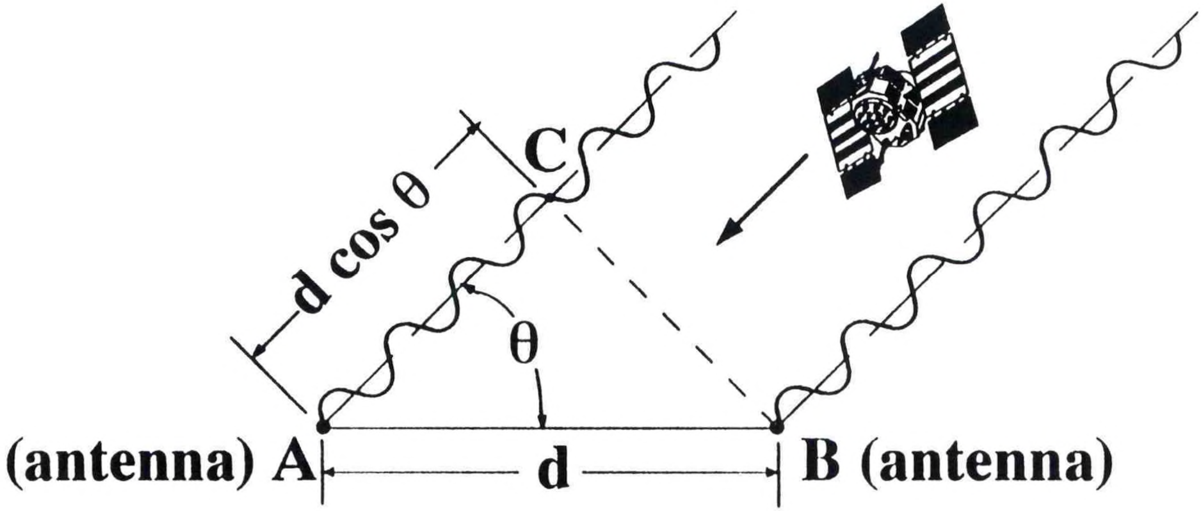
Differential Operation

Error Components



Nav Accuracy ~ GDOP x UERE
~ 2.3 x 1.3 m
~ 3.0 m

Differential Measurement of the Carrier Phase Observable (Interferometry)



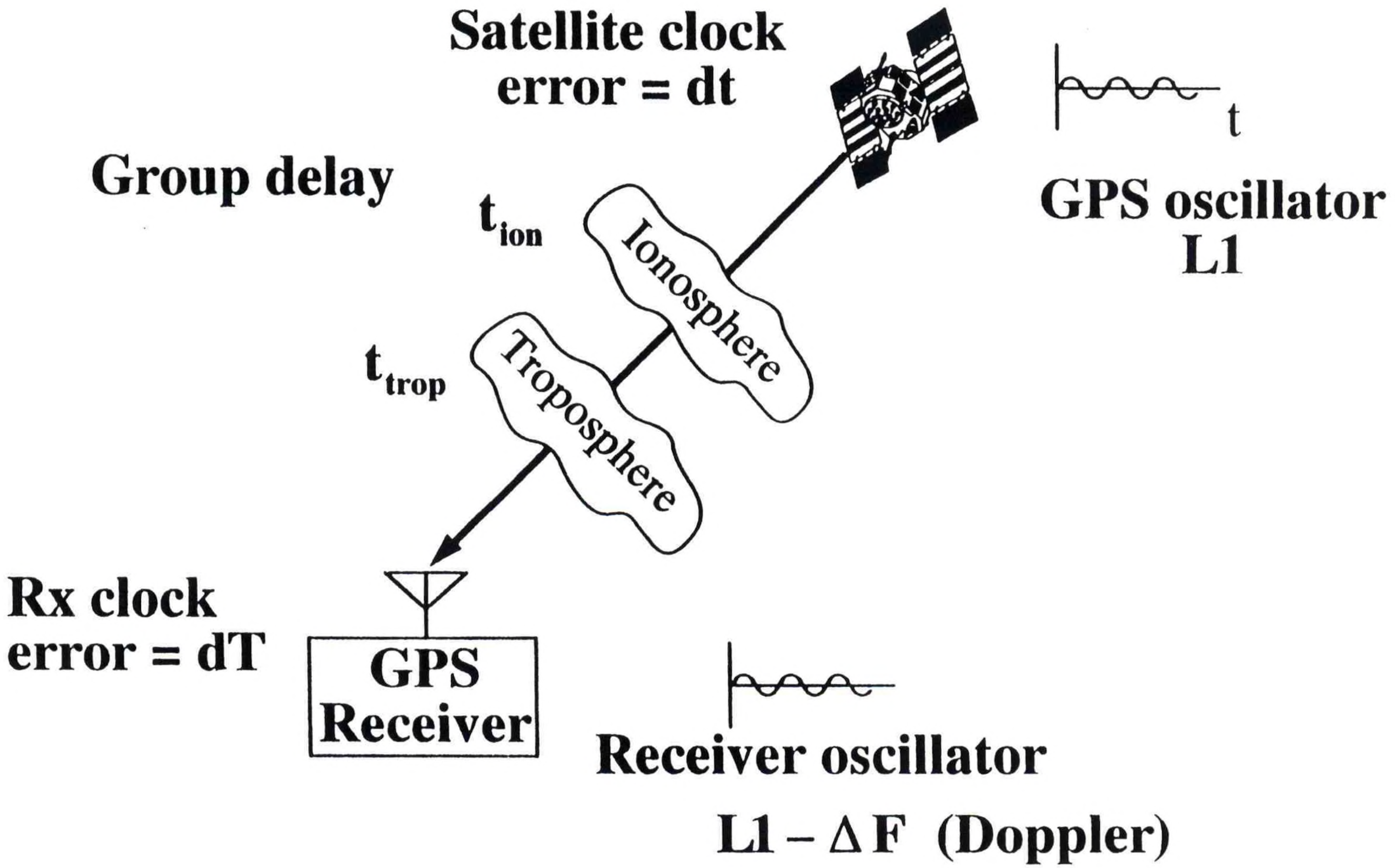
Carrier phase difference measured between antennas A and B is phase difference, m, (in cycles) along distance AC (baseline)

To solve for d: $d \cos \theta = \phi + N \lambda$

Concerns:

- **Unknown integer cycle ambiguity in measured N**
- **Clock bias errors between receivers and among satellites**

Carrier Phase Measurement
(With Carrier or Beat Signal Phase Observable)



Satellite clock
error = dt

GPS oscillator
L1

Group delay

t_{ion}

t_{trop}

Rx clock
error = dT

GPS
Receiver

Receiver oscillator

L1 – Δ F (Doppler)

Carrier phase observable:

$$\phi = \rho / \lambda + f(dT - dt) - f(t_{trop} - t_{ion})$$

GPS Military Applications

• En route navigation

Low-level navigation

Target acquisition

Close air support

Missile guidance

Command and control

All-weather air drop

Sensor emplacement

• Precision survey

• Space navigation

• Approach and landing

Rendezvous

Coordinate bombing

Remotely piloted vehicle operations

Barebase operations

Search and rescue •

Photo-reconnaissance

ELINT annotation

Satellite tracking and navigation •

Range instrumentation •

Inertial update •

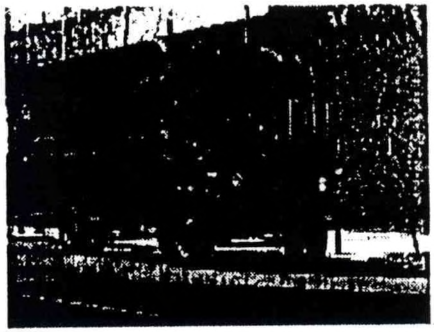
Mine emplacement & countermeasures

• = Common with civil applications

GPS Civil Applications

Static Positioning/Timing

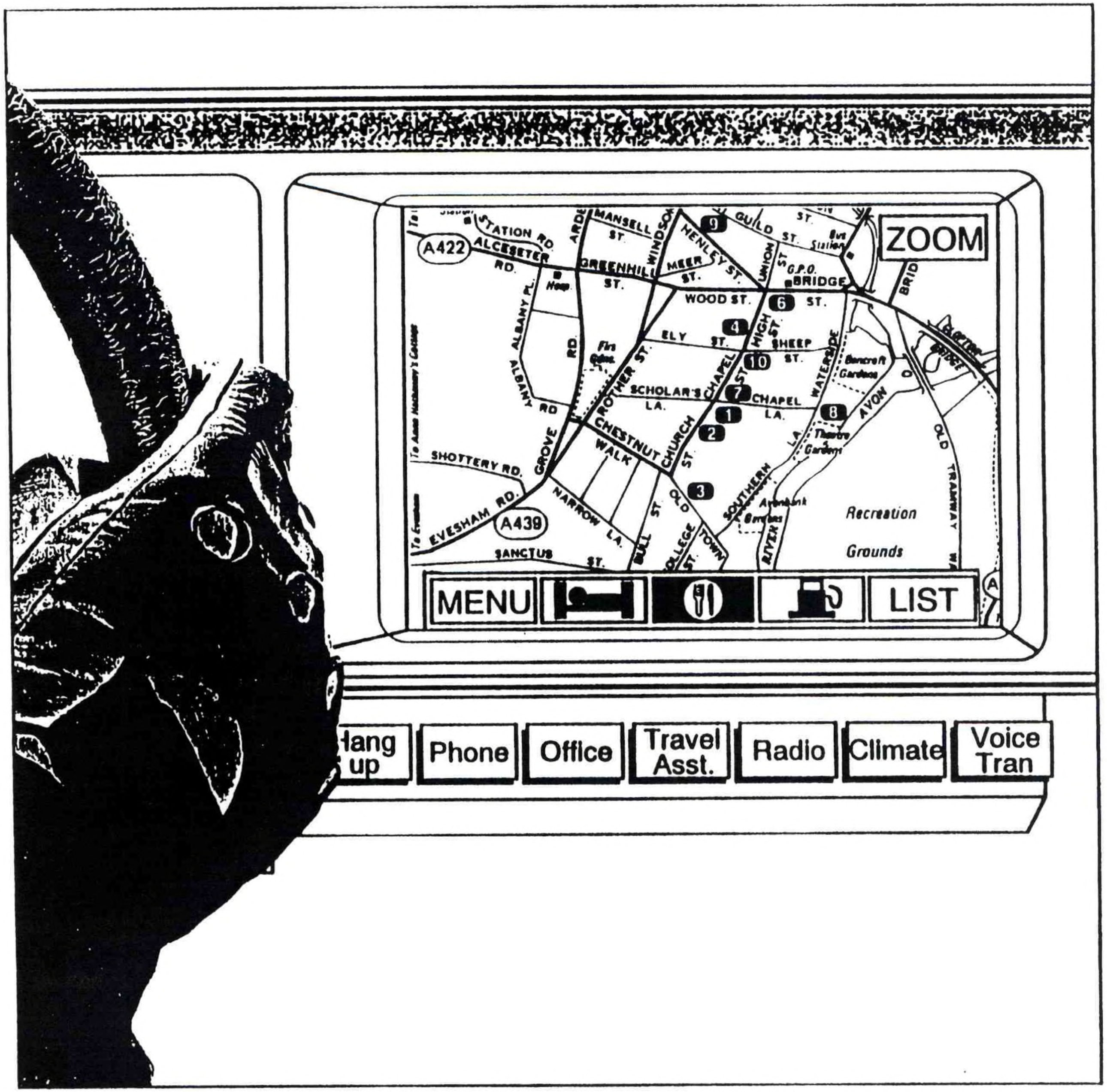
- Offshore resource exploration
- Hydrographic surveying
- Geophysical surveying
- Navigation aid
- Precise time transfer



Land Navigation

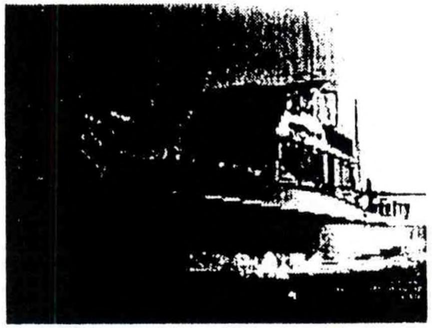
- Vehicle location monitoring
- Adaptive scheduling
- Minimal routing
- Law enforcement

Vehicular Location System Dashboard Display



OV800a

GPS Civil Applications



Maritime Navigation
- Oceanic and coastal regions
- Harbor approach
- Inland waterways
- Vessel location monitoring

Search and Rescue
- Accurate search capability
- Position monitoring
- Search coordination
- Rendezvous precision
- Collision and hazard avoidance

91

Summary

User Equipment

- GPS military equipment buys (Rockwell Collins, SCI)
  - Phase III buy (Collins, SCI) ~27,000+ UE's
  - DoD SLGR's: ~12,000;
  - DoD PLGR's: ~60-100,000
- **Military test program** very successful
- DoD vehicle **integrations** proceeding at a fast pace
- **Accuracy** better than specifications
- **Civil GPS market** developing rapidly
- Approximately 300,000+ civil UE's by end of 1993 (cum.)
  600,000+ civil UE's by end of 1994 (cum.)
  Estimated 2,000,000 + civil UE's by end of 1996
- GPS equipment, systems and services projected to be an $8-10 billion industry by the year 2000

Control Segment

- **OCS operational** by USAF with MCS at CSOC
- 5 monitor and 4 upload (transmit) stations functional

Space Segment

- 27 Block II SV's launched on Delta II's:
  II-1 on 14 Feb 89 (1st)
  II-27 on 12 Sept 96 (most recent)
- **IOC:** 10 Dec 93: **FOC:** 27 April 95
- **Block IIR SV's** in production, storage, or delivery for launch;
  Block IIF's under contract, progressing
- First Block IIR launched 17 Jan 97 - LV failed, satellite destroyed
- GPS constellation providing excellent **worldwide 3D coverage**

Significant GPS Operational Satellite (Block II) Subsystem Features

Delta II Launch

- 1 GPS/MLV
- 26+ planned

TT&C (Tracking, Telemetry & Control)

- S-band SGLS uplink; downlink
- Signal encryption
- 0.5 & 4K data rates

TCS (Thermal Control System)

- Temperature controllers for frequency standards
- 1.67 sq. m. heat louvres
- Multilayer insulation
- Coatings & finishes

AVCS (Attitude/Velocity Control System)

- All-year Δv opportunity
- 2.5 year spin on-orbit storage mode
- Active nutation control
- Stored commands for magnetic momentum dumping

L-Band Signals

- Radio astronomy band protection
- L1 (1575.42 MHz)-160.0 dBw: C/A code
- L1 -163.0 dBw: P code
- L2 (1227.6 MHz) - 166.0 dBw C/A or P code
- Anti-spoof encryption of P code (Y)
- Selective Availability on C/A and P/Y code

Navigation Payload

- 2 Rb + 2 Cs atomic standard clocks
- 14-day nav data storage (IIA:180-day)
- Hardened processor parts

Structure

- Integral box structure
- Thrust cone/cylinder
- 1.95 sq. m. radiating area

Electrical Power

- 7.5 year EOL 700W
- 3 35-AH Nicad batteries

Reaction Control System

- X,Y, & Z axes Δv thrusters
- Minimized plume impingement
- >10-year consumables

Orbit Insertion

- Star 37 XF solid rockets
- 26.5° orbit plane change capability

Lifetime

- 6-year MMD
- 7.5-year design goal

2.4 Wide-Area and Local-Area Augmentation System

Richard R. Domikis

SATNAV

SATELLITE NAVIGATION

FAA GPS WAAS Overview

Richard Domikis
FAA /Overlook Systems Technologies Inc.
WAAS S ystems Engineering Team

Abstract

WIDE-AREA AUGMENTATION SYSTEM

Richard R. Domikis
Federal Aviation Administration
Vienna, VA

Today, no single technology has more broad-reaching potential for worldwide civil aviation than the future applications of satellite technology. These applications represent the greatest opportunity to enhance aviation system capacity, efficiency, and safety since the introduction of radio-based navigation systems more than 50 years ago.

The benefits of satellite navigation over those of traditional navigation systems are significant. Satellite-based systems achieve greater accuracy than most existing land-based systems. Furthermore, because the satellite signals are available over large areas, it represents a unique opportunity for the international aviation community to start converging toward the goal of a single, integrated Global Navigation Satellite System (GNSS). This will eventually allow aviation users to reduce the number of different types of receivers required for navigation services for all phases of flight. Coupled with satellite communications, satellite-based navigation will contribute to increased safety and efficiency of international civil aviation by supporting real-time surveillance of aircraft and reducing the separation requirements—and increasing the number of flights possible—on busy trans-oceanic routes that represent the most favorable routes between origins and destinations.

The transition from various ground-based systems to a common satellite-based navigation system will require tremendous cooperation among international civil aviation authorities, governments, and industry representatives and users. The FAA is extensively involved in this transition and has made the commitment to move from its own ground-based system to one that will rely primarily on satellite navigation. This transition will not only prepare the U.S. National Airspace System (NAS) to meet the demands placed upon it by ever increasing aviation operations, but will serve the goals of the international community by beginning the transition to a seamless worldwide global satellite navigation system.

For aircraft navigation, the basic GPS service does not satisfy all civil aviation requirements. In specific, *Accuracy*: The difference between the measured position at any given time to the actual or *true* position. *Availability:* The ability of the system provide usable navigation service within the specified coverage area (volume). *Integrity:* The ability of the system to provide timely warnings to users, or to safely shut itself down when it should not be used for navigation. Augmenting GPS to fulfill these requirements is critical to the safety of flight and aircraft navigation.

The Wide Area Augmentation System (WAAS) is being developed to meet all En-Route through Precision Approach requirements for civil aviation, by providing a signal that will augment the existing GPS signals. This design will improve navigation accuracy to approximately 7 meters vertically and horizontally, improve system availability through the use of geostationary communication satellites (GEOs) carrying navigation payloads, and to provide timely integrity information about the entire GPS and WAAS GEO constellation.

WAAS is designed to cover a large service volume (Continental US, Alaska, Hawaii and Puerto Rico). Wide area Reference Stations (WRSs) will be linked to a U.S. WAAS communications network. These precisely surveyed ground reference stations collect GPS and WAAS GEO signals. Each station in the network relays the data to the Wide area Master Stations (WMSs) where errors, caused by clock errors, ephemeris errors, ionosphereic delay, and tropospheric delay are quantified. Relevant correction information is computed from these errors. A correction message is prepared and uplinked to a GEO via a Ground Uplink Station (GUS). The message is then broadcast on the same frequency as GPS (L1, 1575.42 MHz) to receivers on board aircraft that are flying within the broadcast coverage area of the WAAS GEOs.

The benefits of WAAS to civil aviation will be substantial. WAAS will improve the efficiency of aviation operations many areas:

(i) Increase the number of operations a runway can support

(ii) Reduced separation standards resulting in increased capacity in a given airspace without increased risk

(iii) More direct enroute flight paths resulting in decreased time in flight

(iv) New precision approach services resulting in an increase of airports supporting PA operations

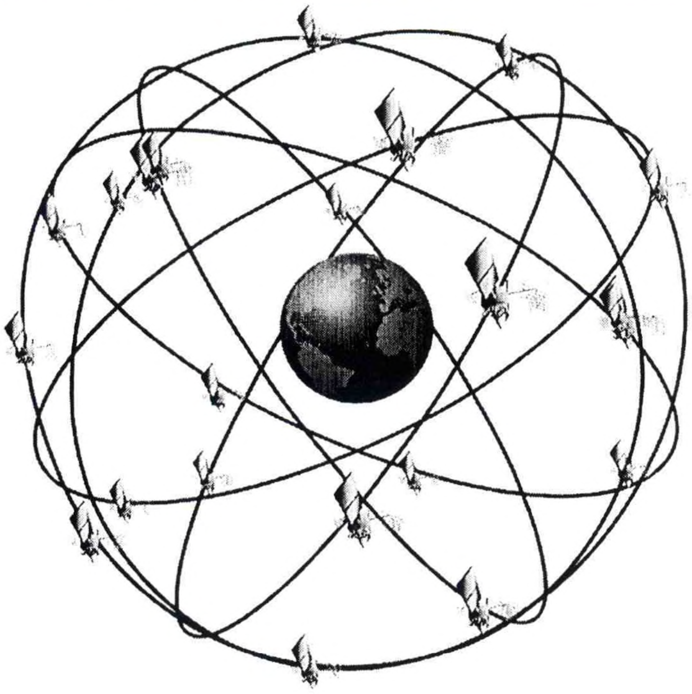
(v) Reduced and simplified equipment on board aircraft

Significant government cost savings due to the elimination of maintenance costs associated with older, expensive ground-based navigation aids (to include NDBs, VORs, DMEs, and most Category 1 ILSs).

Satellite Navigation Program
Objective

- Augment GPS to Enable Satellite Navigation to Become a Primary Means Navigation and Landing System For All Phases of Flight Including Precision Approaches by:
  - Implementing the ***Wide Area Augmentation System (WAAS)*** For All Phases of Flight Down to Category 1 Precision Approaches
  - Implementing the ***Local Area Augmentation System (LAAS)*** to Provide Category 2/3 Precision Approach and Landing Capability and Supplement the WAAS, if Required

Basic GPS System



- **Space Segment**
  - 24 Satellites
  - 6 Orbital Planes
  - 4 Satellites per Plane
  - Orbit at Approximately 11,000 Nautical Miles Above the Earth
  - Orbits Every 12 Hours
- **Ground Control Segment**
  - Master Control Station, Colorado Springs
  - 5 Monitor Stations at Worldwide Locations

Basic GPS
Civil Aviation Benefits

SATNAV
SATELLITE NAVIGATION

Available to All Nations Today, Free of Direct User Charges

- Improves Aviation System Safety
- Available for Primary use in the Oceanic Phase of Flight
- Available for Supplemental use for Enroute, Terminal, and Non-precision Approach Phases of Flight
- Cost Effective Resource for Nations With Limited Air Navigation Infrastructures
- Can Reduce or Eliminate Maintenance Costs Associated With Older, Expensive Ground-based Navigation Aids

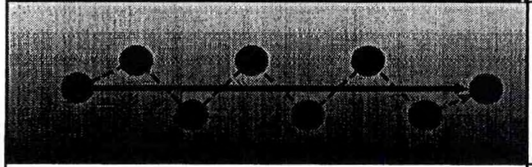
Basic GPS System Limitations

Does not Satisfy Civil Aviation Requirements for Primary Means Navigation:

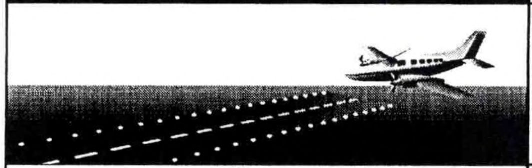
- **Integrity**
  - Notification Time: 15 Minutes or Greater
  - Not Sufficient for Civil Aviation
- **Availability**
  - 24 Satellites - 70%
  - 21 Satellites - 98%
  - Not Sufficient for Primary Means Navigation
- **Accuracy**
  - Enroute Through Non-precision - OK (100m)
  - Not Sufficient for Precision Approaches

Benefits of WAAS

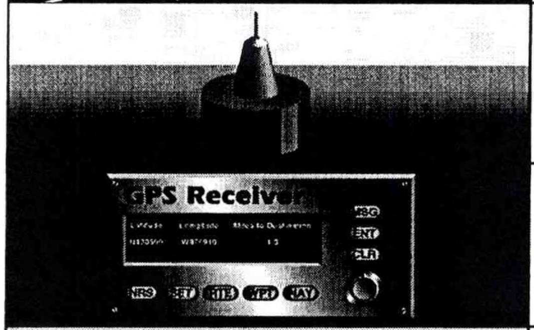
Primary Means of Navigation - Take-Off, En Route, Approach and Landing



More Direct Routes - Not Restricted By Location of Ground-Based Navigation Equipment

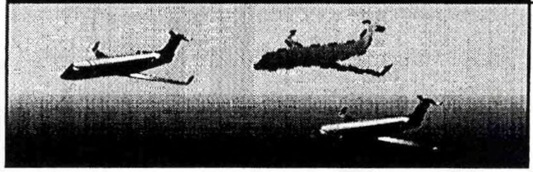


Precision Approach Capability - At Any Qualified Airport in U.S.



Decommissioning of Older, Expensive Ground-Based Navigation Equipment

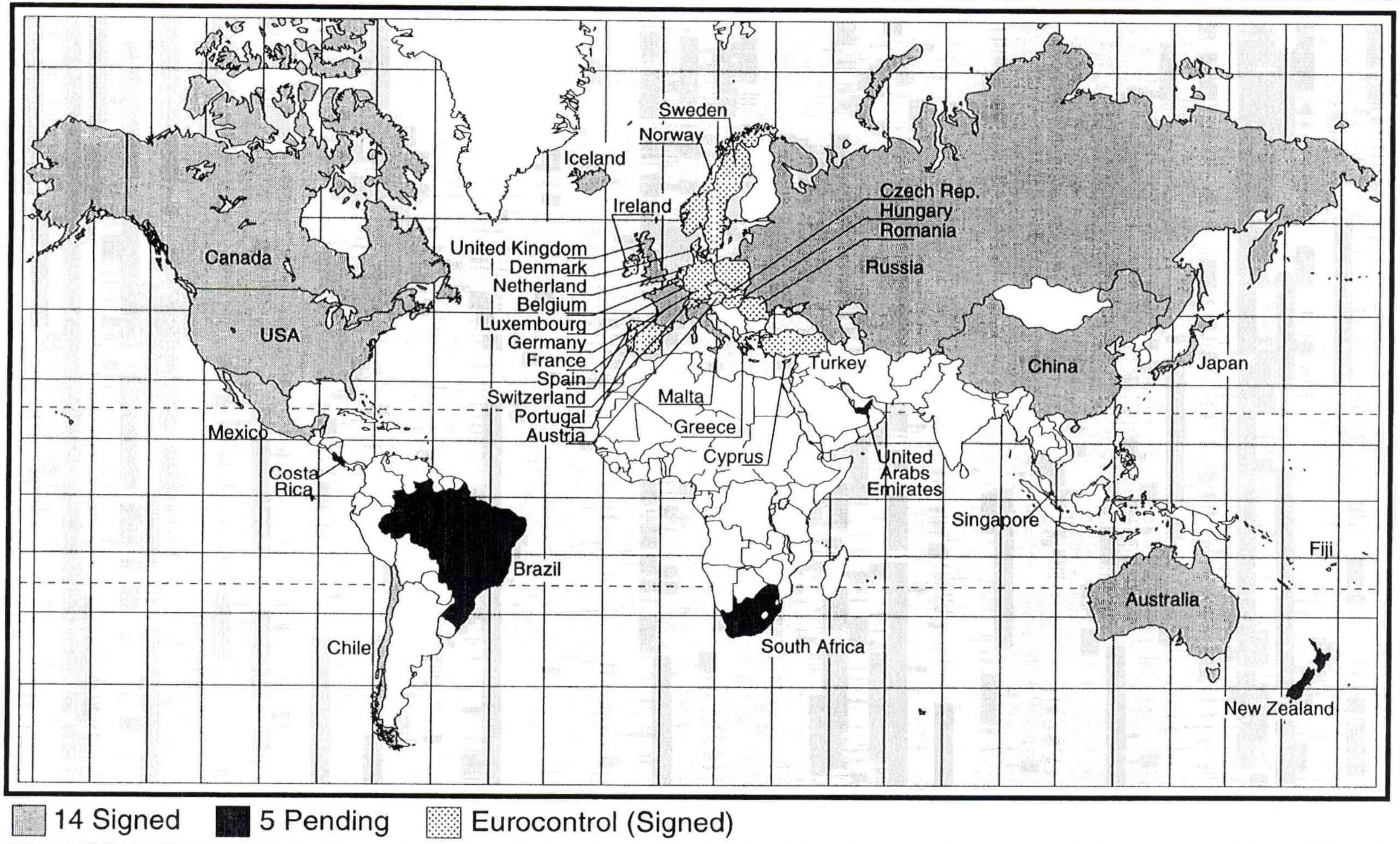
Reduced/Simplified Equipment On Board Aircraft



Increased Capacity - More Aircraft Allowed in Given Airspace Without Increased Risk

Bilateral Satellite Navigation Agreements

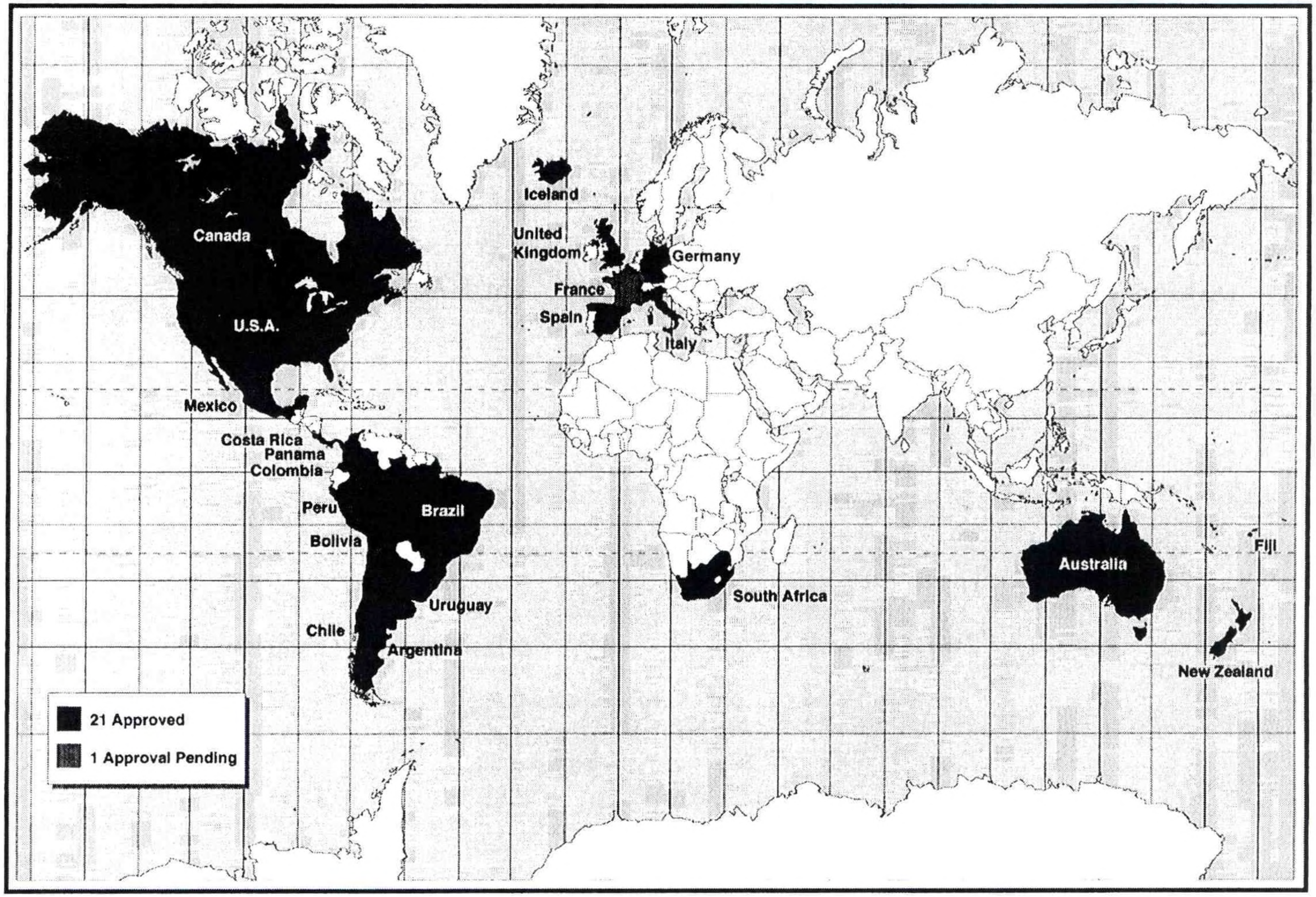
SATNAV
SATELLITE NAVIGATION



10/31/97 Tijuana/NBAA FAA 357- 4

FAA 319-02

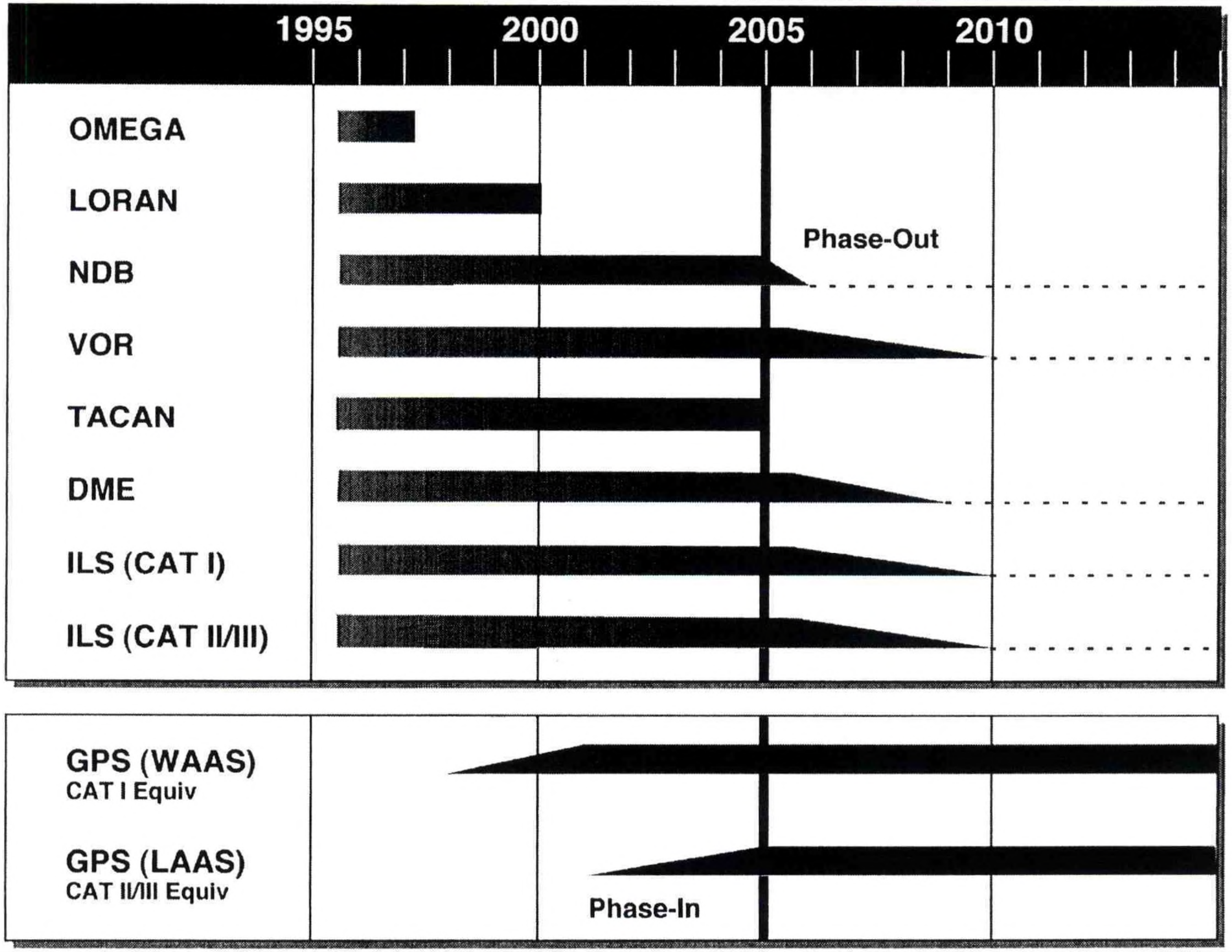
GPS Approved for Supplemental Means of Navigation



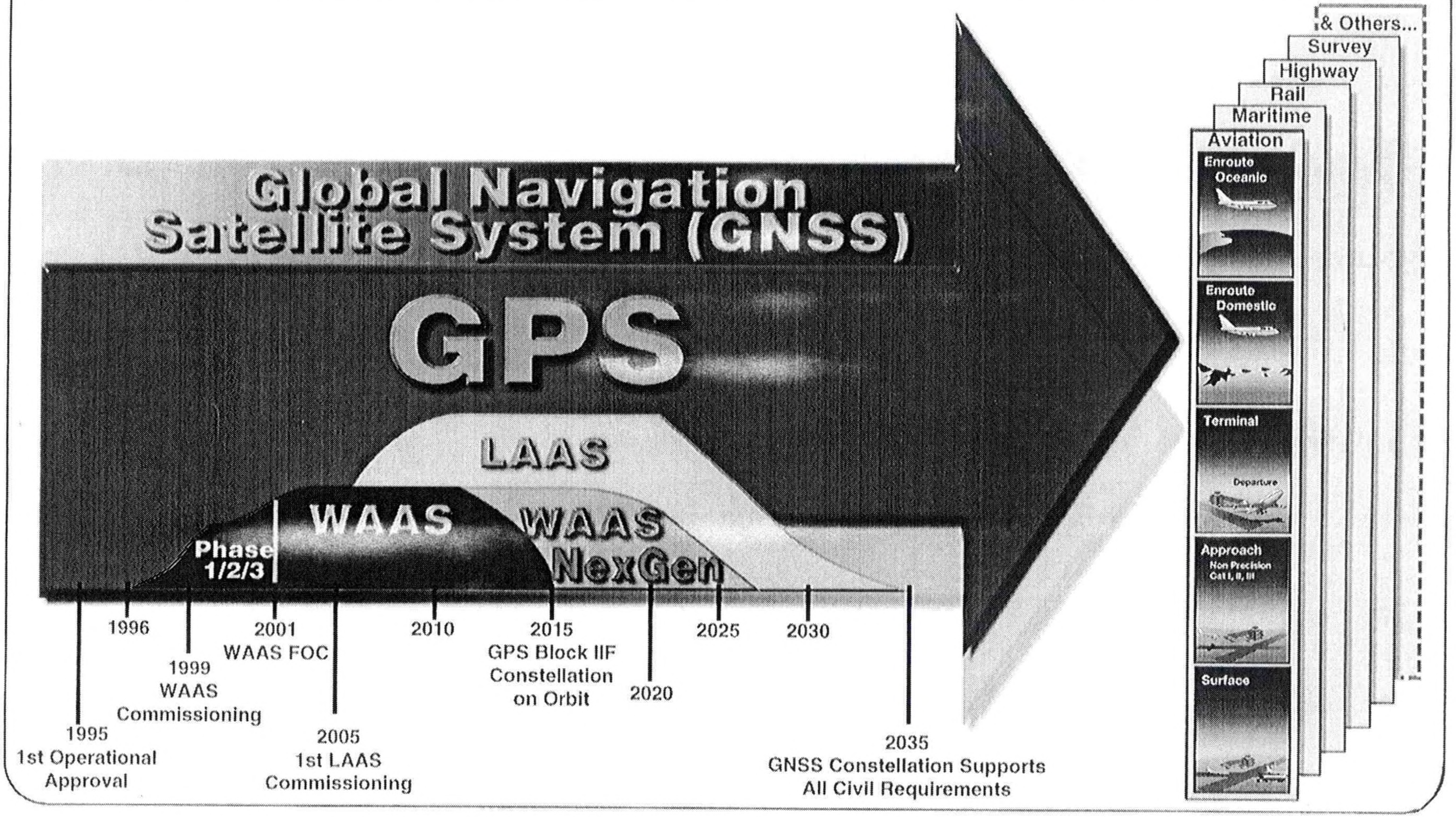
10/31/97 Tijuana/NBAA FAA 357- 3

FAA 345-01

Navigation Transition



Satellite Navigation Implementation



Global Navigation Satellite System (GNSS)

GPS

LAAS

WAAS

Phase 1/2/3

WAAS NexGen

1995 1st Operational Approval

1996

1999 WAAS Commissioning

2001 WAAS FOC

2005 1st LAAS Commissioning

2010

2015 GPS Block IIF Constellation on Orbit

2020

2025

2030

2035 GNSS Constellation Supports All Civil Requirements

& Others...

Survey

Highway

Rail

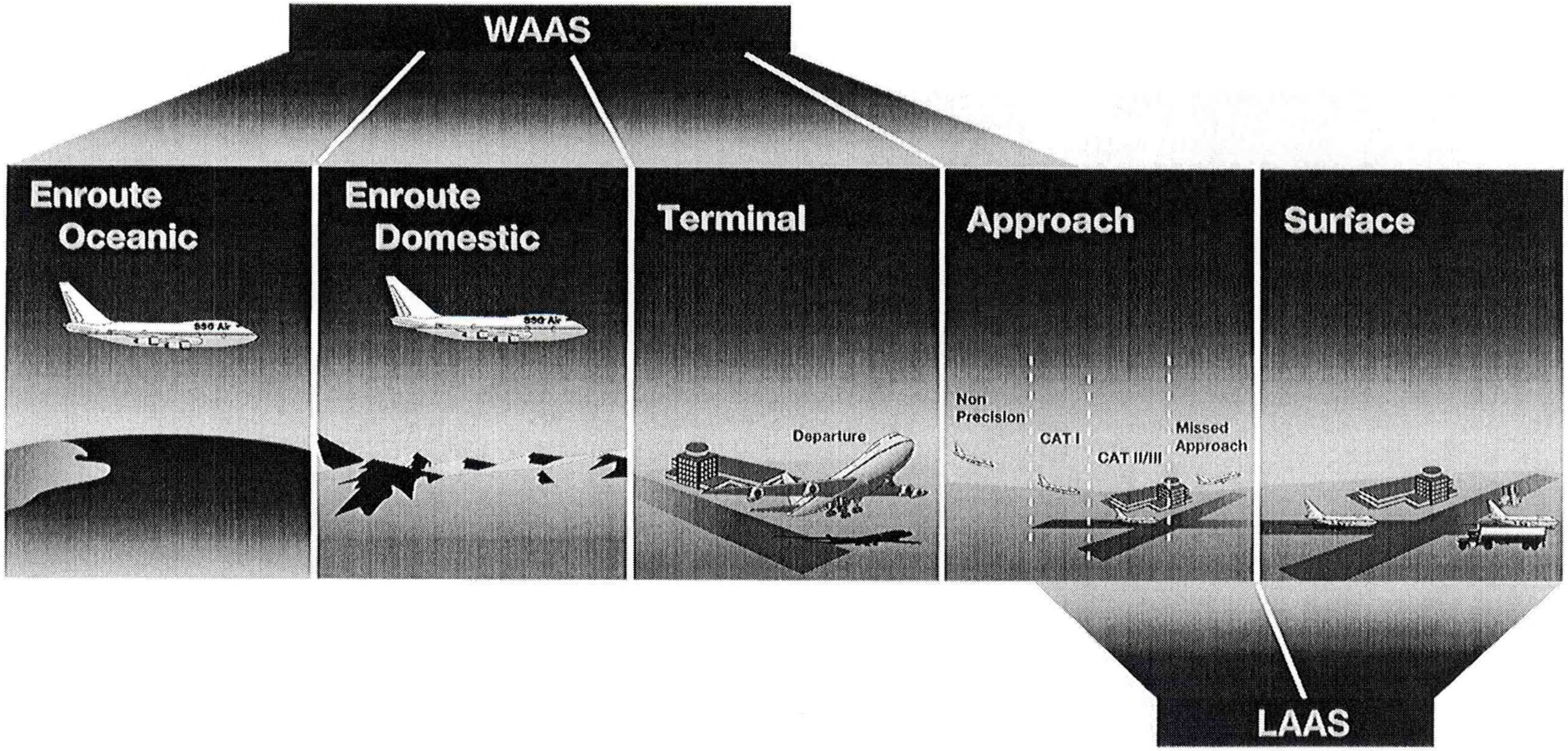
Maritime

Aviation

10/31/97 Tijuana/NBAA FAA 357- 2

FAA 333-10c

Satellite Navigation's Mission
WAAS/LAAS Implementation



WAAS

Enroute Oceanic

Enroute Domestic

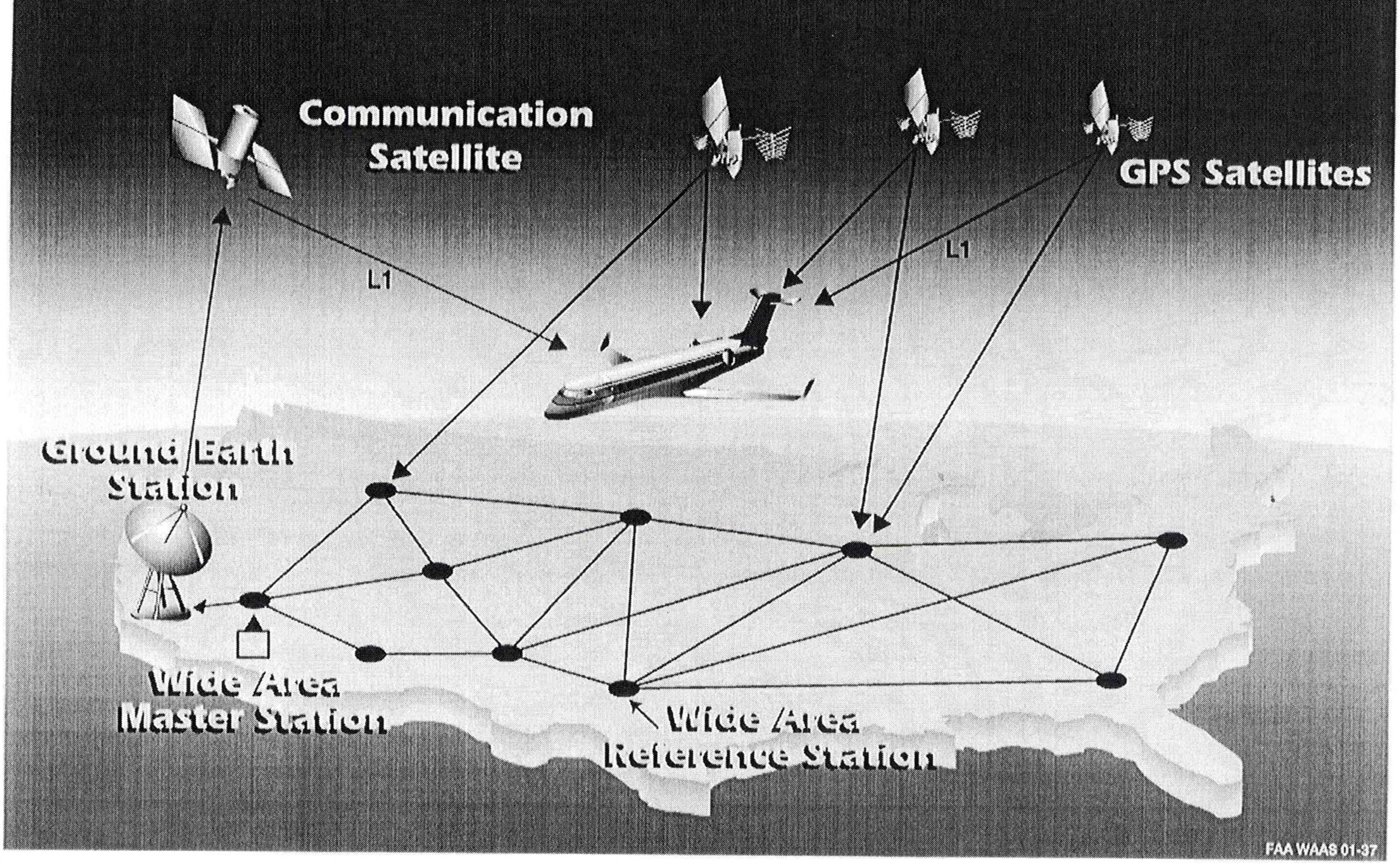
Terminal

Approach

Surface

LAAS

Wide Area Augmentation System



Communication Satellite

GPS Satellites

L1

L1

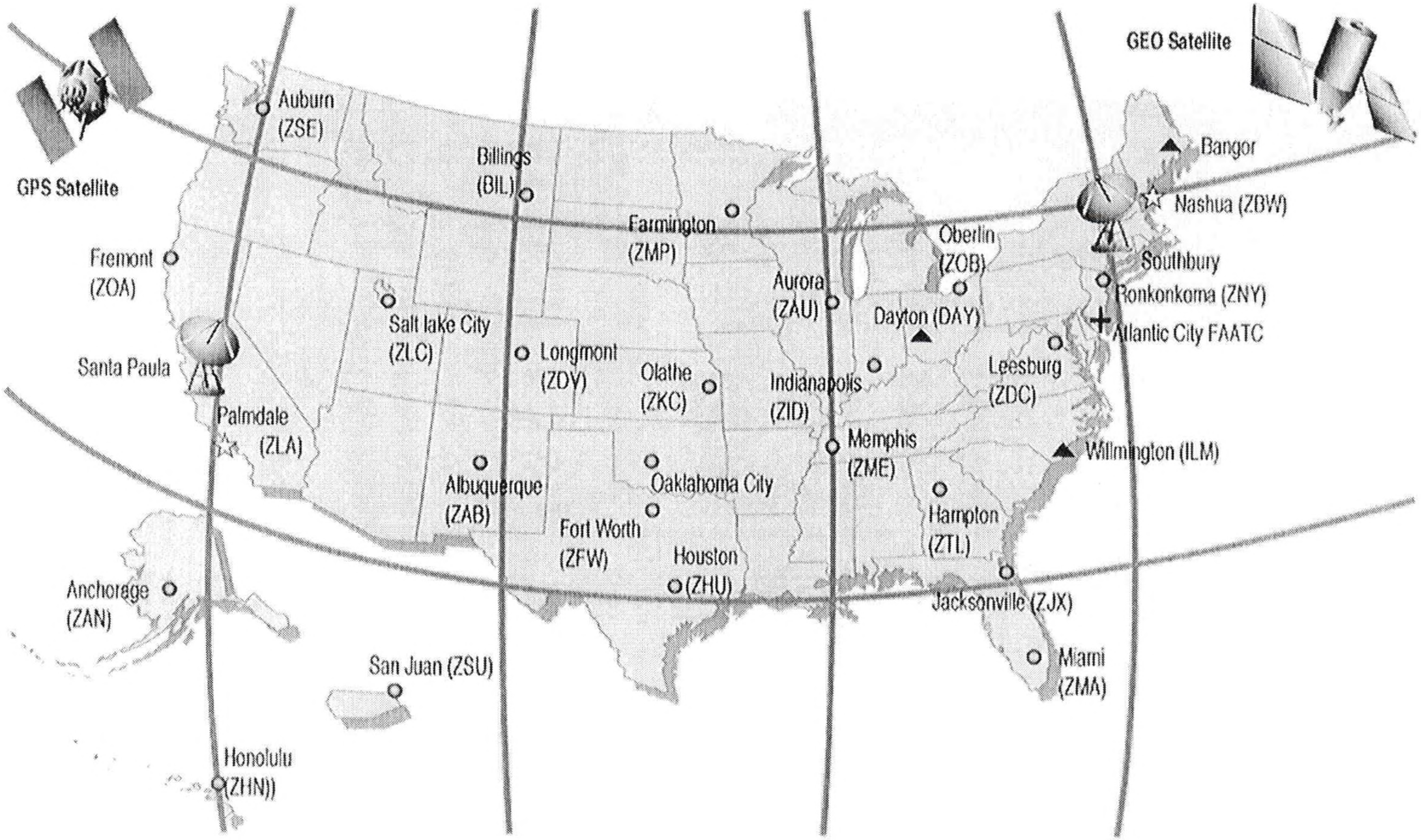
Ground Earth Station

Wide Area Master Station

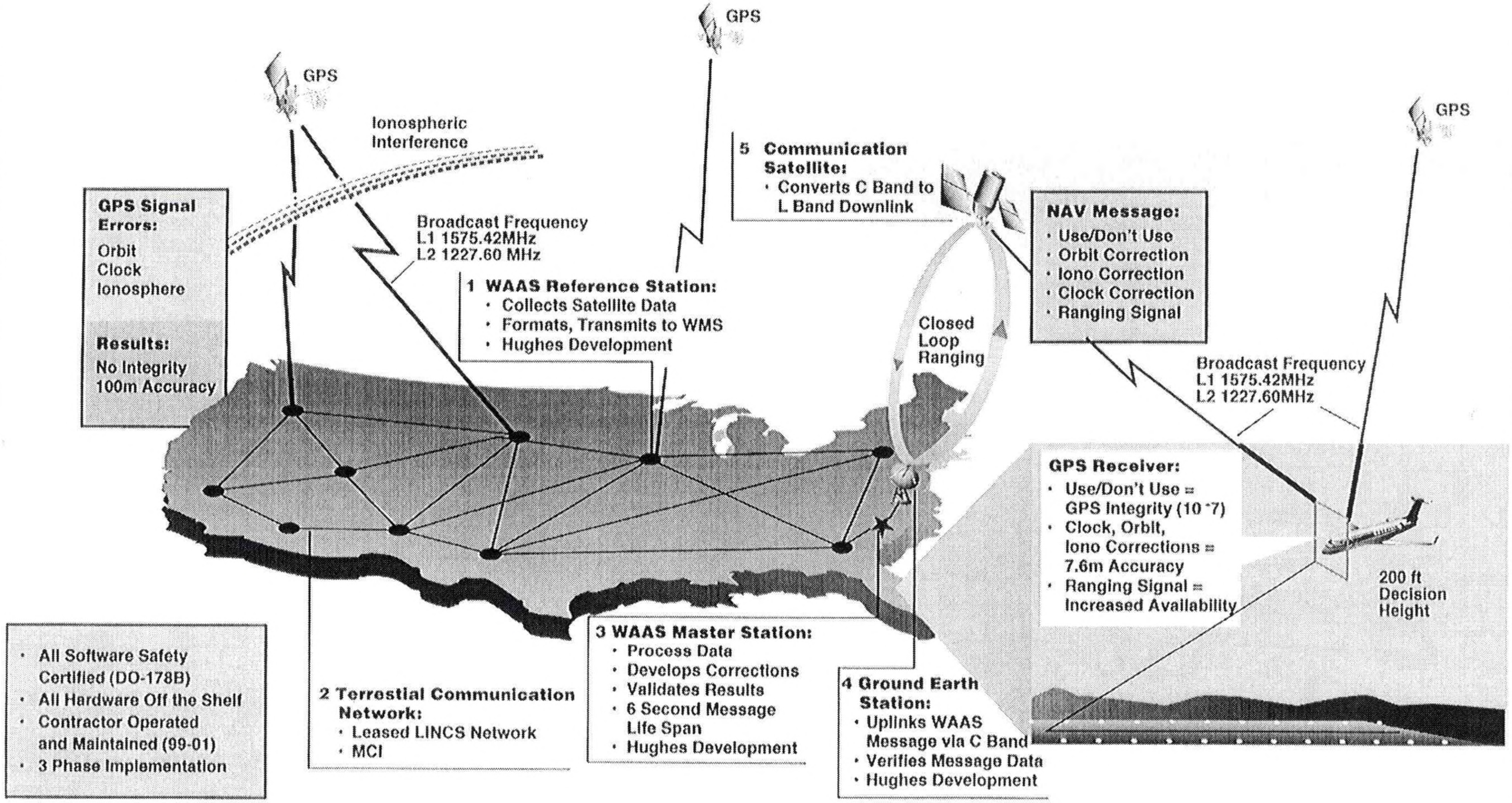
Wide Area Reference Station

FAA WAAS 01-37

Where


GPS Satellite
GEO Satellite
Auburn (ZSE)
Billings (BIL)
Farmington (ZMP)
Fremont (ZOA)
Santa Paula
Palmdale (ZLA)
Salt lake City (ZLC)
Longmont (ZDV)
Olathe (ZKC)
Aurora (ZAU)
Indianapolis (ZID)
Dayton (DAY)
Oberlin (ZOB)
Bangor
Nashua (ZBW)
Southbury
Ronkonkoma (ZNY)
Atlantic City FAATC
Leesburg (ZDC)
Wilmington (ILM)
Memphis (ZME)
Albuquerque (ZAB)
Oaklahoma City
Fort Worth (ZFW)
Houston (ZHU)
Hampton (ZTL)
Jacksonville (ZJX)
Miami (ZMA)
Anchorage (ZAN)
San Juan (ZSU)
Honolulu (ZHN))

Wide Area Augmentation System



GPS Signal Errors:
Orbit
Clock
Ionosphere

Results:
No Integrity
100m Accuracy

Broadcast Frequency
L1 1575.42MHz
L2 1227.60 MHz

1 WAAS Reference Station:
- Collects Satellite Data
- Formats, Transmits to WMS
- Hughes Development

5 Communication Satellite:
- Converts C Band to L Band Downlink

NAV Message:
- Use/Don't Use
- Orbit Correction
- Iono Correction
- Clock Correction
- Ranging Signal

Broadcast Frequency
L1 1575.42MHz
L2 1227.60MHz

GPS Receiver:
- Use/Don't Use = GPS Integrity (10^{-7})
- Clock, Orbit, Iono Corrections = 7.6m Accuracy
- Ranging Signal = Increased Availability

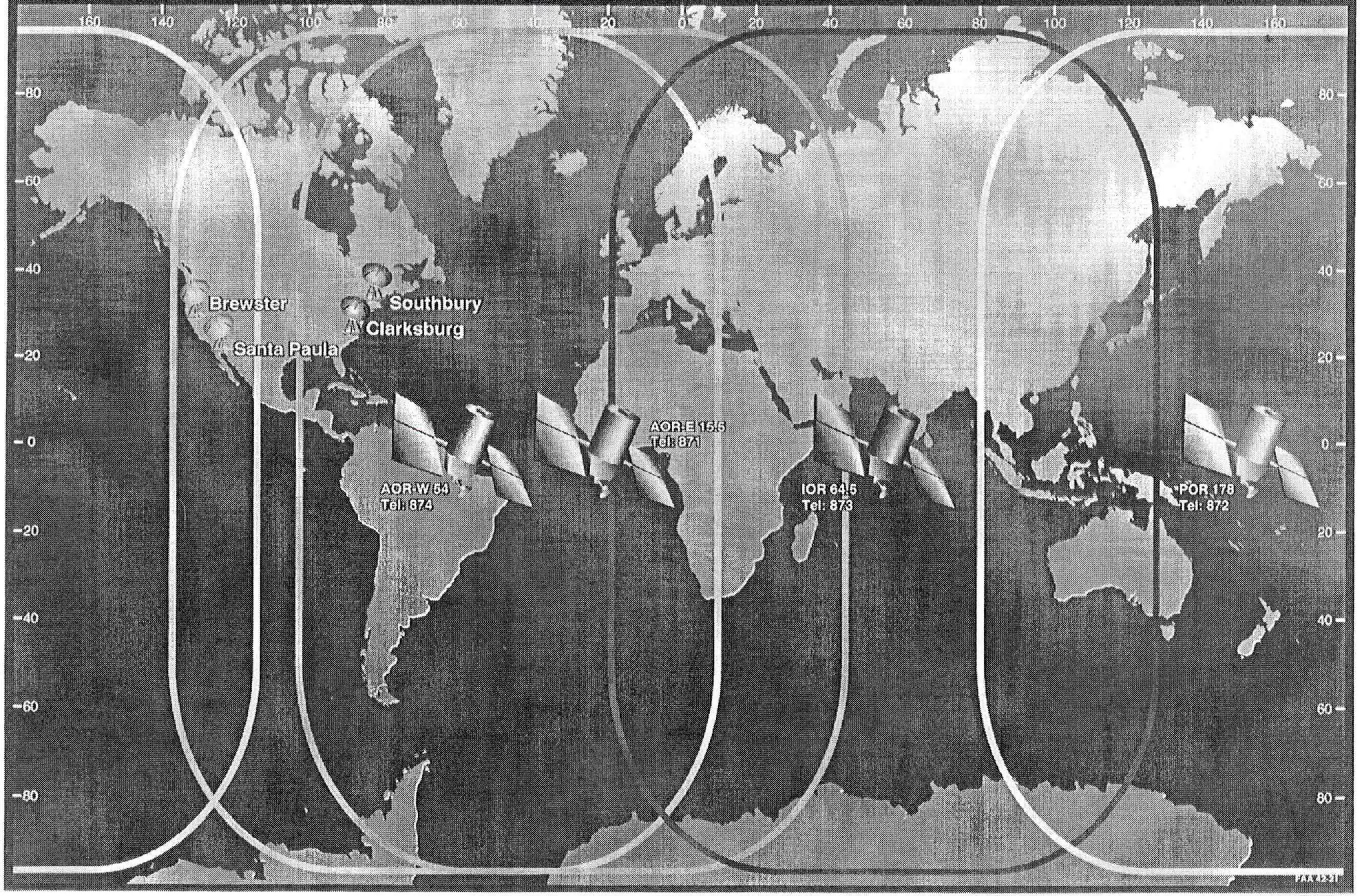
- All Software Safety Certified (DO-178B)
- All Hardware Off the Shelf
- Contractor Operated and Maintained (99-01)
- 3 Phase Implementation

2 Terrestial Communication Network:
- Leased LINCS Network
- MCI

3 WAAS Master Station:
- Process Data
- Develops Corrections
- Validates Results
- 6 Second Message Life Span
- Hughes Development

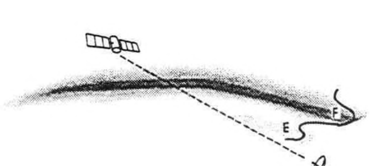
4 Ground Earth Station:
- Uplinks WAAS Message via C Band
- Verifies Message Data
- Hughes Development

Inmarsat 3 Coverage



2.5 Group Delay and Phase Advance due to Ionospheric Total Electron Content

Anthony J. Mannucci, Christian M. Ho, Xiaoqing Pi,
Brian D. Wilson and Ulf J. Lindqwister



Group Delay and Phase Advance due to Ionospheric Total Electron Content

Tony Mannucci
Christian M. Ho
Xiaoqing Pi
Brian D. Wilson
Ulf Lindqwister

Jet Propulsion Laboratory, California Institute of Technology

Abstract

GROUP DELAY AND PHASE ADVANCE DUE TO IONOSPHERIC TOTAL ELECTRON CONTENT

Anthony J. Mannucci, Christian M. Ho, Xiaoqing Pi,
Brian D. Wilson and Ulf J. Lindqwister
Jet Propulsion Laboratory
Pasadena, CA

The propagation of radio signals between space and ground is affected by the presence of free electrons in the Earth's ionosphere. The arrival time is delayed, and the carrier phase is advanced, proportionally to the integral of electron density along the signal path. This total electron content or TEC is a significant, if not dominant source of atmospheric delay for radio signals in the frequency range from UHF to Ku-band. For a given TEC, the magnitude of the delay decreases with increasing transmission frequency (inverse square dependence).

Radio-based communications, navigation and radar systems must be designed with knowledge of how TEC varies temporally and spatially, particularly when auto-calibration using multiple broadcast frequencies is not implemented. TEC varies with the elevation angle of the radio link line-of-sight, and depends strongly on latitude and longitude. Significant TEC changes over periods ranging from sub-hourly to several months duration, are superimposed on longer-term trends that follow the 11-year solar cycle. More abrupt TEC changes are associated with the solar wind disturbances that cause geomagnetic and ionospheric storms; severe events will become more common during the next solar maximum years in 1999-2000.

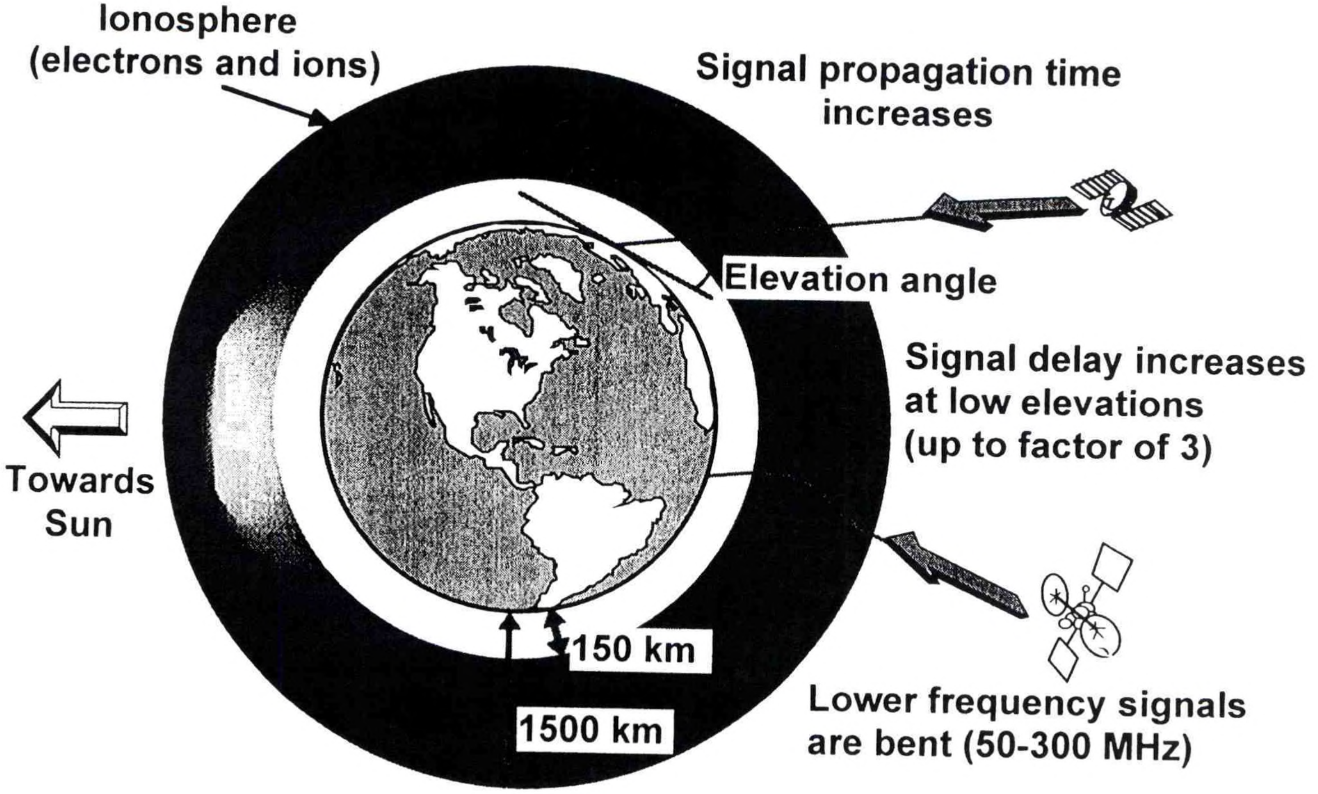
After a discussion of TEC, resources for estimating and correcting ionospheric delay will be discussed, with emphasis on methods that can operate in real-time. The highest accuracy methods are currently based on measurements from dual-frequency Global Positioning System receivers, which are commercially available and can be polled in real-time. An overview of GPS-based TEC monitoring systems, based on regional and global receiver networks, will be presented.

Outline

- Effect of ionosphere on radio waves
- Ionospheric “weather” patterns
  - The global structure and behavior of ionospheric total electron content
- Ionospheric nowcasting/forecasting
  - Monitoring the space weather using Global Positioning System signals

JPL

Ionosphere Effect on Radio Signals



Ionosphere
(electrons and ions)

Signal propagation time
increases

Elevation angle

Signal delay increases
at low elevations
(up to factor of 3)

Towards
Sun

150 km

1500 km

Lower frequency signals
are bent (50-300 MHz)

Space Weather Effects Workshop, October 1997 Ionospheric Total Electron Content Tony Mannucci, October 22, 1997

Trans-ionospheric propagation is affected by ionospheric total electron content (TEC), the column density of electrons along the propagation ray-path, typically expressed in the units: # of electrons per square meter. The signal is delayed, and also bent in the presence of horizontal TEC gradients. Delay is increased at low elevation angles by roughly a factor of three relative to zenith.

JPL

Phase Advance and Group Delay

Group Delay – first order effect

$$\Delta_{gd} = \frac{40.26}{f^2} TEC$$

Phase Advance: opposite sign to group delay

$$\Delta_{pd} = -\frac{40.26}{f^2} TEC$$

Trans-ionospheric Bending

$$\alpha \approx \Delta_{gd} \left[\frac{\Delta TEC/meter}{TEC} \right]$$

Near-zenith incidence

Delay in meters, TEC in electrons/m^2

Formulas for computing the group delay (gd) and phase advance (pd) due to TEC. Signals propagate at the group velocity. The known frequency dependence of ionospheric delay is used in dual-frequency systems to calibrate ionospheric delay (e.g. GPS). Single-frequency receivers that track phase and group delay simultaneously can be used to measure changes in ionospheric delay over a phase-connected arc of data. The bending formula is approximate, and applies to near-zenith incidence. Horizontal TEC gradients are in the range 10^{-4} to 10^{-5} TECU/meter. 1 TECU = 10^{16} electrons/m^2.

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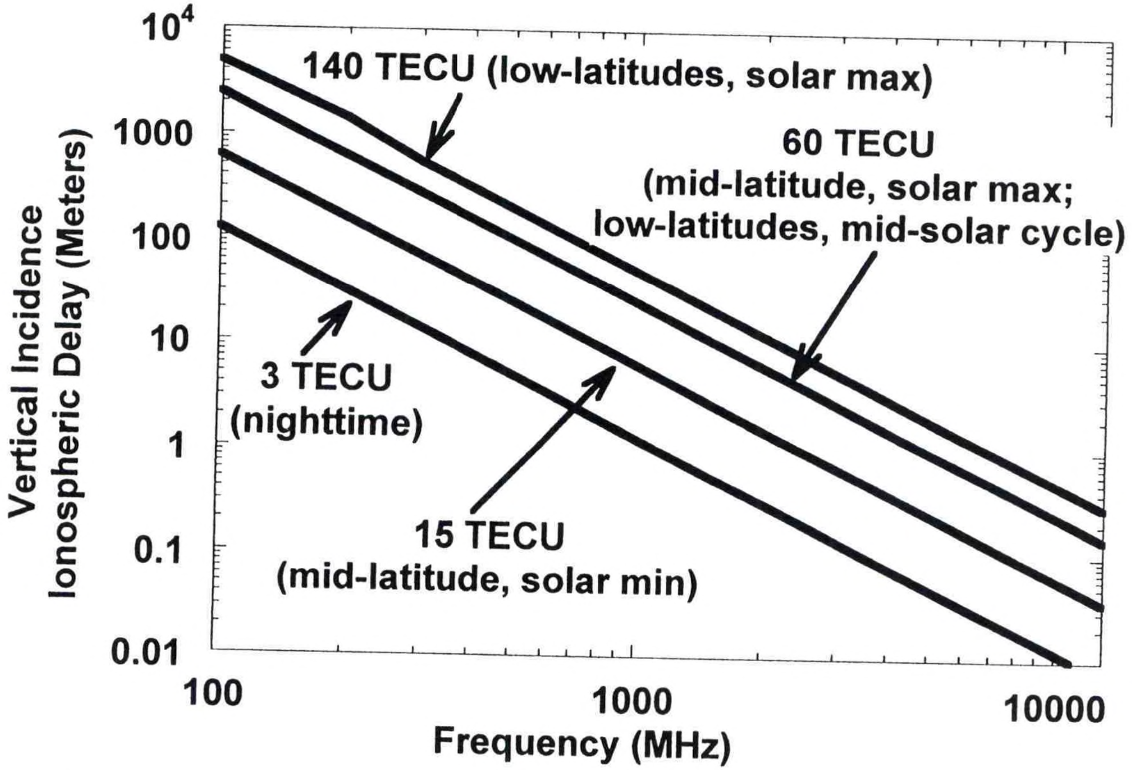
Magnitude of Ionospheric Delays



Group delay as a function of frequency. TEC values are typical daytime maximum values, except where noted.

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Ionospheric Structure

Properties that affect communications and navigation

- Magnitude of delay
- Spatial gradients
- Variability

Important time/space factors

- Local Time
- Solar cycle phase
- Latitude
- Season

Space-weather events

- Ionospheric storms disrupt “nominal” TEC behavior

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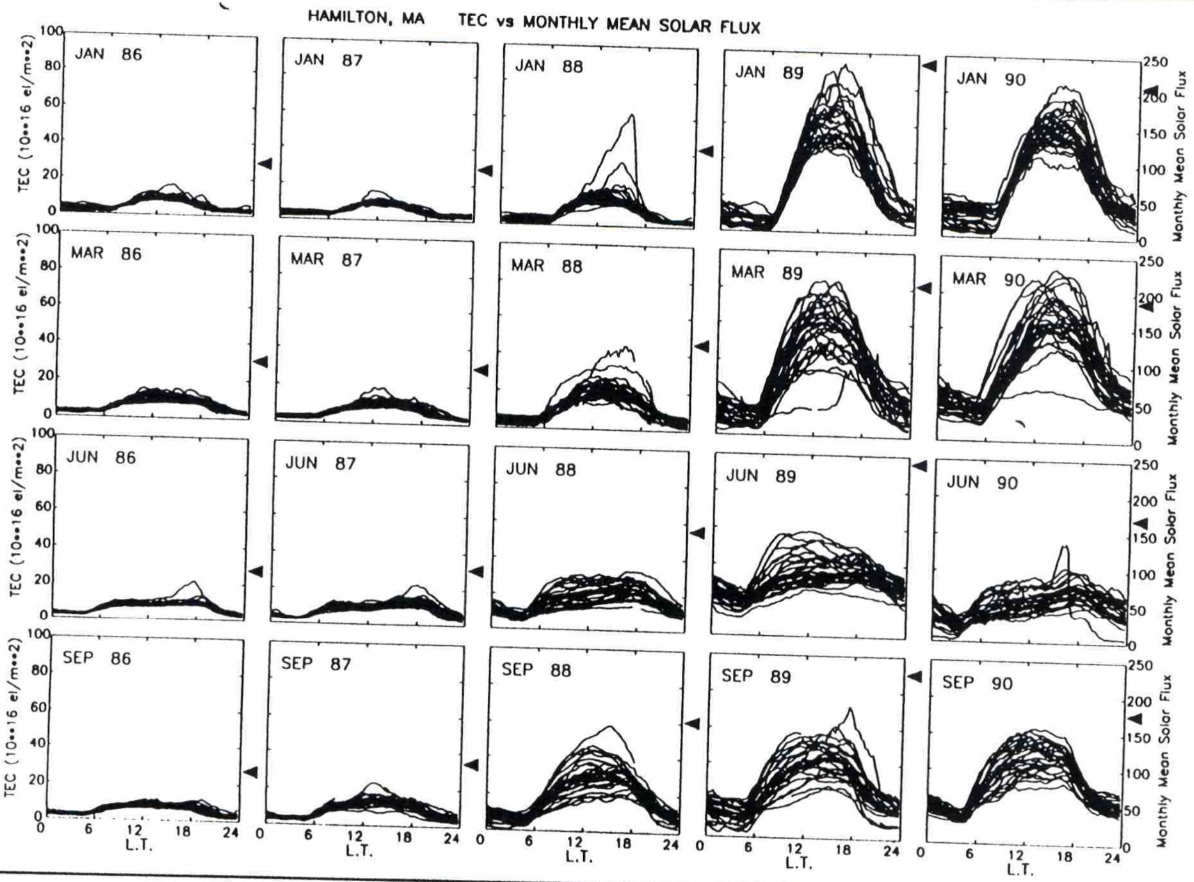
Diurnal Behavior of TEC



Space Weather Effects Workshop, October 1997 Ionospheric Total Electron Content Tony Mannucci, October 22, 1997 7

Long-term plot of TEC data from Hamilton MA (38.7 N, 70.7 W), near vertical incidence. Each chart is a plot of diurnal TEC behavior for each day in the month indicated. Note the large day-to-day variability. Dependence on solar cycle is displayed from left to right (solar minimum in 1986 to maximum in 1990). Seasonal dependence for a given year is displayed from top to bottom. Ionospheric storms (related to geomagnetic disturbances) can cause exceptionally large deviations from the monthly mean. This plot was obtained with kind permission from Pat Doherty and Jack Klobuchar.

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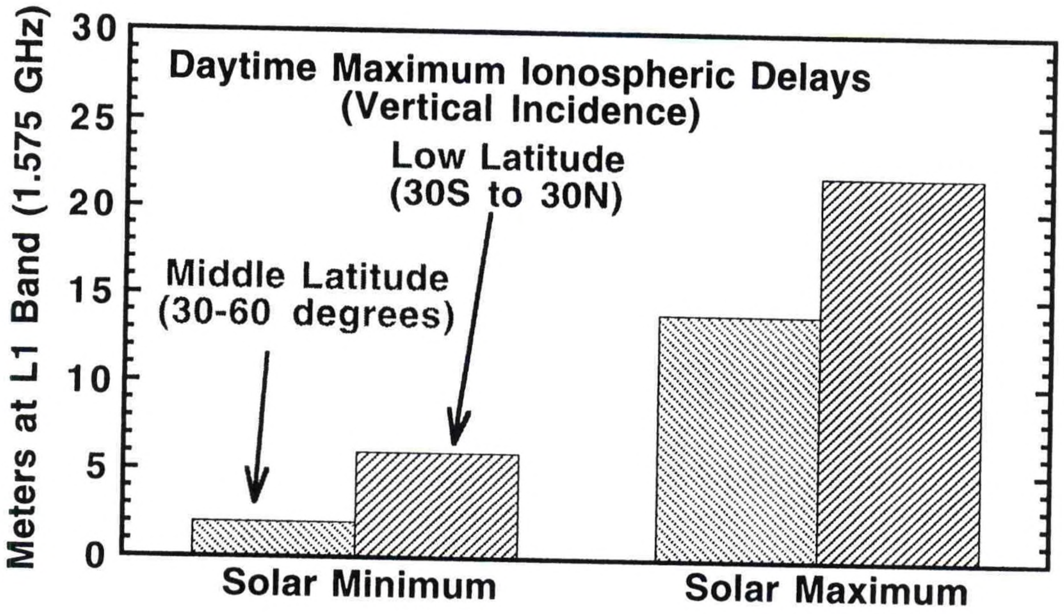
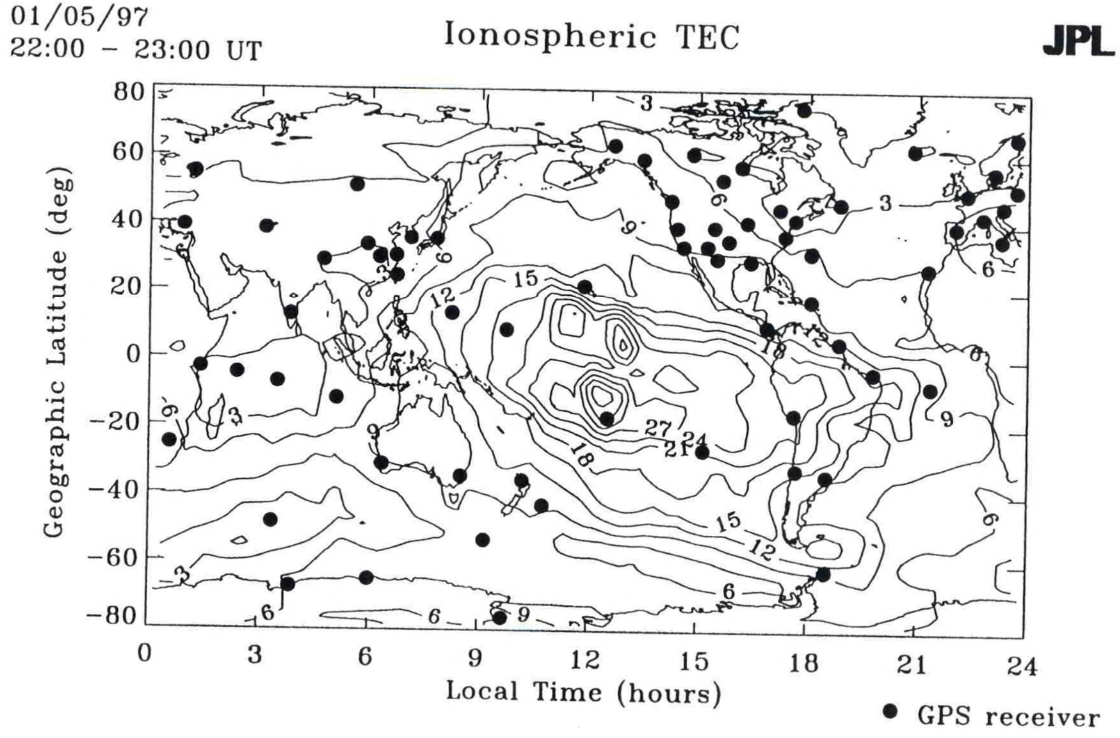
Solar Cycle Effect

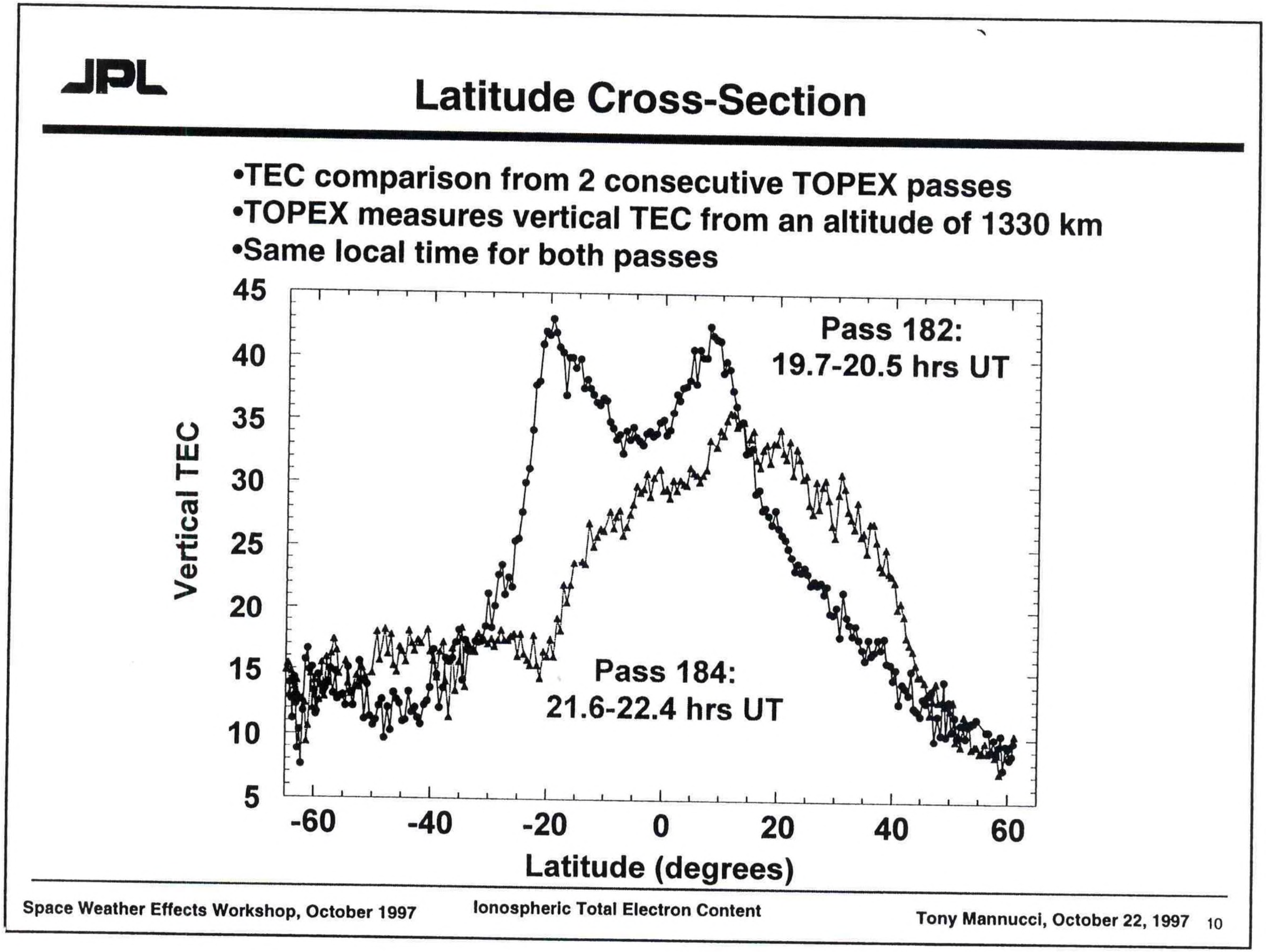


Daytime maximum delays, vertical incidence. Summary of quiet-time behavior, showing latitudinal variation.

Global Ionospheric Map



Global "snapshot" of TEC derived from a world-wide network of GPS receivers, plotted as a function of latitude and local time. Low-latitude maximum is evident, along with asymmetry with respect to 12 noon (daytime peak occurs around 2pm local time). The equatorial anomaly feature, consisting of two peaks about the magnetic equator, is retrieved near local noon. This map is derived by performing a global simultaneous fit of the TEC data on a two-dimensional surface, with time smoothing. The TEC surface is interpolated in a local-time/geomagnetic coordinate system.



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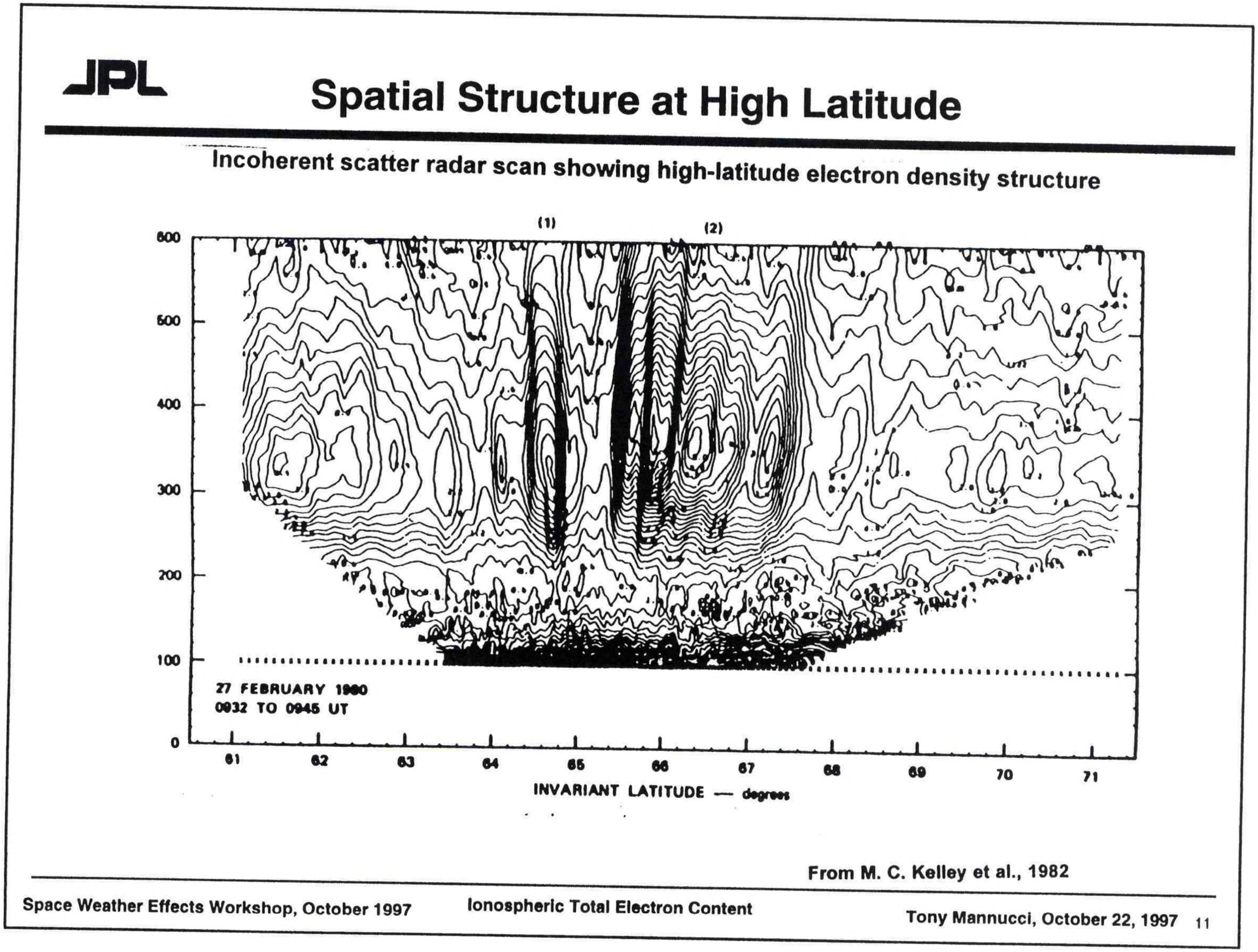
Latitude Cross-Section

- TEC comparison from 2 consecutive TOPEX passes
- TOPEX measures vertical TEC from an altitude of 1330 km
- Same local time for both passes

Space Weather Effects Workshop, October 1997 Ionospheric Total Electron Content Tony Mannucci, October 22, 1997 10

TEC "weather" at low latitudes is highly dynamic, controlled by electrodynamic mechanisms discussed in the talk by M. Kelley. Two consecutive TOPEX passes are separated by only 2 hours, but show a large variation in TEC. The twin-peaked anomaly has been "turned off" between passes 182 and 184. This sort of variability is not unusual at low latitudes even during quiet conditions. At mid-latitudes, for the same local times, TEC variation is generally smaller, unless a storm is present.



Spatial Structure at High Latitude

Incoherent scatter radar scan showing high-latitude electron density structure

From M. C. Kelley et al., 1982

Space Weather Effects Workshop, October 1997 Ionospheric Total Electron Content Tony Mannucci, October 22, 1997 11

Ionospheric physics at high latitudes causes significant spatial structure in the TEC. An example of latitudinal striation is shown in this contour plot of electron density obtained with an incoherent scatter radar.

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Ionospheric Storms

- Solar events deposit energy into the upper atmosphere at high latitude, and alter magnetosphere
- Disrupt the nominal “quiet time” behavior of the global ionosphere
- Cause TEC increases and decreases (positive and negative effects)
- Most significant TEC effects at high and middle latitudes
- Consequences for technology
    - Challenging tracking conditions – large ΔTEC/Δt
    - Altered propagation paths – large ΔTEC/Δx
    - Thermosphere heating, increased satellite drag
    - Spacecraft environment, electrostatic effects
    - Disrupt satellite attitude

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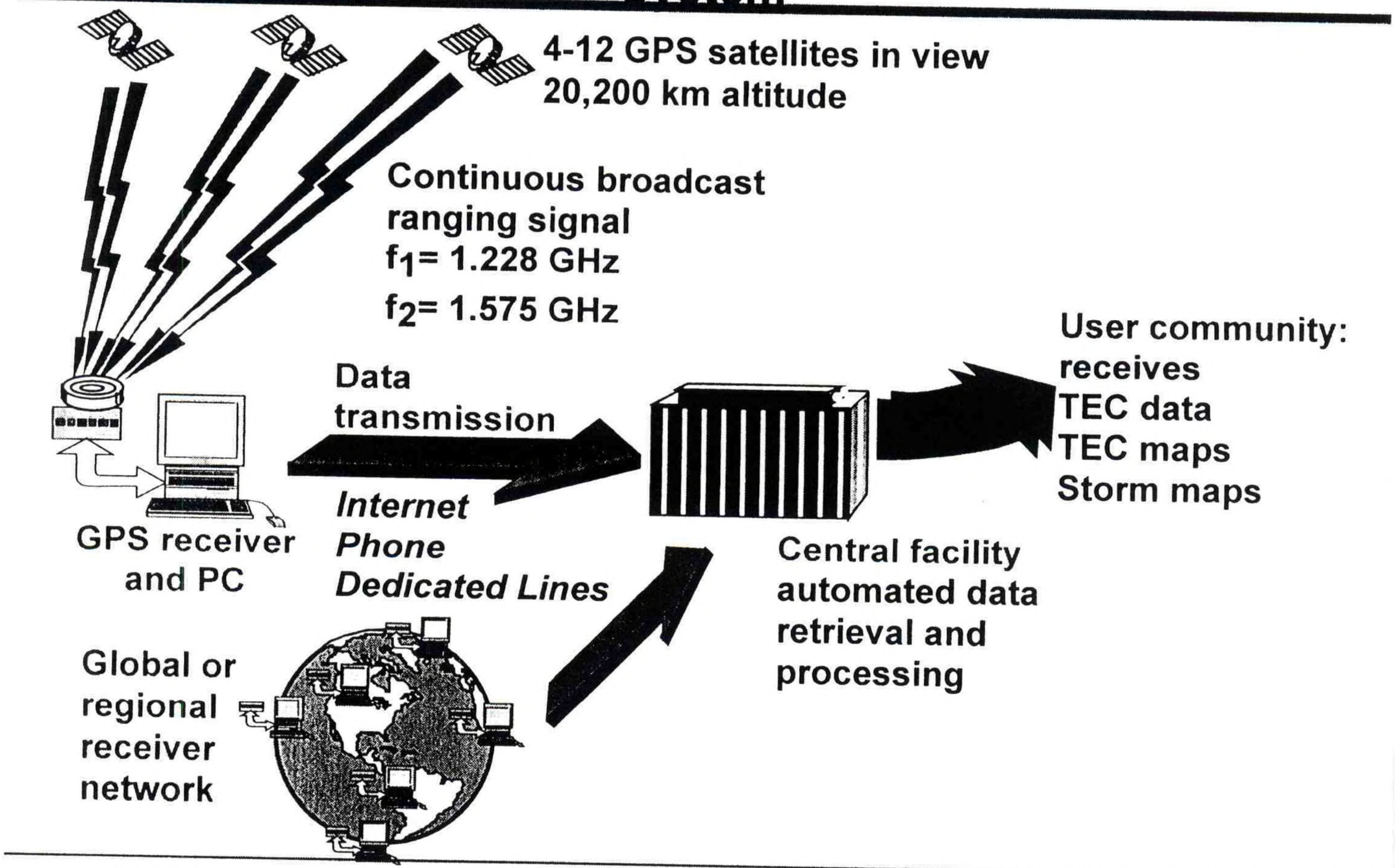
Ionospheric Storms and TEC

Important parameters:

- Duration of significant storms
  - 1-3 days
- Frequency of occurrence
  - Significant storms occur 1--2 /month
  - Very intense events occur every few years
- Magnitude of delay increase/decrease
  - Factors of 2-3 in 1-2 hours
  - Extreme variation recorded: 30 TECU/minute (5 meters/minute at 1.575 GHz)
- Storm severity increases near solar maximum

Nowcasting TEC with the Global Positioning System



4-12 GPS satellites in view
20,200 km altitude

Continuous broadcast
ranging signal
f_1= 1.228 GHz
f_2= 1.575 GHz

GPS receiver
and PC

Data
transmission

Internet
Phone
Dedicated Lines

Global or
regional
receiver
network

Central facility
automated data
retrieval and
processing

User community:
receives
TEC data
TEC maps
Storm maps

The most promising approach for mitigating the effect of TEC storms is real-time nowcasting of ionospheric conditions. Since several GPS satellites are always in view, nowcasting TEC can be accomplished relatively inexpensively using networks of commercially available dual-frequency GPS receivers. For TEC work, data rate requirements are modest and existing communication infrastructure can be used, such as Internet.

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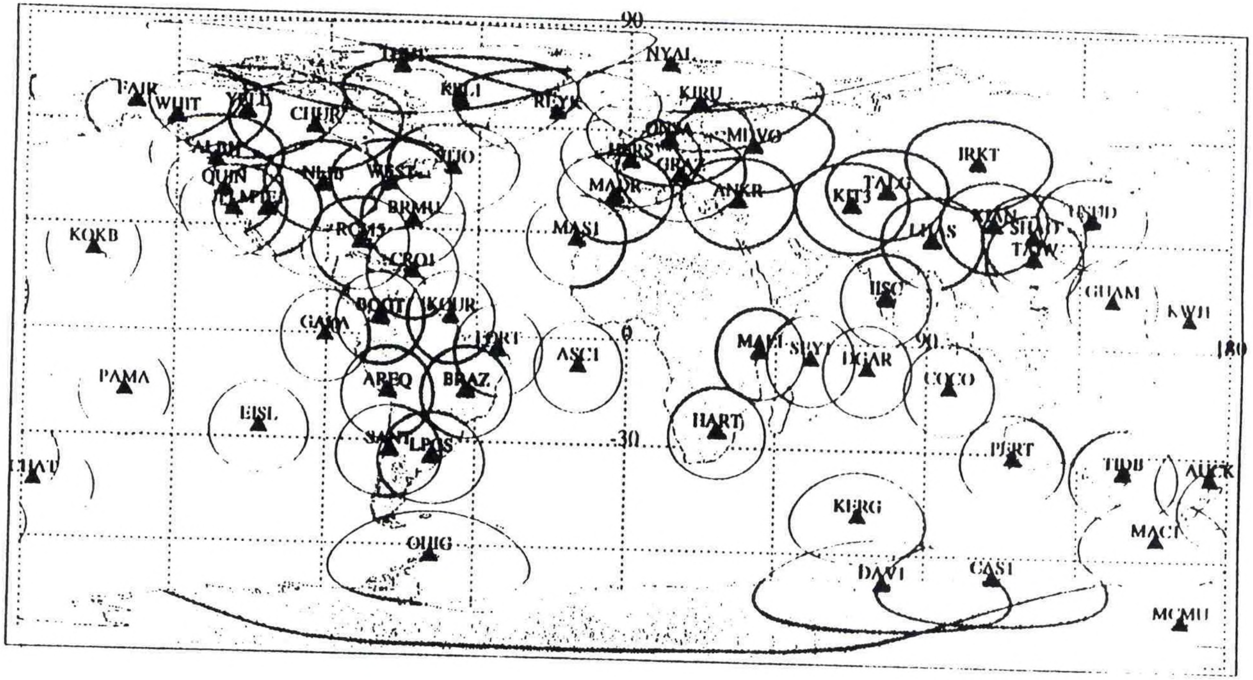
Global GPS Network

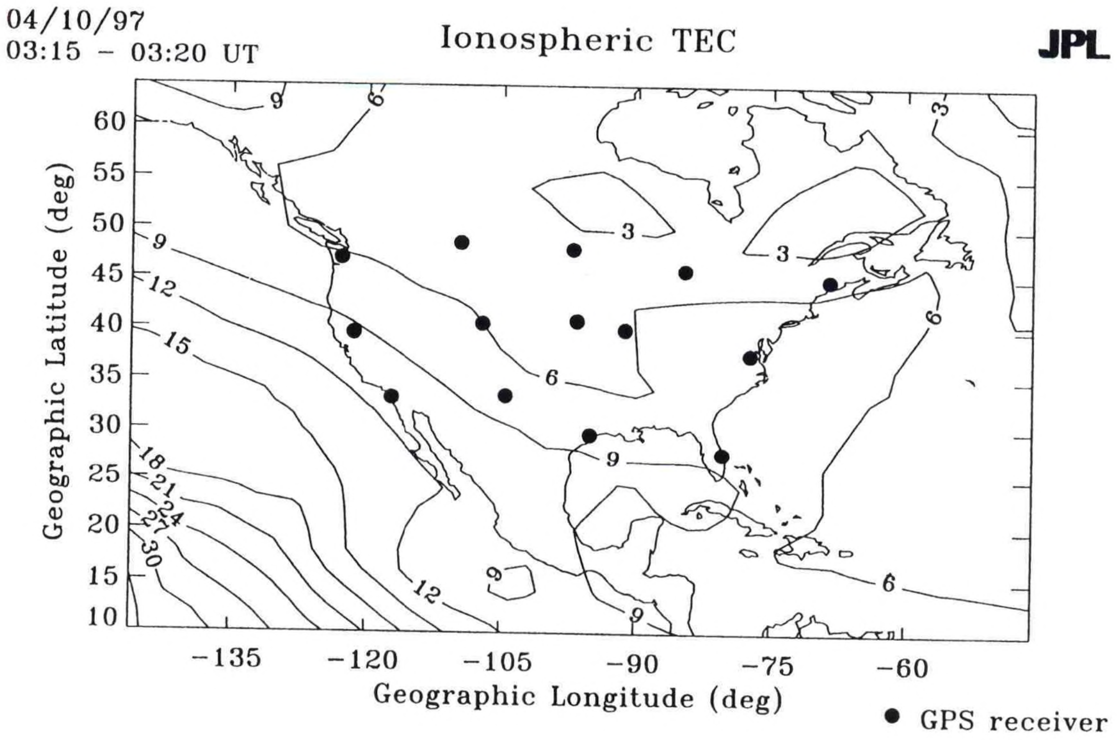
Global GPS Network (fiducial sites): Coverage at Ionospheric Altitudes



10 degree elevation mask. Effective shell height of 450 km.

The global GPS network, implemented primarily for geodetic studies, is a valuable resource for global-scale TEC nowcasting. Each receiver generally tracks 5-7 satellites simultaneously. The intersections of the receiver-transmitter lines-of-sight with an "ionospheric shell" at 400 km altitude occur within the circles plotted around each receiver.

Nowcasting TEC over US – Quiet



Nowcasting TEC over North America is currently performed by the SATLOC corporation in real-time using data from a 14-station network of receivers. Data are transmitted to JPL, where TEC maps are updated every five minutes. This map shows the quiet-time distribution from April 10, 1997, one day before a significant TEC storm.

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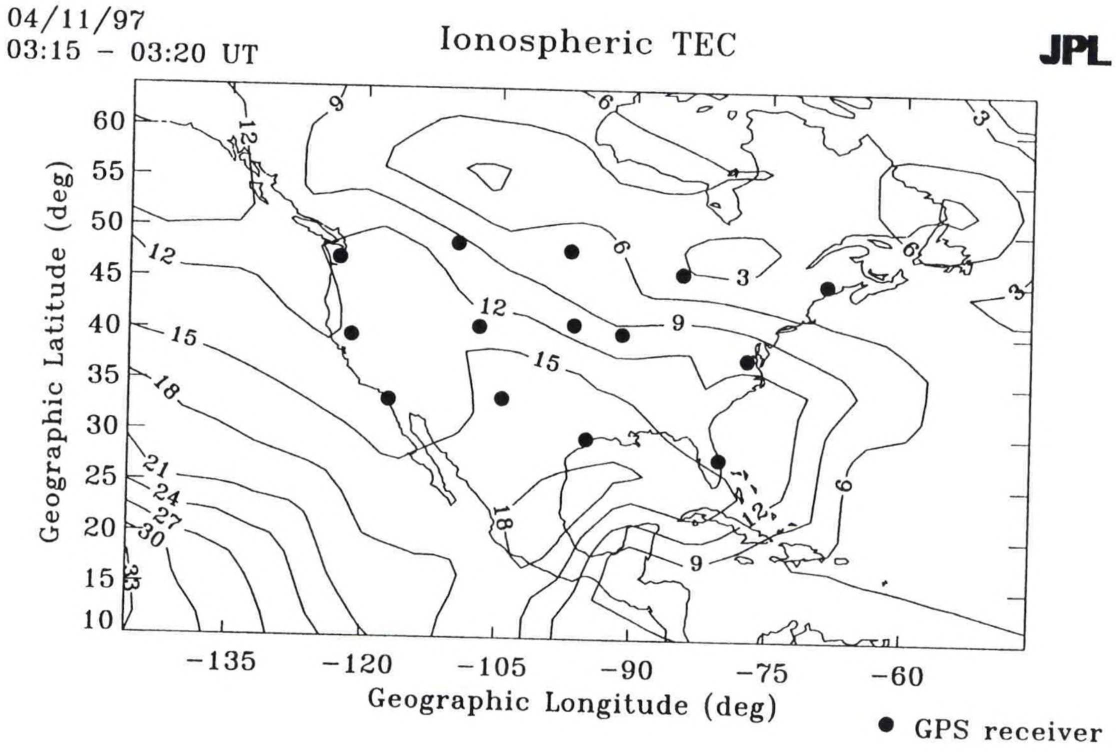
Nowcasting TEC over US – Storm



A geomagnetic and ionospheric storm on April 11 caused significant changes in the TEC distribution, as displayed in this nighttime map (compare with previous slide).

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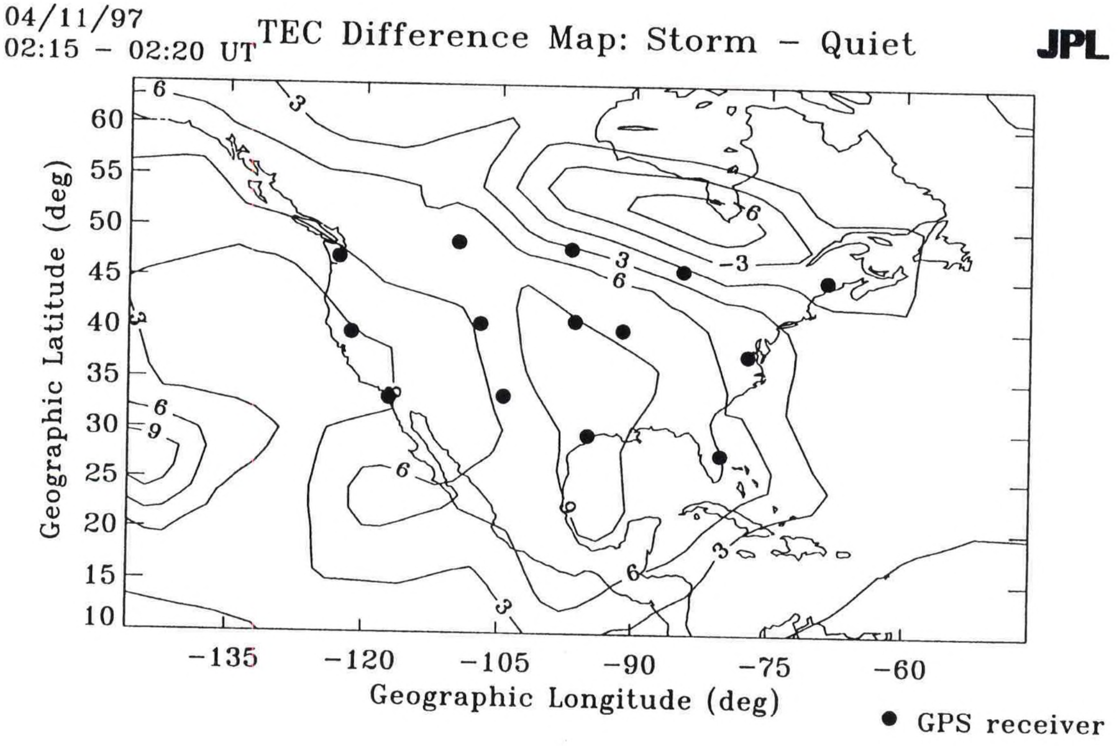
TEC "Storm Fronts"



Storm features are highlighted in this differential TEC map. The TEC distribution of April 10, 1997 at 02:15-02:20 UT is subtracted from the corresponding TEC nowcast from April 11. The TEC enhancements and depletions shown here represent large fractional deviations (50-100%), so the disturbance is significant. Not surprisingly, disruption of HF communications was reported coincident with this period, probably due to altered propagation paths.

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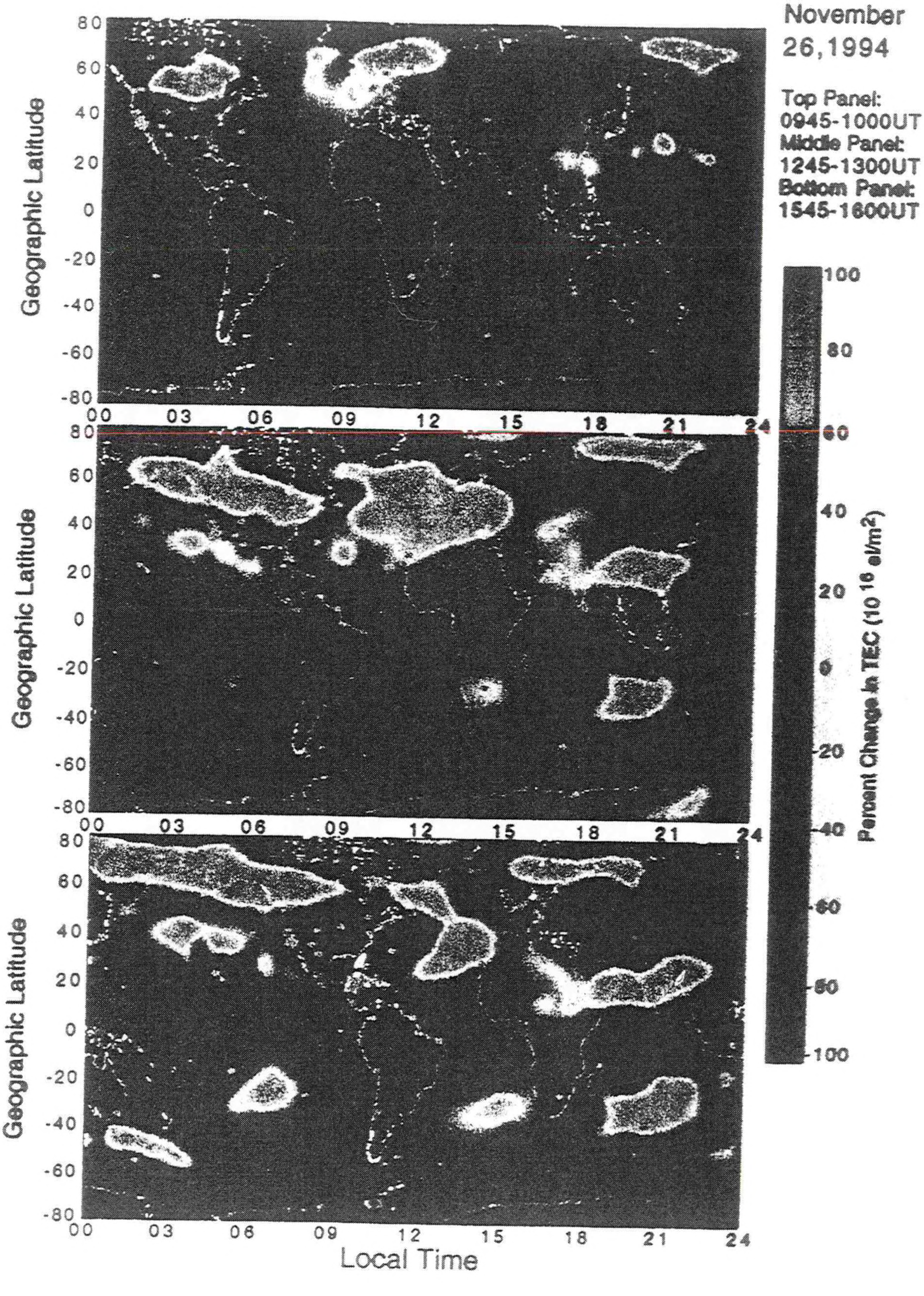
Traveling Storm Front

See next page

This differential map, based on percent TEC change, shows a traveling "storm front" that propagates southward over Europe. Both TEC and ionosonde data were independently used to derive a front velocity of about 460 m/sec. By contrast, the enhancement in North America does not propagate southward, perhaps due to the different local time in this sector. A color version of this plot can be found in: C. M. Ho, A. J. Mannucci, U. J. Lindqwister, X. Pi, B. T. Tsurutani, "Global ionosphere perturbations monitored by the worldwide GPS network", *Geo. Res. Lett.*, **23**, pp 3219-3222, 1996.


November
26,1994
Top Panel:
0945-1000UT
Middle Panel:
1245-1300UT
Bottom Panel:
1545-1600UT
Geographic Latitude
80
60
40
20
0
-20
-40
-60
-80
00
03
06
09
12
15
18
21
24
Local Time
Percent Change in TEC (10^16 el/m^2)
100
80
60
40
20
0
-20
-40
-60
-80
-100

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Space Weather Forecasting

- Extend now-casting to short-term TEC forecasts (1-6 hours)

- Data-oriented ionospheric storm prediction
  - Tracking motion of storm front
  - Earth-rotation relative to storm feature (local-time fixed)
  - Correlations with past storm patterns
  - Prototype available

- Data + Model-based storm prediction
  - TEC data ingested into coupled thermosphere-ionosphere models – data assimilation
  - Probably requires a few years further development
  - e.g. UARC campaign

Contact Information

- JPL Web-page for TEC
  http://sideshow.jpl.nasa.gov/gpsiono

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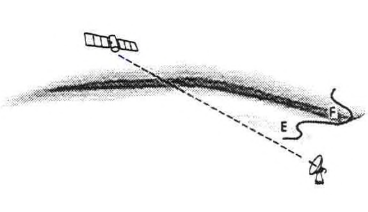
2.6 Communication Satellites and the Ionosphere

John V. Evans



COMMUNICATION SATELLITES

AND THE IONOSPHERE

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Bethesda, Md 20817

September 1997

TABLE OF CONTENTS

Communication Satellites and the Ionosphere

1. **Introduction**

Most commercial communications satellite services are provided in two bands (C and Ku-band) set aside for this purpose. These bands are roughly 4 and 6 GHz and 12 and 14 GHz, respectively, (where the higher frequency is the uplink) and are largely unaffected by ionospheric propagation effects.[1] Mobile services are presently offered at L-band (roughly 1.6 GHz) allowing simple antennas to achieve a large collecting area. Still lower frequencies, 150 MHz and 400 MHz (or VHF or UHF, respectively) have been used by the military, radio amateurs, and university groups.

Considerable commercial interest in satellite communications has recently developed as a result of several factors. These are:

i) There is an explosive growth in telecommunications occurring world wide fueled by deregulation and the availability of new services, e.g., cellular phone and internet access.

ii) The United States is pressing hard for countries to open up their telecom markets to U.S. suppliers via WTO talks and in other fora.

iii) Some U.S. aerospace companies are looking to enter new markets as a result of the decline in defense spending.

iv) Satellites provide almost "instant infrastructure" obviating the need for costly civil works.

As a result of a these factors a large number of satellite systems have been proposed to serve mobile and fixed users. Fixed services are to be offered at Ka-band (20-30 GHz) and the mobile services at VHF, UHF and L-band. Among the mobile systems are two classes of satellites in low-earth-orbit some of which are now being constructed. The so-called "little LEO's" are satellites intended to provide data-messaging services to small terminals and will operate at VHF and UHF frequencies. The so-called "big LEO's" are intended to provide mobile users with telephony

---

[1] Although there have been reports of large C-band antennas failing to track properly when viewing a satellite at night through the equatorial ionosphere and operating in a closed-loop mode. The solution has been to go to a programmed track mode.

via handheld radios that will resemble cellular phones. Most of the big LEO's will operate at L-band.

We describe in the next Section one of the "little LEO" systems, known as "Orbcomm". In Section 3, we briefly review the existing L-band services provided by Inmarsat via geostationary satellites, and in Section 4 two of the "big LEO" systems now under construction known as "Iridium" and "Globalstar".

All of these systems are potentially subject to disturbance due to ionospheric scintillation effects, which are most severe over the goemagnetic equator at night and at auroral latitudes during all times of day. The amplitude and phase fluctuations tend to be somewhat benign on the older analog (FM) system (Standard A) used by Inmarsat, since the human ear can tolerate considerable distortion before speech intelligence is lost. Increasingly, however, there has been a move to digital voice encoding (compression), so that most of the newer services (and the big LEO systems) will operate with digital bit streams of 4.8 or 2.4 kb/s. Also link margins in some of the proposed new systems will be as little as 3-6 dB, inviting the possibility that the receiver modem not be able to maintain phase-lock during periods of severe scintillation and data will be lost.

2. **"Little LEO" Systems**

The acronym "LEO" stands for low-earth-orbit. Virtually, all civilian two-way communications satellites (as distinct from broadcast) have till now been placed in geostationary earth orbit (GEO). This is a circular orbit in the earth's equatorial plane at a distance of approximately 40,000 km with a period of 24 hours. To a terrestrial observer, a satellite placed in such an orbit, appears to be stationary above a point on the earth's equator. This greatly simplifies all of the operations of the ground segment, since none of the earth station antennas are required to track the satellite and can be left in fixed positions.

The principal drawbacks of geostationary satellites are:

i) their distance is so large that to achieve reliable link margins moderately large antennas (diameters in meters) must be used both on the ground and on the satellite.

ii) they provide poor coverage of the polar regions of the earth.

iii) while fixed users can employ antennas that are not required to track, this advantage is lost for mobile users.

Because much of the Soviet Union is at high latittudes that are poorly served by geostationary satellites the soviet military has employed low-earth orbiting communications satellites operating at VHF. Three different systems have been deployed. The first were satellites launched singly into a circular orbit inclined at 74° at 790 km altitude. Subsequently, there were launches of six satellites at a time (sextets) into circular orbits inclined at 82.6° at 1400 km. A commercial version of this system called "Gonets" was developed (Morgan and Riportella, 1994).

Other communication satellites operating in low earth orbit have been built by the radio amateur community and the University of Surrey, U.K. (e.g. Allery et al, 1995). Some of these have provided real-time communications between users that share a common access to the satellite, while others operated in a "store-and-foreward" mode delivering data messages between users.

Several U.S. companies have proposed to build satellite systems to provide cellular-like telephony service. First of these was Motorola who proposed a 77-satellite (later changed to 66 satellite) system known as Iridium. These large systems became known as the "big LEO's" while the lower cost, messaging systems involving fewer satellites were termed the "little LEO'S".

A number of companies have applied for licenses to build little LEO systems and some of these have been described in the technical literature (e.g. Serene and Dribault 1996). Owing to the need to provide a low-cost global message delivery service, the little LEO systems intend to operate at VHF and UHF (though, in some instances, the exact frequencies are still in dispute). The reason for using these low frequencies is that a simple quarter-wave whip antenna can be utilized, providing the subscriber adequate signal capture without the need for careful pointing. By adopting a low earth orbit, the satellites themselves can also be built and launched at low cost (relative to geostationary satellites) thereby greatly reducing the up-front capital cost. The one significant drawback of this approach is that instantaneous global coverage can be offered only if a large fleet of satellites is launched into an appropriate constellation. Some proposers plan to offer service with as few as two satellites, in which case only a "store and forward" message delivery service can be provided. This would still be adequate, however, to support activities such as environmental monitoring or overseas relief operations, that are not time sensitive (for review see Kiesling 1996).

2.2 **Orbcomm**

The Orbcomm system is to be fielded by the Orbital Sciences Corporation (OSC) of Dulles, Virginia, U.S.A. The parameters of this system are given in Table 1. (Deckett 1994). Two satellites are to be placed in orbits inclined at 70° to provide coverage at high altitudes, while a larger number (24) arranged in 3 planes with 8 satellites per plane are in circular orbits inclined at 45° to provide better coverage of the earth's more populated regions. The satellites will be launched by the Orbital Sciences Pegasus launch vehicle, which is deployed from under the wing of an aircraft. Two Orbcomm satellites have been launched to-date.

Figure 1 shows the locations of the four gateway earth stations in the United States. These operate under the control of a Network Control Center located in Virginia and provide access to the satellites for both delivering and collecting short messages. Also illustrated in Figure 1 are some of the services to be offered. These include monitoring e.g., of well sites, pipelines, and other environmentally sensitive systems, tracking of vehicles and emergency services.

Figure 2 provides an artists sketch of the satellite, which is designed to operate in an earth-facing mode using active magnetic control and gravity gradient assistance. The satellites are designed to collapse into a 41" diameter cylinder 6.5" high, so that as many as 8 can be launched by a single Pegasus vehicle.

Messages received (or sent) by users can be displayed on an alpha-numeric display, and Figure 3 shows a subscriber using a simple hand-held terminal. Other terminals will be vehicle mounted or in fixed locations, where they can be interconnected with a PC for message generation and storage.

Orbcomm intends to offer a world-wide service and is in discussion with licensees, who will provide services in other parts of the world. Figure 4 shows the countries in which such arrangements have already been established. It should be evident that the Orbcomm system is perhaps the largest of the "little LEO's" and that Orbital Sciences Corporation appears serious about moving the project forward.

3. **The Inmarsat System**

The commercial use of satellites for mobile communications began with the COMSAT/Marisat system in 1976 (Lipke et al 1977). Satellites operating at UHF and L-band were launched on February 19 and June 9 of that year into positions over the Atlantic and Pacific oceans, respectively. The UHF capacity was utilized by the U.S. Navy, while the L-band capacity was intended to inaugurate a commercial service for mariners. Shipboard terminals typically consisted of an above-deck 1-m-diameter antenna gimballed to remain locked on the satellite and protected from the elements by a radome, while below decks would be a telephone handset, fax, and/or teleprinter (Figure 5). Feeder links for these satellites were provided at C-band via "coast" earth stations at Southbury, Connecticut, and Santa Paula, California, which were connected to the public switched network.

The system subsequently become global with the addition of a third satellite over the Indian Ocean and, in 1979, was turned over the newly formed Inmarsat intergovernmental organization to manage. Inmarsat, which is headquartered in London, is a treaty organization with 81 members. Initially, it leased its satellite capacity from COMSAT, and later from the European Space Agency MARECS satellites (Dumesnil et al, 1981). During the latter half of the 1980s, capacity was provided by INTELSAT, which added maritime packages to some its V-Series satellites.

In 1991, Inmarsat deployed four Inmarsat-2 satellites constructed to its own specifications. Two were placed over the Atlantic ocean and became known as Atlantic East and Atlantic West (See Figure 6) to handle the large amount of traffic in that ocean region. These satellites, like their predecessors, employ a single L-band global beam for servicing mobile users. Combined with the limited band of frequencies (28 MHz) available for this service at L-band, this restricts the number of simultaneous users. In response to the growth in traffic, two approaches have been taken to increase the availability of a circuit. One involves terminal design, and the other entails frequency reuse (Swearingen et al, 1997).

The original (Standard-A) terminal employed analog (FM) modulation of the L-band signals and 50-kHz channel spacing. About 20,000 such terminals are currently installed on vessels around the globe. Some terminal manufacturers repackaged their products for use on land (Figure 7), and about 5,000 of these are also in existence today. They are often used in remote locations, in disaster situations or peacekeeping operations, but their purchase price and high operating costs have discouraged more widespread use. This has, however, created a market for smaller, lighter weight, less-expensive terminals. To satisfy this demand, as well as to create more channels, Inmarsat introduced three new services known as Standard-B, -C, and -M (Haugli 1990), as described in Table 2. The Standard-B terminal is viewed as a replacement for the Standard-A. It employs digital offset, quadrature, phase-shift keying (O-QPSK)) modulation of the carrier with 20-kHz channel spacing. Voice is carried using adaptive predictive coding at a 16-kb/s rate, and most terminals can be operated at 64 kb/s for data. The Standard-M terminal uses a voice coded to provided synthesized speech at 4.8 kb/s which, with error protection, is transmitted at 6.4 kb/s in a 10-kHz-wide channel. The Standard C terminal provides only data at 300 b/s (which, with error protection, is transmitted at 600 b/s) and is useful for functions such as low-rate messaging and position reporting. The Standard-M terminal can be built into a regular-size briefcase, and approximately 10,000 of these units have been sold at prices ranging between one-half and one-third the cost of the original Standard A.

In 1996, the first two of five Inmarsat-3 satellites were launched. These satellites reuse the authorized frequencies in up to five "spot" beams, which can be selected for their coverage over land (Figure 8). These spot beams provide higher EIRP, making it possible for still-smaller terminals to operate within the system, and a "mini-M" terminal the size of a laptop computer was introduced early in 1997. It sells for about US$3,000, with a usage charge (fully terminated) of $3.00 per minute. The owner/operators of the Inmarsat system hope this service will attract a large number of new users (consumers), as distinct from the commercial accounts, which currently make up the bulk of the revenue.

A number of regional mobile satellite systems are now also in service (in the United States, Canada, Mexico, Australia) using geostationary satellites and serving subscribers with vehicles or fixed-site terminals. However, their capabilities are not significantly different from the Inmarsat M system described above. Truly revolutionary will be new systems capable of providing voice service to a hand-held terminal about the size of a cellular telephone and we describe two such systems next.

4. Big LEO Systems

4.1 General

A large number of companies (almost all of them in the U.S.) have announced plans to construct and operate satellite communications systems that would provide personal communications around the globe, and a number of these systems have been discussed and compared in the literature (Wu et al, 1994; Comparetto and Hulkower, 1994 Johansen, 1995). Much of this activity was spurred by a bold plan put forth by Motorola – to create a global personal satellite communications system employing 77 (later changed to 66) satellites in low-earth orbit (LEO) known as Iridium. Other proposals for low-earth-orbiting systems followed, causing Inmarsat to consider what type of personal communications system it might launch. Guided to some extent by design studies performed by TRW, Inmarsat adopted a system employing satellites placed in 6-hr orbits at 10,000-km altitude (i.e., above the Van Allen radiation belts). This system is now being built by an affiliate company called ICO-Global.

Figure 9 shows the amount of earth's surface visible from low-earth orbit (LEO), intermediate circular orbit (ICO) and geostationary orbit (GEO). The higher the satellite altitude, the fewer the number of satellites that are required to provide global coverage. However, to preserve the link margin on the handheld-to-satellite link, the spot size of the beam on the earth's surface must be kept small. This requires that larger satellite antennas be employed the further out the satellites are placed, and each antenna must form a larger number of spot beams in order to maintain overall coverage. Thus LEO satellites tend to be smaller, lighter, and cheaper than ICO spacecraft, which in turn are likely to be less expensive than GEO. This offsets to some extent the benefit of developing systems with fewer satellites.

Market studies performed by the proponents of these systems have identified four potential markets:

i) *International Business Travelers.* Primarily business travelers from the developed world traveling to less-developed countries.

ii) *National Roamers.* Primarily business travelers who need mobile communications in their own countries, but who travel beyond the reach of terrestrial cellular systems.

iii) *National Rural Fixed Service.* An extension of the national fixed services to regions where they are presently unobtainable.

iv) *Government Agencies.* Law Enforcement, fire, public safety, and other services.

The designs of the various proposed global systems represent different assumptions concerning the business to be attracted from these four segments. Table 3 summarizes six systems that have been licensed. Of these, the Iridium, Globalstar and ICO systems appear to have the best chance of being fielded and the financing of the others remains to be completed. Table 4 summarizes the operating characteristics of these three systems. It can be seen that ICO operating at S-band is less likely to be affected by ionospheric effects than Iridium or Globalstar.

4.2 Iridium

From the technical standpoint, the Iridium system proposed by Motorola, and currently being constructed by that company in conjunction with Lockheed Martin, Raytheon, and other contractors, is the most ambitious of the six listed in Table 3 (Sterling and Harlelid 1991). The system is being purchased and will be operated by a separate company (Iridium, Inc.), which has secured investment from many parts of the world (Brunt 1996). The design employs 66 satellites placed in circular polar orbits at 750 km altitude. The satellites will be deployed into six equipspaced orbital planes, with 11 satellites equally separated around each plane. Satellites in adjacent planes are staggered with respect to each other to maximize their coverage at the equator, where a user may be required to access a satellite that is a low as 10° above the horizon.

Users employ small handsets operating in frequency-division-multiplexed/time-division multiple access (FDM/TDMA) fashion to access the satellite at L-band. Eight users will share 45-ms transmit and 45-ms receive frames in channels that have a bandwidth of 31.5 kHz and are spaced 46.7 kHz. That is, users are synchronized so that they all transmit and all receive in the same time windows, alternately. This approach is necessary because (three) phased array antennas are used for both transmitting and receiving. Figure 10 is a sketch of the satellite, and Figure 11 shows the 48 spot beams formed at L-band projected onto the earth at the equator.

The Iridium system requires on-board processing to demodulate each arriving TDMA burst route it and retransmit it to its next destination. This can be to the ground if a gateway earth station is in view or, failing that, to one of the four nearest satellites: the one ahead or behind in the same orbital plane, or the nearest in either orbital plane to the east or west. These satellite cross-links operate at 23 GHz. The links to the gateway earth stations are at 20 GHz, and Figure 12 shows these pathways schematically.

The use of cross links greatly complicates the design of the system, but allows global service to be provided with a small number of gateway earth stations. To properly route the traffic each satellite must carry a set of stored routing tables from which new routing instructions are called every 2.5 minutes.

The cross-links to the satellite ahead and behind are the easiest to implement, since those satellites remain at a fixed distance and in a fixed viewing direction. The cross-links to the satellites in the adjacent orbital planes have constantly changing time delays and antenna pointing requirements. To mitigate this problem a circular polar orbit (actually an inclination of 86.5°) was chosen. Even so, it is necessary to drop these cross-links above 68° latitude, as the angular rates for the tracking antennas become too high.

The on-board processor is being constructed using very large-scale integrated circuits designed specifically for the project. It includes 512 demodulators whose outputs are used to control the subscriber units via the signaling channel to center the arriving handheld bursts in frequency and time. The observed Doppler shift of these arriving bursts is routed to the intended destination gateway earth station to determine the user's location. Service is then provided (or denied) based on country-by-country service agreements.

A model of the Iridium handheld terminal is depicted in Figure 13. Services to be provided include voice (probably at 2.4-kb/s) encoding, although Table 4 lists 4.2 kb/s) data at 2.4 kb/s, and high-penetration paging which affords 11 dB more power than the regular signal. The design, however, already provides a link margin (~16 dB) that is higher than any of the competing systems. This is because Motorola required that the handheld unit be usable from inside a vehicle (e.g., at taxi), and this in turn was dictated by the business plan, which depends heavily on serving international business travelers.

One of the complicating aspects of the Iridium system is the need to hand off a subscriber from beam to beam as a satellite flies by. Since a typical satellite pass takes less than 9 minutes and the average international call duration is about 7 minutes, there is also a need to hand off some calls to the next satellite to appear above the horizon. This will be in one of the adjacent orbits and hence in a somewhat different direction from the first, raising the possibility of the call being dropped if buildings block the view. This issue has been examined at COMSAT Laboratories (Sandrin, 1995), and by Carter and Beach (1995), and others.

A further complicating aspect of the Iridium system is the need to turn off beams as the satellites move away from the equator to ensure that a subscriber can access only a single beam. The Globalstar system described below, attempts to exploit dual-satellite visibility as a means of mitigating shadowing effects, and its designers claim that this is preferable to designing for high link margins.

The Iridium satellites are station-kept using on-board propulsion in order to overcome atmospheric drag and have sufficient fuel for an 8-year life. To-date Motorola has launched one third of its satellites and plans to have the entire system in operation in 1998.

4.3 Globalstar

The Globalstar system is being purchased by a limited partnership in which Loral and Qualcomm of the U.S. are principal partners. The satellites are currently being built by Loral, while Qualcomm is developing much of the ground segment (Wiedeman et all 1992, Smith 1994).

Unlike the Iridium system, which offers a true *global* service, Globalstar's business plan calls for launching the space segment and franchising its use to partners in different countries. Over 90 such relationships have been established.

The Globalstar system will employ 48 satellites organized in eight planes of six satellite each (Figure 14). The satellite orbits are circular, at 1414 km and 52° inclination. The use of an inclined orbit concentrates the available satellite capacity at lower latitudes where the largest populations exist; little or no coverage is provided beyond ±70° latitude (Figure 15). As can be seen in Figure 15, two or more satellites are visible (above 10° elevation) between 25° and 50° latitude at all times, and from the equator to 60° latitude 80 percent of the time. Like the Iridium satellites, the Globalstar spacecraft are three-axis-stabilized, with a mission life of 7.5 years (minimum).

The Globalstar system employs no satellite cross-links; thus a subscriber can gain access to the system only when a satellite in view can also be seen by a gateway earth station. Typically this means that service areas are within 1,000 miles of each gateway earth station. To achieve truly global coverage would require the construction of more than 200 earth stations, which seems unlikely to happen Thus, Globalstar is more likely to serve national roamers than international business travelers.

In contrast to Iridium, each Globalstar satellite covers a comparable area of the earth's surface with only 16 spot beams. This, together with the sharing of the receive channels on board the satellite by many more users, reduces the available link margins to about 3- 6 dB. Access to and from the satellite is at L- and S-band, respectively, (Table 4), utilizing code-division multiple access (CDMA) in channels that are 1.25 MHz in bandwidth. Voice is encoded at a variable rate (1-9 kb/s approximately) depending on speaker activity. The satellites employee simple "bent pipe" transponders with the feeder links at C-band (Hirschfeld 1996).

A problem for this type of a system (and also for Odyssey) is that, while frequency reuse can be employed at L- and S-band, the feeder links must occupy the full band of all of the signals that can be transmitted through the satellite. Therefore, securing an adequate feeder link allocation becomes almost as critical as an L- and S-band allocation.

Since all beams of all of the 48 satellites are always active, each satellite that is in view of a subscriber will pick up the subscriber's signal and retransmit it in its feeder link. Thus, by tracking the several satellites that are in view of a given gateway earth station, two channels can be kept open to the subscriber. The channel providing the stronger signal can then be selected for connection to the public-switched network. This feature should mitigate blocking by buildings and provides and automatic "soft" handoff from satellite to satellite. The advantage offered by diversity routing has been examined by Akturan and Vogel (1997) and found to be quite considerable. Globalstar hopes to have its system in operation by late 1998 or early 1999 .

5. Discussion

The possibility that ionospheric scintillation can disrupt mobile satellite communications is only one of the propagation effects that needs to be considered in the design of a mobile satellite system. As illustrated in Figure 16 signals arrive at the subscriber terminal via multiple paths. Fortunately, the high elevation of the source makes the time dispersion of the signals much less of a problem than is encountered in terrestrial cellular systems. The chief difficulty instead is the blockage of the direct ray which can be severe in urban environments (see for example Haugli et al 1993).

Even in the countryside tree-lined roads can cause severe fading of the arriving signals as can be seen in Figure 17. This problem has been extensively studied, for example by Vogel and Goldhirsh (1990) at a wide-range of frequencies. At L-band, absorption by foliage is a relatively small effect (~2dB) compared with the scattering caused by branches, which is responsible for the deep nulls in Figure 17. While these nulls are relatively localized and could be avoided by a subscriber on foot, they cause the receiver in a vehicle considerable difficulty in maintaining phase lock on the arriving carrier.

The current approach to combating signal fading effects is to employ coding of the digital bit stream. Typically a "convolutional code" is employed, which adds redundant bits according to an algorithm in such a fashion that the decoder can detect and correct errored bits. This is known as "Forward Error Correction" (FEC). In the Inmarsat Standard-M system, for example (Table 2), an FEC rate of ¾ is employed meaning that a fourth redundant bit is added for every three data bits. Unfortunately, once coding is introduced the errored bits are no longer random, since if the code is not powerful enough to correct a sequence of bits that are in error and fails, there is then a *burst* of errors. Fortunately, the human ear is quite tolerant of vocoded speech at average error rates as high as 10^{-3}. Similarly, text fax messages can usually be interpreted correctly at comparable error levels. More serious are likely to be the effects on short data messages, for example, in position reporting. Fading effects encountered in the University of Surrey microsatellite program have been examined by Sun et al (1995) and lead to adoption of a novel architecture for their coherent MSK demodulator that would acquire faster and over a wider frequency range that than standard "de Buda" demodulator.

Other strategies for dealing with errored messages have long been employed in radio systems (such as ARQ) in which the receiver requests the retransmission of any message imperfectly received. Such end-to-end control schemes are ill-suited to long transmissions made via geostationary satellites because of the round trip delays involved (~0.5 seconds). However, they could be quite acceptable for short messages delivered via LEO Satellites.

Table 1: Specifications of the Orbcomm^{sm} System

Spacecraft	2 satellites inclined at 70° (orbit 700 km circular)
	24 satellites inclined at 45° (3 planes of eight) (orbit 775 km circular)
Frequencies	148.0 - 149.9 Mhz Uplink 137.0 - 138.0 MHz Downlink 400.05 - 400.15 MHz
Data Rate	2400 bps inbound 4800 bps outpound
Addressing	X.400 (CCITT 1988)
Message Size	6-250 Bytes typical no maximum
Subscriber Unit	
Power	5 watts
Weight	12 ounces
Antenna	50 cm whip

Table 2: Comparison of Inmarsat Voice Systems

FEATURES	STANDARD-A	STANDARD-B	STANDARD-M	"MINI"-M
Mobile to/from Satellite, L-Band (GHz)	1.6/1.5	1.6/1.5	1.6/1.5	1.6/1.5
Fixed to/from Satellite, C-Band (GHz)	6/4	6/4	6/4	6/4
Minimum Channel Spacing (kKz)	50	20	10	5
Users/Carrier	1	1	1	1
Access Method	FDMA	FDMA	FDMA	FDMA
Modulation	Companded FM	O-QPSK	O-QPSK	O-QPSK
FEC Coding Rate	N/A	3/4	3/4(for subband bits)	2/3 (for subband bits)
Speech Coding Algorithm	N/A	Adaptive predictive coding (APC)	Improved Multiband excitation (IMBE)	Advanced multiband excitation (AMBE)
Voice Coding Rate (kb/s)	N/A	16	6.4 (including error correction bits)	4.8 (including correction bits)

Table 3: Proposed New Satellite PCS Systems

PARAMETER	IRIDIUM	GLOBALSTAR	ODYSSEY	ICO-GLOBAL	ELLIPSO	AIRES (ECCO)
COMPANY	Motorola	Loral/Qualcom	TRW	ICO-GLOBAL	Mobile Communication Holdings	Constellation Communications Inc.
NO. OF ACTIVE SATELLITES	66	48	12	10	17	46
ORBIT PLANES	6 circular polar (86.5°)	8 circular inclined (52°)	3 circular inclined (55°)	2 circular inclined (45°)	2 elliptical inclined (116.6°) 1 circular equatorial	7 circular inclined 1 circular equatorial
ORBIT ALTITUDE(Km.)	750	1,414	10,356	10,355	N.A. 8,060 equatorial	? 2,000 equatorial
SATELLITES PER ORBIT PLANE	11	6	4	5	5 in each elliptical orbit 7 in equatorial orbit	5 in each inclined orbit 11 in equatorial orbit
BEAMS/ SATELLITE	48	16	37	163	61	1
REPORTED COST ($B)	4.7	2.5	3.2	4.6	0.56	1.15

Table 4: Communications Characteristics of Some Proposed New Satellite PCS Systems

Parameter	Iridium	Globalstar	ICO-Global
Mobile User Link			
Frequency, Up/Down. (GHz)	1.62135-1.6265	1.6100-1.62135/ 2.4835-2.49485	1.980-2.010/ 2.170-2.200
Bandwidth (MHz)	5.15	11.35	30
Spot Beams/Satellite	48	16	163
Voice Bit Rate (coded) (kb/s)	4.2(6.25)	2.4 (average)	4.8 (6.0)
Feeder Link			
Frequency Up/Down (GHz)	30/20	5.1/6.9	5.2/6.9
Gateway Antenna G/T (dB/K)	24.5	28.5	26.6
User Terminal			
Multiple Access	TDMA-FDMA	CDMA-FDMA	TDMA-FDMA
Carrier Bandwidth (kHz)	TDD, 31.5	1250	25.2
Carrier Bit Rate (kb/s)	50	2.4	36
Modulation	DQPSK	PN/QPSK	QPSK
RF Power (W)	0.45	0.5	0.625
G/T (dB/K)	-23.0	-22.0	-23.8
Nominal Link Margin (dB)	16.5	3-6*	10
NominalCapacity/Satellite(ckts)	1,100	2,400	4,500

* For a small number of channels this can be raised to 11 dB.

Figure Legends

Figure 1: Locations of the Gateway Earth Stations and Network Control Center in the United States for the Orbcomm System. Also illustrated are some of the services to be offered (Courtesy of Orbital Sciences Corp.)

Figure 2: Artists Sketch of the Orbcomm (Microstar^{tm}) Satellite. Showing the various components. The satellite is designed to collapse into a 41" diameter cylinder 6 ½" high (Courtesy of Orbital Sciences Corp.)

Figure 3: Picture of a subscriber using an Orbcomm hand-held terminal.

Figure 4: Locations in the world where the Orbcomm System has licensed local service providers to offer its services.

Figure 5: Shipboard Inmarsat terminal radome-enclosed antenna.

Figure 6: Coverage patterns of the Inmarsat-2 satellites and locations of the coast earth stations operated by COMSAT.

Figure 7: Standard-A Inmarsat terminal used on land.

Figure 8: Beam patterns of an Inmarsat-3 satellite system, showing the spot beams, four of which can be activated to provide coverage of land areas.

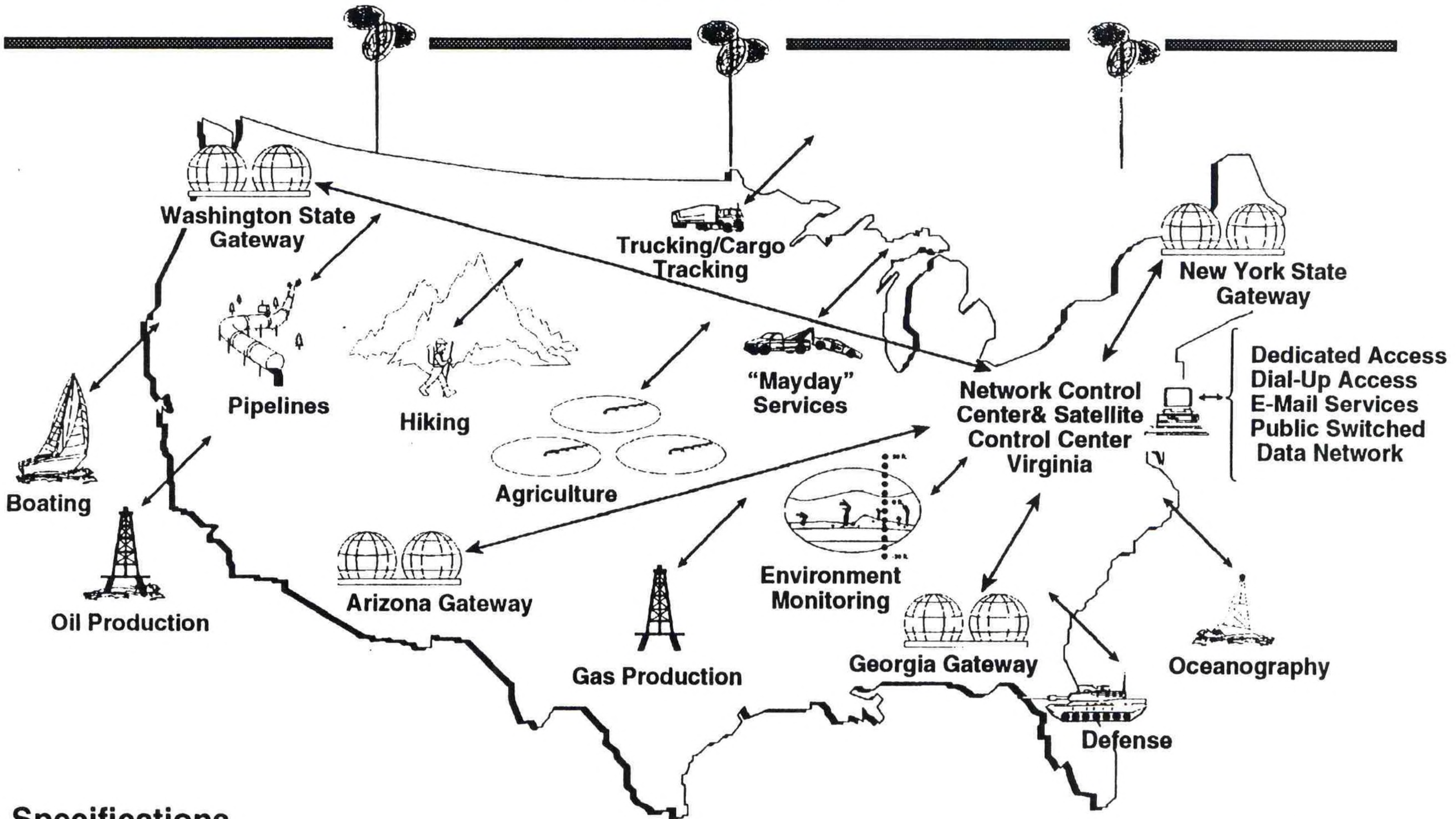
Figure 9: Relative amounts of earth coverage afforded by satellites in low earth orbit (LEO), intermediate circular orbit (ICO), and geostationary orbit (GEO).

Figure 10: Sketch of the Iridium system satellite. The 48 spot beams (Figure 11) are formed by the three phased-array antennas cantilevered from the three sides of the spacecraft. (Courtesy Motorola Corporation).

Figure Legends

Figure 11:	Service (L-band) spot beams formed by an Iridium satellite over the equator.
Figure 12:	Connections possible in the Iridium system between users, the satellite, and the ground.
Figure 13:	Model of a handset proposed for the Iridium system. (Courtesy Motorola Corporation).
Figure 14:	The Globalstar constellation (D. Smith, 1994).
Figure 15:	Multiple-satellite coverage provided to users (at elevations above 10°) by the Globalstar constellations (Wiederman et. al, 1992).
Figure 16:	Propagation effects encountered in a mobile satellite system.
Figure 17:	Example of the fading encountered along a tree-lined road at L-band.

ORBCOMM℠



Specifications

• Data Rate	2400 b/s Inbound 4800 b/s Outbound
• Frequencies	
Uplink	148.00 – 149.90 MHz
Downlink	137.00 – 138.00 MHz 400.05 – 400.15 MHz

• Addressing	X.400 (CCITT 1988)
• Message Size	6 – 250 Bytes Typical, No Maximum
• Space Segment	
Spacecraft	4 Near-Polar 32 Inclined 45°
Altitude/Orbit	775 km Circula

Subscriber Communicator (Typical)

Power Output	5 Watt
Weight	12 Oz
Antenna	50 cm Whip
• Positioning Resolution (1 Pass)	500 m

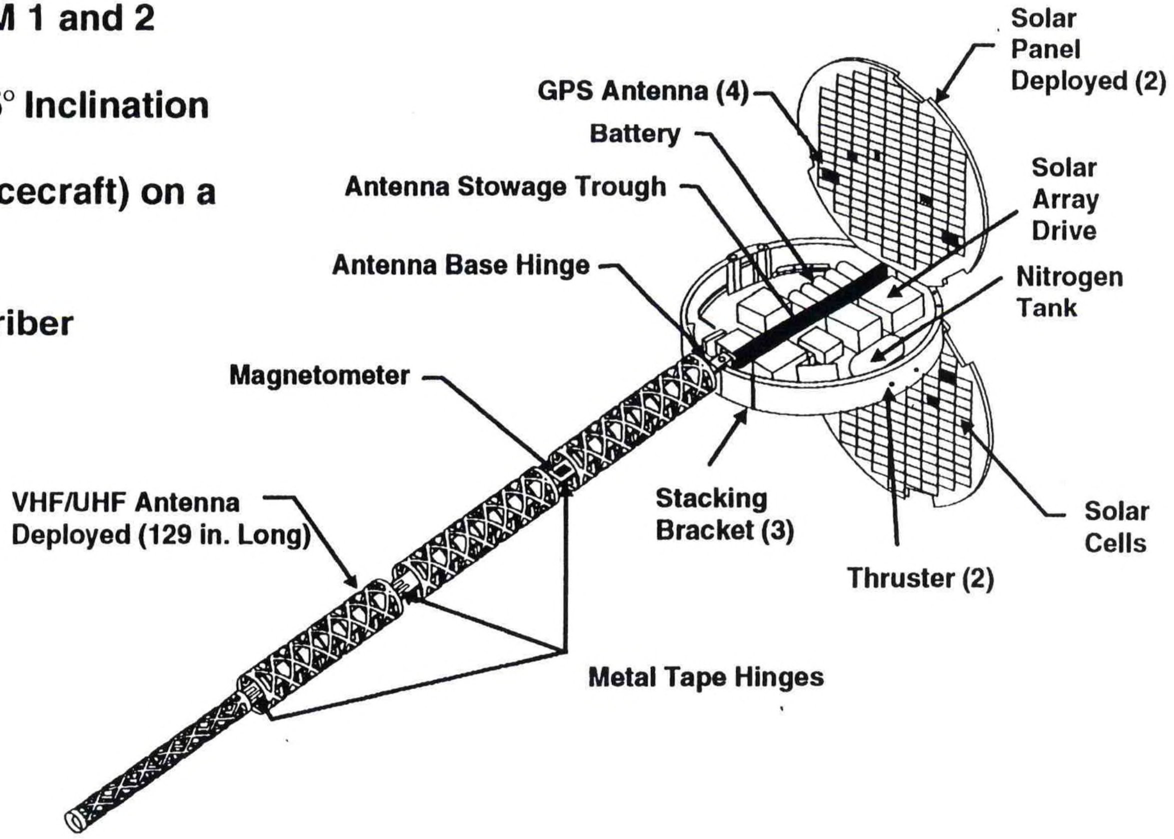
970266- 1

Figure 1

COMSAT CORPORATION

ORBCOMM Satellite

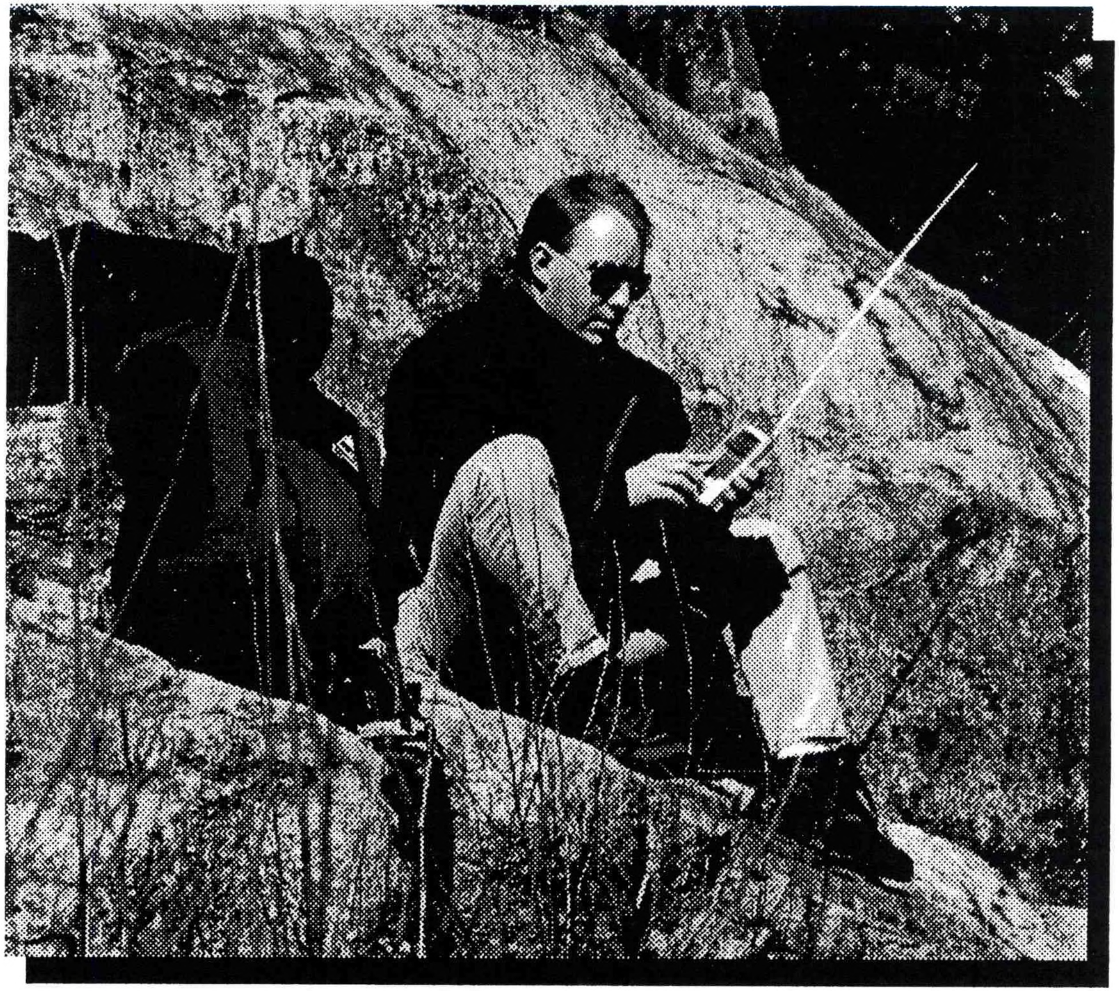
- Constellation
  - 2 Spacecraft @ 70° Inclination
  - 24 Spacecraft (3 Planes of 8) @ 45° Inclination
- 700 km Circular Orbit for FM 1 and 2
- 775 km Circular Orbit for 45° Inclination
- Launch Entire Plane (8 Spacecraft) on a Single Pegasus
- Support ORBCOMM Subscriber and Gateway Links at the Assigned Frequencies
- Program Goals
  - Minimum Cost
  - Minimum Development
  - Full Qualification and Acceptance Testing



970266-2
Figure 2

165

ORBCOMM Communications & Positioning Capability Ideal for Outdoor Recreationists

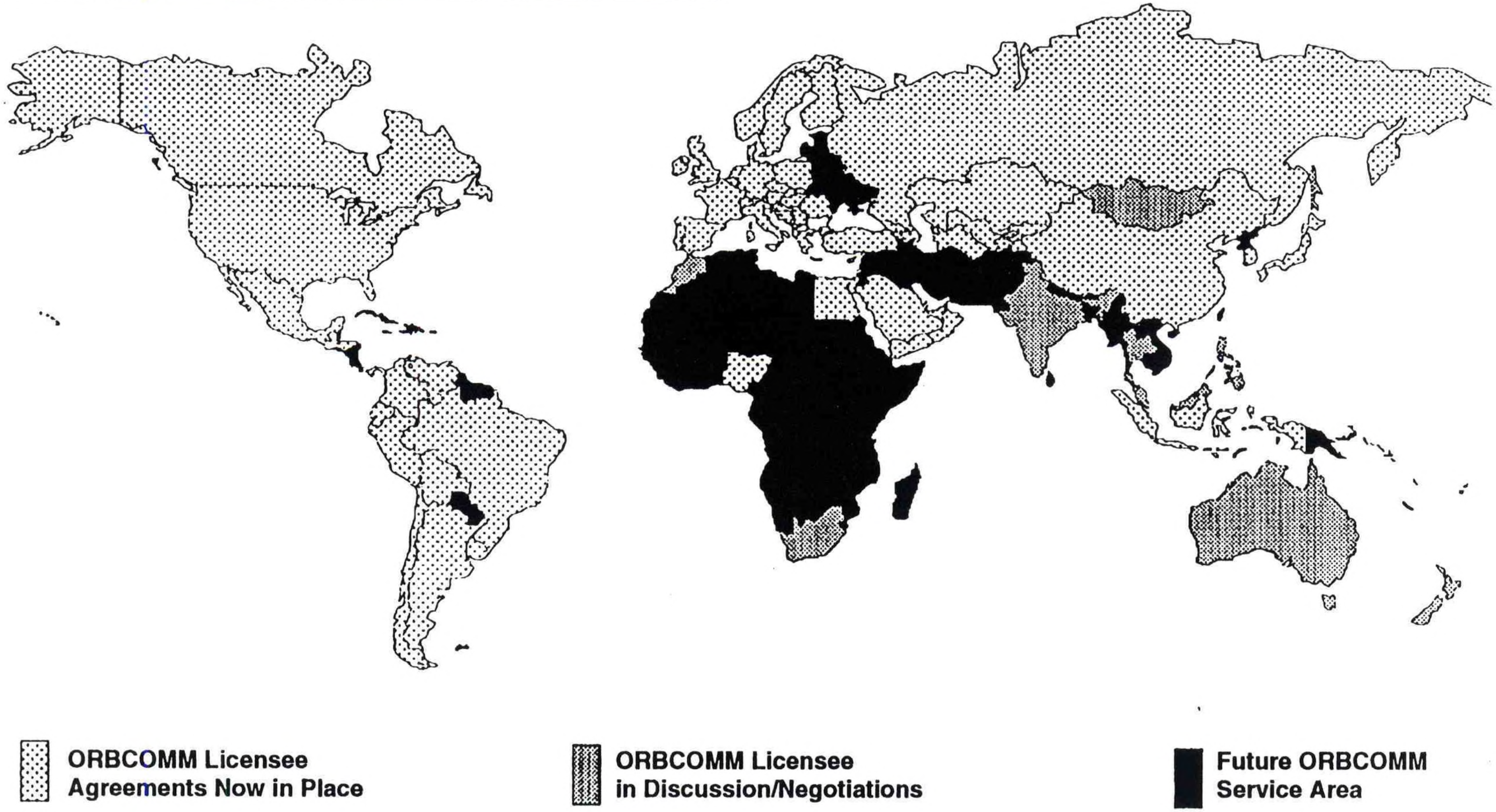


970266- 7
Figure 3

ORBCOMM Opportunities Are Truly Global

ORBCOMM USA and International Licensees

- Present 23 (3.0 billion People, 60% of World)
- 1996 40 (4.6 billion People, 90% of World)



970266- 3

Figure 4

COMSAT CORPORATION

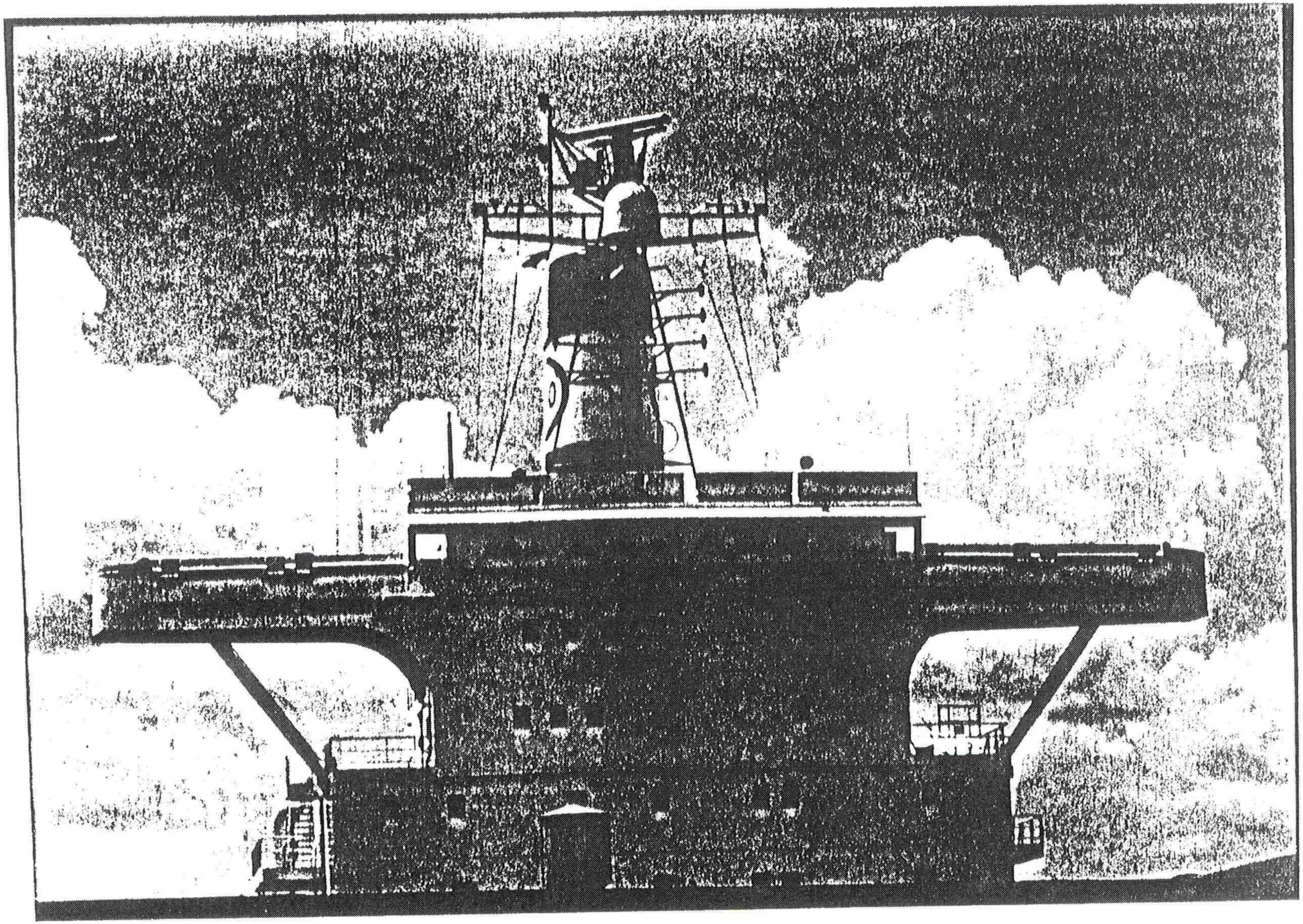


Figure 5

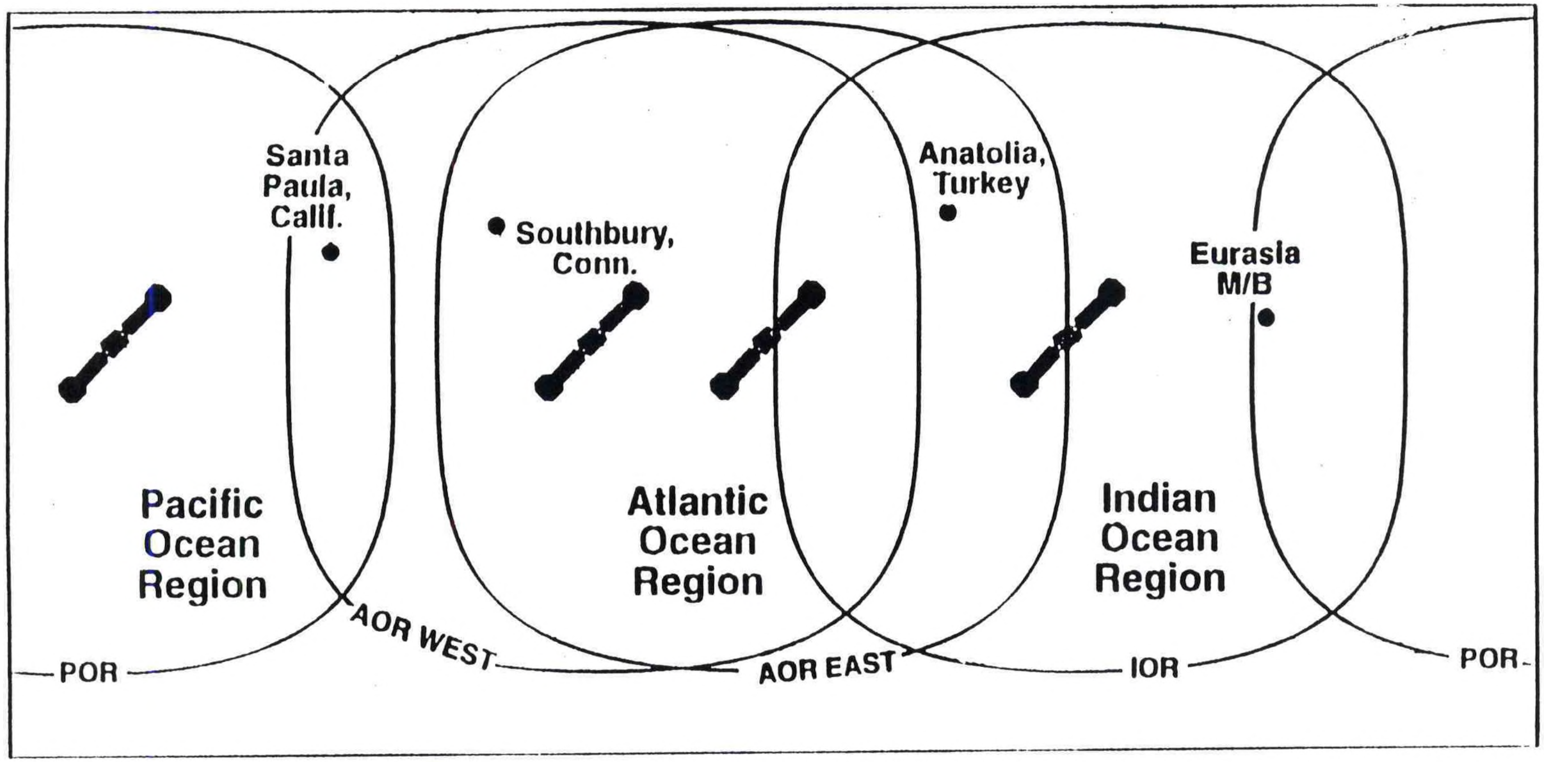

Santa
Paula,
Calif.
Southbury,
Conn.
Anatolia,
Turkey
Eurasia
M/B
Pacific
Ocean
Region
Atlantic
Ocean
Region
Indian
Ocean
Region
POR
AOR WEST
AOR EAST
IOR
POR

Figure 6

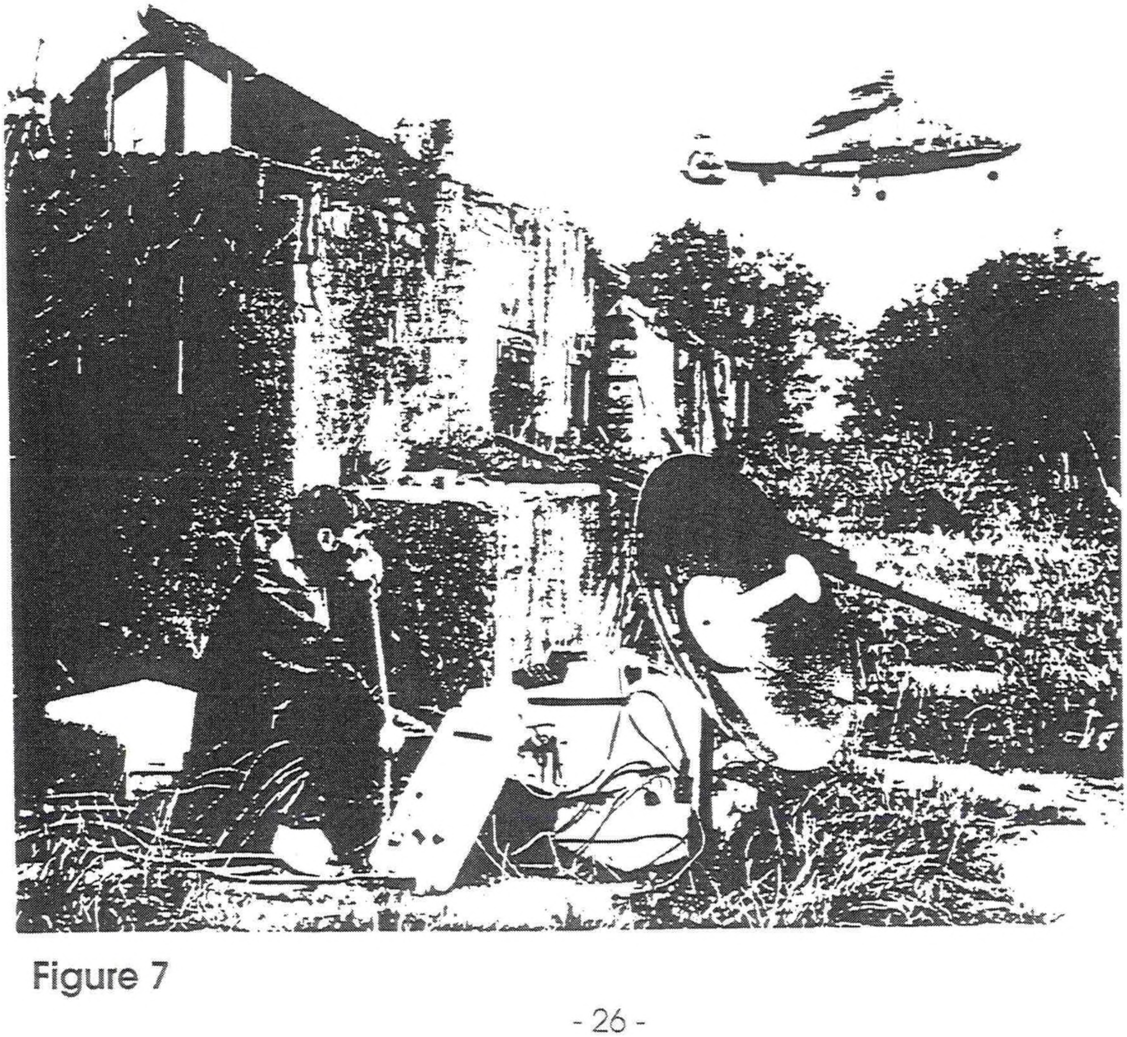


Figure 7

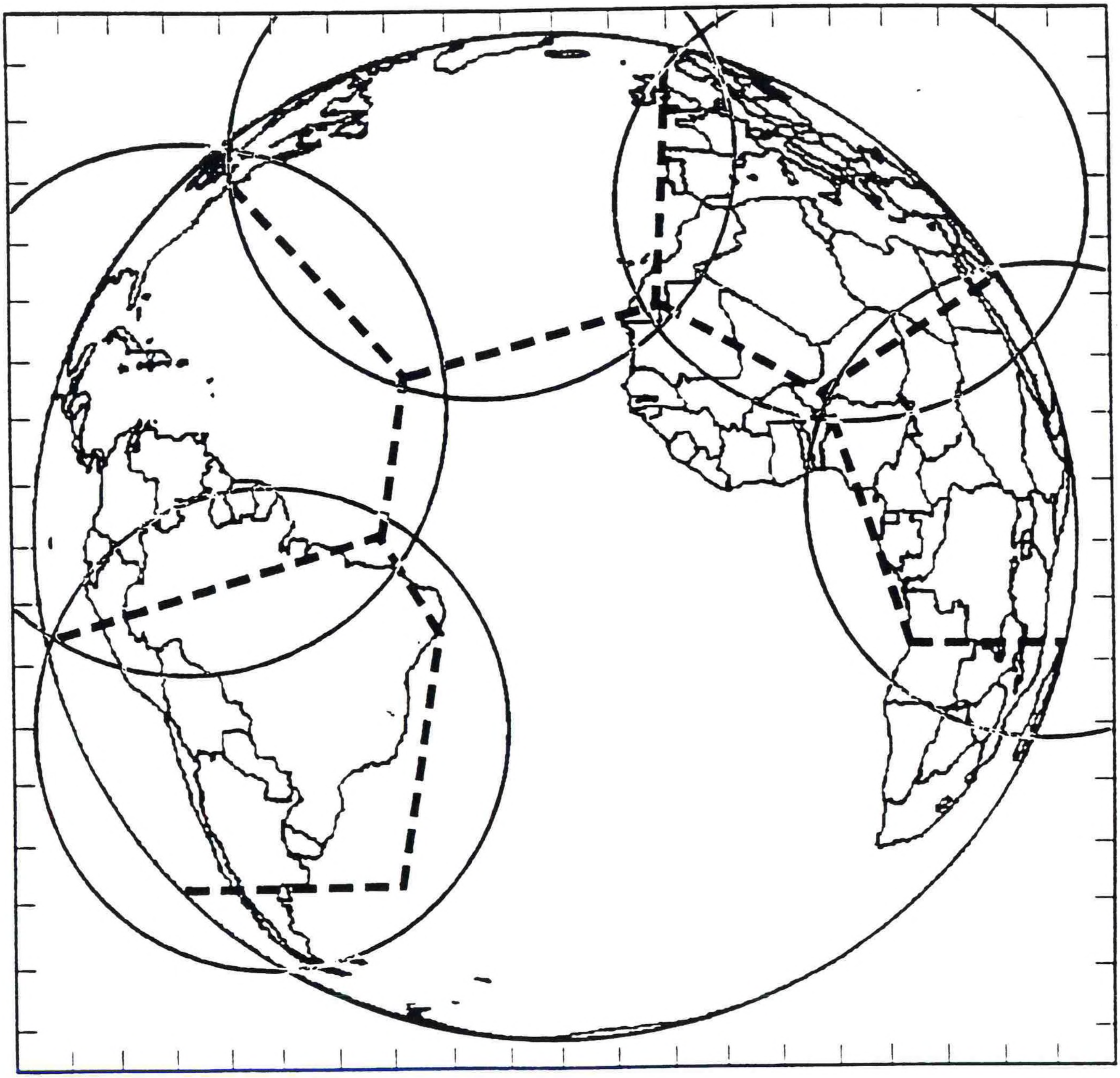


Figure 8

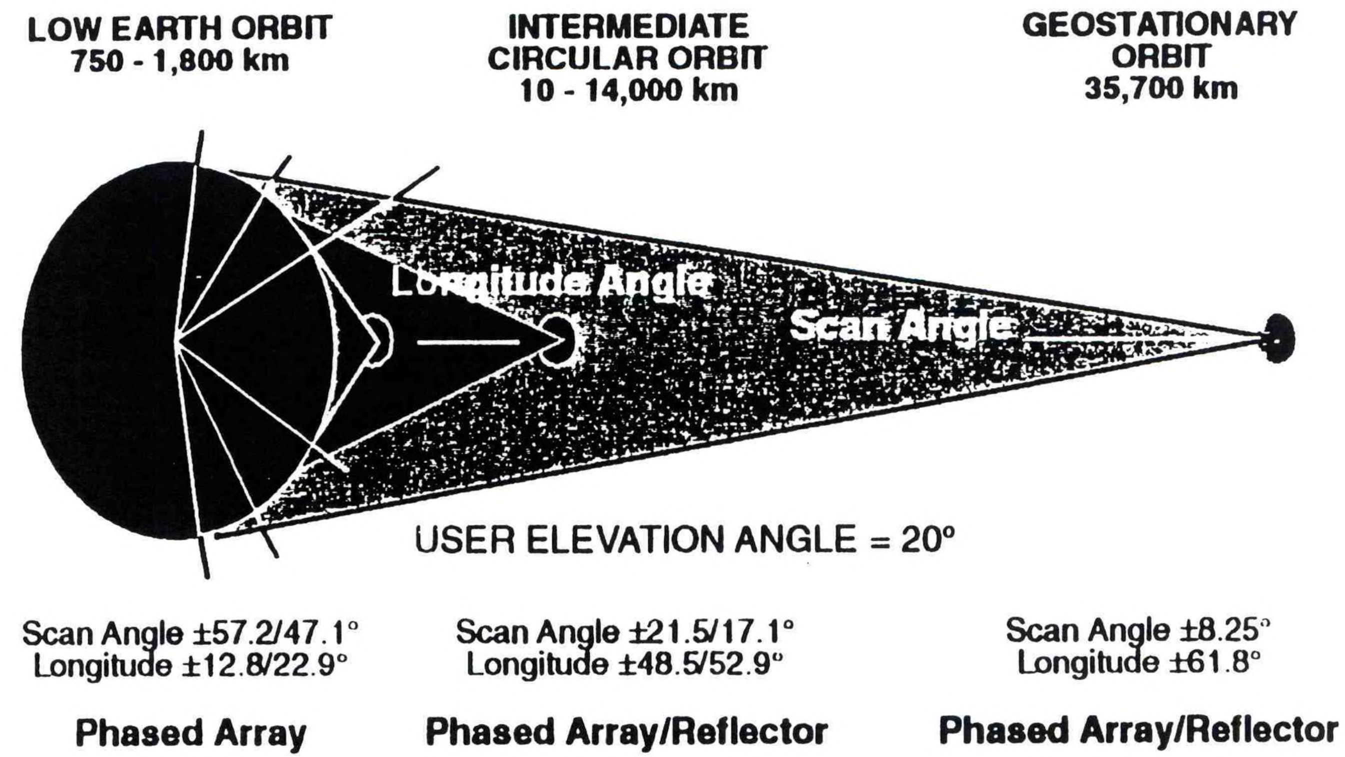

LOW EARTH ORBIT
750 - 1,800 km
INTERMEDIATE
CIRCULAR ORBIT
10 - 14,000 km
GEOSTATIONARY
ORBIT
35,700 km
Longitude Angle
Scan Angle
USER ELEVATION ANGLE = 20°
Scan Angle ±57.2/47.1°
Longitude ±12.8/22.9°
Phased Array
Scan Angle ±21.5/17.1°
Longitude ±48.5/52.9°
Phased Array/Reflector
Scan Angle ±8.25°
Longitude ±61.8°
Phased Array/Reflector

Figure 9

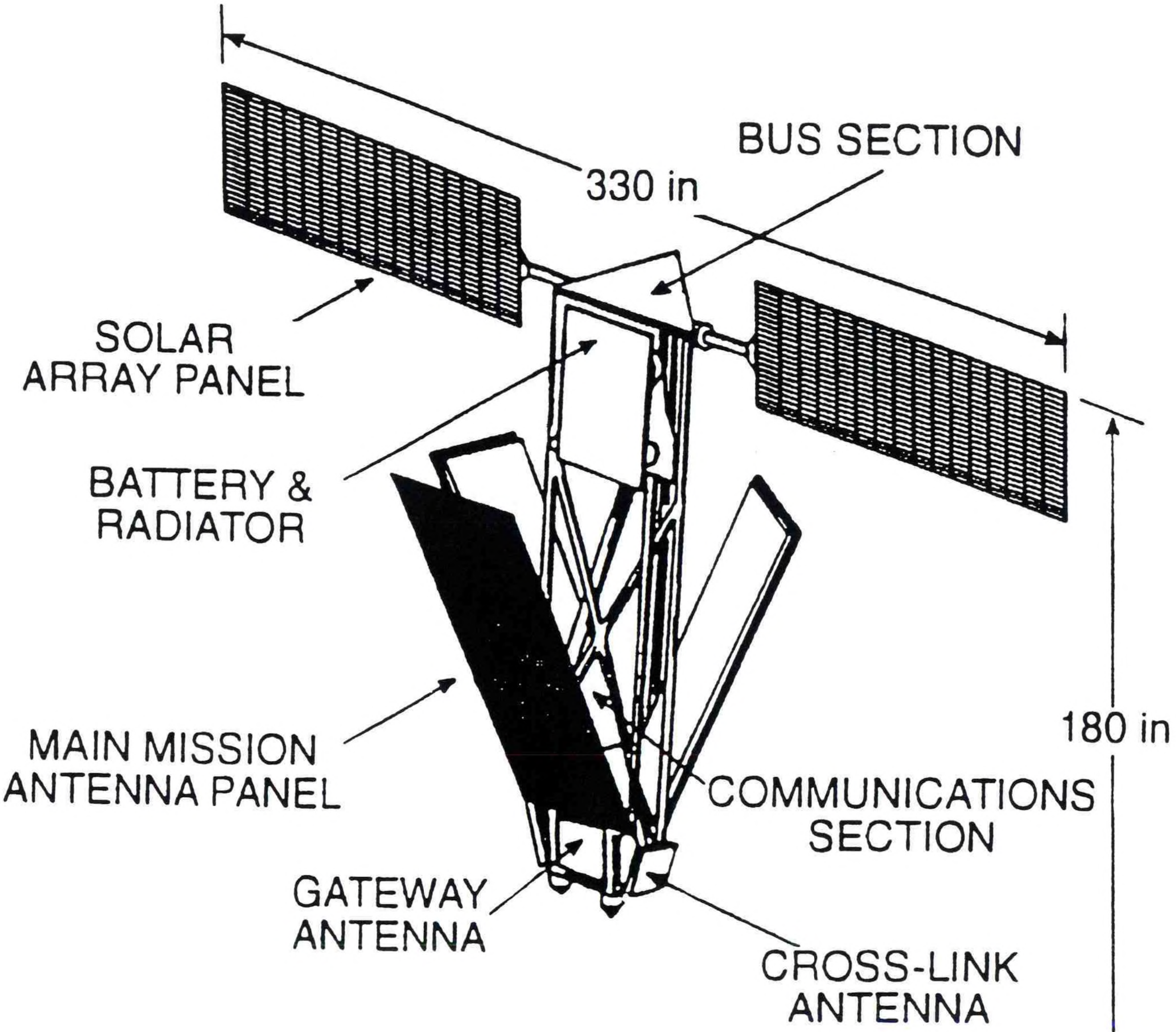

330 in
BUS SECTION
SOLAR ARRAY PANEL
BATTERY & RADIATOR
MAIN MISSION ANTENNA PANEL
180 in
COMMUNICATIONS SECTION
GATEWAY ANTENNA
CROSS-LINK ANTENNA

Figure 10

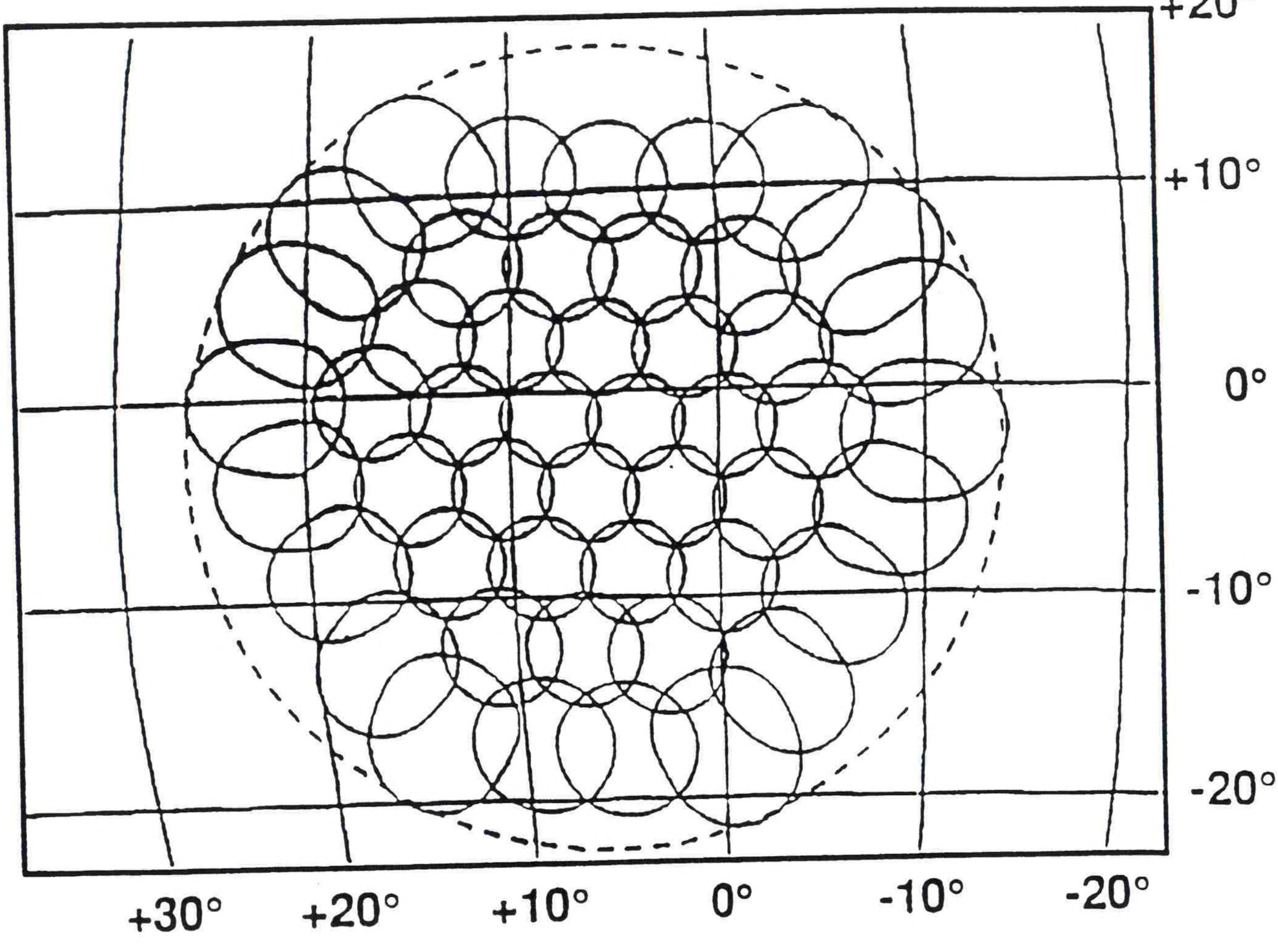


Figure 11

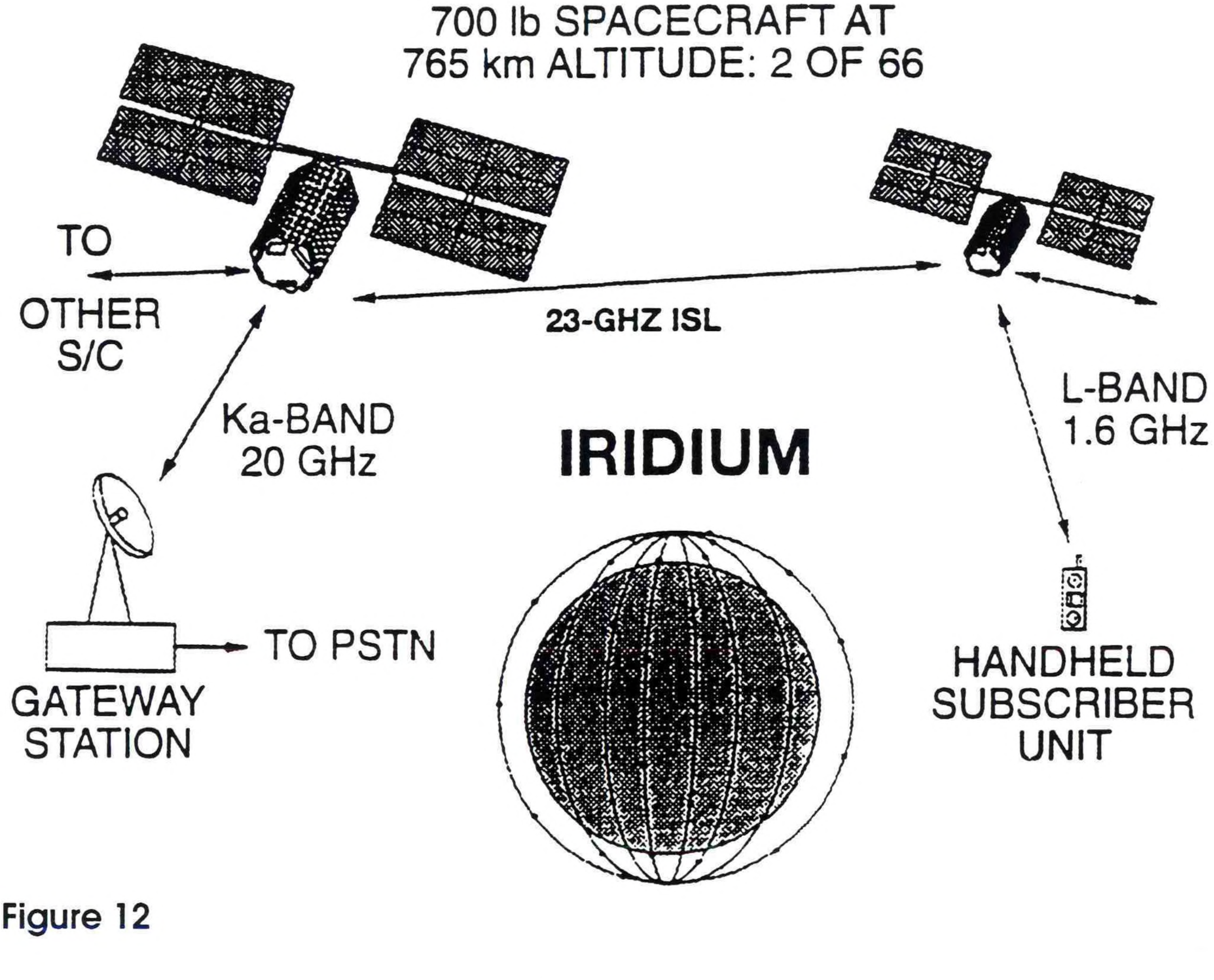

700 lb SPACECRAFT AT
765 km ALTITUDE: 2 OF 66
TO
OTHER
S/C
23-GHZ ISL
Ka-BAND
20 GHz
IRIDIUM
L-BAND
1.6 GHz
TO PSTN
GATEWAY
STATION
HANDHELD
SUBSCRIBER
UNIT

Figure 12

Figure 13

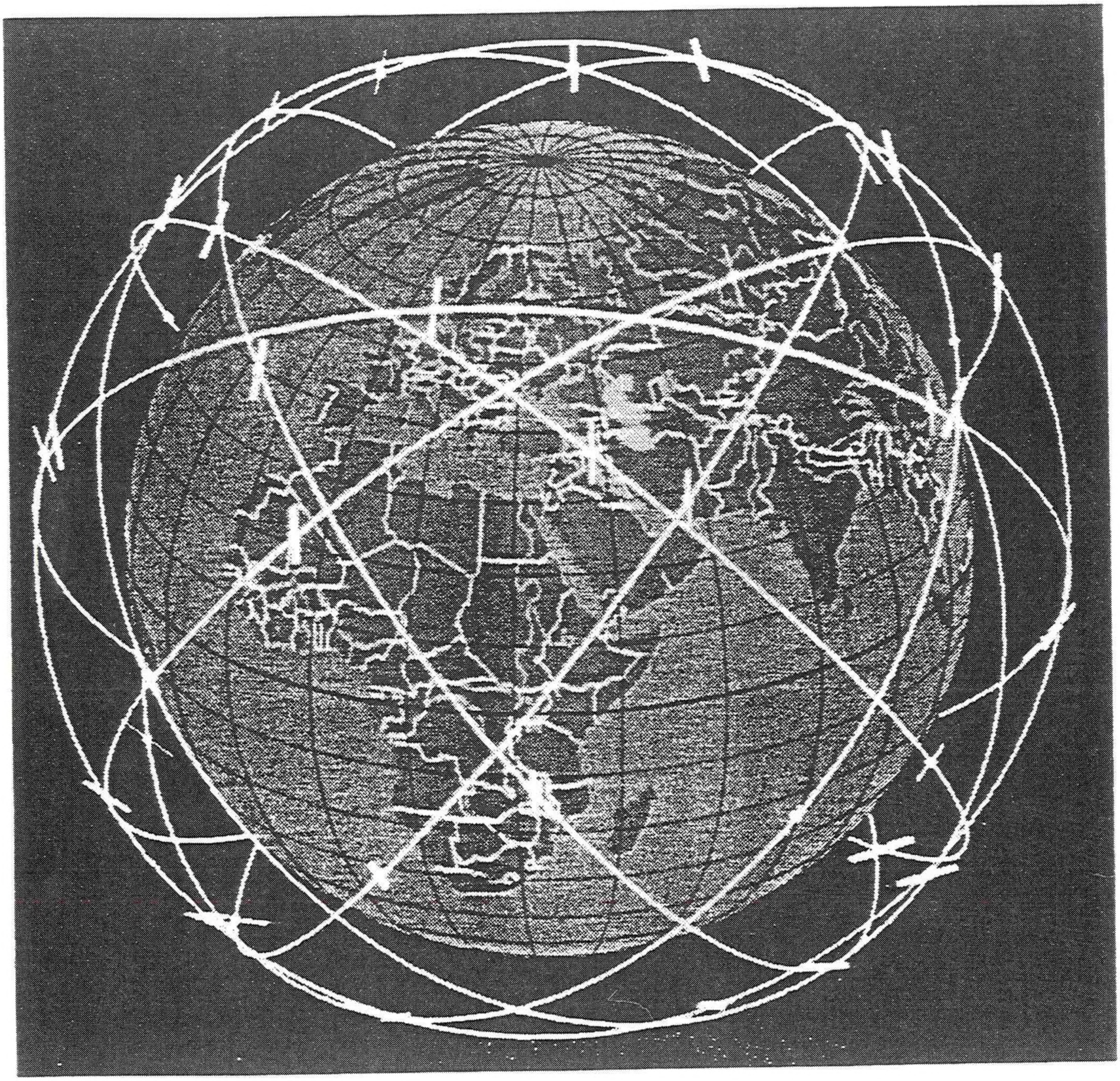


Figure 14

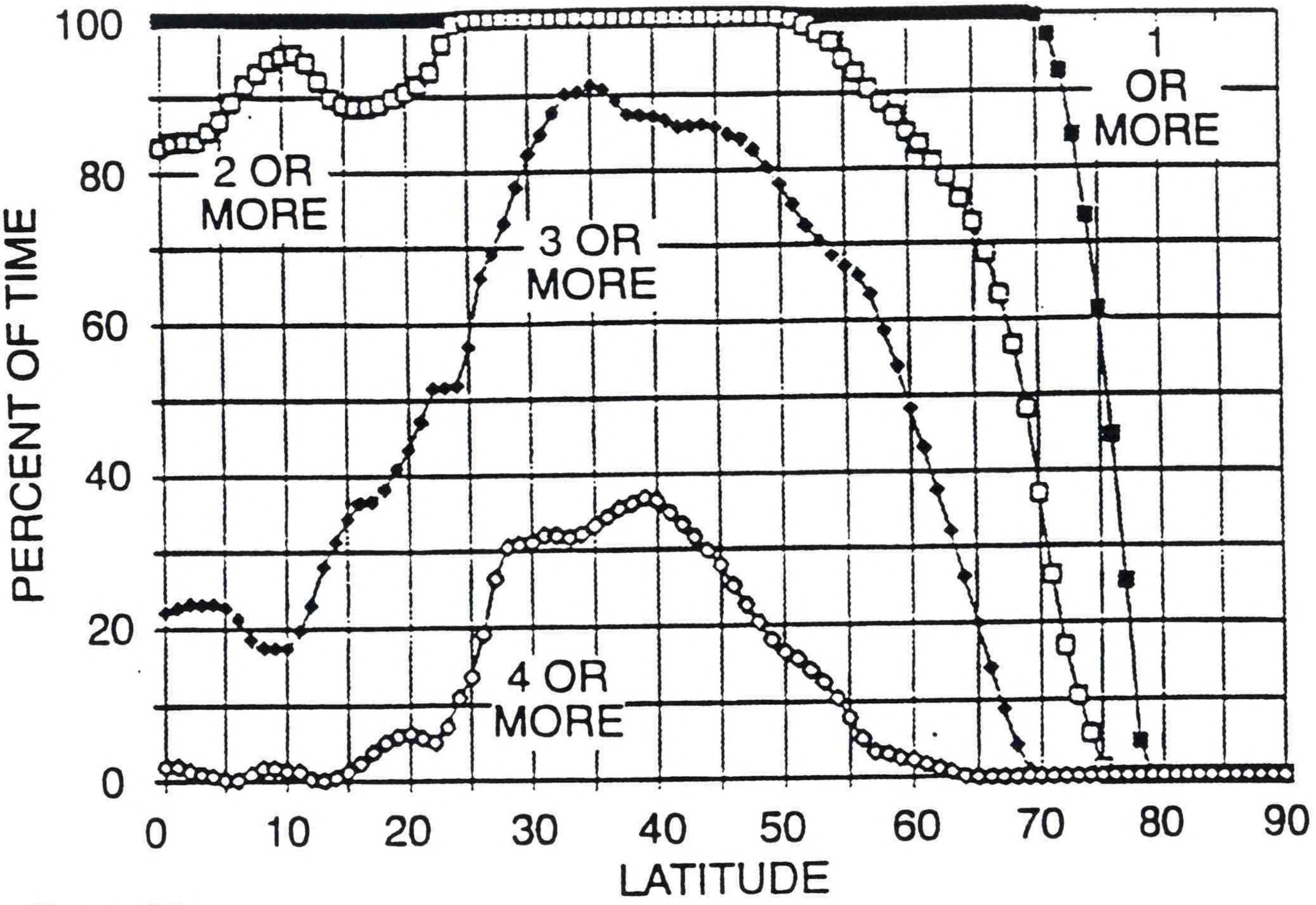

100
80
60
40
20
0
PERCENT OF TIME
0
10
20
30
40
50
60
70
80
90
LATITUDE
1 OR MORE
2 OR MORE
3 OR MORE
4 OR MORE

Figure 15

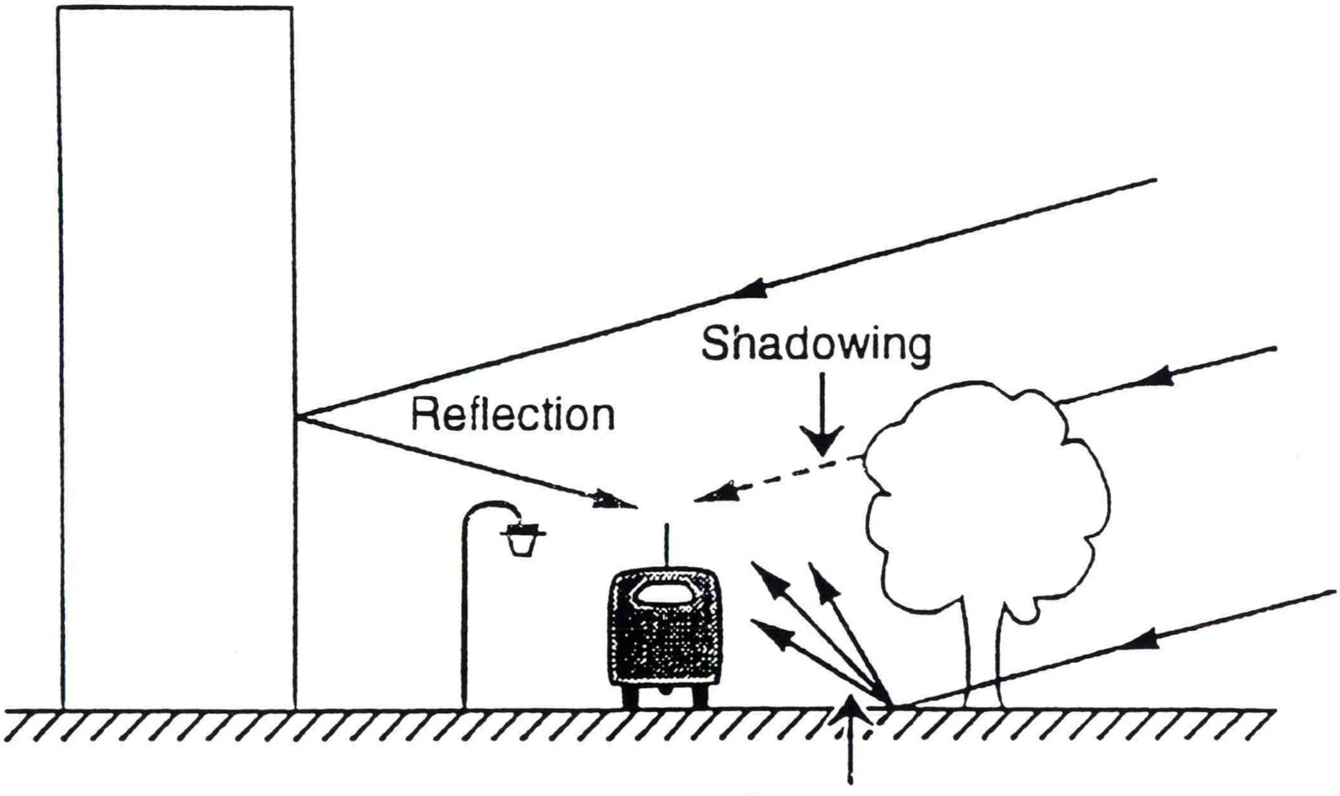


Figure 16

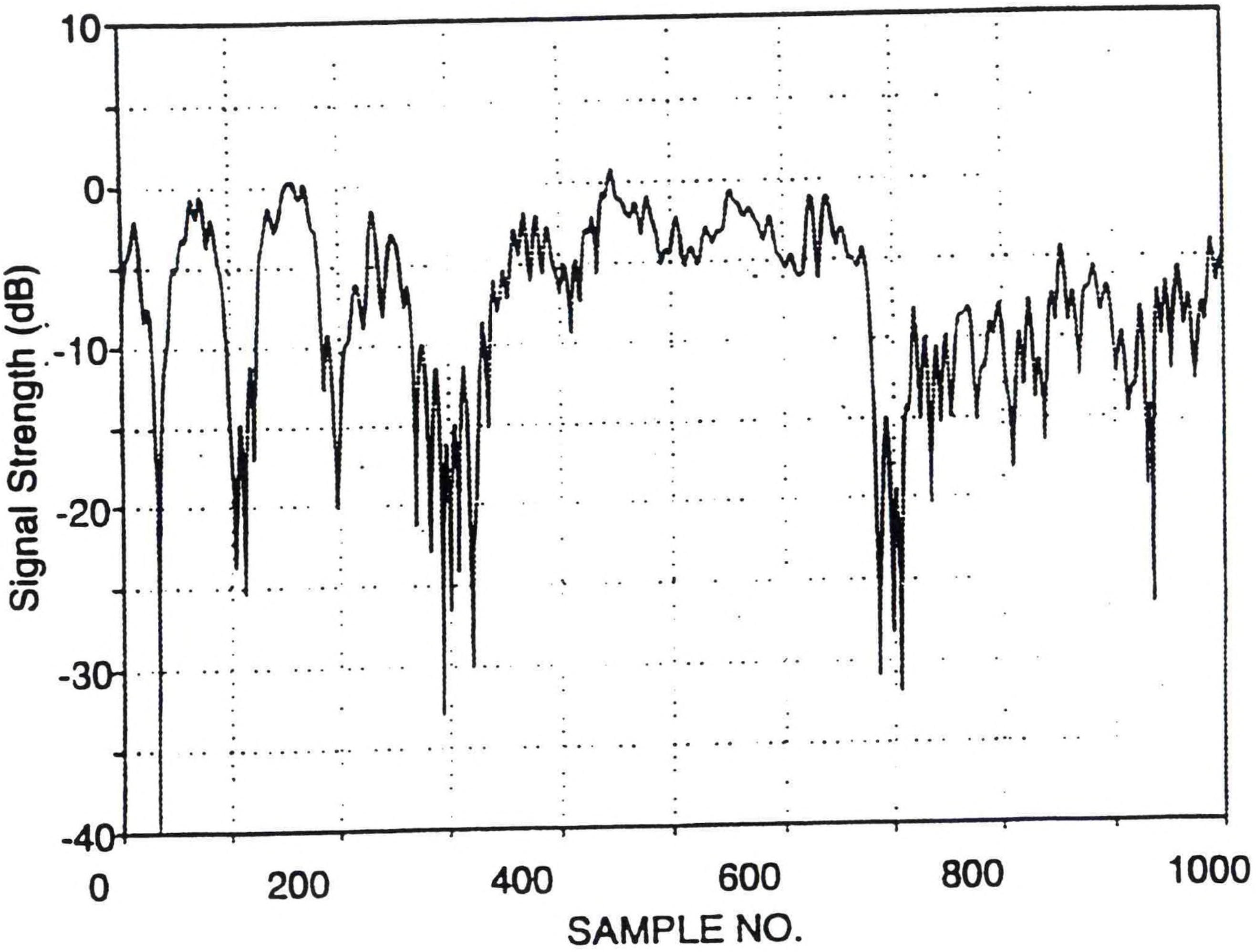

10
0
-10
-20
-30
-40
Signal Strength (dB)
0
200
400
600
800
1000
SAMPLE NO.

Figure 17

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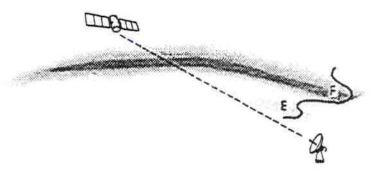
2.7 Signal Statistics of Transionospheric Scintillation

Edward J. Fremouw



SIGNAL STATISTICS OF TRANSIONOSPHERIC SCINTILLATION

Edward J. Fremouw
NorthWest Research Associates
Bellevue, WA

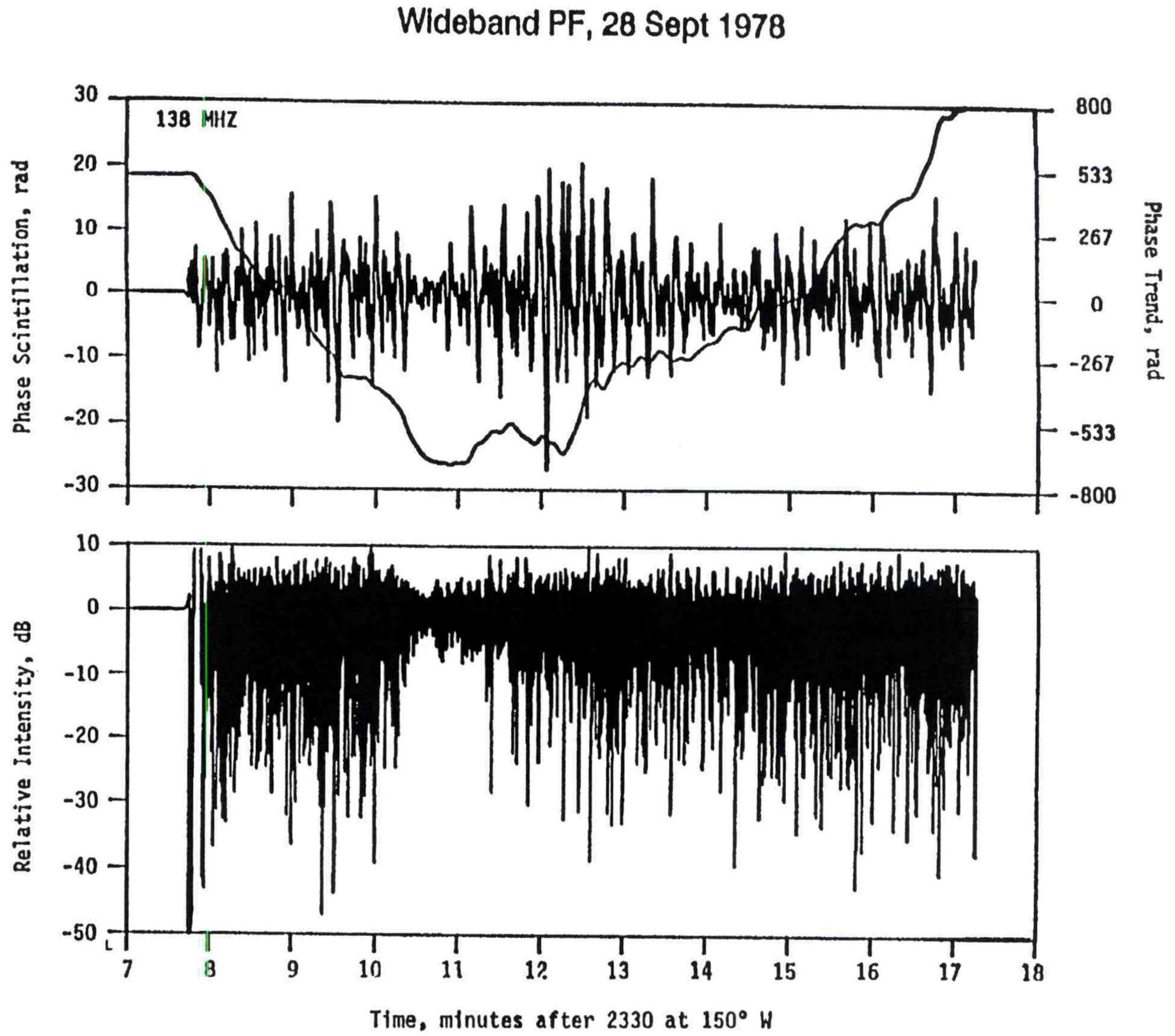
Scintillation comprises intensity and phase fluctuations imposed by refractive and diffractive scattering. The scatterers are plasma-density irregularities that constitute structures in the real part of the radio refractive index on scales much larger than the radio wavelength. They produce only phase variations at the exit plane of the ionosphere, with intensity structures developing in post-scattering propagation via focusing/defocusing and generation of a diffraction pattern. The spatial structures are converted to temporal fluctuations through relative motion between the radio line of sight and the plasma-density irregularities, which drift and reconfigure in the ionosphere.

This tutorial presented the signature of a particular scatterer as identified in complex signals received at VHF, UHF, and L-Band. Seldom can the effects of such individual scatterers be isolated in scintillation records under conditions of operational interest. Rather, an assembly of irregularities is encountered, and they are characterized in terms of their spatial statistics, producing a "red-noise" spectrum of phase fluctuations. The corresponding spectrum of intensity scintillation is truncated at its low-frequency (large-scale) end by "Fresnel filtering" and broadened by multiple scatter. Realizations of first-order signal statistics were illustrated on the complex plane, and examples of phase and intensity scintillation spectra were presented.

The irregularities that produce scintillation are anisotropic. When the radio line of sight nearly coincides with an elongation axis, signal fluctuations are enhanced by quasi-coherent integration of the phase perturbations imposed. Such enhancement is prominent for propagation nearly along the geomagnetic field and may be encountered at off-field angles close to the local L shell at auroral latitudes.

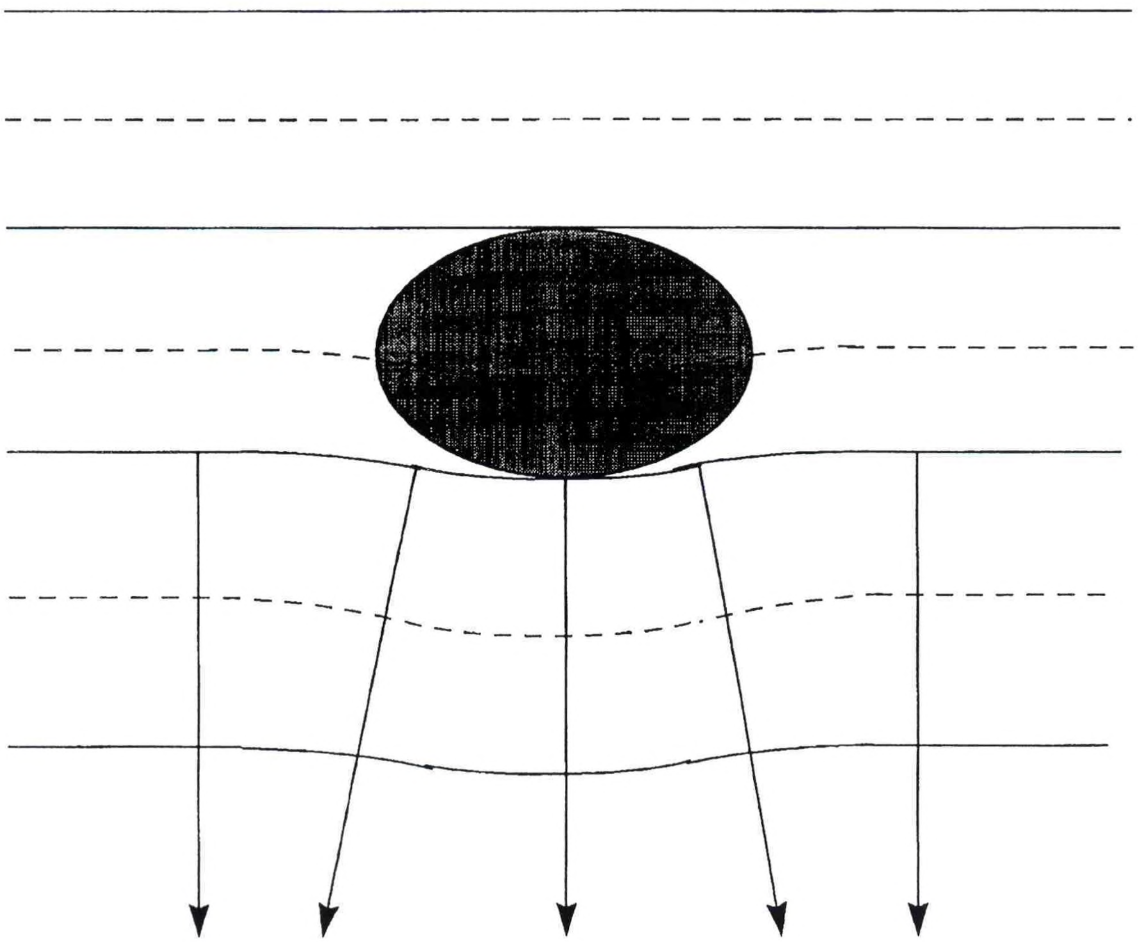
Given the stochastic nature of scintillation, its effects are quantified by means of signal-statistical moments ("scintillation indices"). Much work has been done on compiling the global climatology of intensity and phase scintillation indices, and the scattering theory that unifies them is well developed. Scintillation is strongest at the lowest frequencies that penetrate the ionosphere, but it does arise well above L Band. It is most prevalent at equatorial and auroral-to-polar latitudes, and its occurrence frequency increases substantially as solar activity builds.

The foregoing behaviors and the dependence of scintillation on time of day, longitude, season, and global geomagnetic activity, all of which have been committed to a computer model, were described at this workshop in a companion talk by Santimay Basu. Outputs from the climatological model may be accessed at 'http://www.nwra.com/nwra/scintpred'. That model now needs to be supplemented with forecast (or at least nowcast) tools for dealing with individual space-weather events.

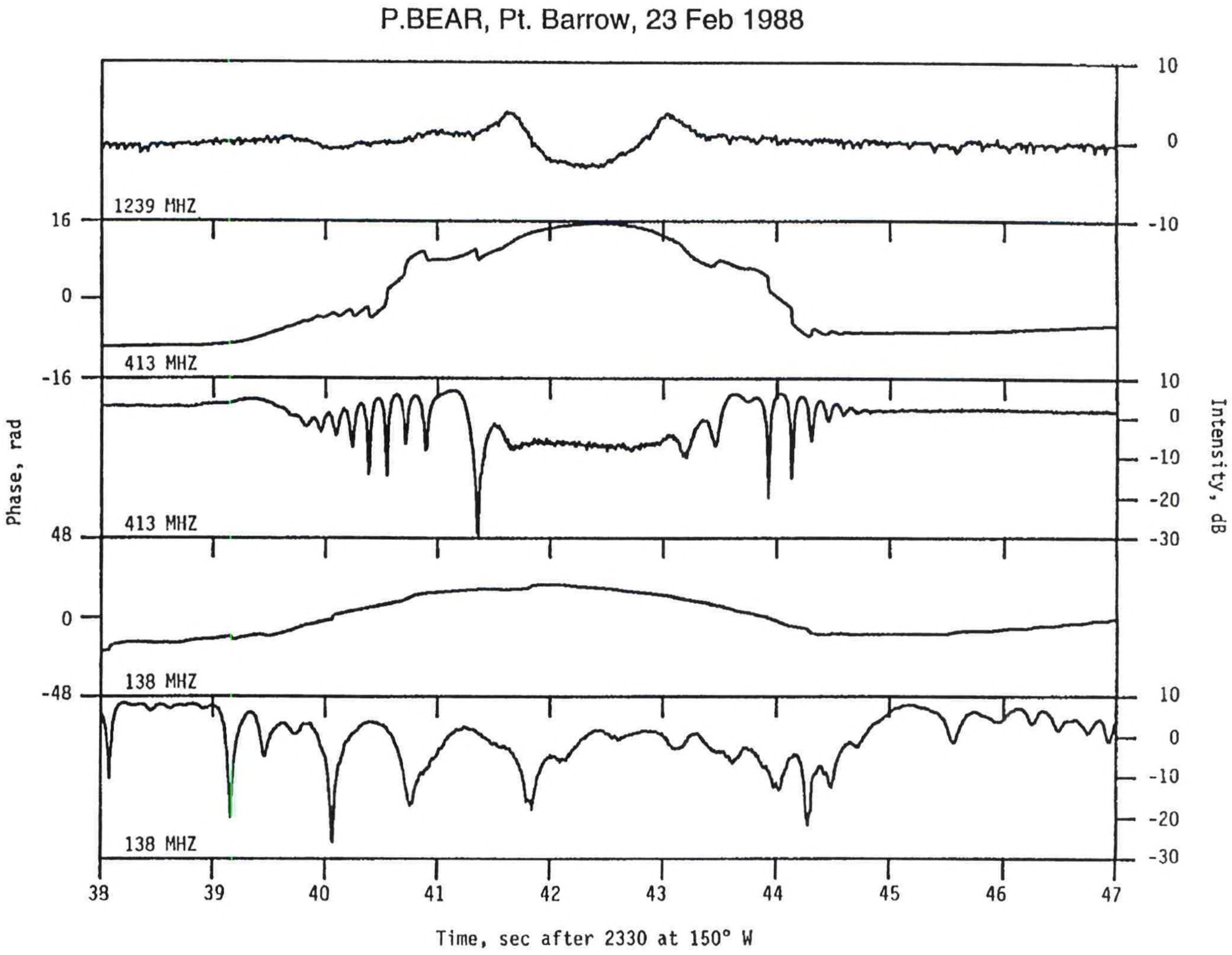


Scintillation consists of random fluctuations in phase (top) and intensity (bottom). Illustrated here is a pass of the Wideband experimental satellite over Poker Flat, AK. Phase fluctuations are presented relative to a trend (also illustrated) isolated by means of a low-pass filter with a cutoff frequency of 0.1 Hz. Note intensity fades to several tens of dB.

Refraction by a Single Irregularity



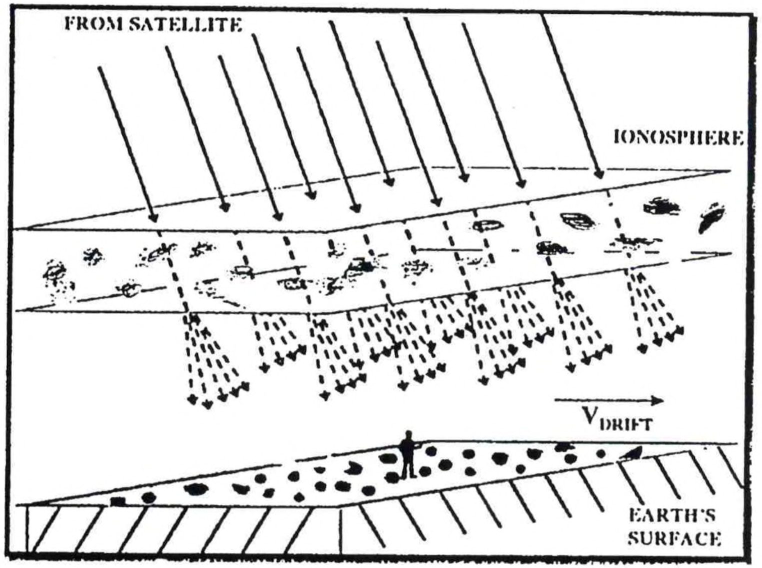
Refraction by a single lens-like excess of plasma density (refractive index) results in a localized phase advance and rays that produce a weak defocus and two adjacent foci on a distant plane.



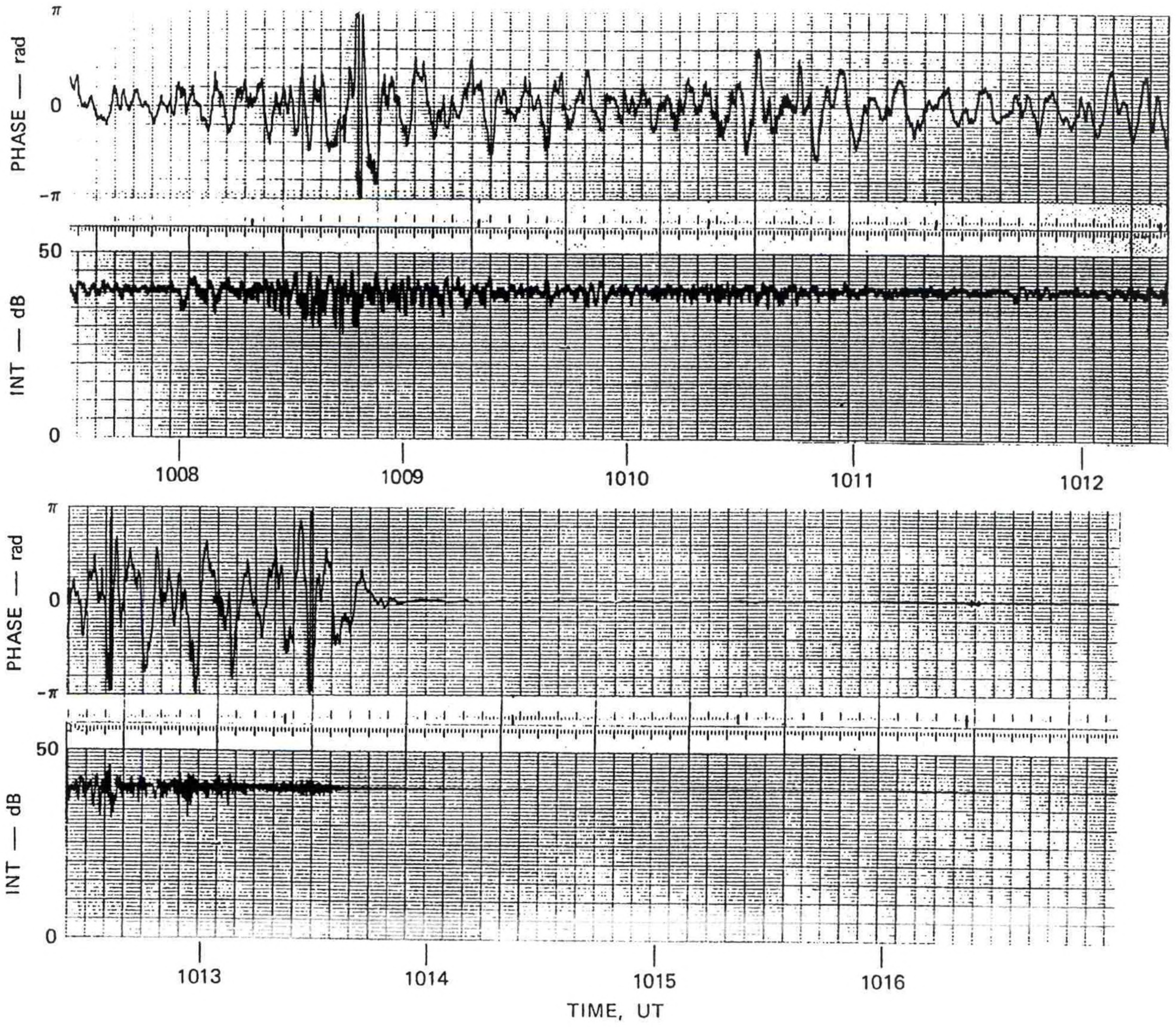
Refractive multipath signature of an isolated "radio lens" encountered by the Polar BEacon and Auroral Research satellite on a pass over Point Barrow, AK. Top to bottom: L-band inensity, showing weak defocus and two adjacent foci; UHF phase showing overall "lens" signature and multi-path phase jumps; UHF intensity showing distinct multipath nulls near twin "focal points"; VHF phase showing expanded lens signature and phase jumps; VHF intensity showing nulls encountered beyond the radio "focal plane."

SCINTILLATION

- Large scale (~ km) irregularities in electron density cause diffraction of incident radio waves
- Interference pattern changes in time and space
- User observes rapid fluctuations of signal amplitude and phase

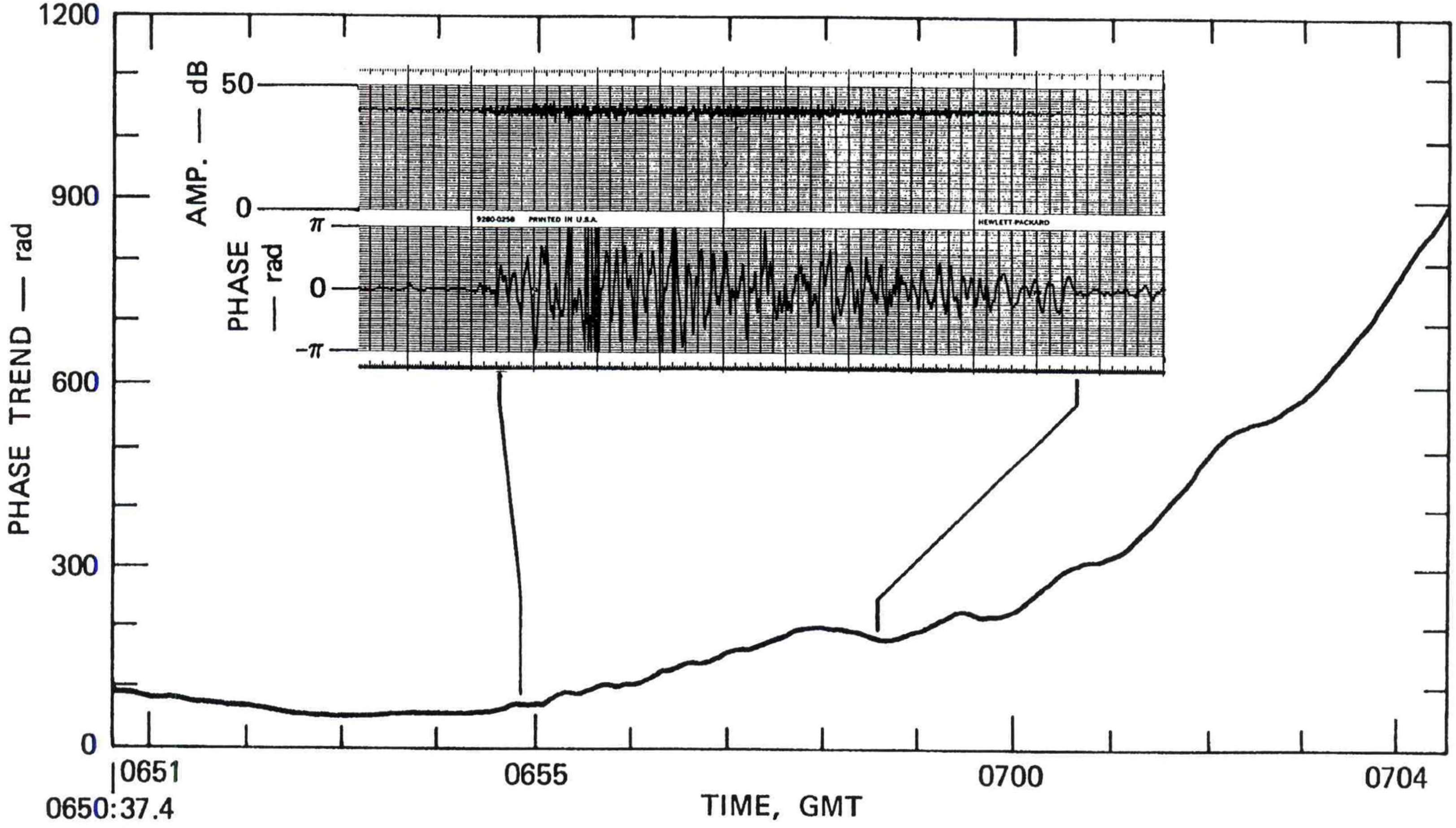


From Keith Groves, AFRL



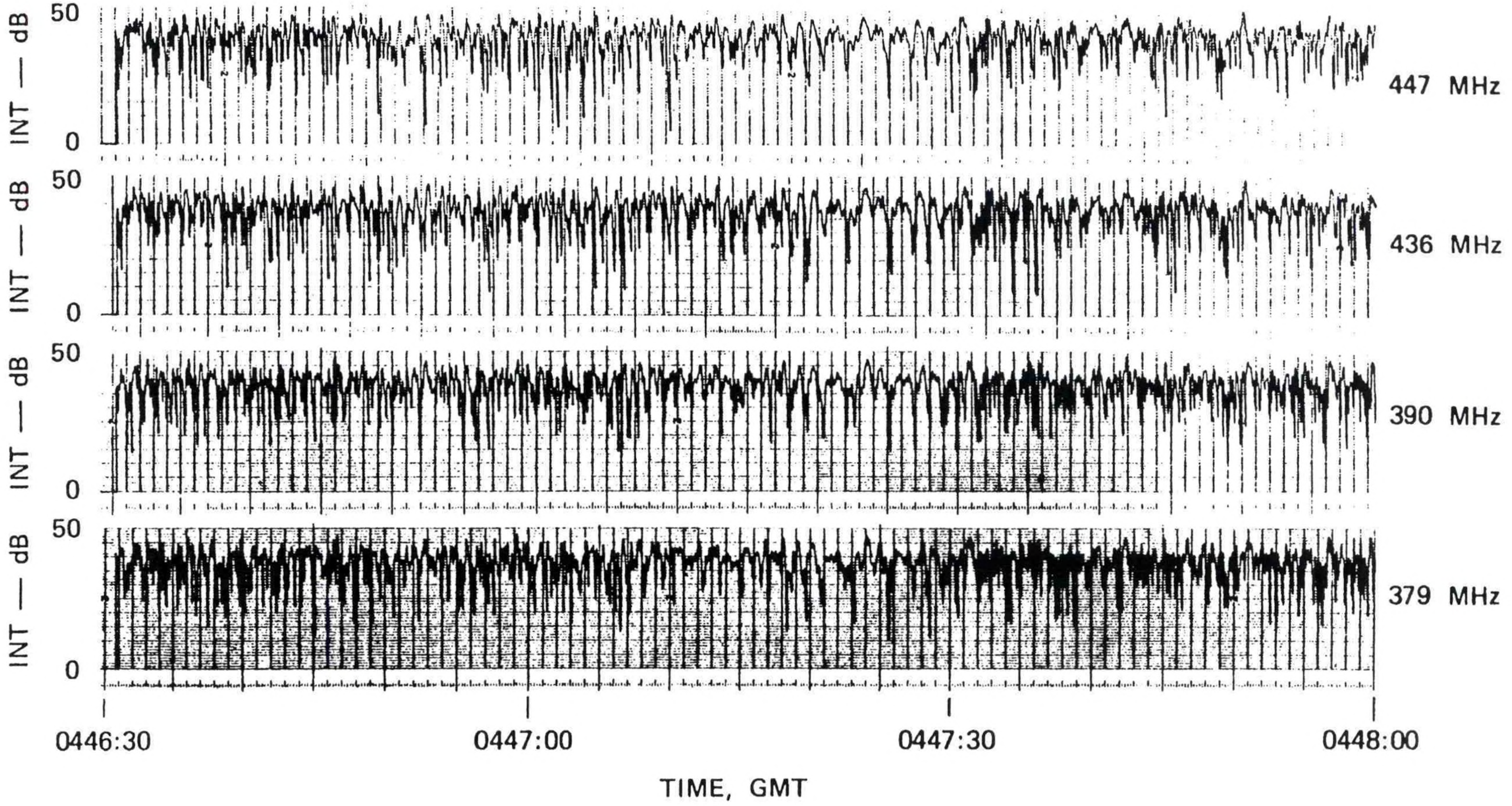
VHF phase and intensity from a Wideband Pass over Poker Flat, AK, showing sudden cessation of moderate scintillation as line of sight crossed from structured auroral ionosphere to smooth "mid-latitude trough."

PASS OVER STANFORD; 7 JULY 1976 GMT



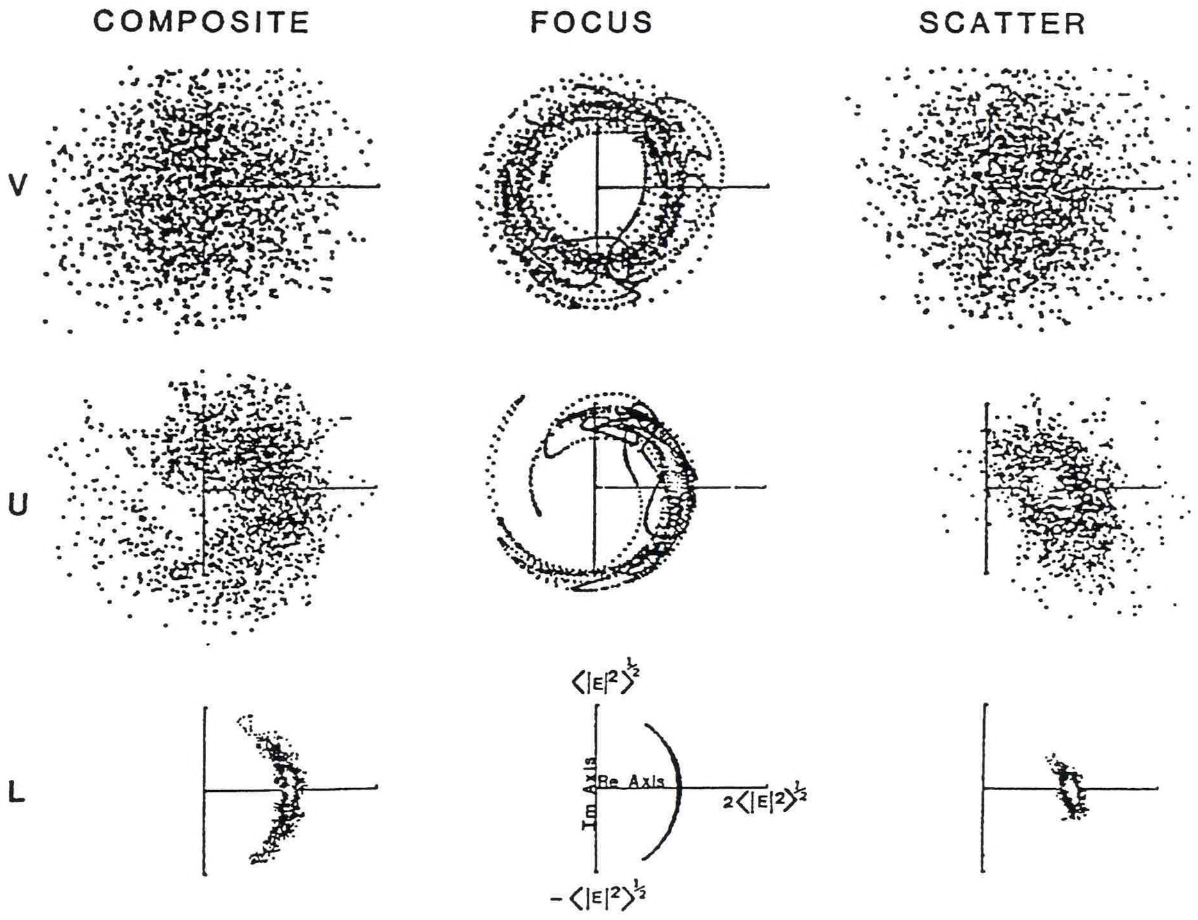
Mid-latitude scintillation tends to be weak and patchy, even at VHF as shown here from a nighttime pass of Wideband over Stanford, CA. Exceptions (stronger scintillation) occur as space-weather events during major geomagnetic storms.

WIDEBAND OVER ANCON, PERU

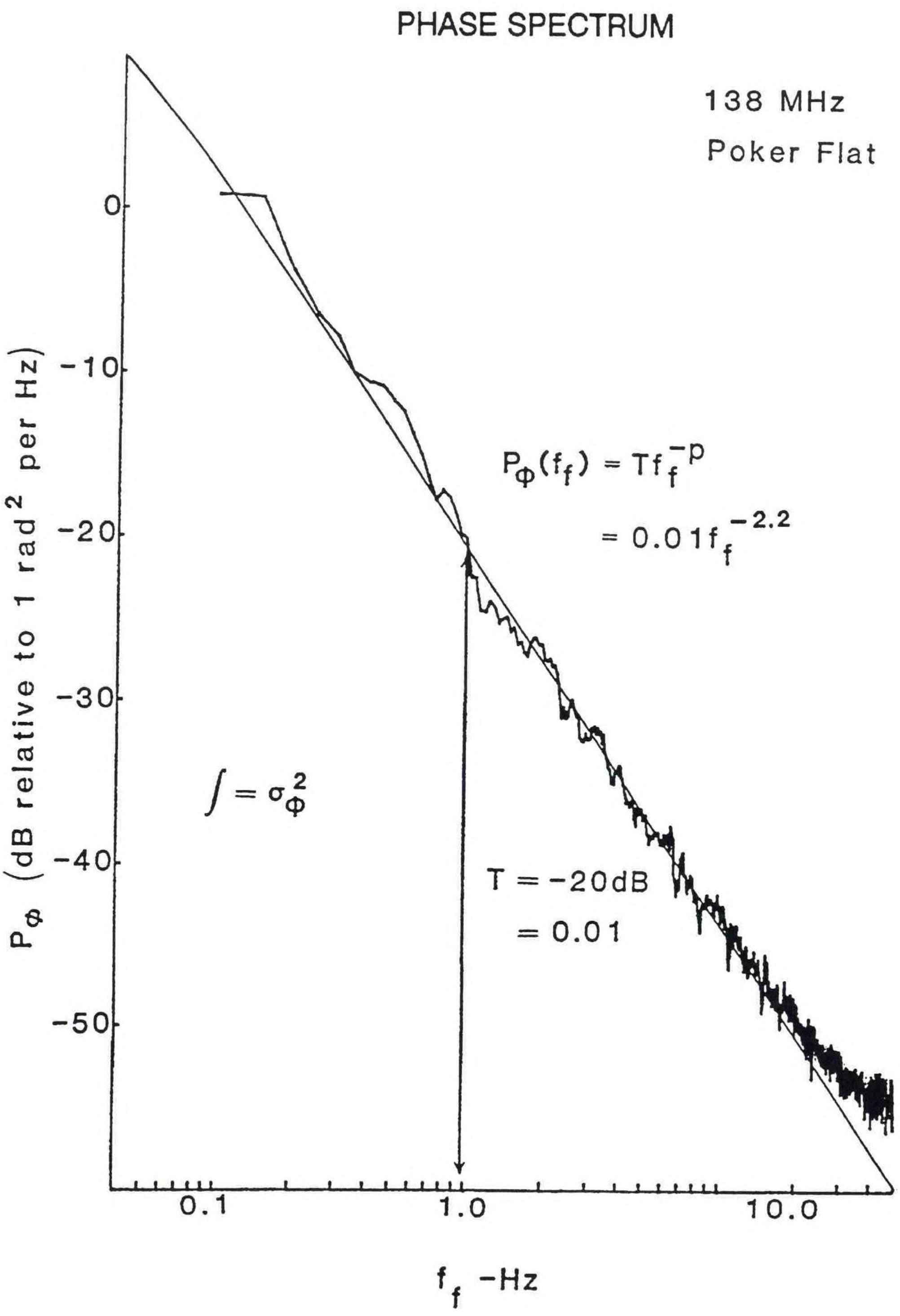


Strongest scintillation occurs in the geomagnetic equatorial region. Intensity scintillation illustrated was observed simultaneously on four UHF signals transmitted from Wideband on a pass over South America. Note partial (but incomplete) correlation between multi-dB fades across a bandspread of 68 MHz.

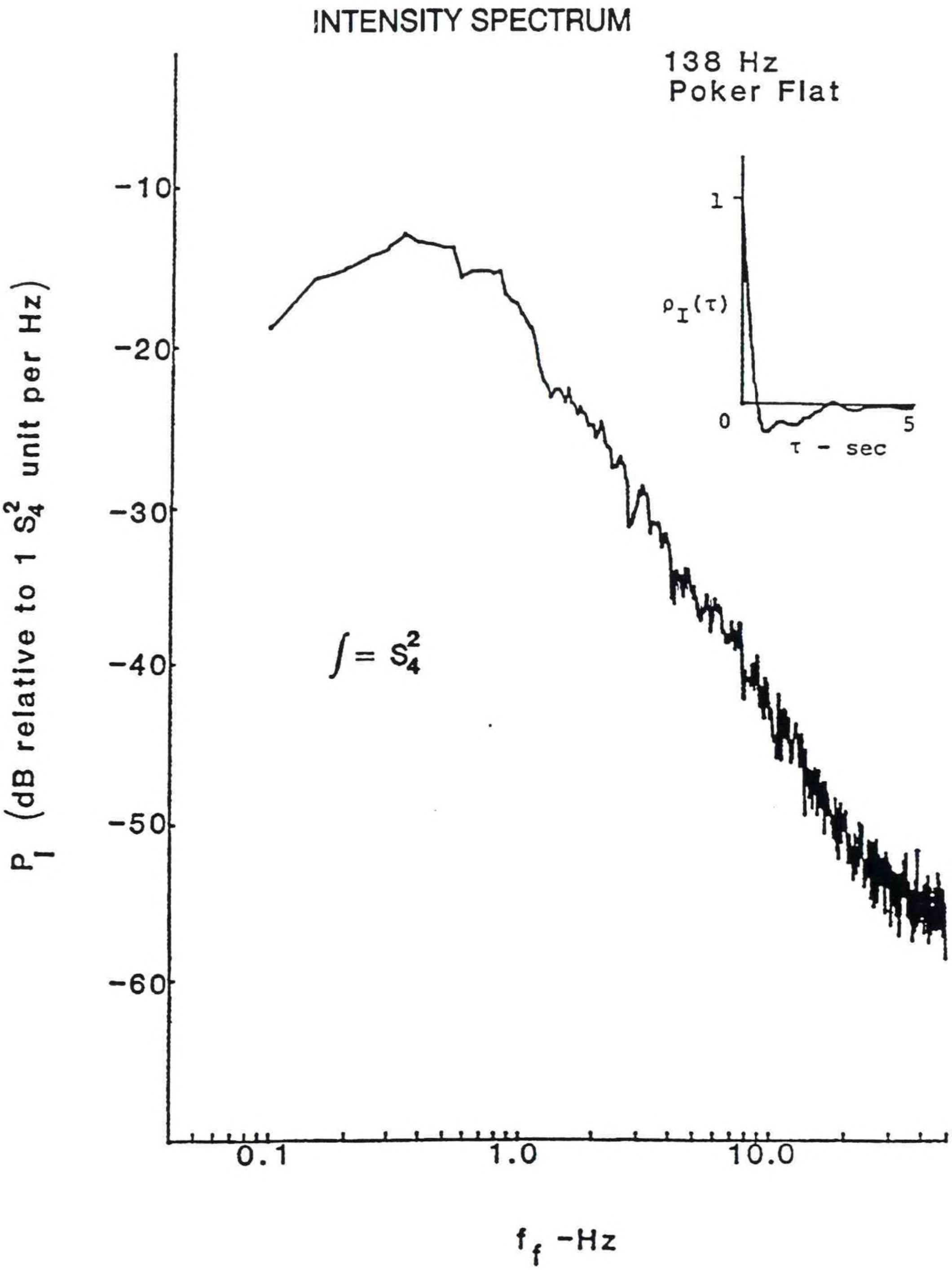
COMPLEX-SIGNAL STATISTICS



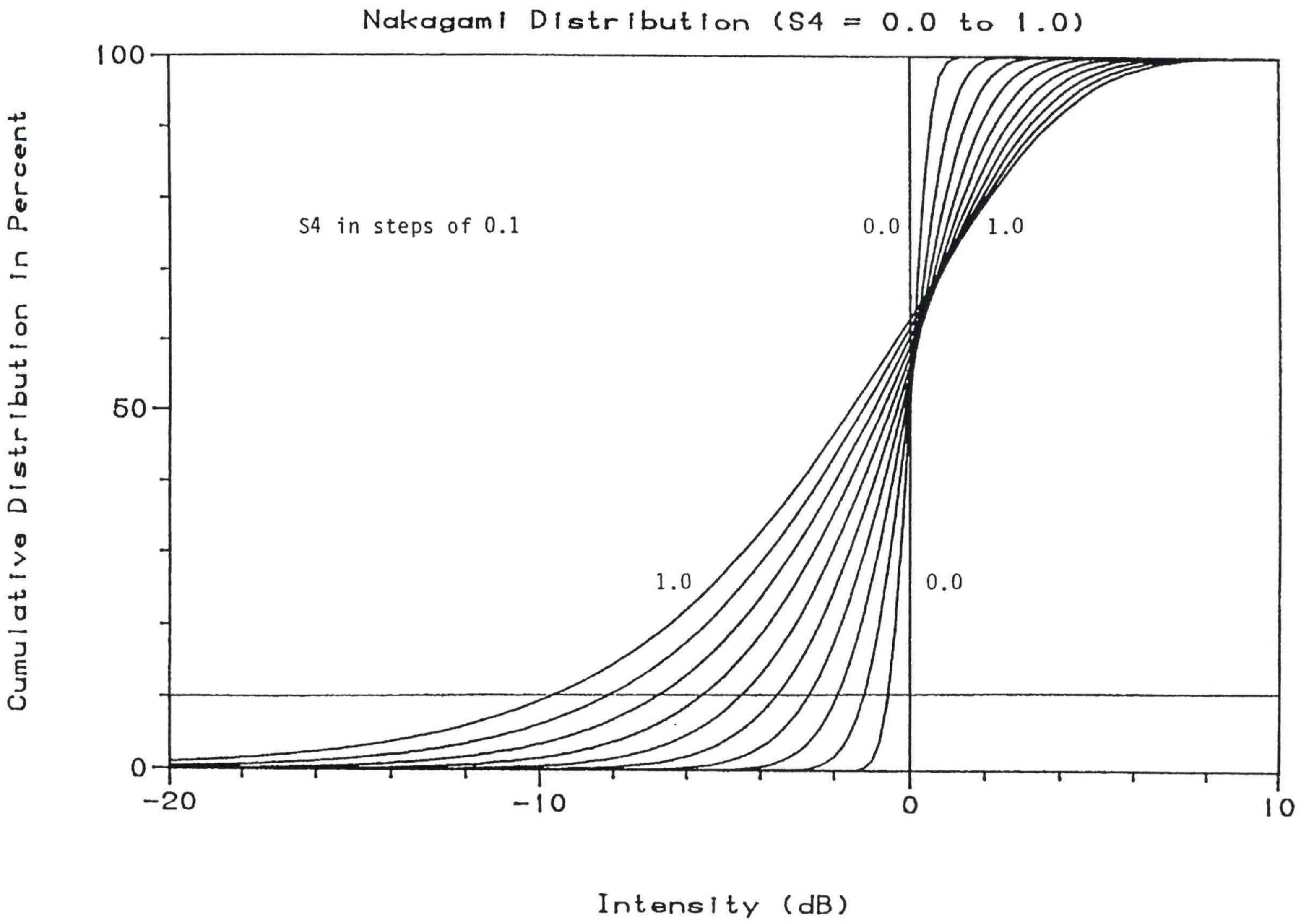
Scatter plots of VHF (top), UHF (center), and L-band (bottom) radiowave phasors on complex plane. "Snail-shell" pattern of composite UHF signal (left) illustrates correlation between intensity and phase, stemming from geometric-optics behavior of "focus" component (center); faster fluctuations (right) are aptly modelled stochastically by means of a diffractive-scatter approach. Signal statistics tend toward those of Rayleigh scatter when scintillation is strong (as for VHF here).



Power spectrum of phase fluctuations often is well characterized by a simple power law, fully quantified by means of a strength parameter, T, and a spectral index, p. The rms phase fluctuation, σ_ϕ, is sometimes quoted as a phase-scintillation index. Since it is the square root of the integral (variance) under this spectrum, it is very dependent on the spectrum's low-frequency cutoff. The cutoff almost always is set by a system or data-processing factor and not by nature.

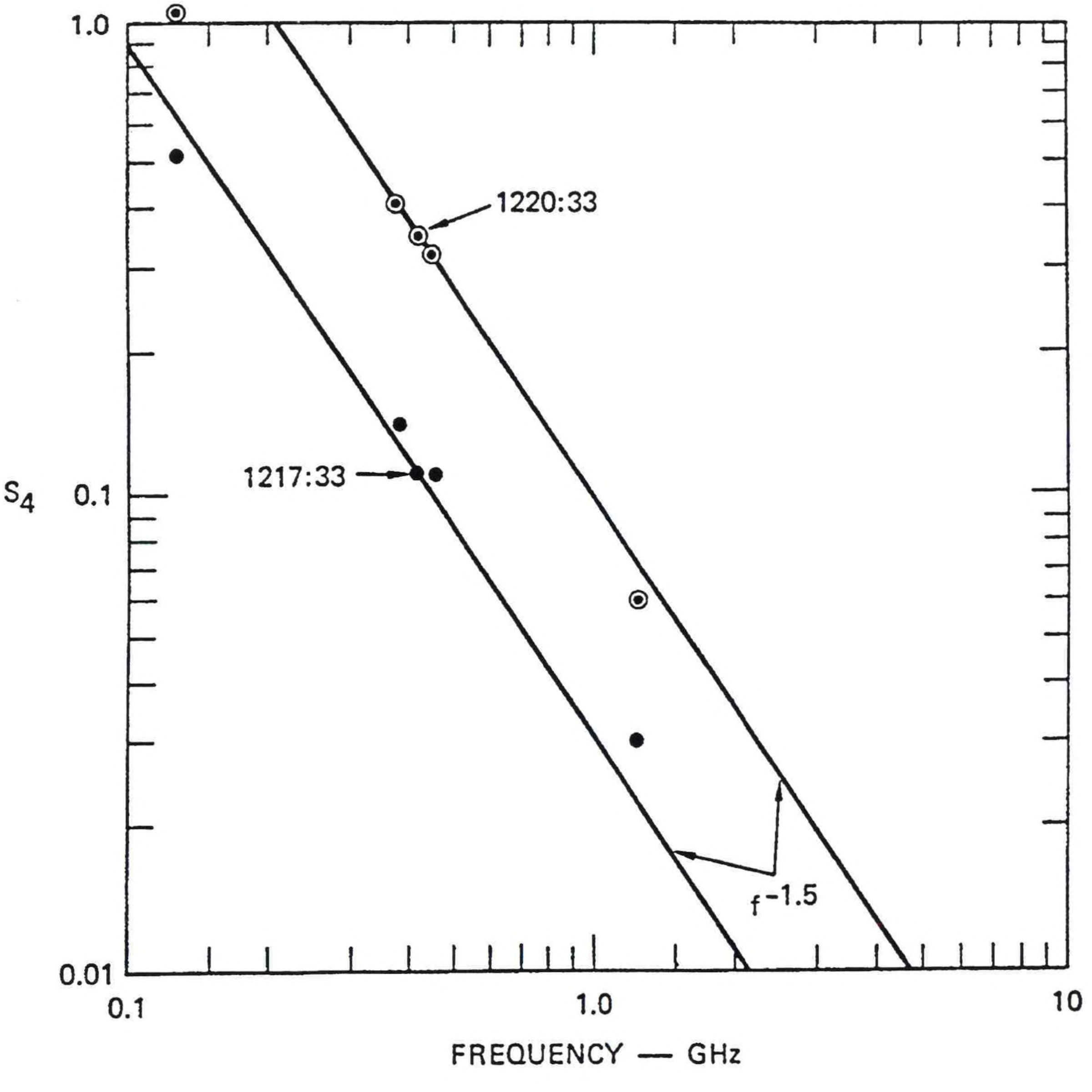


The intensity spectrum **is** cut off by nature, via the propagation effect referred to as "Fresnel filtering." This stems from the fact that large-scale irregularities (which produce low-frequency phase fluctuations) cannot produce diffraction nulls and peaks or focus-defocuses at the distance of the observing plane (e.g., the earth's surface) from the ionosphere. Consequently, the integral under this spectrum (the intensity variance) is a robust measure of intensity scintillation. Its square root (rms intensity fluctuation), when normalized by the mean intensity, often is used as a scintillation index, called S_4.



The distribution of intensity for a given value of S_4 is known, so fade-margin curves can be constructed, as illustrated here. For instance, an S_4 of unity results in fading deeper than 10 dB 10% of the time. The signal is below 3dB 10% of the time for an S_4 of 0.4.

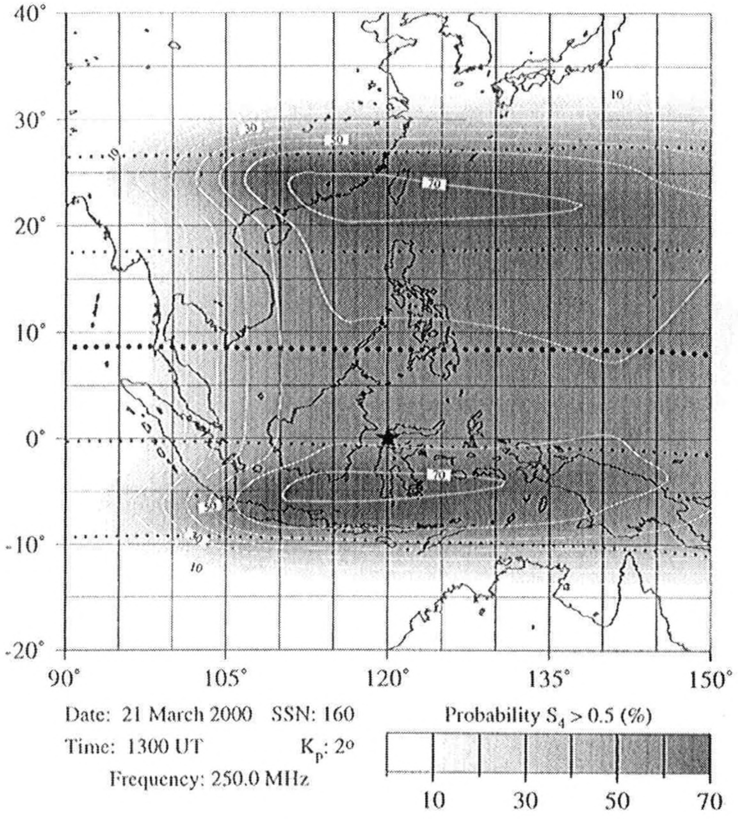
FREQUENCY DEPENDENCE OF S_4



The frequency dependence of both phase and intensity scintillation is well known. For phase, T goes as f^{-2}. The dependence for intensity is controlled by the index of the power-law spatial spectrum of plasma-density irregularities. A representative dependence for S_4 is $f^{-1.5}$, as illustrated here from Wideband data. Strong scintillation saturates S_4 near unity. Multiple scatter – typically encountered at lower frequencies – broadens the intensity spectrum, producing faster fluctuations, but not stronger ones.

Scintillation Forecast — Far East Sector

URL: http://www.nwra.com/nwra/scintpred/



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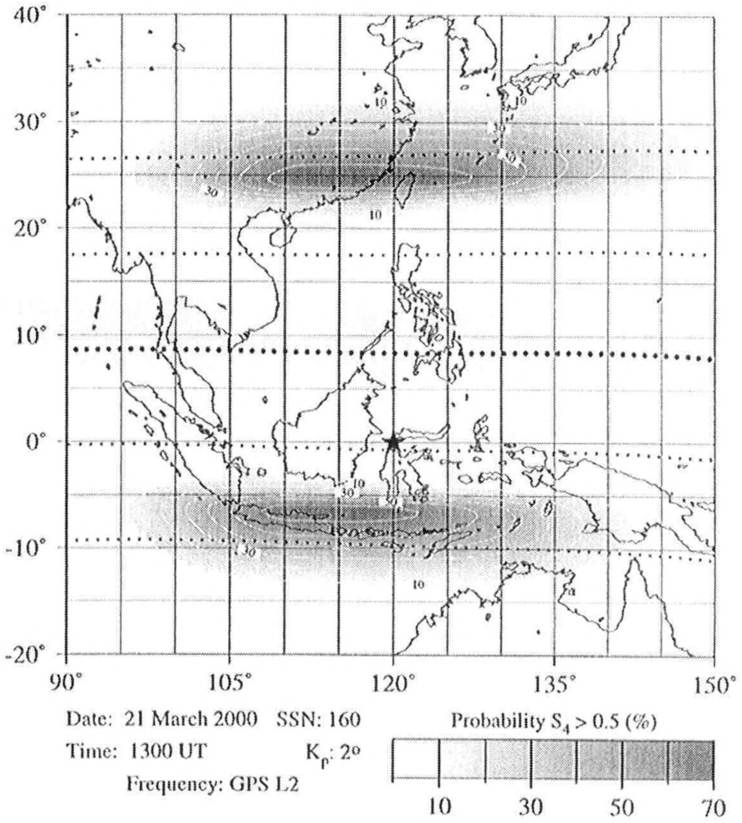

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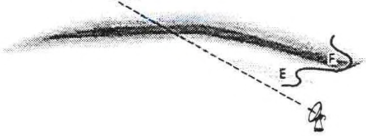
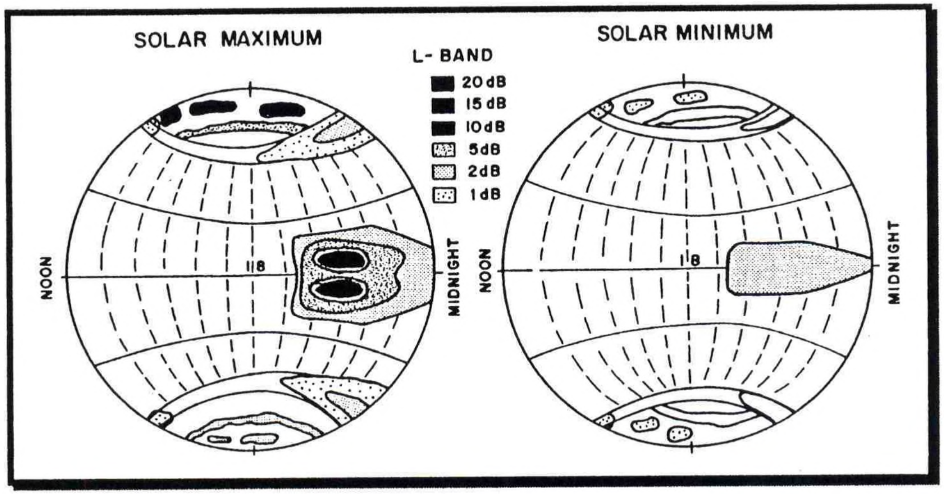
Due to time limitations, this talk necessarily omitted some scintillation behaviors – including enhancements on raypaths nearly aligned with the magnetic field. These and other geometrical effects may be calculated from scattering theory. The theory and relevant ionospheric parameters are included in an available scintillation model. A representative output from that model is illustrated here, for ground-based reception of signals from a geostationary satellite located at 120° E longitude (star). For receivers located on a lat-lon grid in the post-sunset region of the equatorial far east near solar maximum, the program has contoured the probability that S_4 will exceed 0.5 at 150 MHz (left) and for GPS (right). Other outputs may be found at the URL indicated at the top of this figure.

2.8 Climatology of Transionospheric Scintillation

Santimay Basu



CLIMATOLOGY OF TRANSIONOSPHERIC SCINTILLATION



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HANSCOM AFB, MA

Space Weather Effects on Propagation of Navigation and Communication Signals

COMSAT Corp., October 1997

Climatology of Transionospheric Scintillation

Santimay Basu

Air Force Research Laboratory
Hanscom AFB, MA 01731

Abstract. The F-region of the ionosphere, typically above 150 km, at times becomes turbulent and develops small scale (< 1 km) irregularities of electron density. These irregularities scatter radio waves from satellites and generate amplitude and phase scintillations. When sufficiently intense, these irregularities may cause significant scintillations to impact not only VHF, but L-band satellite communication and navigation systems, as well. Scintillations are pronounced in the polar and equatorial regions and are minimal at middle latitudes. Polar and equatorial scintillations show a marked solar cycle variation and are expected to attain intense levels during the upcoming solar maximum period around year 2000. At that time, GPS receivers are expected to encounter 8-10 dB intensity scintillations within the central polar cap, such as Resolute Bay, Canada and Thule, Greenland. During the current solar minimum period, GPS receivers have recorded large scale (~ tens of km) phase variations corresponding to ionospheric range delays exceeding 0.3 meters/minute. This delay is expected to increase by a factor of 3 to 5 during the solar maximum period due to increased irregularity amplitudes. Scintillations are most intense in the equatorial region and especially along two belts which straddle the magnetic equator at magnetic latitudes of 15 degrees north and 15 degrees south. Along these belts, known as the equatorial anomaly regions, the electron density of the F-region ionosphere is much enhanced through the so-called 'fountain effect' which transports plasma from the magnetic equator to these regions. After sunset, the high density plasma in the F-region often becomes unstable, and develops intense irregularities of electron density which strongly scatter L-band signals. As a result, scintillations exceeding 20 dB at 1.5 GHz are quite common and occasionally may be as high as 6 dB at 4 GHz. These magnitudes will be considerably enhanced at low elevation angles, and for magnetic field aligned propagation. It is shown that the above climatology of scintillation is fairly well established and robust scintillation models are available, but weather models of scintillation have yet to emerge. At high latitudes, the onset of scintillation during magnetic storms can, in general, be forecast by following the trail of energy from the sun. In the equatorial region, on the other hand, intense scintillations are obtained during magnetically quiet conditions and are, therefore, triggered by internal rather than external forcing functions. The on-going development of specification and short-term forecast of equatorial scintillation based on observation of scintillation and plasma motion are described.

Results

Figure 1 shows the global distribution of ionospheric irregularities which cause scintillations. It may be noted that the irregularities are primarily located at high and low latitudes and that the midlatitude region is normally benign. At high latitudes, the irregularities are distributed in the auroral and the polar cap regions. Among these two regions, polar cap irregularities cause more enhanced scintillations. Globally, most intense scintillations are encountered at low latitudes and, especially, in the equatorial anomaly regions which correspond to two belts of enhanced ionization density around ± 15° magnetic latitudes. Equatorial scintillation is a nighttime phenomenon and its onset occurs after sunset. The irregularities arise in successive structures which are separated by 50 - 100 km. The irregularity structures have limited east-west width of several hundred kilometers but are elongated several thousand kilometers in the magnetic north- south direction.

Figure 2 shows that signal fading associated with scintillations cause data losses and rapid phase scintillations may cause loss of phase lock. At the user terminal, the effects of scintillation are not usually recognized and such outages are interpreted in terms of satellite or receiver malfunction. Such misinterpretation results in loss of resources. The mitigation of scintillation effects is feasible with some systems where coding and interleaving scheme can be adopted. Alternatively, scintillation effects may be reduced by using of a satellite in another direction or by choosing another channel of transmission at a much higher frequency.

Figure 3 illustrates a schematic of worst case scintillation magnitudes at GPS frequencies (1-2 GHz). During the solar maximum (left hand panel), scintillations cause signals to fade below the 20 dB level in the equatorial anomaly region and, in the polar cap, signal fadings may exceed 10 dB. The right hand panel shows that, during the solar minimum, GHz scintillations are drastically reduced. This reduction is caused by a decrease of the ionospheric electron density by a factor of 3 to 5.

Figure 4 shows the solar cycle variation of polar scintillation at 250 MHz. The data were recorded at Thule, Greenland, which is located within the central polar cap. The top panel shows the decrease of sunspot number from the solar maximum in 1979 to the solar minimum in 1985. The bottom panel shows the per cent occurrence of 250 MHz scintillation for signal fadings > 5 dB, >10 dB, > 15 dB and > 20 dB. The overall decrease of scintillation with decrease of sunspot number may be noted. In addition, there is an annual minimum in the local summer months of May, June and July. The decrease of scintillations with the sunspot number is a result of the decrease of ionospheric electron density with decreasing sunspot number. The minimum in the summer is caused by increasing ionization density in the E-region during these months which helps to short out the F-region electron density irregularities.

Figure 5 shows one example of scintillation of GPS signals at 1.2 GHz which was recorded at Thule, Greenland during the solar minimum year, 1984.. The right hand panel shows the variation of the amplitude scintillation index, S4, at the top and the total electron content variations at the bottom. During this solar min. period, polar cap patches with electron content varying between 5 - 15 TEC units (1 TEC unit = 10^{16} electrons/m^{-2}), were associated with amplitude scintillations varying between S4 = 0.1 - 0.2, at 1.2 GHz. The bright ring in the left hand panel shows the auroral oval as imaged by the DE-1 satellite in the ultraviolet at 130.4 and 135.6 nm. The central dark portion corresponds to the polar cap where TEC and scintilllation measurements were performed.

Figure 6 shows that the equatorial irregularity belt which causes intense scintillations occupy a substantial 34% of the earth's surface.

Figure 7 shows that equatorial irregularities evolve in successive plasma density depletions or bubbles. These discrete structures are approximately 250 km wide in the east-west direction and are spaced a few tens of kilometers. These structures extend more than 1000 km in the vertical direction and become extended several thousand kilometers along the magnetic field in the north-south direction. Scintillations occur as propagation paths to satellites intercept these structures and scintillations disappear in the intervening regions. In the anomaly region, scintillations exceeding 20 dB are encountered at GPS frequencies. These structures contain irregularities of virtually all scale sizes from tens of centimeters to tens of kilometers. As a result, intense radar backscatter also results from these structures in the VHF-UHF range.

Figure 8 illustrates the case when scintillations were simultaneously recorded at 257, 1541, and 3954 MHz transmissions from one satellite The data was acquired in the anomaly region at Ascension Island in the Atlantic during the solar maximum year of 1981. Scintillations caused > 20 dB fadings at 1541 MHz which is close to GPS L1 frequency. At 4 GHz, 5 dB fadings were encountered. At VHF (257 MHz), the fading rate was so fast that the receiving system could not respond to it and, as a result, the depth of fading became smaller than at L-band. It may be noted that such high levels of scintillation were attained in the anomaly region for vertical propagation. At low elevation angles and for near field-aligned propagation, these scintillation magnitudes will be enhanced by a factor of 2-5.

The left hand panel of Figure 9 shows that an all sky 6300 A imager detects plasma bubbles as dark bands in view of reduced emissions from plasma depleted bubbles. In the top frame, scintillations are detected on both GPS satellites 21 and 22 when these intercepted a dark band or plasma bubble. In the bottom frame, scintillations disappear on satellite 22 as it emerges out of the dark band. Scintillations continue on satellite 21, since it continued to remain within the bubble. The right hand panel shows how single frequency GPS receivers can be used to determine scintillations as well as relative TEC variations from the Doppler data. Note scintillations are associated with TEC depletions.

Figure 10 shows the occurrence statistics of >6, >10 and >20 dB fadings of MARISAT satellite signals at 1.5 GHz as determined in the equatorial anomaly region at Ascension Island in the Atlantic during the premidnight period, 20-24 LT. The top and bottom panels show respectively the occurrence for magnetically quiet and disturbed periods between the solar minimum (1984) and solar maximum (1989). The drastic variation of the occurrence with the solar cycle may be noted. The diagram shows that, during the solar maximum, signal fadings >20 dB do occur for 20 per cent of the time. Such levels of scintillation may impact even robust communication and navigation systems. The diagram also illustrates the important fact that scintillations during magnetically quiet periods exceed those during the magnetically disturbed periods. We thus conclude that a major fraction of scintillation in the equatorial region cannot be related to solar transients, such as, solar eruptions or geomagnetic storms but instead are related to internal forcing functions such as ionospheric tides, winds etc.

A climatological model of scintillation, WBMOD, was initially developed by using scintillation data obtained from multifrequency transmissions from the Defense Nuclear Agency's (DNA) sun-synchronous Wide Band satellite. The model has recently been upgraded by using the time continuous equatorial scintillation observations of the Air Force Research Laboratory and high latitude scintillation data from DNA's HiLat and Polar Bear satellites. The upgraded WBMOD is a robust global model of scintillation and is easy to operate. The top and bottom panels of Figure 11 illustrate the model predictions of 250 MHz scintillation, respectively, for July 1 and October 1, within the footprint of a geostationary satellite located at 15° W. The model shows that in July there is no equatorial scintillation in this longitude sector but, during the equinox, in October, intense scintillations are observed in the equatorial anomaly region from shortly after sunset through the post midnight period. This agrees with the average climatological pattern of equatorial scintillation.

In order to overcome the limitation of climatological models, a nowcast and short-term scintillation forecast system has been developed. It is based on the established fact that equatorial scintillation onset occurs at the magnetic equator and the latitude extent of scintillation increases as the irregularities upwell at the magnetic equator and map north and south along the magnetic field. Further, the scintillating regions usually drift eastwards at night which can be measured. The Scintillation Network Decision Aid (SCINDA), shown in Figure 12, utilizes the above knowledge to provide a nowcast system. It incorporates scintillation receivers at two stations, one at Ancon, Peru, at the magnetic equator and the other at Antofagasta, Chile, at a magnetic latitude of 11° south. At each station, scintillation measurements are performed with two satellites, one in the west and the other in the east. In addition, each station performs spaced antenna scintillation measurements to determine the eastward drift of the scintillating regions. The data is sent over Internet to the user terminal where the information on scintillation magnitudes and drift reported by the two stations are combined to obtain 3-dimensional maps of scintillating regions. The weak, moderate and severe levels of scintillation as defined by the user are colored green, yellow and red. As time progresses, these regions expand north-south and move eastward in accordance with the measurements. This is illustrated in the left hand panel of Figure 13. The right hand panel shows the projections of these 3-d structures on the ground as viewed from the satellite. If the user is located within the projected red, yellow or green areas, will suffer severe, moderate and weak scintillations when it uses that particular satellite at that time.

Equatorial scintillation has extreme night-to-night variability and, on a given night, considerable spatial variability as well. For example, a given longitude interval may remain turbulent through a given night whereas an adjacent longitude swath may remain totally benign. From a theoretical standpoint, it is known that the destabilizing forces are driven by zonal electric fields which develop through the action of neutral winds. On the other hand, the stabilizing forces are related to the meridional neutral winds and the ionization distribution along magnetic flux tubes. To forecast scintillation, with a few hours of advance warning, we need to probe the driving forces, namely, electric fields and neutral winds in the equatorial ionosphere. We need to detect irregularity formation and estimate their scintillation effects and validate these estimates against actual scintillation measurements. These requirements can be met by an equatorial satellite (Figure 14), which may measure these physical parameters and the resulting electron density and irregularity structures. An equatorial satellite with an inclination of 12° may perform these tasks with a 90 min orbital period. In the initial phase, an elliptical orbit (900 km x 300 km) will investigate the forecast capability of such measurements. Later, the orbit will be made circular at an altitude >550 km when the satellite will support users with forecast and specification of scintillation.

SCOPE OF PRESENTATION

- SCINTILLATION OF SATELLITE SIGNALS AT 250 MHz - 4 GHz
  - CAUSED BY SPATIAL FLUCTUATIONS OF ELECTRON DENSITY IN THE IONOSPHERE WITH SCALE SIZES ~ 1.5 km - 50 m
- GLOBAL DISTRIBUTION OF SCINTILLATING REGIONS AND SOLAR CYCLE VARIATION OF SCINTILLATION MAGNITUDES
- CLIMATOLOGICAL MODEL OF SCINTILLATION
- EMERGING NOWCAST SYSTEMS FOR EQUATORIAL SCINTILLATION
- EQUATORIAL SATELLITE: A FORECAST TOOL FOR LOW LATITUDE SCINTILLATION

DISTURBED IONOSPHERIC REGIONS

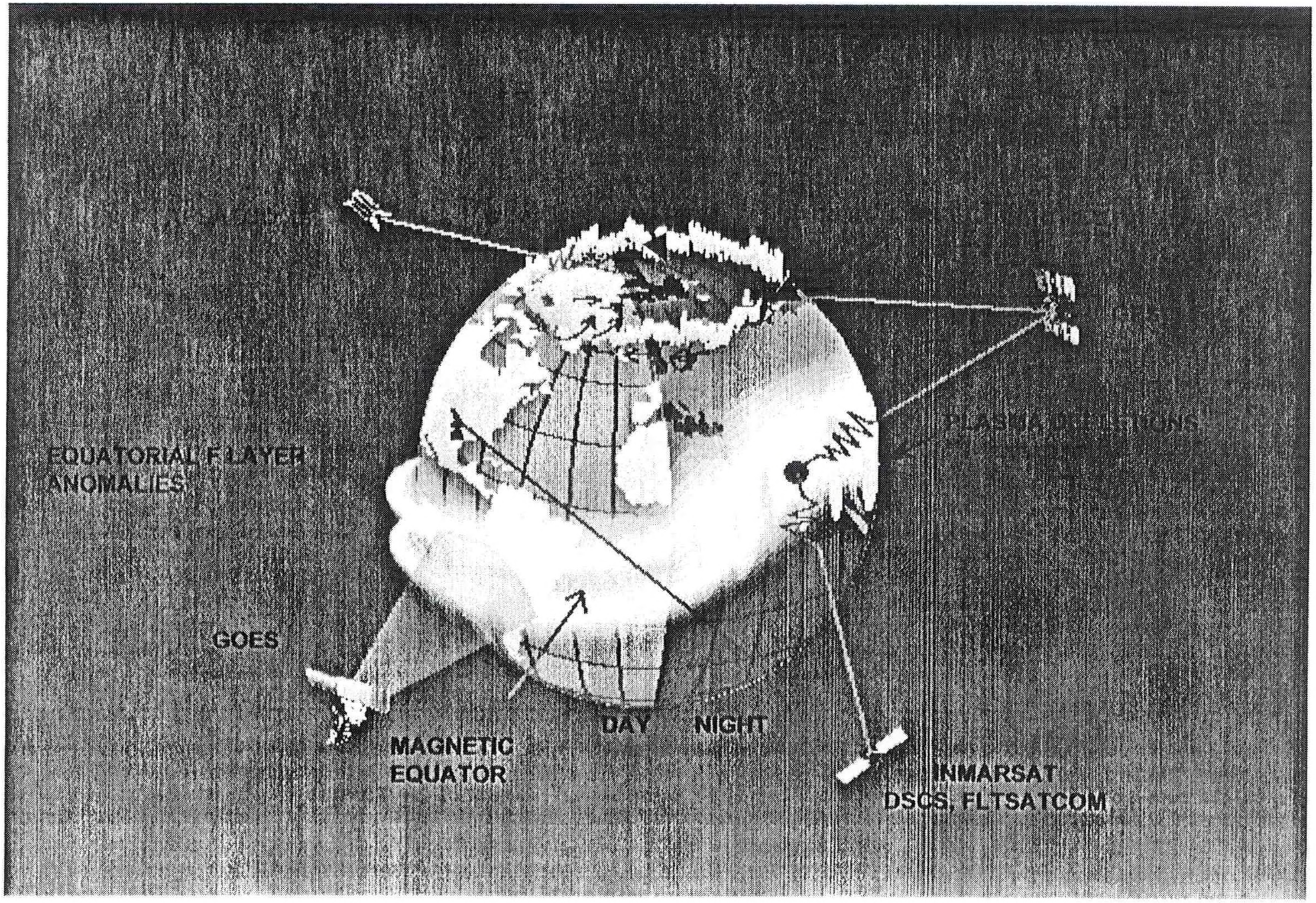
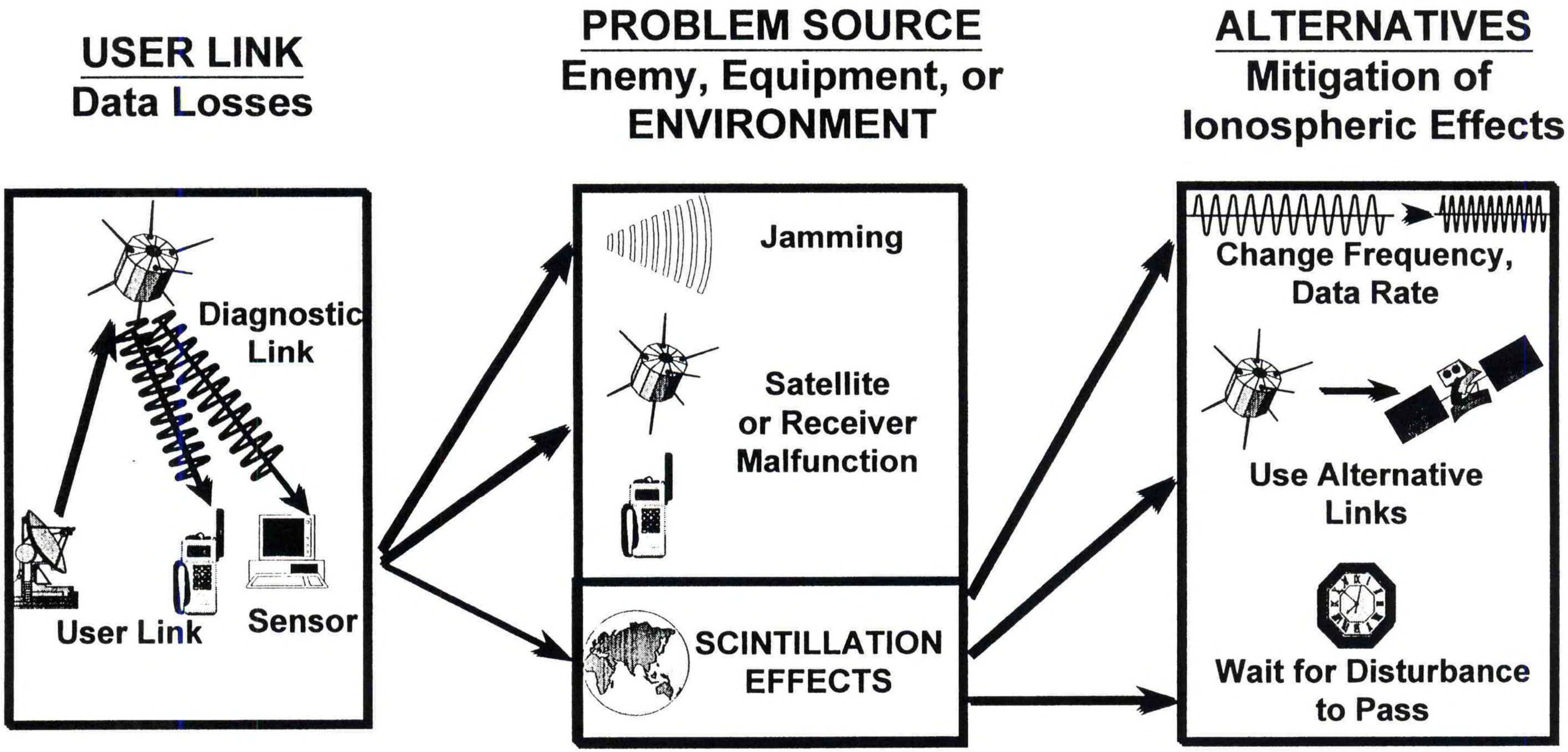


FIG 1

OUTAGES: EQUIPMENT or ENVIRONMENT?



USER LINK
Data Losses

Diagnostic Link

User Link

Sensor

PROBLEM SOURCE
Enemy, Equipment, or ENVIRONMENT

Jamming

Satellite or Receiver Malfunction

SCINTILLATION EFFECTS

ALTERNATIVES
Mitigation of Ionospheric Effects

Change Frequency, Data Rate

Use Alternative Links

Wait for Disturbance to Pass

FIG 2

"WORST CASE" FADING DEPTHS AT L-BAND

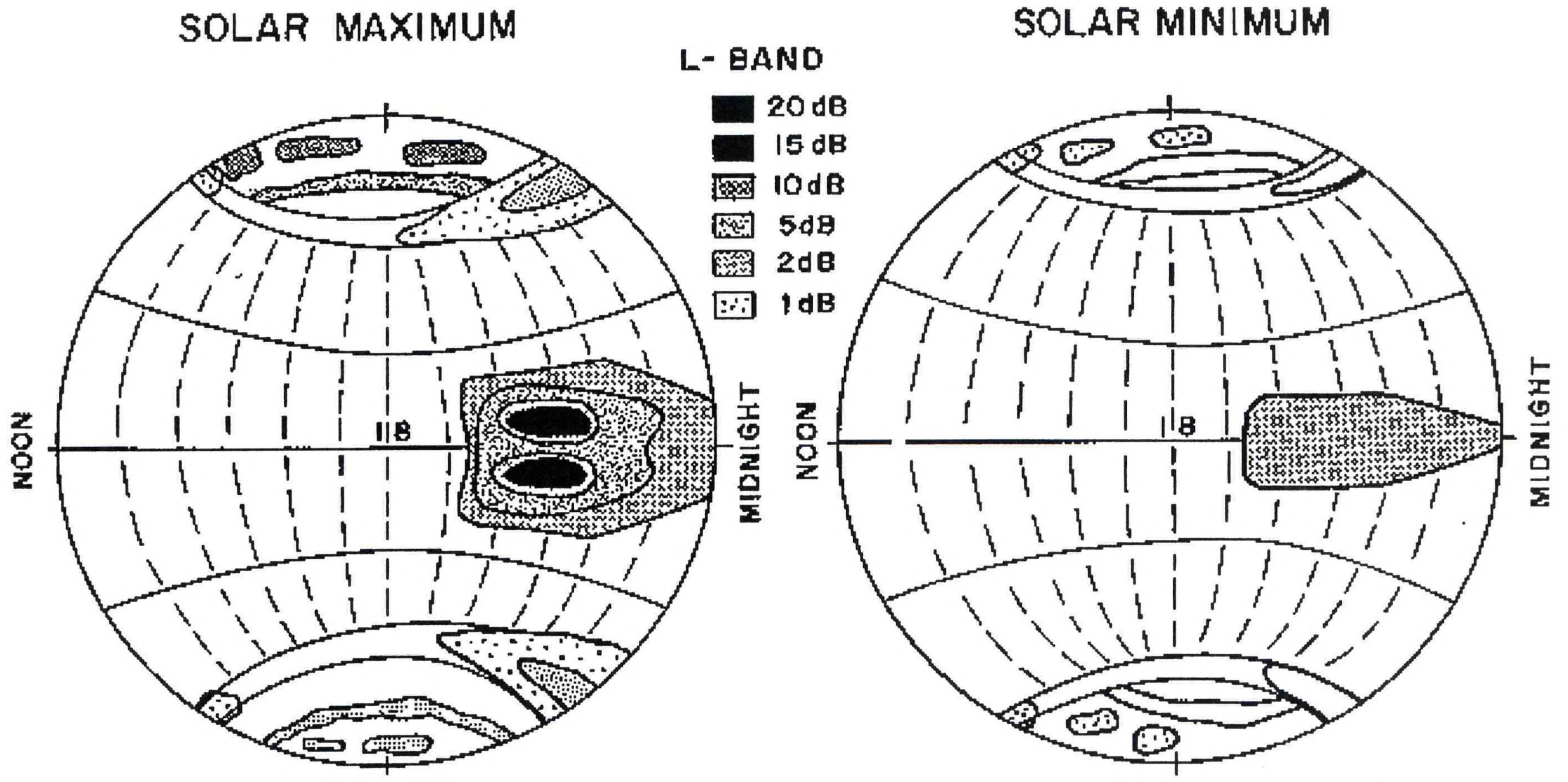


FIG 3

POLAR CAP SCINTILLATION VARIATION WITH SOLAR CYCLE

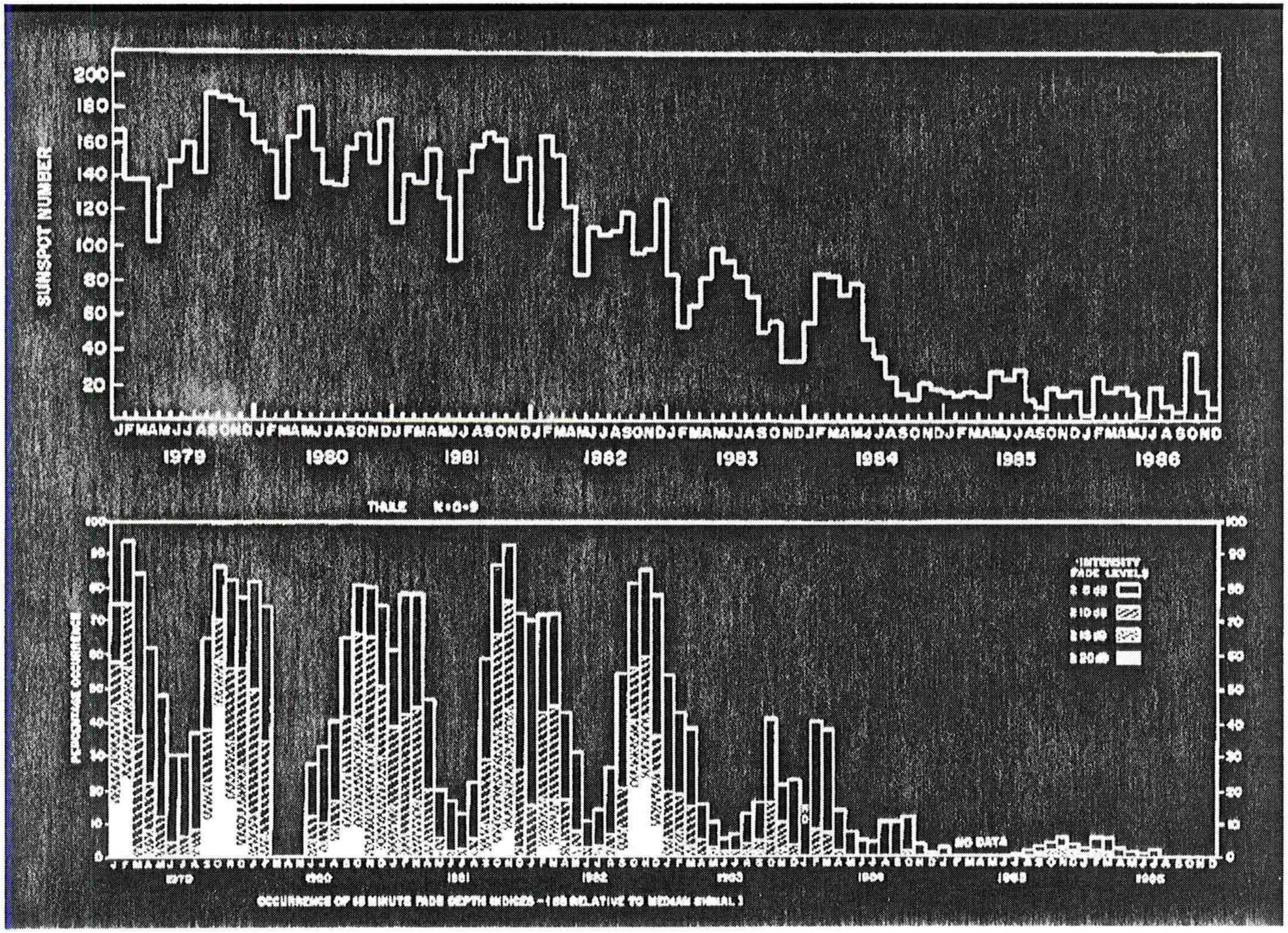
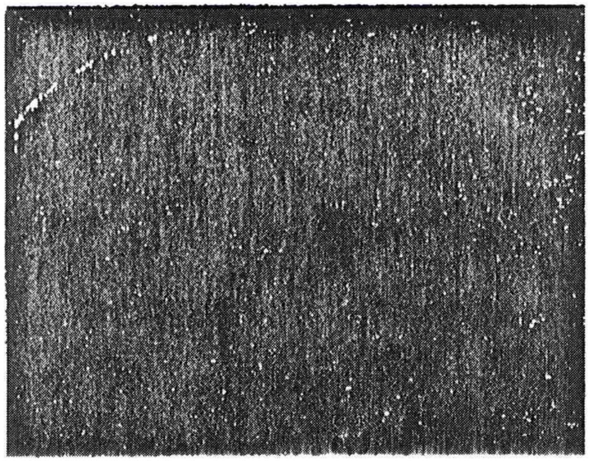


FIG 4

POLAR SCINTILLATION

EXAMPLE OF POLAR CAP GPS SCINTILLATION



UV AURORAL IMAGE

THULE 3/4 FEB 1984

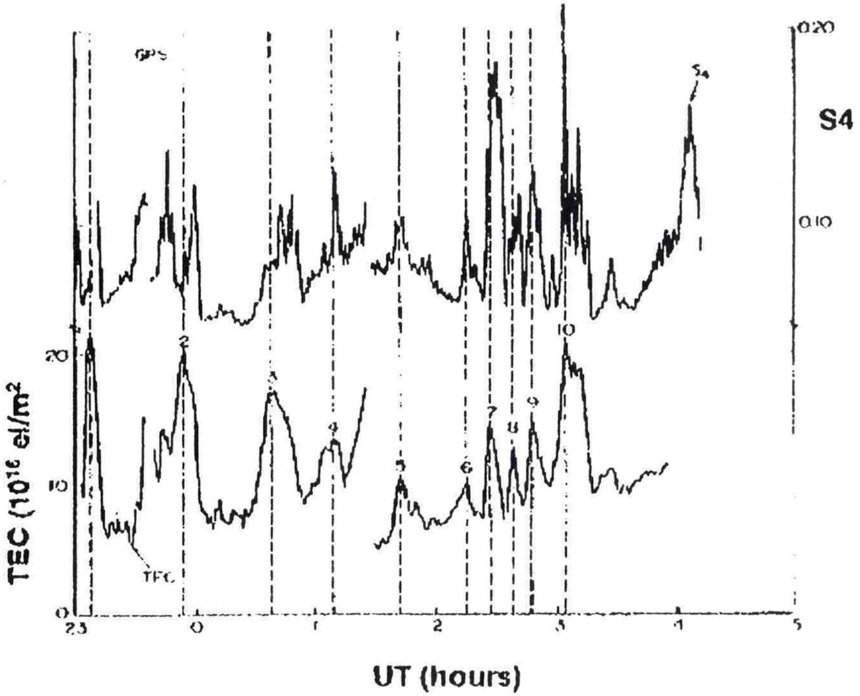


FIG 5

SUMMARY OF HIGH LATITUDE SCINTILLATIONS

- MOST INTENSE IN THE POLAR CAP (> 75^{O} ΛLAT) DURING SOLAR MAX PERIOD

- SCINTILLATIONS MAY BE OBSERVED AT ANY UT
  - SEASONAL VARIATION PRONOUNCED: MINIMUM IN MAY-JUL IN NORTHERN POLAR CAP

- ENHANCED DURING IMF B_Z SOUTHWARD CONDITIONS

- DURING 1999 - 2004, WORST CASE SCINTILLATION:
  - AT 250 MHz, FADE DEPTH OF 25 dB AND PHASE SCINTILLATION OF 3 RAD (90 SEC DETREND)
  - AT GPS L1 (1575 MHz), FADE DEPTH OF 15 dB AND PHASE SCINTILLATION ~ 1 RAD

IONOSPHERIC EFFECTS
EQUATORIAL SCINTILLATION ACTIVITY REGION
(34% OF EARTH'S SURFACE)

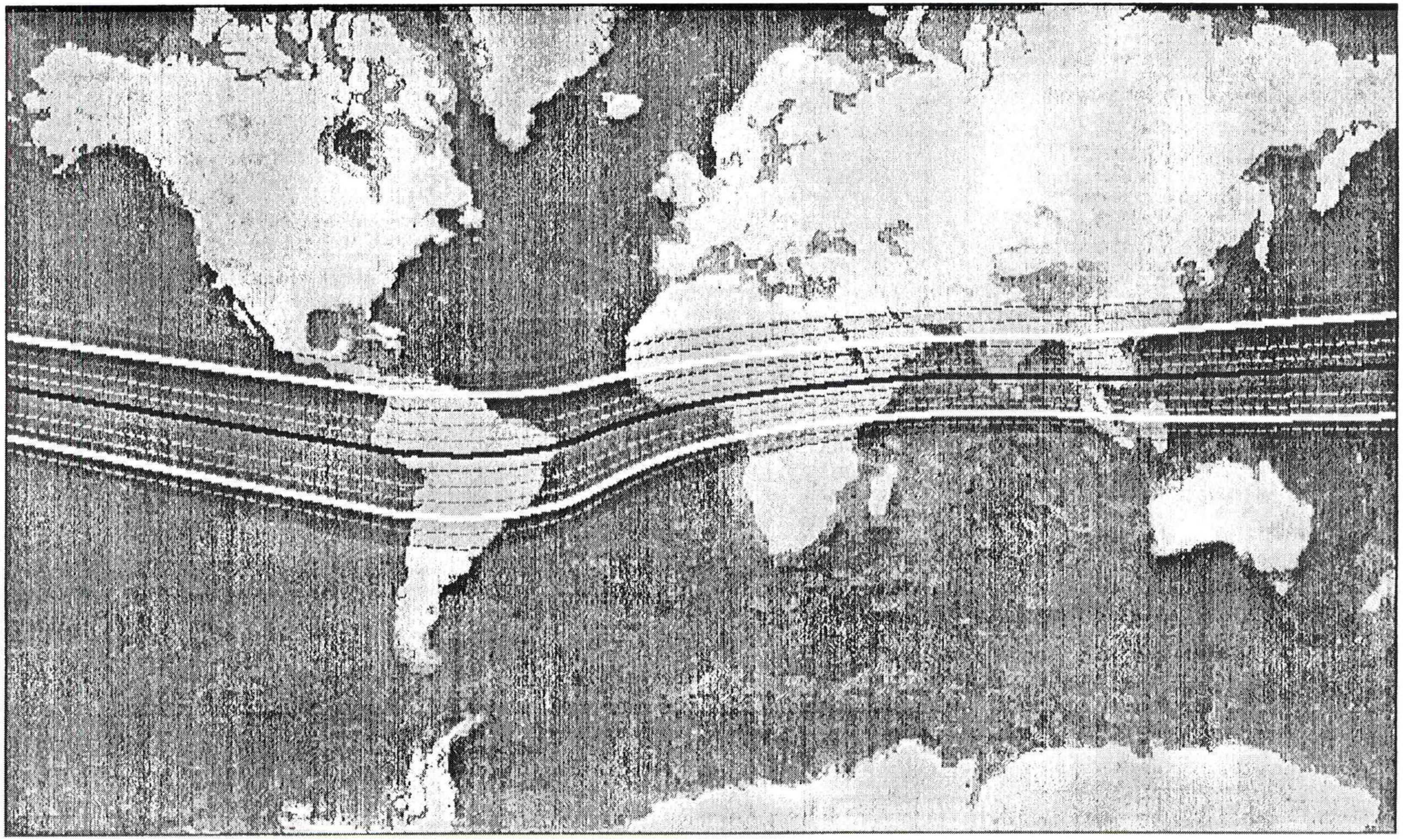


FIG 6

IONOSPHERIC EFFECTS
EQUATORIAL PLASMA DEPLETIONS

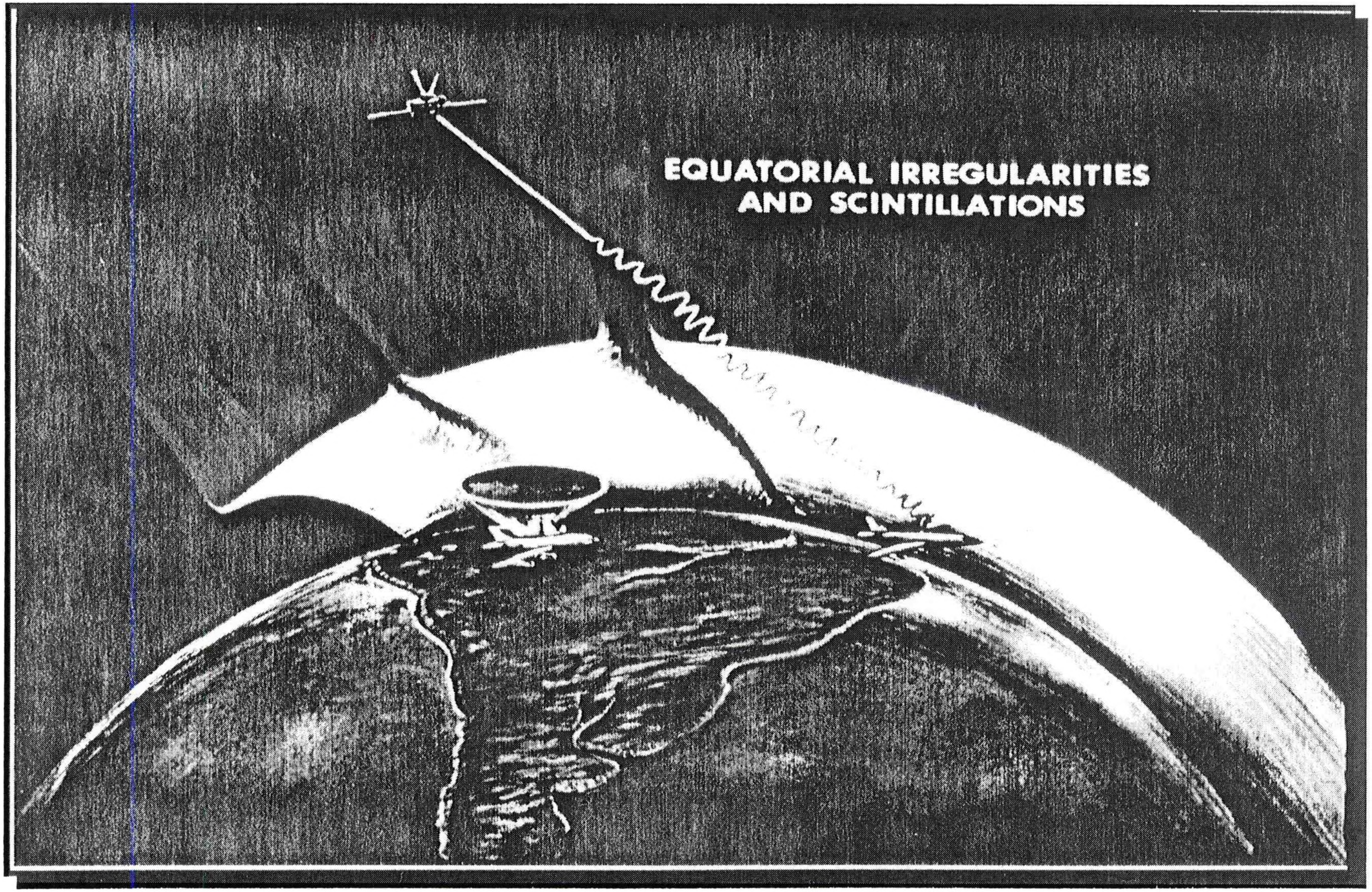


FIG 7

FREQUENCY DEPENDENCE OF SCINTILLATION STRUCTURE

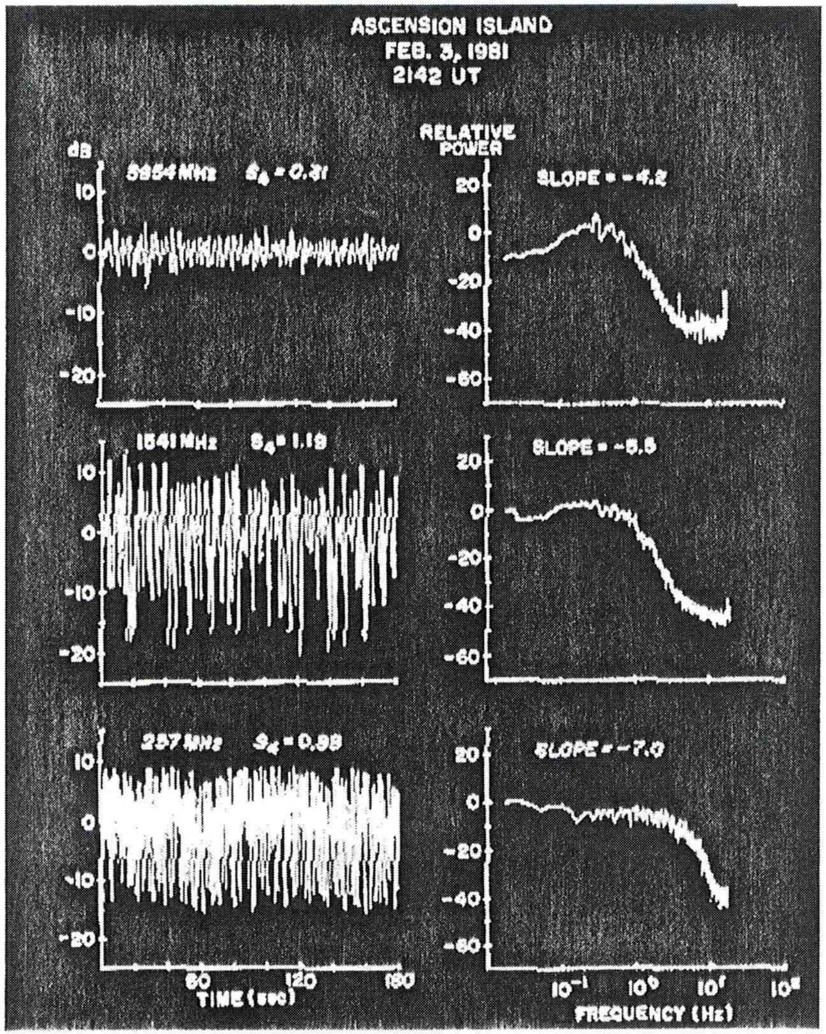
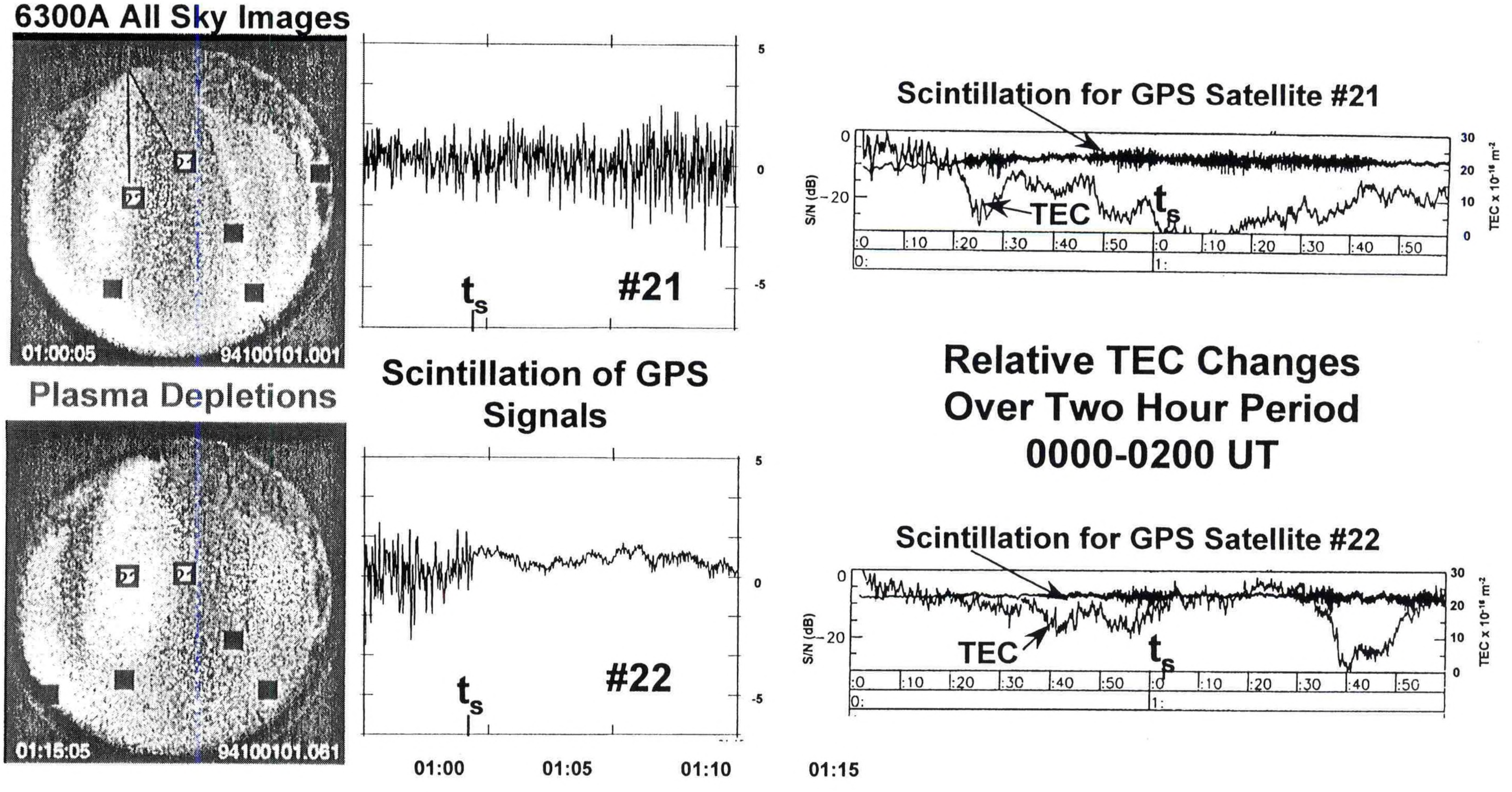


FIG 8

IONOSPHERIC EFFECTS
PLASMA DEPLETIONS SCINTILLATION OF GPS
TEC VARIATIONS
CHILE: 1 OCTOBER 1994



6300A All Sky Images

Plasma Depletions

Scintillation of GPS Signals

Scintillation for GPS Satellite #21

Relative TEC Changes
Over Two Hour Period
0000-0200 UT

Scintillation for GPS Satellite #22

FIG 9

1.5 GHz SCINTILLATION AT EQUATORIAL ANOMALY - DURING MAGNETIC QUIET AND DISTURBED PERIODS

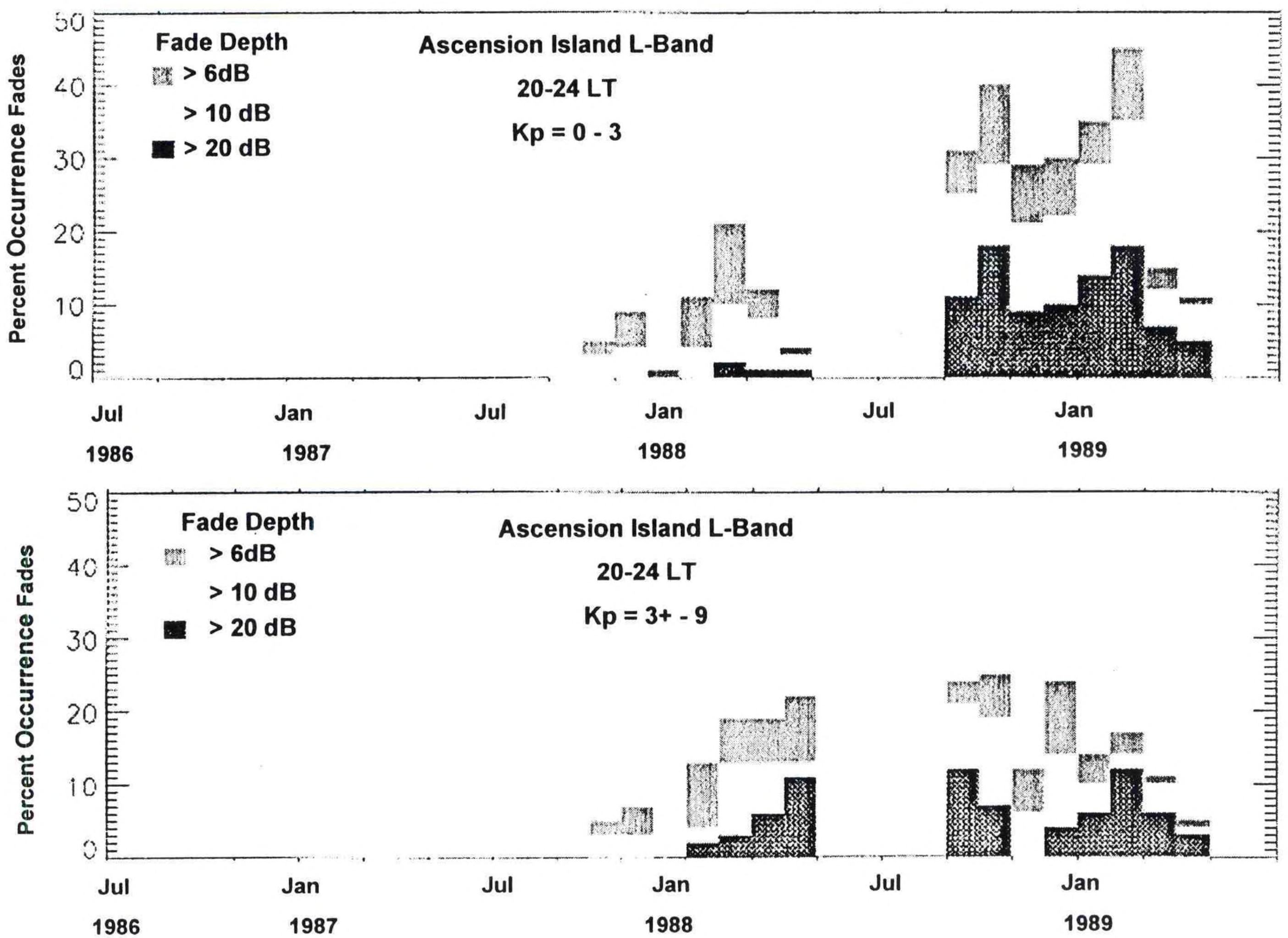


FIG 10

SUMMARY OF EQUATORIAL SCINTILLATIONS

- GLOBALLY MOST INTENSE IN THE EQUATORIAL ANOMALY REGION (± 15^{o} DIP LATITUDE)
- SCINTILLATIONS ONLY AT NIGHT AFTER SUNSET
  - AT GPS FREQUENCIES, 20 - 01 LT;
  - AT 250 MHz, 20 - 04 LT
- EXTREME NIGHT-TO-NIGHT VARIABILITY
- VARIES WITH SEASON:
  - MAXIMUM DURING EQUINOXES AT MOST LONGITUDES;
  - ALSO HIGH IN NOV-DEC AND MINIMUM IN JUL-AUG BETWEEN 0^{o} - 75^{o} W AND OPPOSITE AROUND 150^{o} E

SUMMARY OF EQUATORIAL SCINTILLATIONS
(Continued)

- **SCINTILLATIONS OCCUR DURING MAGNETICALLY QUIET AND DISTURBED PERIODS**
  (CAN'T TRACK IT ALL BY FOLLOWING THE TRAIL OF ENERGY FROM THE SUN)

- **DURING 1999-2004, WORST CASE SCINTILLATION MAGNITUDES:**
  - **AT 250 MHz , FADE DEPTHS > 30 dB AND PHASE SCINTILLATIONS ~ 6 RAD (FOR 90 SEC DETREND) (40 % OCURRENCE BETWEEN 20 - 24 LT)**
  - **AT GPS L1 (1575 MHz), FADE DEPTHS > 20 dB AND PHASE SCINTILLATIONS ~ 1 RADIAN (20% OCCURRENCE BETWEEN 20 - 24 LT)**

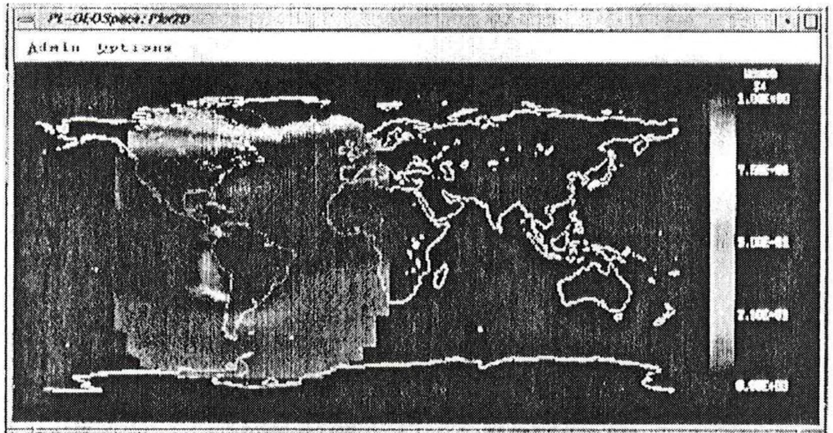
WIDE BAND MODEL (WBMOD) SCINTILLATION CLIMATOLOGY

S4 (90 PCT)

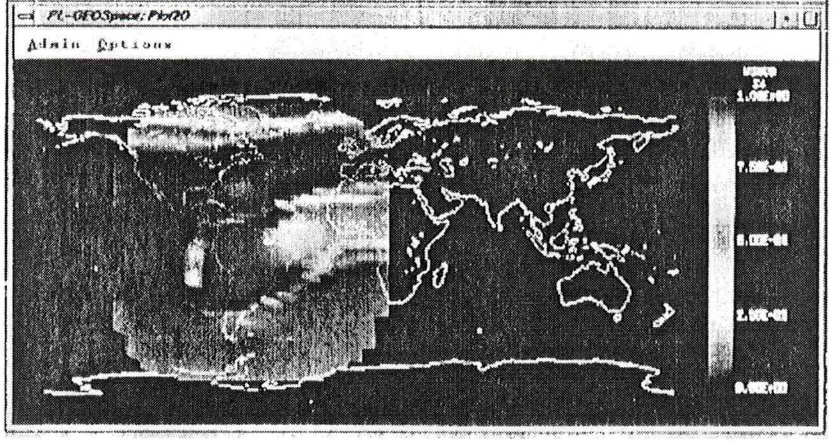
01:00 UT

F10.7 = 200

Kp = 0.7



JULY 1



OCTOBER 1

F/G 11

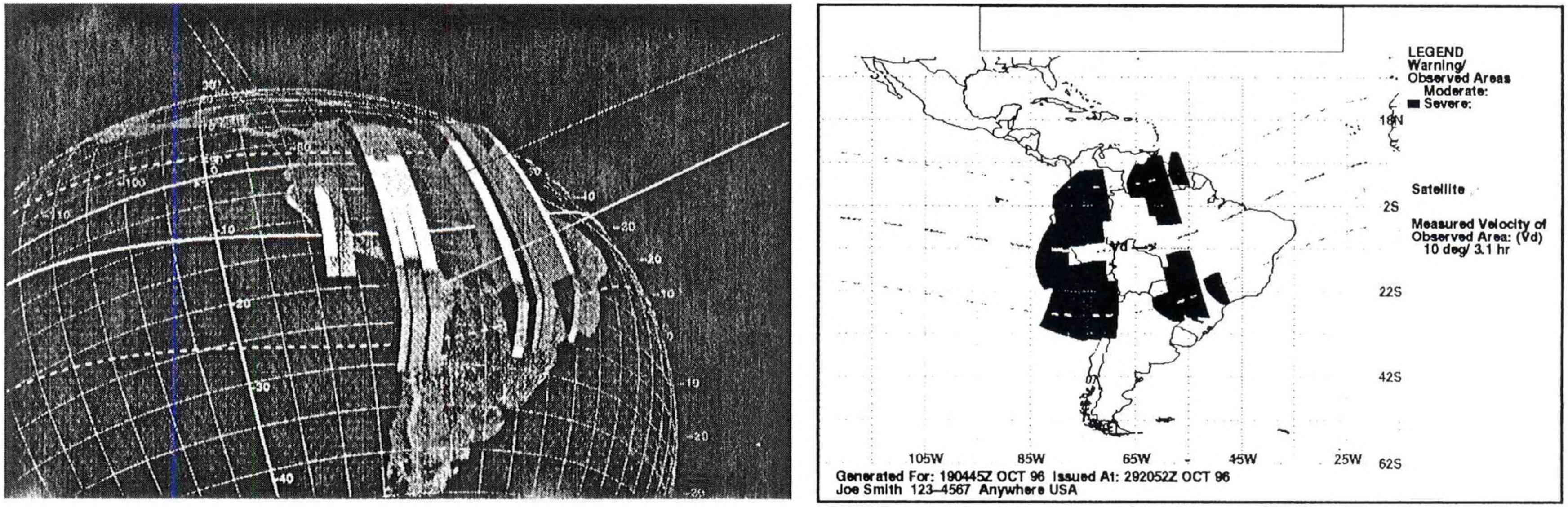
SCINTILLATION NETWORK DECISION AID (SCINDA)

Scintillation Receiver System

- Dedicated UHF / L-Band Scintillation Receivers
- PC Based Data Processing (Scintillation Intensity and Drift Velocity)
- Automated Real-Time Data Retrieval via Internet
- Monitors Multiple Satellite Comm Links Simultaneously

FIG 12

EQUATORIAL SCINTILLATION DISTURBANCE STRUCTURE



SEVERE

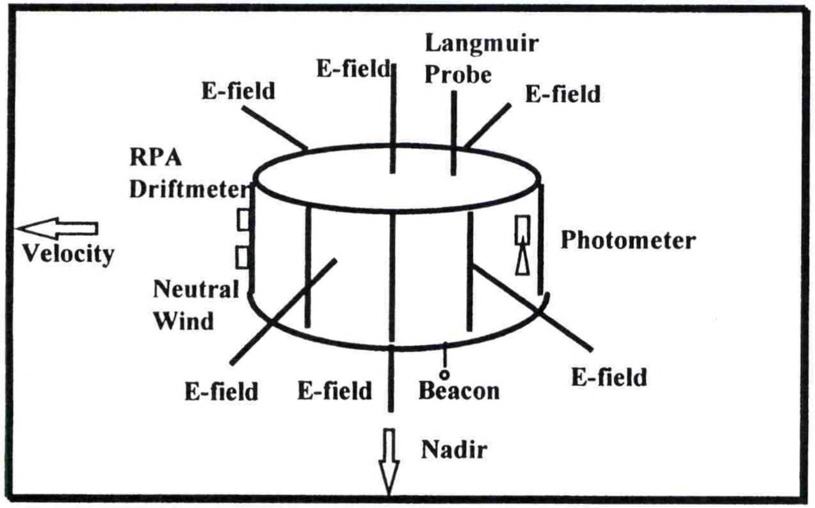
MODERATE

WEAK

Actual Display of Ionospheric Disturbances Measured by Air Force Scintillation Network Decision Aid (SCINDA)

FIG 13

PROPOSED SPACE-BASED SENSOR SYSTEM



PAYOFF:

- Real-time Specification of Global Equatorial Scintillation
- Enable Accurate Forecast Capability > 4 Hours
- Quantify Ionospheric Effects Over Multi-Frequency Range
- Reduced Dependence on Ground-Based Sensors

ORBIT:

- PHASE I- Forecast Demonstration 900 x 300 km Orbit - 12° Inclination
- PHASE II - Operational Prototype 550 km Min. Altitude - Circular Orbit

SENSORS:

- In-Situ Ion Drift Meters, Electric Field Probes, Neutral Wind Meter, Magnetometer and UV Photometer
- Multi-Frequency Beacons - UHF, L and S Bands

FIG 14

SUMMARY

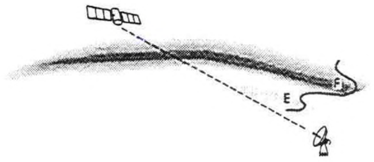
- **SCINTILLATIONS AT HIGH AND LOW LATITUDES DURING SOLAR MAX (1999 - 2004) WILL BECOME MUCH ENHANCED**
- **SATELLITE BASED PERSONAL COMMUNICATION SYSTEMS WITH LIMITED FADE MARGIN ARE VULNERABLE TO SOLAR MAX SCINTILLATION**
- **GPS USERS SHOULD BE AWARE OF THE DELETERIOUS EFFECTS OF SCINTILLATION AT LOW AND HIGH LATITUDES**
- **MULTIPOINT MEASUREMENTS WITH GPS RECEIVERS PROMISING FOR IONOSPHERIC RESEARCH AND FOR QUANTIFYING PROPAGATION EFFECTS IN SYSTEMS DESIGN**
- **EQUATORIAL SATELLITE AND PHYSICS BASED SCINTILLATION MODEL NEEDED FOR SCINTILLATION FORECAST SYSTEM**

2.9 Air Force Space-Environmental Requirements in Support of Communications and Navigation

Gretchen Lindsay

for

Russell A. Kutzman



Air Force Communications & Navigation User's Space Environment Requirements

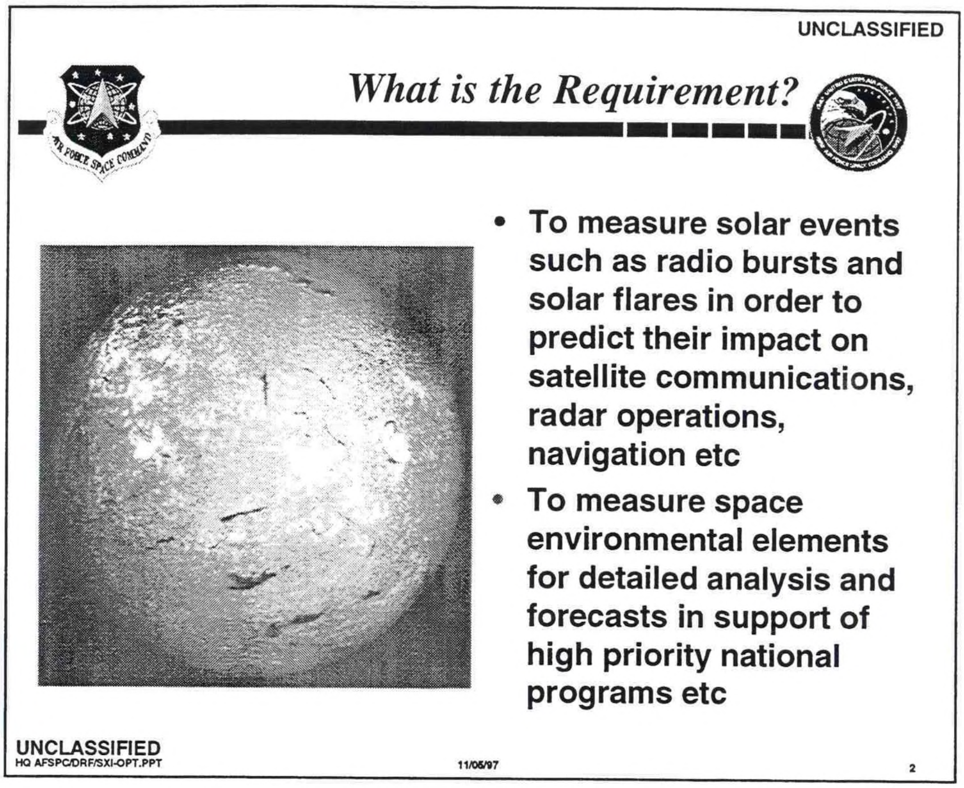
Gretchen Lindsay
Aerospace Corporation
for
Maj Russ Kutzman
HQ AFSPC/DRFE

Abstract

AIR FORCE SPACE-ENVIRONMENTAL REQUIREMENTS IN SUPPORT OF COMMUNICATIONS AND NAVIGATION

Russell A. Kutzman
Air Force Space Command
Peterson Air Force Base, CO

Satellite communications and GPS-based navigation capabilities are fundamental to DoD operations. Each technology utilizes electromagnetic signals that propagate through and are affected by the ionosphere. Because of the ionospheric effects, users of these capabilities have "space environmental requirements" that vary according to the user's application and operational constraints. For example, communicators have a need for assured communications capability. However, communicators are often assigned a fixed satellite frequency. To plan the use of communications assets to assure connectivity, these communicators will want to know when space environmental conditions may make using their frequency difficult or impossible. Likewise, communicators also need to know what the space environmental conditions were during a period of time when they could not communicate. GPS users have position accuracy requirements. For those accuracy requirements to be met, the GPS system must account for, in real-time, the ionospheric range delay in the received GPS signal. This support is essentially handled by the GPS receiver and transparent to the user. Future utilization of precision guided munitions (PGM) and unmanned aerial vehicles (UAVs) may dictate more sophisticated space environmental requirements in support of dual-frequency GPS application. However, no end-to-end studies have been performed to establish space environmental sensitivities of PGM and UAV operational capabilities.



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What is the Requirement?

- To measure solar events such as radio bursts and solar flares in order to predict their impact on satellite communications, radar operations, navigation etc
- To measure space environmental elements for detailed analysis and forecasts in support of high priority national programs etc

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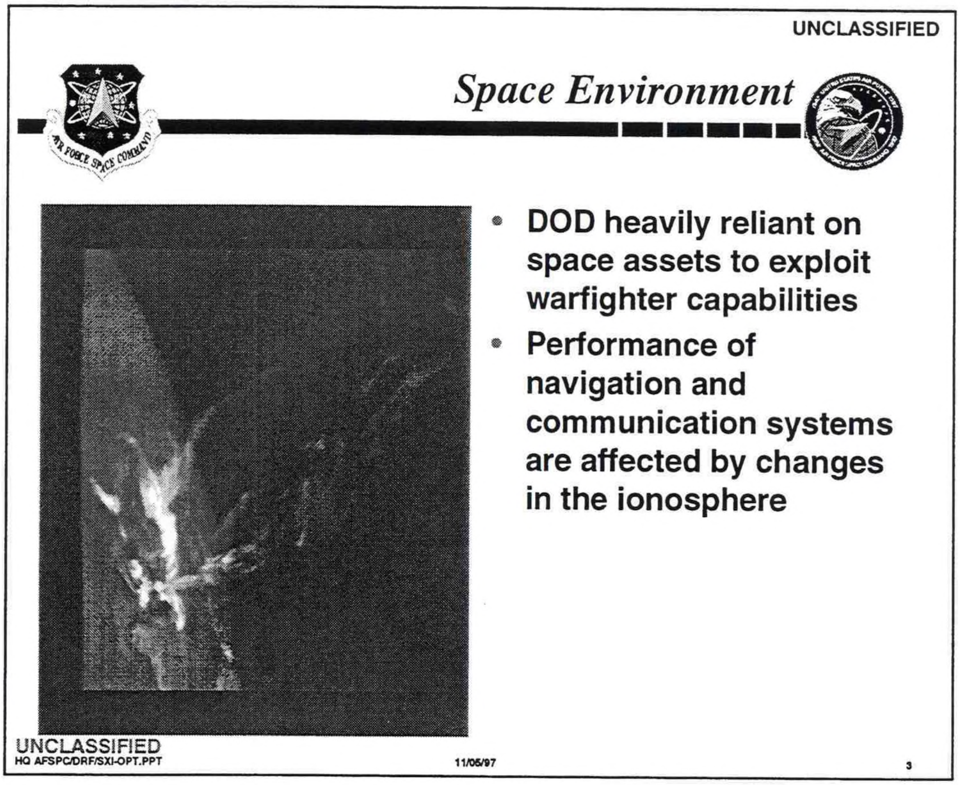
The Air Force is directed by (source) to provide space environmental support to the DoD. As the DoD provider, the Air Force has the top-level need to observe and measure solar, solar wind, magnetospheric and ionospheric phenomena. Solar-geophysical data is then used to facilitate and enhance DoD operations.



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Space Environment

- **DOD heavily reliant on space assets to exploit warfighter capabilities**
- **Performance of navigation and communication systems are affected by changes in the ionosphere**

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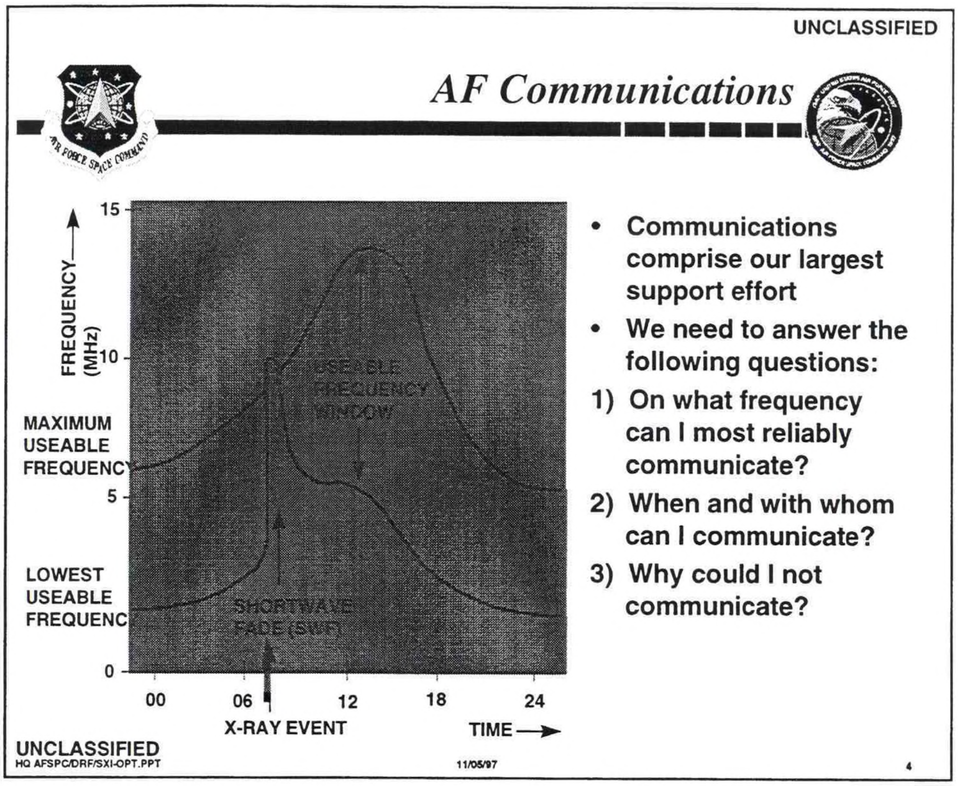
The DoD cares about the space environment because successful communication and navigation capabilities are essential to the execution of routine and contingency operations. Navigation and communications capabilities within the DoD rely heavily on electro-magnetic signals that propagate through and within the ionosphere. Variations in the ionosphere can alter, or even prevent, the propagation of those signals, hence, degrading or preventing navigation and communications capabilities.



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AF Communications

- Communications comprise our largest support effort
- We need to answer the following questions:

1) On what frequency can I most reliably communicate?

2) When and with whom can I communicate?

3) Why could I not communicate?

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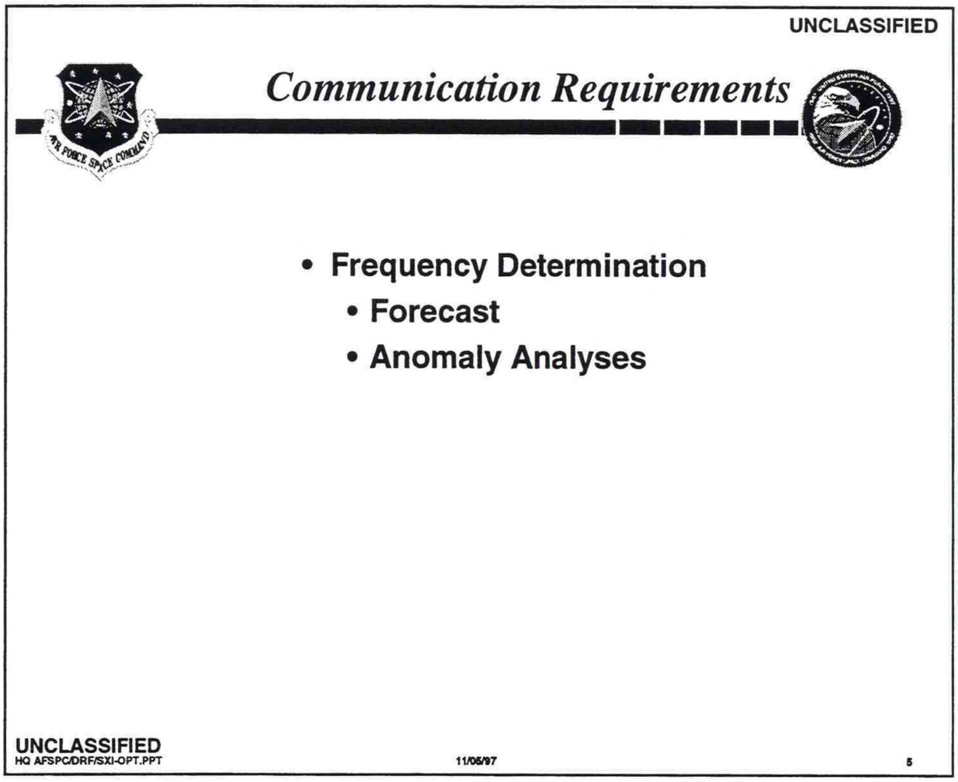
Communications users needs are simple - they want assured communications capabilities all the time. However, many factors contribute to the success of those communications capabilities, the conditions of the space environment being just one of those factors.

From the space environment perspective, users want to know: 1) On what frequency can I reliably communicate; 2) When and with whom can I communicate; and 3) Why couldn't I communicate? Answering questions 1 and 2 are necessary activities for the planners who design the communications networks days, weeks, or months in advance and the Commanders in Chief who must be apprised of the status of their assets. Answering question 3 allows communicators to assess whether the source of a communications anomaly was environmental, mechanical, or operator error.



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Communication Requirements

- Frequency Determination
  - Forecast
  - Anomaly Analyses

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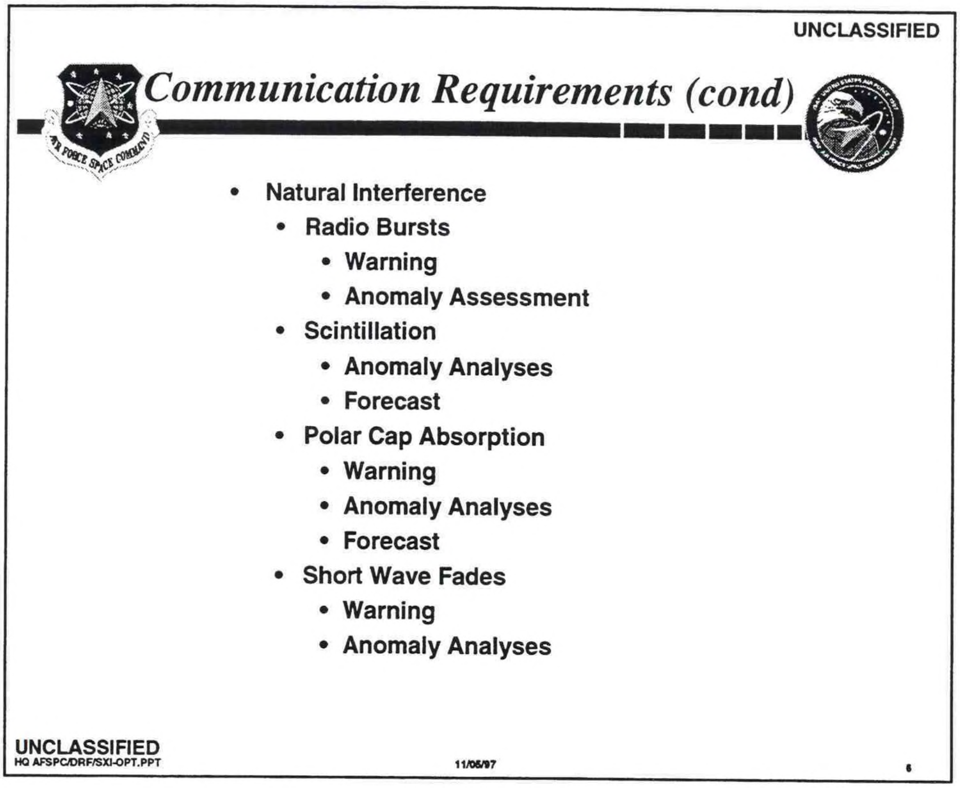
Frequency determinations are primarily used by HF Communicators. 55 SWXS provides frequency forecasts in several ways: 1) Generic assessments of the propagation conditions by geographical regions; 2) Supplying F10.7 and smooth sunspot number (SSN) forecasts that a warfighter employs in their own in-house model; 3) Tailored propagation forecasts (generally based on F10.7 and SSN as input) that take into account receiver and transmitter characteristics, location and time of transmission.

Frequency determinations may also be used to assess why a communications path did not function as expected. Post-anomaly analysis can be based on model runs using observed F10.7 or SSN as input, assessment of frequency characteristics based on ionospheric soundings, or anecdotal reports of other HF communicators observations.



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Communication Requirements (cond)

- Natural Interference
  - Radio Bursts
    - Warning
    - Anomaly Assessment
  - Scintillation
    - Anomaly Analyses
    - Forecast
  - Polar Cap Absorption
    - Warning
    - Anomaly Analyses
    - Forecast
  - Short Wave Fades
    - Warning
    - Anomaly Analyses

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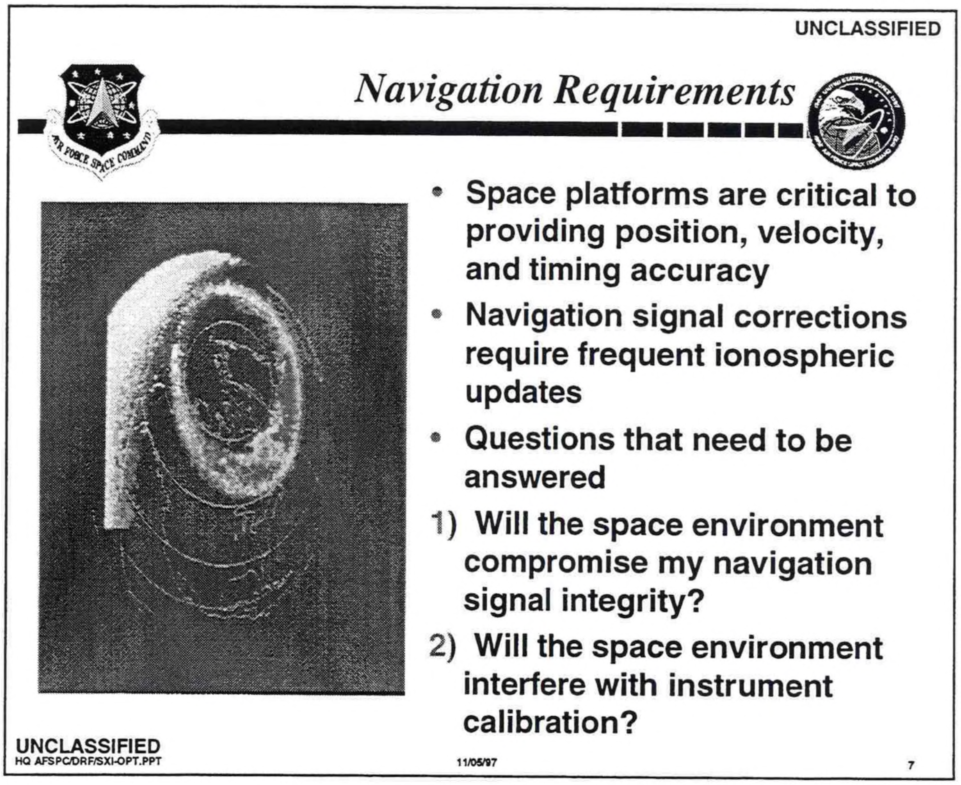
Observations of conditions that may severely interfere with or negate the capability to communicate (i.e.. solar radio bursts, polar cap absorption, and shortwave fades) are relayed via warning reports. Warning reports note the phenomena that was observed, where and when it was observed, how long it is expected to persist, and which communications paths it might effect.

Warning reports must reach the warfighter within minutes of observation to be effectively incorporated into the real-time operations decision process (i.e.. reconfigure the network, delay communications, use backup capabilities) and to allow the Commander in Chief to maintain adequate situational awareness.

The same observations used in warning reports are archived so that post-facto anomaly analysis can be performed. An anomaly analysis is performed on an "as requested" basis when a communicator calls 55 SWXS and reports a problem. The value of the space environmental information is that it allows the communicator to narrow the focus of the anomaly investigation to either environmental, mechanical, or operator error sources.

Scintillation forecasts and anomaly analyses are the primary support provided to satellite communicators. Scintillation support is currently handled with a climatological model. Satellite communicators generally have a fixed frequency and specific satellite to use and do not have a lot of operational flexibility other than in the time at which communication is made. Forecasts allow them to know when is an ideal time to communicate and when to expect any problems.



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Navigation Requirements

- Space platforms are critical to providing position, velocity, and timing accuracy
- Navigation signal corrections require frequent ionospheric updates
- Questions that need to be answered

1) Will the space environment compromise my navigation signal integrity?
2) Will the space environment interfere with instrument calibration?

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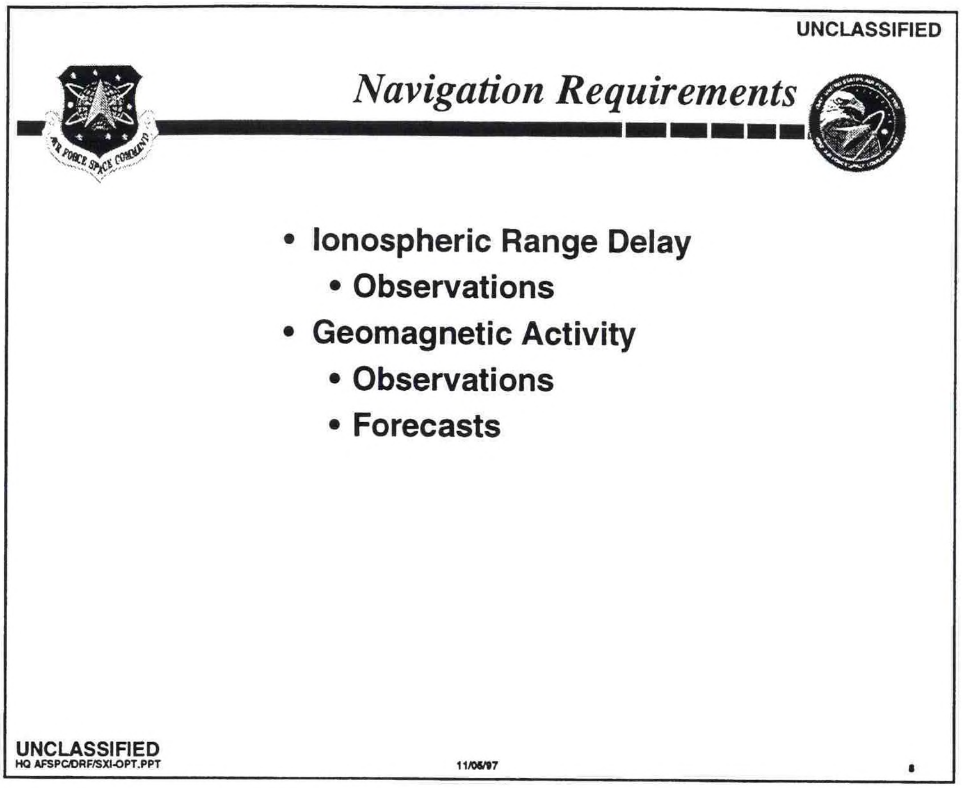
Navigators want an infallible, perfect navigation capability. What space environment support is needed centers around answering two questions. The first question, “Will the space environment compromise my navigation signal integrity?” is of particular interest to GPS users. The second question “Will the space environment interfere with the calibration of my instrument?” is a concern of inertial navigation system users.



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Navigation Requirements

- **Ionospheric Range Delay**
  - **Observations**
- **Geomagnetic Activity**
  - **Observations**
  - **Forecasts**

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Most single frequency GPS users do not realize that they currently get space environmental support. That support arises via the ionospheric correction applied by the single frequency GPS receiver processing. The ionospheric correction is based on F10.7 and corresponding Klobuchar coefficients and attempts to account for the range delay imposed by the ionosphere on the GPS signal.

The concept of single frequency correction is the archetype in space environmental support: It happens near-real-time, it is well integrated into the operation of the system, and it is transparent to the warfighter. Transparency to the warfighter allows them to concentrate on the mission at hand and not the idiosyncrasies of the tools used to accomplish the mission.

INS technicians cannot perform calibration activities when the geomagnetic environment is highly disturbed. Therefore, these technicians call 55 SWXS for Ap forecasts prior to planning a calibration activity and observed Ap for verifying that an activity took place during a period of minimal geomagnetic activity.

55SWXS can't yet answer quantitatively how much single and dual frequency GPS capabilities are compromised by uncorrected ionospheric errors or scintillation. To answer question 1), requires studies that take into account receiver type and sensitivities, location and terrain, mode of operation (WAAS, LAAS, redundant systems employed...etc), and timing of operation.

2.10 Space Weather and US Navy Requirements

Gus K. Lott

Space Weather & US Navy Requirements

CDR Gus K. Lott, Ph.D., P.E., Assistant Professor[1]
Naval Postgraduate School, Monterey, CA US

Abstract

The US Navy has a continuing need for improved space weather information. The primary needs are in improved communications (HF and UHF satellite), higher precision GPS navigation, trans-ionospheric geopositioning, RF mission planning, and the over-the-horizon HF RADAR. This paper addresses the first four requirements.

USN Space Weather Consumer

The overall US Navy user's question is "Can better space weather information improve my operational readiness?"

The typical US Navy user effected by space weather is the operating ship at sea. This ship can range globally with increasing presence in the equatorial regions and a continuing presence in the Arctic areas.

Under this scenario, the communications system is primarily UHF (250-400 MHz) satellite with HF (3-30 MHz) as a backup. The user navigates today using autonomous single or dual frequency Global Positioning System (GPS) receivers. To protect the fleet, the user uses passive geopositioning techniques to identify potential hostile forces. To plan a mission, the user must have forecast information (from models) for periods 30 to 90 days in advance. This forecasted space weather parametric data are inputs into communications models.

Space weather is an important environmental parameter to consider when conducting operations as described above.

UHF Satellite User

The USN consumer's question is "Can improved space weather information improve my knowledge of UHF satellite communications availability?"

With increased equatorial region operations, the path from the ship to the UHF Fleet Satellite System suffers more and more from the effects caused by the equatorial region ionosphere. In particular, the evening equatorial anomaly can cause serious scintillation degradation to the UHF satellite signals. Particular questions a user will ask are:

- What is the most likely cause of my reduced satellite circuit reliability? Is it:
    - Equipment malfunction
    - Space weather caused disruption
    - Hostile interference
- When should I consider shifting to another communications means?

Improved space weather information can allow the user to assess the probability of space weather causes. Space weather information feeding scintillation prediction models must be of such fidelity that the path prediction models can accurately predict fade depth, fade repetition rate, and probability of scintillation.

HF Communications

The USN consumer's question is "Can improved space weather information improve HF communications circuit reliability, throughput, and covertness?"

Most HF communications circuits use the ionosphere for long distance communications. The US Navy continues as a HF ground wave circuit user for intra-fleet communications.

Models used for HF circuit planning (PROPHET, IONCAP, etc.) are mid-latitude, mean-parameter predictors of the communications path. Predictions are reasonably good for quiet ionospheric conditions on mid-latitude paths. They are not as good of predictors for operations during disturbed ionospheric periods, nighttime equatorial mid-point paths, or in the Arctic and Auroral regions. Research shows that reliable communications paths exist, but the USN does not use them because the mean models fail to include the possibilities, such as Auroral-E.[2]

Improved space weather information (specifically ionospheric specification) should allow use of ray-tracing communications path models. These improved communications path modeling techniques are extremely sensitive to the ionospheric specification. Mean sunspot number or 10.7 cm flux values are not enough.

Using this improved information, the USN can provide a better assessment of HF circuit reliability and supported data rates, better frequency selection to minimize monitoring by a hostile country, and a better understanding of the HF path limitations. The USN cannot rely on automatic link establishment (ALE) techniques since the control transmissions are beacons to the world of a user's presence and location.

Space weather information improvements are the key to HF circuit optimization, which involves this problem:

- ☐ Choose an HF frequency
  - ✓ which maximizes the probability of circuit availability, AND
  - ✓ which minimizes the probability of bit error, AND
  - ✓ which minimizes the probability of detection by a hostile service.

Some of the previously unpredicted modes are excellent candidates for circuit optimization. This is especially true if the frequency planning extends into the lower VHF range. Trans-equatorial modes, Sporadic-E, and Auroral-E support the increased frequency set, which can greatly improve circuit covertness.

Space weather information must be of fidelity to provide identification of unusual modes, accurate layer height, and a layered structure for a ray-tracer to calculate through. Space weather information should identify E-layer structures, such as Auroral-E and equatorial Sporadic-E. This requires specification fidelity on the order of 0.1 total-electron-content-units (TECU).

Passive Navigation and Geopositioning

The USN consumer's question is "Can improved space weather information allow me to correct my GPS position to the required accuracy?"

Higher precision autonomous or wide-area differential GPS navigation provide the USN user with excellent navigation. However, there are missions that require higher precision navigation and geopositioning. Not all USN units will have dual-frequency GPS receivers, and those dual-frequency receivers available may not all use optimal ionospheric correction algorithms. So the focus is on the low-price, single-frequency equipment user.

Space weather information should provide specification to allow corrections for these levels of user accuracy (assuming wide-area differential service):

- Mine-laying and recovery (10 cm)
- Feature or infrastructure identification and recovery (1 m)
- Search-and-rescue and imbedded beacon recovery (10's m)

Passive geopositioning techniques (non-GPS) are essential for threat identification and warning and strike mission planning. Experiments have shown that improved ionospheric specification, through computerized ionospheric tomography, can improve passive HF geopositioning.[3] For trans-ionospheric techniques, the ionospheric-caused error can dominate for frequencies below 800 MHz.

Space weather ionospheric specification must be of the fidelity to allow ray-tracing to improve signal-path determination.

Mission Planning

The USN consumer's questions for operational mission planning include those like:

- Should delay my mission because the UHF satellite circuit will not be available for the next four hours? Have space weather conditions changed?
- Why can't I hear the adversary? Is he not there, or have space weather conditions changed so that my initial planning is wrong?

I speak to mission planning as tools for answering the "What if...?" and the "Why?" questions that arise when planning the command, control, communication, and intelligence (C^3I) needs for today's USN operations.

The USN uses the RF Mission Planner (RFMP), which is a communications modeling tool developed for the Joint Maritime Command Information System (JMCIS). Since it's inception, design included the need for improved space weather information. The need arises from RFMP's unique approach to statistical communications circuit description.[4] RFMP allows the user to select the best model available, many of which are not mean models, based on the circuit and environmental specification. As with the passive geopositioning systems, space weather specification is an essential requirement.

RFMP depends on receiving this space weather information from standard USN communications circuits, which always operate at capacity during a crisis. As such, the need for locally derived or direct sensor-to-user space weather information is more important now than ever before. Space weather providers must plan on the type and fidelity of information needed and the means for providing that to the user.

Where will the space weather information come from? Will it come via:

☐ Communications-channel based (push-pull)
☐ Broadcast communications channels (with other environmental data)
☐ Direct from local sensors
☐ Direct from national sensors

Clearly, the days are over for centralized modeling centers sending large quantities of time-delayed information using conventional communications channels. Computer processing power on USN ships is adequate for distributed space weather product creation.

The space weather information's timeliness and fidelity determine the final mission planning product. How can the RFMP operator use the results? What is the common data format, if there is one? Will enough space weather information be available for:

☐ local tomographic reconstructions for ray-tracing,
☐ identification of upcoming modes (bell-ringer), or
☐ planning vs. real-time differences (plan vs. now) assessments

Operational planning using tools like RFMP require timely, high-fidelity, space weather information. Otherwise, RFMP and the operational decision maker loose a key specification from the mission environment.

Conclusion

What's the answer to the overall question, "Can better space weather information improve my operational readiness?"

The answer appears to be YES. With this given, the next questions for the space weather community are:

☐ How can I best obtain and use space weather information (source to model)?
☐ How good must the space weather information be (fidelity to mode)?
☐ Can improved space weather information provide new operational options?

---

[1] CDR Gus K. Lott, Code EC/LT, Spanagel hall (Bldg. 232), Room 422, Naval Postgraduate School, 833 Dyer Rd., Monterey, CA 93943-5121 US, tel: 408-656-3798, fax: 408-656-2797, e-mail <**Error! Bookmark not defined.**> or <lott@nps.navy.mil>

[2] Robert D. Hunsucker, Robert B. Rose, Richard W. Adler, and Gus K. Lott, "Auroral-E mode oblique HF propagation and its dependence on the auroral oval position," *IEEE Transactions on Antennas and Propagation*, v44 n3, Mar 96.

[3] G.S. Bust, J.A. Cook, G.R. Kronschnabl, and G.K. Lott, "Mid-America computerized ionospheric tomography experiment 1993 (MACE-93)", *Proceedings of the 6th International Conference on HF radio Systems and Techniques*, IEE conf. pub. 392, Jul 94.

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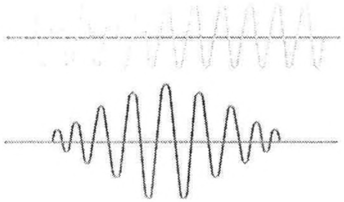
[4] D. Brant, G.K. Lott, S.E. Paluszek, and B.E. Skimmons, "Modern HF mission planning combining propagation modeling and real-time environmental monitoring," *Proceedings of the 6th International Conference on HF radio Systems and Techniques*, IEE conf. pub. 392, Jul 94.

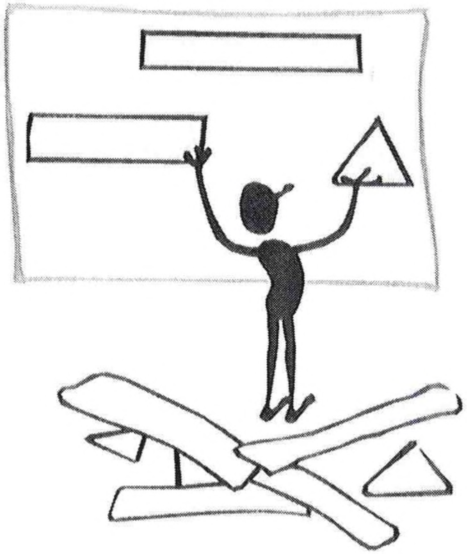
Space Weather & US Navy Requirements

CDR Gus K. Lott, Ph.D., P.E.
Naval Postgraduate School
Monterey, CA

The Users

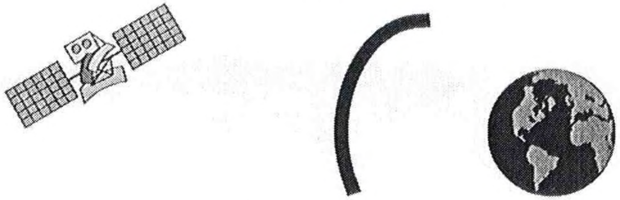
- Address user issues
  - Communications
  - Navigation
  - Passive Geopositioning
  - Mission Planning
- Can a better space weather picture help improve operational systems performance?



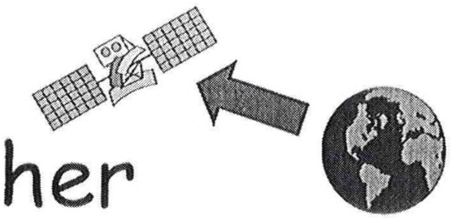


UHF Satellite User

- Is it space weather caused disruption (scintillation),
    - or



- Is it an enemy attack (Information Warfare jamming)?



- Can real-time space weather information help me isolate the likely cause?

HF Communications User

- Most HF communications models use mean, mid-latitude ionospheric predictors
- Can ray-tracing with real-time space weather information improve:
  - Circuit reliability?
  - Circuit covertness?
  - Planning & understanding?

HF Communicaitons User (cont)

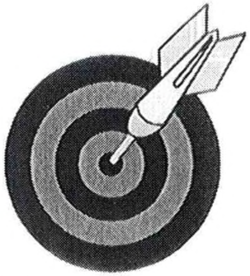
- Example
  - Choose an HF frequency for local operations
    - *Minimize probability of bit error*
  - Choose a frequency that doesn't support propagation to my adversary
    - *Minimize probability of detection*
- Covertness needed in systems like the USN HF e-mail system
- Can real-time space weather make this an "optimal" system?

VHF/UHF Communications User

- Exploit communications means usually considered "unusual"
  - Trans-equatorial VHF
  - Sporadic-E VHF
  - Auroral-E VHF
- Covertness - above predicted MUF
- Reduce loading on satellite circuits
- Exploit an adversary remotely

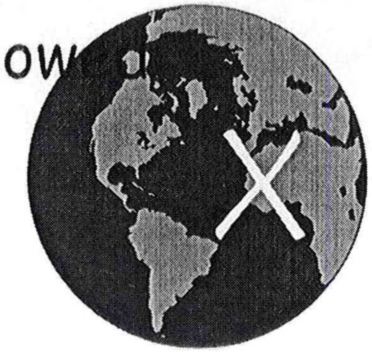
Passive Navigation User

- High-precision GPS (autonomous)
  - Mine laying and recovery (10's cm level)
  - Infrastructure or feature identification and recovery (1's m level)
  - Imbedded device identification and recovery (10's m level)
- Can real-time space weather allow me to correct to the required accuracy?



Passive Geopositioning User

- Ray tracing thru space environment
  - HF single-site-location techniques
    - MACE 93 tomography experiment show accuracy improvement
    - Doing more with fewer sites
  - VHF and lower UHF
    - Dominate error ionospheric and tropospheric induced
- Can real-time space weather provide the fidelity to improve?

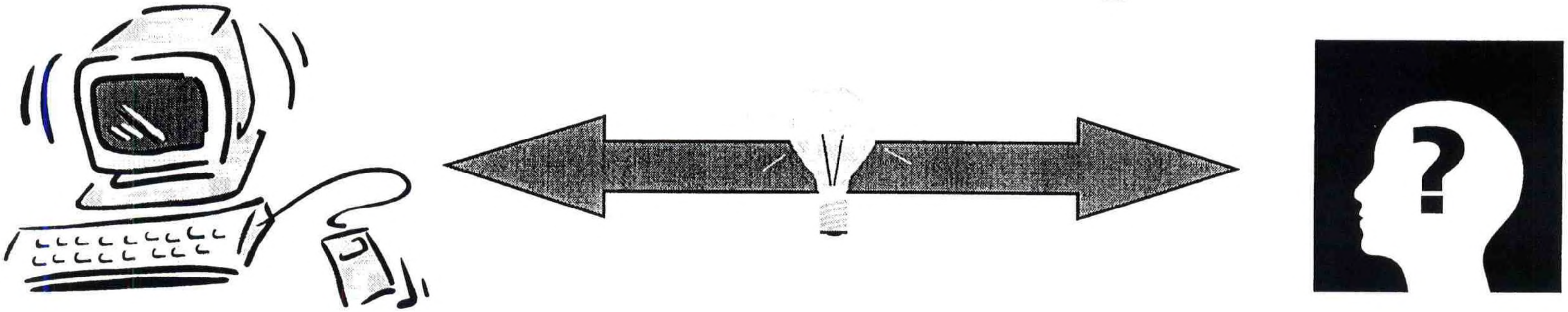


Mission Planning (all users)

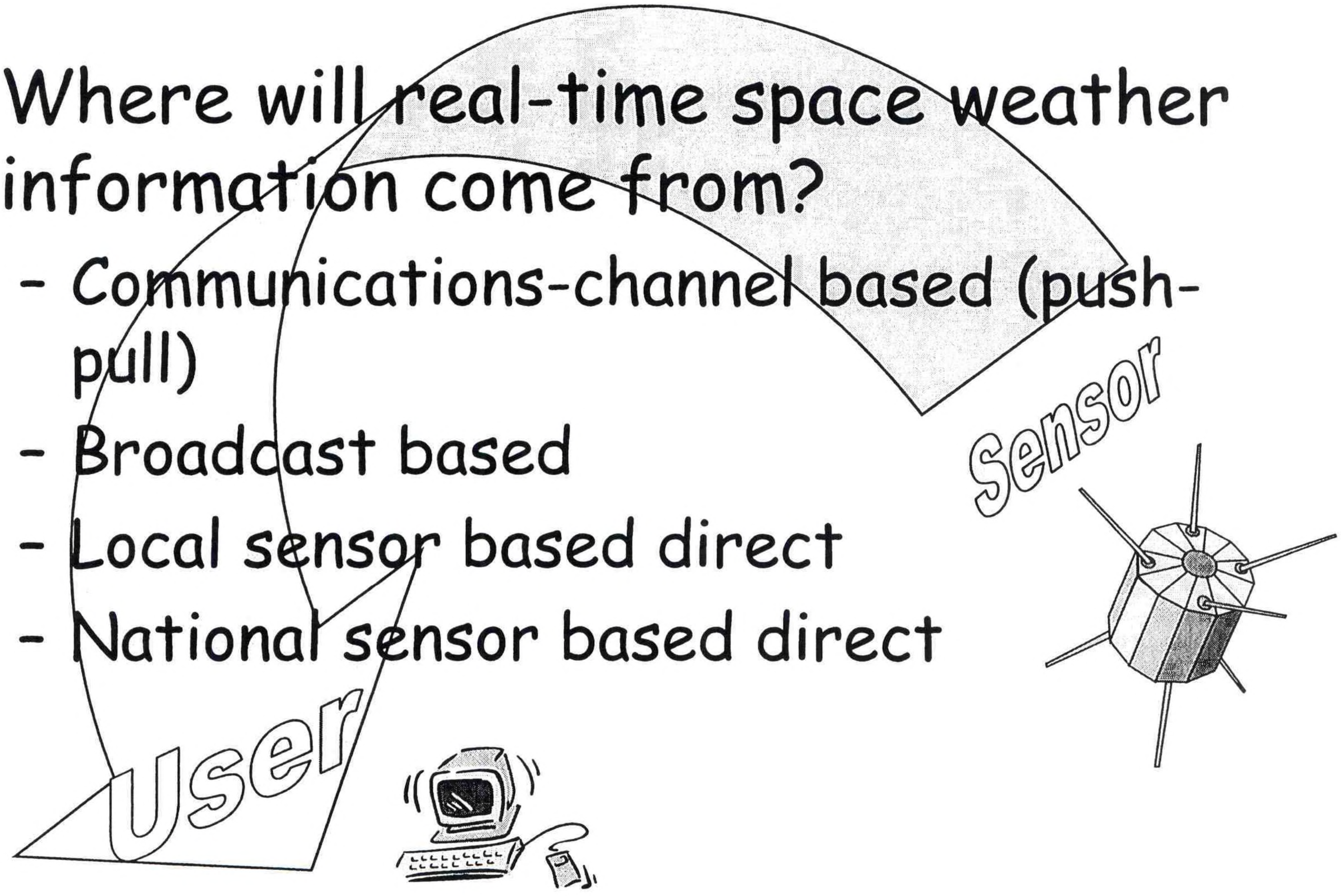
- Can real-time space weather help me answer the "now" questions?
  - Should I delay because the satellite circuit will return to operation
  - Why can't I hear an adversary? Using an "unusual" communicaitons path?
  - What if…?
  - Why…?

RF Mission Planning User

- How can real-time space weather sensors improve operational planning?
  - JMCIS certified
  - Multiple models
  - Interactive (What if... and Why...?)
  - RF environment understanding



RF Mission Planner (cont)



- Where will real-time space weather information come from?
  - Communications-channel based (push-pull)
  - Broadcast based
  - Local sensor based direct
  - National sensor based direct

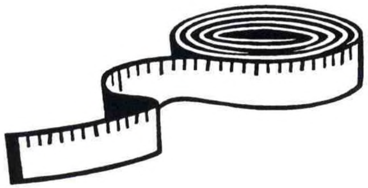
RF Mission Planner (cont)

- How will I use?
  - Local reconstructions
  - Bell-ringer
  - Difference (plan vs. now)
- One best data format for all?
- Required resolution for job?
  - Sporadic-E <0.05 TECU
  - 10 meter geopositioning accuracy < ? TECU

10101010

or

ABCDEF



RF Mission Planning System

- Built from start with goal of incorporating real-time space weather information ☒
  - local sensor
  - national resource
- Built from start with goal of real-time space weather capable algorithms ☒

Space Weather Questions

- Can a better space weather picture help improve operational systems performance?
  - Yes - clearly has the potential
  - How to do it?
  - How to best use it?
- What are the **NEW** operational options?

2.11 DoD Space-Weather Services

USAF Space Weather Operations

Michael S. Christie

and

USAF Operational Models Providing Space Weather Information

David N. Anderson

USAF Space Weather Operations

Major Michael Christie (HQ AFSPC/DORW)

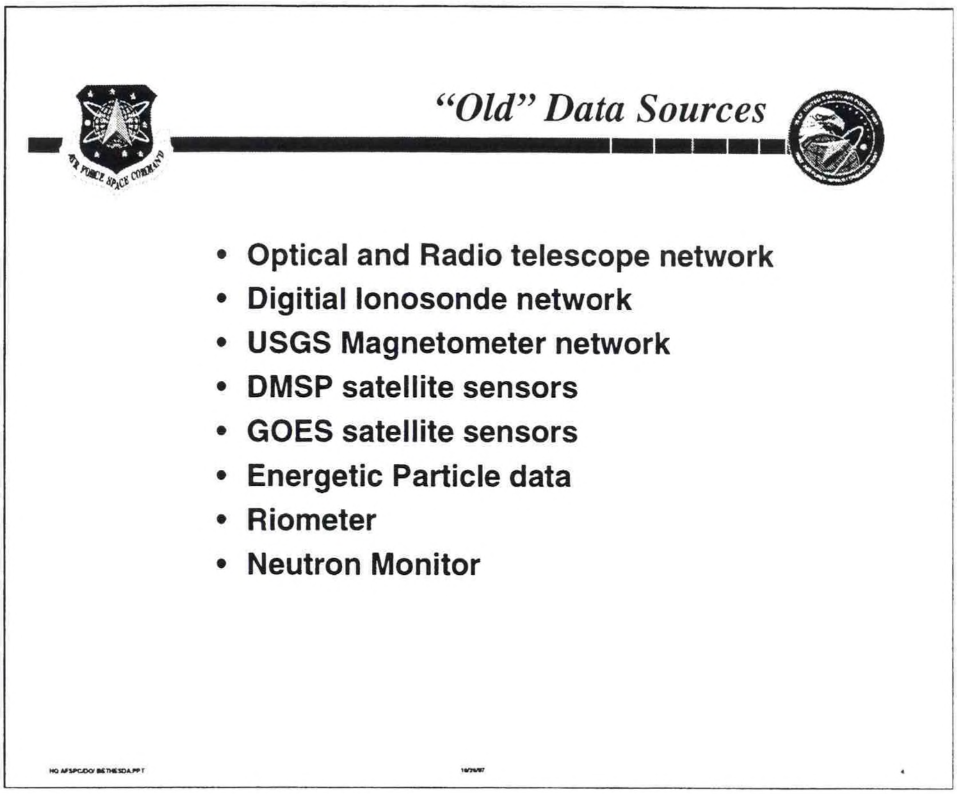
Abstract

Air Weather Service (now the Air Force Weather Agency) recently transferred lead command responsibility for space weather services to Air Force Space Command (AFSPC). AFSPC is now responsible for providing space weather system acquisition and modernization in addition to performing the operations and maintenance functions. AFSPC's 55th Space Weather Squadron provides products that are designed to support the communication, navigation and warning needs of DoD. Efforts are underway to ingest and use new data sources to run what would otherwise be data-starved, essentially climatological models, in an attempt to significantly improve operational support. We are concentrating improvements in ionospheric applications because 60% of the DoD space weather customer base requires this type of support. However, we are also working to upgrade other areas as well. AFSPC is striving to improve access to, and the format of, many existing antiquated products to better meet user needs worldwide. Part of that effort includes upgraded models and a better understanding of how good those models are operationally.

Early in 1997, Air Force Space Command (AFSPC), located at Peterson Air Force Base in Colorado Springs, conducted a review of how it conducted space weather operations. This review lead to a Concept of Operations (CONOPS), published 30 May 97, that documented how it performs these operations now and presented a vision for how they should be conducted in the future. This briefing summarizes that CONOPS.

Before we begin, it is important to highlight some organizational changes. AFSPC assumed the lead operating command function from Air Weather Service (AWS, now the Air force Weather Agency (AFWA)) in mid April of this year. This means AFSPC is now responsible for not only the space weather operations and maintenance functions, but also for the *acquisition and modernization* functions as well. AWS retains the functional manager role which I will not discuss here. As a result, there is now a single program office that oversees ground- and space-based system acquisition and modernization. In addition, the former Air Force Space Forecast Center, also known as the 50th Weather Squadron, was recently renamed the 55th Space Weather Squadron (55 SWXS) and designated as an "operational" squadron performing only operational functions. The 55 SWXS is aligned under the 50th Space Wing at Falcon Air Force Base and is located approximately 9-miles east of Colorado Springs.

Figure 1 shows many of the operational data sources received in real-time at the 55 SWXS. This list is not meant to be an exhaustive list of the data received. It simply illustrates the variety of data available to the 55 SWXS. It is important to note these are "operational" data that may not be as "clean" final or research data. Many of the data sources listed here are familiar and don't require a detailed explanation.



"Old" Data Sources

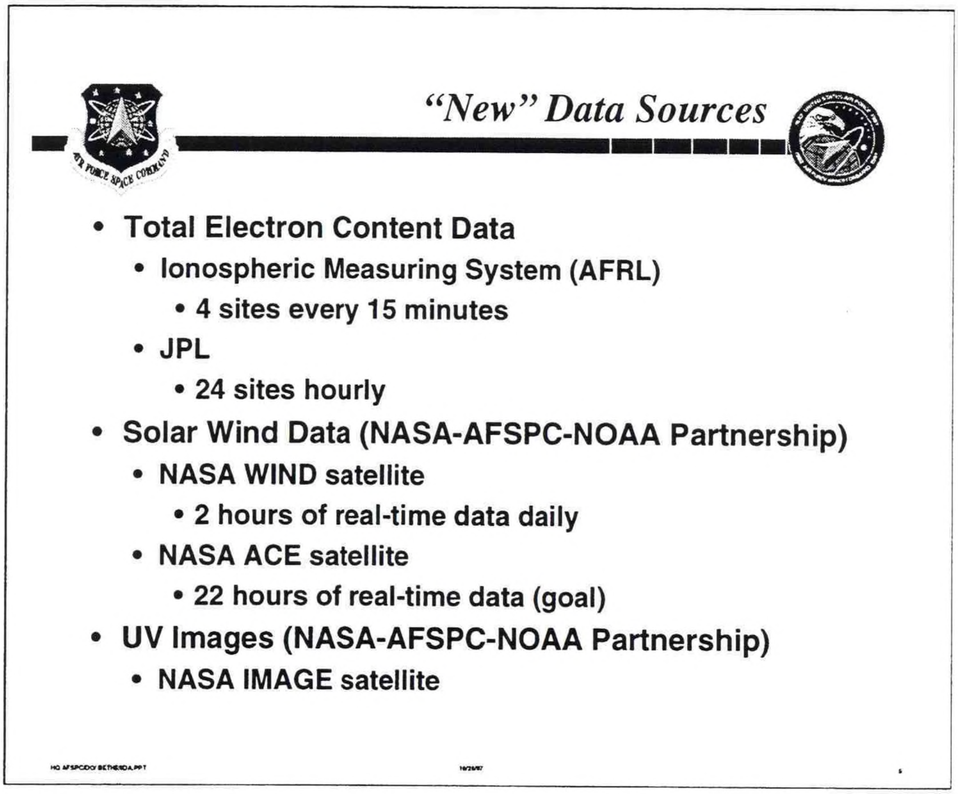
- Optical and Radio telescope network
- Digitial Ionosonde network
- USGS Magnetometer network
- DMSP satellite sensors
- GOES satellite sensors
- Energetic Particle data
- Riometer
- Neutron Monitor

HQ AFSPC/DO/ BETHESDA.PPT

4

Figure 1: Current operational real-time data sources received by the 55 SWXS.

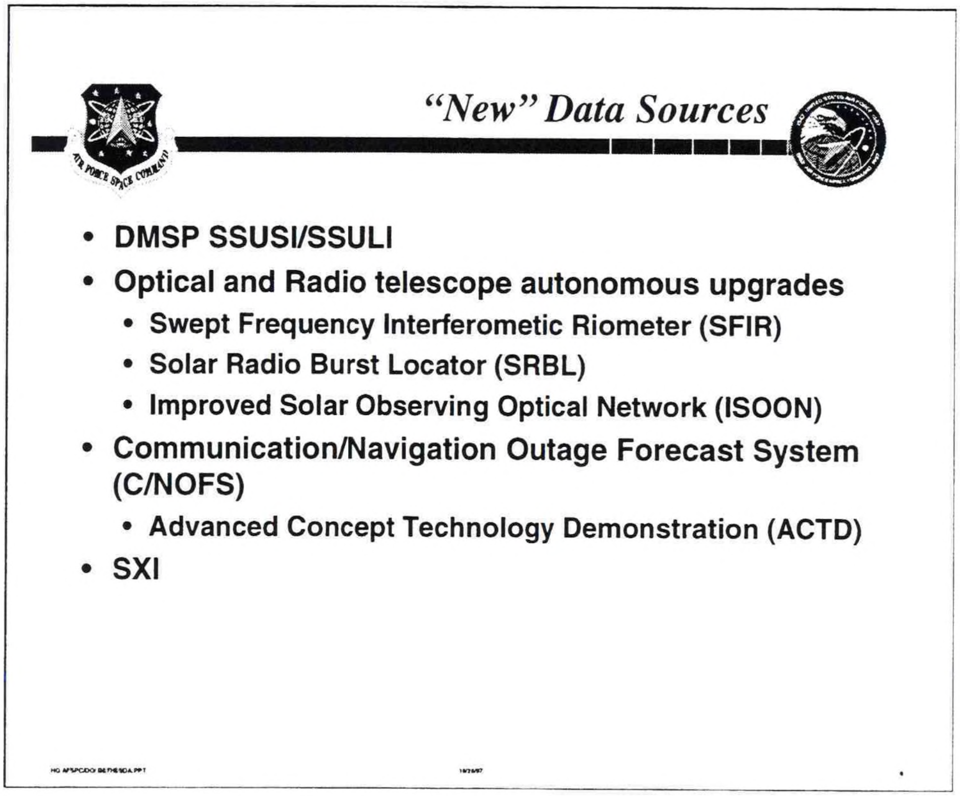
Figures 2 and 3 show new data sources that the 55 SWXS is currently receiving or will be receiving in the not too distant future. These data sources include GPS derived Total Electron Content data from a series of DoD and non-DoD assets. In addition, we are leveraging a tri-agency cooperative effort to obtain solar wind and ultraviolet data from NASA owned satellites. We are working to ingest planned Defense Military Satellite Program (DMSP) ultraviolet data into the operations center at the 55 SWXS. We are working to upgrade an aging solar optical and radio telescope network with new autonomous sensors. We are working to obtain a scintillation forecasting capability through the Advanced Concept Technology Demonstration program that allows the Air Force to field essentially unproven technology, test it, and provide some sort of residual capability at the end of the test if it proves useful. And finally, we are leveraging off our cooperative efforts with NOAA to build and fly a Solar X-ray Imager (SXI) that may ultimately replace ground-based solar optical telescopes.



"New" Data Sources

- Total Electron Content Data
  - Ionospheric Measuring System (AFRL)
    - 4 sites every 15 minutes
  - JPL
    - 24 sites hourly
- Solar Wind Data (NASA-AFSPC-NOAA Partnership)
  - NASA WIND satellite
    - 2 hours of real-time data daily
  - NASA ACE satellite
    - 22 hours of real-time data (goal)
- UV Images (NASA-AFSPC-NOAA Partnership)
  - NASA IMAGE satellite

Figure 2: New data sources that are, or soon will be, available to the 55 SWXS.

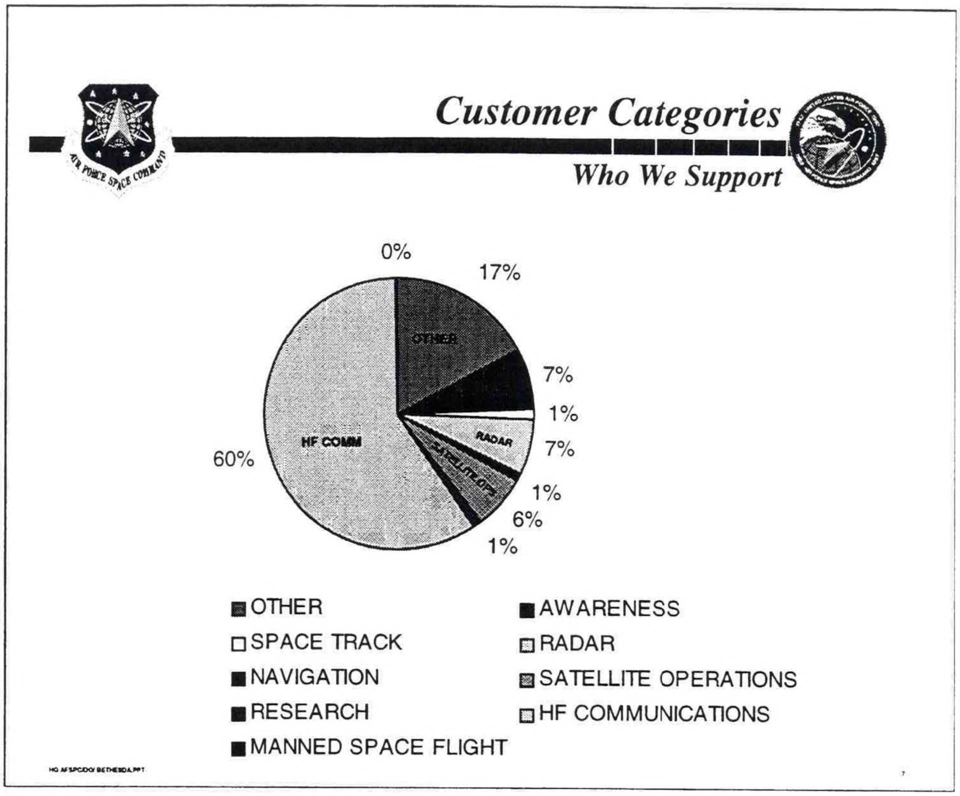


"New" Data Sources

- DMSP SSUSI/SSULI
- Optical and Radio telescope autonomous upgrades
  - Swept Frequency Interferometic Riometer (SFIR)
  - Solar Radio Burst Locator (SRBL)
  - Improved Solar Observing Optical Network (ISOON)
- Communication/Navigation Outage Forecast System (C/NOFS)
  - Advanced Concept Technology Demonstration (ACTD)
- SXI

Figure 3: New data sources that are, or soon will be, available to the 55 SWXS.

The categories of support we provide to a variety of customers are shown in figure 4. The bulk of our current support is geared towards High Frequency Communications which implies the importance we must place on the ionosphere.

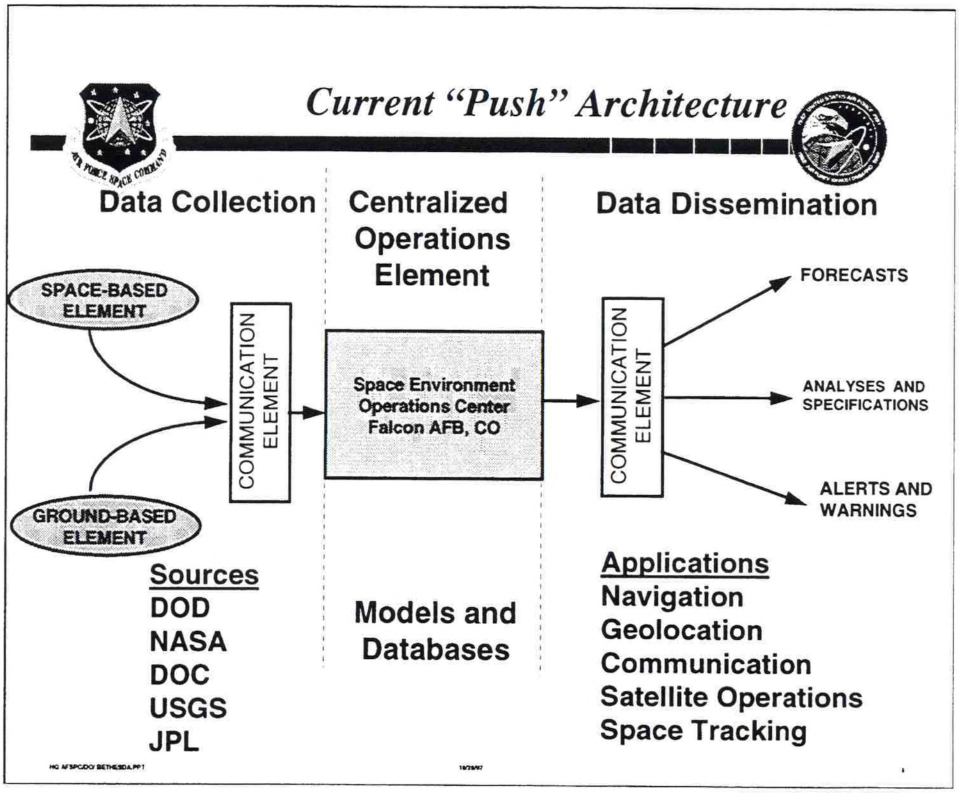


Customer Categories

Who We Support

Figure 4: Categories of customers, by percentage, receiving 55 SWXS products.

Our existing operations center around a "push" architecture (figure 5) in which the 55 SWXS ingests a variety of ground- and space-based data through a communications network. These data are analyzed, quality controlled and used to build *tailored* products which are "pushed" to literally hundreds of customers worldwide. The bulk of these customers are DoD with the NOAA Space Environment Center providing support to the civilian side of the house. Figure 6 shows an example of an existing scintillation product we currently provide to users. The point of this figure is to illustrate the alphanumeric nature of the products we provide. The are not very user-friendly.



Current "Push" Architecture

Data Collection

SPACE-BASED ELEMENT

GROUND-BASED ELEMENT

COMMUNICATION ELEMENT

Sources
DOD
NASA
DOC
USGS
JPL

Centralized Operations Element

Space Environment Operations Center Falcon AFB, CO

Models and Databases

Data Dissemination

COMMUNICATION ELEMENT

FORECASTS

ANALYSES AND SPECIFICATIONS

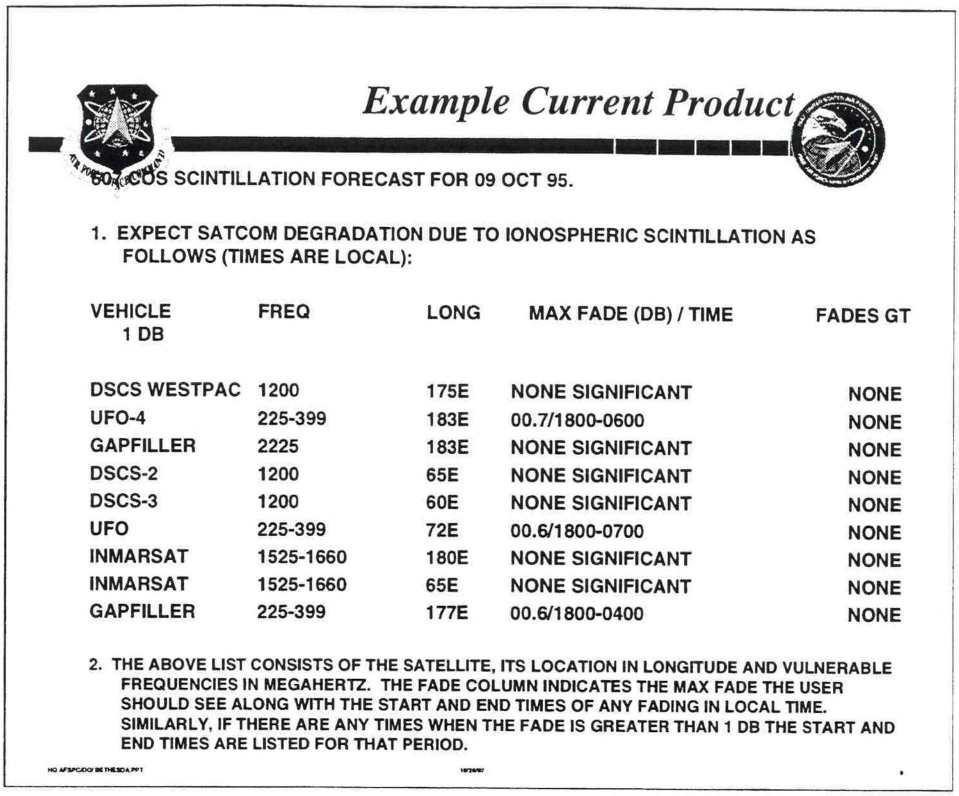
ALERTS AND WARNINGS

Applications
Navigation
Geolocation
Communication
Satellite Operations
Space Tracking

Figure 5: Pull architecture currently employed by the 55 SWXS.

The architecture we would like to adopt in the future is more of a "pull" architecture as shown in figure 7. Data are still gathered from ground- and space-based sensors, analyzed and quality controlled at the 55 SWXS Space Environment Operations Center (SEOC). However, users can now "pull" the data needed for their specific application or they can use generalized products produced by the SEOC. A push capability will still exist for alerts and warnings as well as for those users that have a specific tailored application for which the 55th produces a product. This architecture also includes a *broadcast* method of distribution in which customers can receive products transmitted as part of a continuous data stream. It also includes *functional* distribution methods in which customers can receive space weather products over standard weather distribution networks either as stand-alone products or as fused terrestrial and space weather products. Figure 8 shows an example of what a new graphical scintillation product could look like. It is much more user-friendly and conveys much more information than the alphanumeric product shown in figure 6.

All of this leads to the need to assign operational priorities. Figure 9 shows that our operational priorities will continue to be dominated by the ionosphere, so we can meet the communication and navigation needs of our military users. In addition, procedurally, we need to ensure we make effective use of the capabilities we have and understand how good we perform those functions so military users worldwide can have confidence in the products we provide them.



Example Current Product

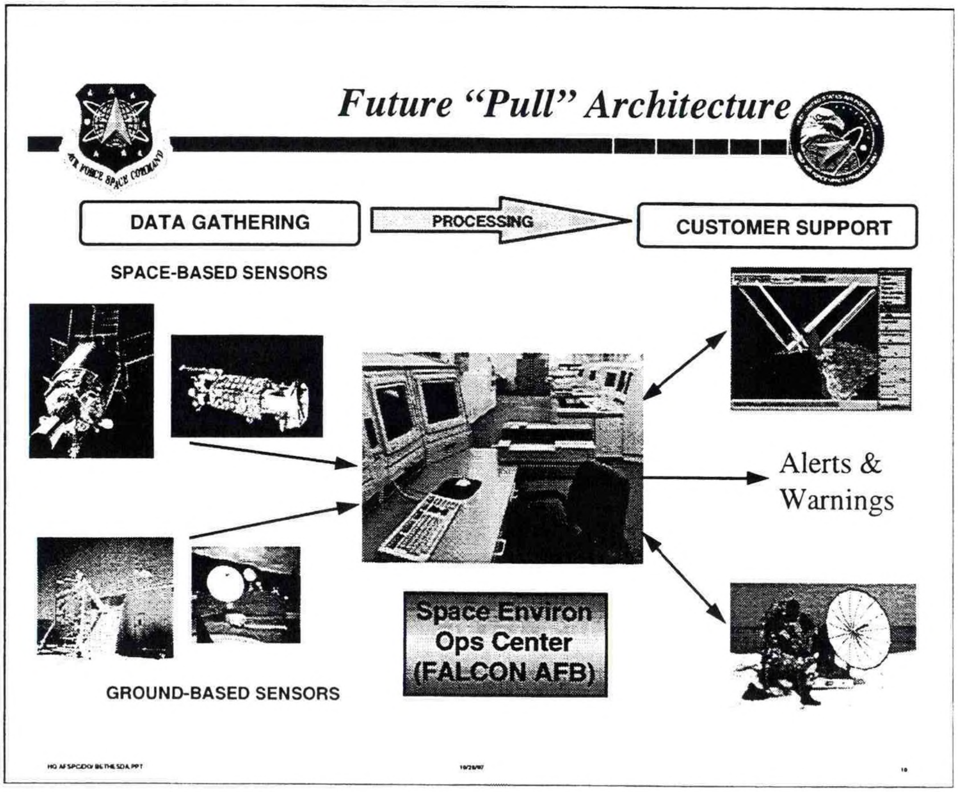
607[illegible]COS SCINTILLATION FORECAST FOR 09 OCT 95.

1. EXPECT SATCOM DEGRADATION DUE TO IONOSPHERIC SCINTILLATION AS FOLLOWS (TIMES ARE LOCAL):

VEHICLE	FREQ	LONG	MAX FADE (DB) / TIME	FADES GT 1 DB
DSCS WESTPAC	1200	175E	NONE SIGNIFICANT	NONE
UFO-4	225-399	183E	00.7/1800-0600	NONE
GAPFILLER	2225	183E	NONE SIGNIFICANT	NONE
DSCS-2	1200	65E	NONE SIGNIFICANT	NONE
DSCS-3	1200	60E	NONE SIGNIFICANT	NONE
UFO	225-399	72E	00.6/1800-0700	NONE
INMARSAT	1525-1660	180E	NONE SIGNIFICANT	NONE
INMARSAT	1525-1660	65E	NONE SIGNIFICANT	NONE
GAPFILLER	225-399	177E	00.6/1800-0400	NONE

2. THE ABOVE LIST CONSISTS OF THE SATELLITE, ITS LOCATION IN LONGITUDE AND VULNERABLE FREQUENCIES IN MEGAHERTZ. THE FADE COLUMN INDICATES THE MAX FADE THE USER SHOULD SEE ALONG WITH THE START AND END TIMES OF ANY FADING IN LOCAL TIME. SIMILARLY, IF THERE ARE ANY TIMES WHEN THE FADE IS GREATER THAN 1 DB THE START AND END TIMES ARE LISTED FOR THAT PERIOD.

Figure 6: Sample alphanumeric scintillation product provided by the 55 SWXS.



Future "Pull" Architecture

DATA GATHERING

PROCESSING

CUSTOMER SUPPORT

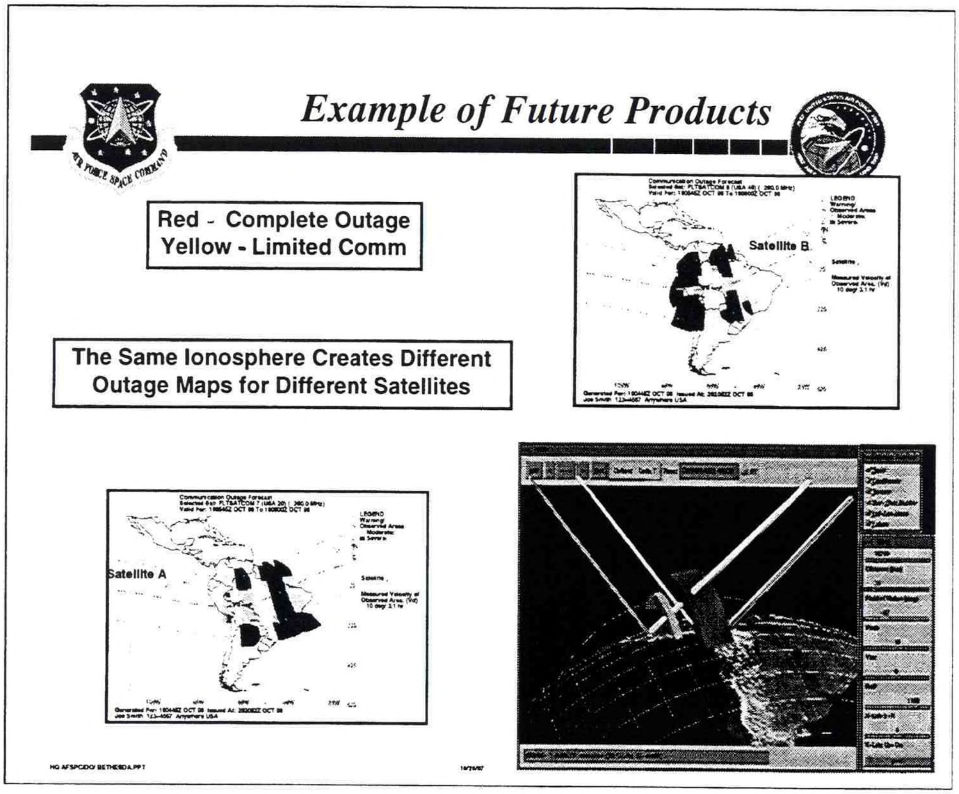
SPACE-BASED SENSORS

GROUND-BASED SENSORS

Space Environ
Ops Center
(FALCON AFB)

Alerts &
Warnings

Figure 7: Pull architecture envisioned for future space weather operations.

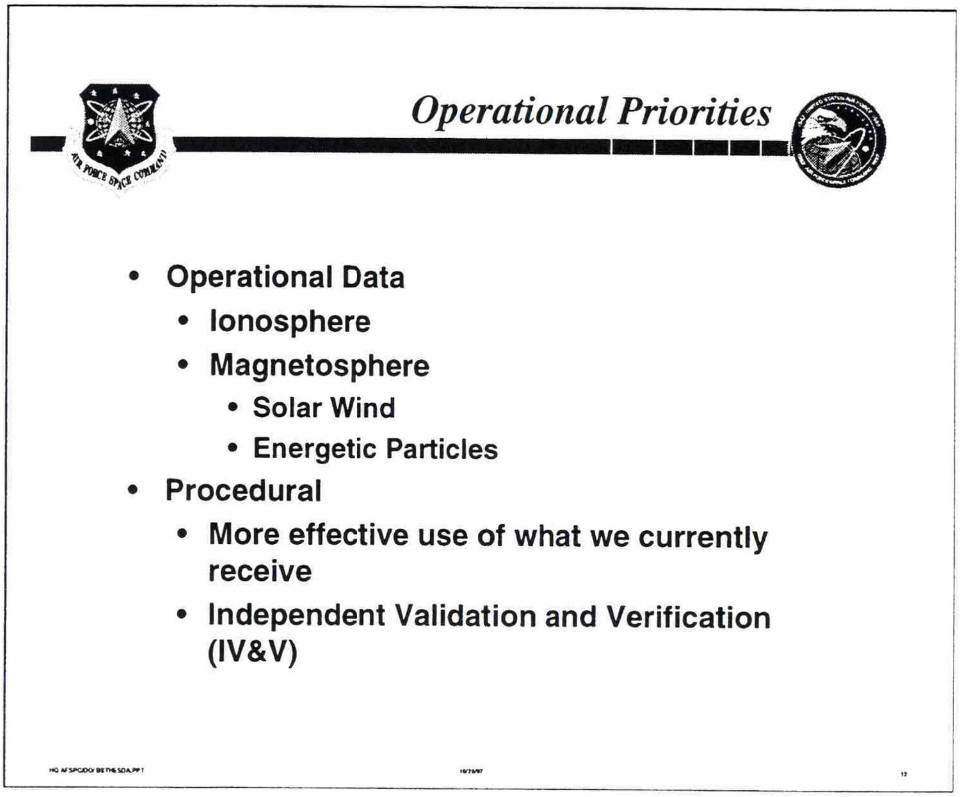


Example of Future Products

Red - Complete Outage
Yellow - Limited Comm

The Same Ionosphere Creates Different Outage Maps for Different Satellites

Figure 8: Sample graphical scintillation product of the future.



Operational Priorities

- Operational Data
  - Ionosphere
  - Magnetosphere
    - Solar Wind
    - Energetic Particles
- Procedural
  - More effective use of what we currently receive
  - Independent Validation and Verification (IV&V)

Figure 9: Operational priorities employed by AFSPC.

USAF OPERATIONAL MODELS

PROVIDING SPACE WEATHER INFORMATION

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SPACE MODELS BRANCH
AIR FORCE RESEARCH LABORATORY

We would like to describe now the operational models that have been developed and are being developed in providing space weather information to the DOD Navigation and Communications customers. We will also discuss some specific tailored products which are being developed and how these are being transitioned to 55 SWXS. (Figure 1.)

The Parameterized Realtime Ionospheric Specification Model (PRISM) is operational at 55 SWXS. It has been designed to accept all near realtime data available including both ground-based as well as satellite sensor data. It provides global electron density profiles from 90 to 1600 km and has recently been extended to include the H+ and He+ ions in the plasmasphere out to 22,000 km. The objective of the operational model development effort is to provide realistic, global, realtime neutral atmosphere and ionospheric specification and forecast models, to transition these to AFSPC and other customers, and to develop these in such a way as to be able to ingest all present and future realtime sensor data. The models are derived from first principles and can be thought of as "theoretical" climotology models in contrast to "empirical" climotology models based on an historical database of observations. The payoff is to improve operational performance and reliability for Navigation and Communication systems. (Figure 2.)

In order to generate a global, computationally-fast ionospheric specification model, the first principle models which describe the low, mid and high latitude ionosphere are run under a wide variety of solar, season and geomagnetic conditions and the resulting ion and electron density profiles are described analytically by Empirical Orthonormal Functions (EOFs). The coefficients of these functions are, in turn, described analytically as a function of latitude while the UT variation is given in tabular form. The resulting Parameterized Ionospheric Model (PIM) is described in detail in the article by Daniell et al. (1996). PIM forms the basis for PRISM which is driven by as much ground-based and spaced-based realtime data as possible to provide global "weather" nowcasting of the ionospheric parameters. (Figure 3.)

In comparing Theoretical versus Empirical climotology there are three important distinctions to make. In theoretical climotology, where first principles models are used to calculate global ionospheric parameters, it is important that the correct, relevant physics be included in the calculations. For empirical climotology , it is important that there exist an historical database since this is the basis for any global, empirical model. The generation of a theoretical climotological model depends on the accurate knowledge of the physical processes in the ionosphere, while the empirical model depends on the quality and completeness of the data. Herein lies an important difference. Since the empirical model depends on observations, there can exist a significant gap in this database for the ocean area coverage, the low latitude coverage and the polar cap coverage. The theoretical model doesn't suffer from this drawback if the relevant physics is known, globally. Another major distinction lies in the horizontal structure and variability which exists in the two approaches. The theoretical approach tends to reproduce the spatial structure while the empirical approach, with its inherent averaging process tends to "smooth" the spatial structure. Examples of the theoretical climotological models include PRISM, PIM and FAIM (Fully Analytic Ionospheric Model) while examples of the empirical climotological models include the International Reference Ionosphere (IRI) and the Ionospheric Conductivity and Electron Density Model (ICED). (Figure 4.)

PRISM is driven by near realtime data that is available at 55 SWXS. This includes both ground-based and satellite borne sensor data. There are seventeen ground-based ionospheric sounders providing realtime data on F region peak parameters Nmax and Hmax and E region parameters providing peak E region electron densities and altitudes, hmE. In addition, ground based, dual frequency GPS receivers give total electron content (TEC) values at least hourly and these are supplied by five Ionospheric Measuring System (IMS) receivers and 24 JPL/GPS receivers. PRISM incorporates this information and adjusts Nmax until the integrated TEC value matches the TEC input. The two DMSP satellites at 840 km provide in-situ electron densities and temperatures which are used to adjust the topside scale height in PRISM, and the energetic particle precipitation fluxes and energy which adjust the size or the auroral oval and the auroral E region densities. Two future UV imagers, the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) and the Special Sensor Ultraviolet Limb Imager (SSULI) will provide important cross-track information on ionospheric parameters, and in-track realtime measurements of neutral density and electron density profiles, respectively. (Figure 5.)

Before PRISM was transitioned to 55 SWXS, a limited validation was carried out which compared global RMS errors of peak parameters NmF2 and HmF2 between PRISM and ICED. The data that was used consisted of mid and high latitude ground-based sounder data and DMSP data taken during the last solar cycle maximum period for an equinoctial season. The bottom-line showed that the improvement in PRISM ionospheric specification over ICED was approximately 60% which is significant and persuaded AFSPC to transition PRISM to full operational status. There remains, however, a vital need to continue validation of PRISM as an operational model to determine where and when it performs well and where it performs poorly. (Figure 6.)

In the left-hand portion of this figure is depicted the Ionospheric Forecast Model (IFM) which is a stream-lined, first principles, global ionospheric model designed to forecast the global ionospheric parameters 12 hours in the future. It uses PRISM as the initial or current ionospheric specification. Since IFM forecasts the global ionosphere, the challenge is to be able to forecast the inputs to IFM which include the neutral atmosphere, the global electric field, the solar ionizing radiation and the high latitude particle precipitation patterns. IFM has been delivered to AFSPC and is currently being transitioned to operational status at 55 SWXS. IFM has been coupled, self-consistently, to a streamlined Thermospheric Forecast Model (TFM) developed by Tim Fuller-Rowell at the Space Environment Center (SEC) at NOAA and this Coupled Ionosphere Thermosphere Forecast Model (CITFM) is being validated to assure its reliability. The outputs of IFM, electron and ion densities and temperatures are inputs to TFM, which in turn supplies neutral densities, winds and temperatures to IFM. The missing link to a completely coupled, self-consistent, space weather model is the electrodynamics. Initial efforts to supply a self-consistent low/mid latitude electric field are underway and in the future a self-consistent auroral particle precipitation and high latitude electric field model will be added. These coupled models are crucial in being able to realistically forecast the global ionosphere-thermosphere-electrodynamic system after the onset of geomagnetic disturbances. (Figure 7.)

The necessity of coupling models to reflect the importance of the last statement is depicted in this figure. The left-hand portion illustrates the change in neutral composition, specifically the increase in the N2/O ratio due to high latitude energy input and the consequent effects on the ionosphere depicted in the right hand portion. It is well known and understood that increases in the N2/O ratio causes a decrease in ionospheric peak electron density due to the change in the production/loss ratio. This simulation used the Coupled Thermosphere Ionosphere Model (CTIM) developed at SEC and has been reproduced by the streamlined CITFM model. (Figure 8.)

For navigation systems GPS is the solution. The dual frequency GPS receivers accurately correct for ionospheric effects in achieving high precision position accuracy. However, the three million users of single frequency GPS receivers must correct for ionospheric effects. The current 8 coefficient ionospheric correction algorithm imbedded in each receiver was developed 20 years ago and was designed to correct for 50% of the mid latitude ionosphere. It significantly underestimates the correction needed in the low latitude regions. Improvements to the current algorithm are being developed under a Small Business Innovative Research (SBIR) grant. (Figure 9.)

It is known that the old algorithm does not meet stated requirements. The Army has ordered 100,000 Precision Lightweight GPS Receivers (PLGRs) and it is critical that the position error introduced by an inaccurate ionospheric correction be understood. To this end, AFSPC is developing a tailored product which will provide the realtime position error for single frequency GPS receivers located at the 24 JPL/GPS ground-based sites utilizing the hourly slant TEC measured by these GPS dual frequency receivers. If the technique is successful, the capability will be expanded by providing global maps of position error based on PRISM realtime outputs of slant TEC. (Figure 10.)

The "New Way" of doing business is to improve the process of transitioning models and tailored products from the science community to the 55 SWXS, and other customers. The process involves the PL-Rapid Prototyping Center (RPC) with its principal software (PL-GEOSPACE) operating on a Silicon Graphics computer. The philosophy is to engage the 55 SWXS operators in continuous feedback with the model developers so that the end products are useful to the customers and improve the end-user systems. The RPC 1.) emulates the 55 SXWS input databases and processing system, 2.) is able to provide operator-oriented displays and products and 3.) performs extensive validation and verification. Not until the models and tailored products have passed these various tests will operational software development (OSD) begin. (Figure 11.)

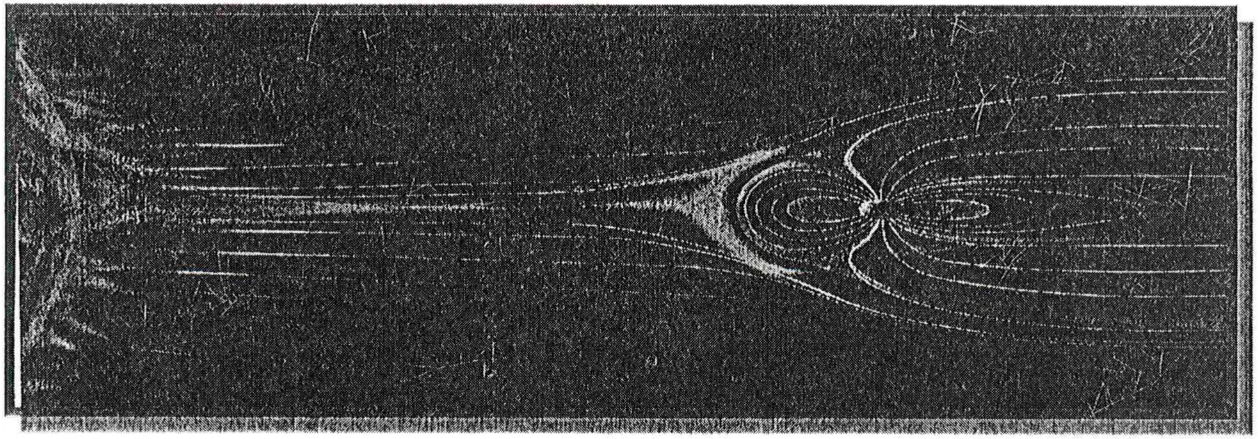
An example of a model/tailored product on GEOSPACE is the PRISM/Jones-Stephenson 3-D raytrace model. This combination provides the ability to produce and visualize the propagation path of an HF signal transmitted from any location on the earth, through an ionosphere specified by PRISM/PIM, and view where that signal can be received as it propagates from the receiver. Pictured in the upper left are the contours of peak electron density, Nmax, superimposed on the earth and a "slice" of the ionosphere in the plane of the propagation path, where the geographic location of the transmitter is completely arbitrary, as is the azimuth of the propagation direction. In the upper right is the electron density profile at a specified location along the "slice". A slide bar is used to select any location along this slice and the latitude and longitude are displayed as well as range from the transmitter location. In the lower portion of the figure, the various rays that have been chosen are displayed. The frequency of the signal can be arbitrarily chosen as well as the elevation angle from the transmitter. For this example, the transmitter is located at Bangor, Maine, and the azimuth is 180 degrees and there are three combinations of frequencies and elevation angles chosen. For one combination the HF radiowave propagates through the ionosphere and is not reflected while the other two cause the propagation to be reflected between the ionosphere and the ground. One of the paths actually propagates between the northern and southern hemispheres in a "whispering gallery" mode and is not reflected by the earth between 4800 and 11,000 km down range. (Figure 12.)

Another tailored product that uses the 3-D Jones-Stephenson raytrace model is called "ground-to-satellite homing". Here a PRISM-specified ionosphere provides the electron density distribution and the operator selects a ground location for the transmitter and defines the frequency of the HF radiowave. A satellite ephemeris is chosen to locate satellites of interest and the "homing" tailored product determines the elevation and azimuth of the HF signal at the specified frequency that is required in order to reach the specified satellite location. This product will provide the operator with the optimal information to successfully communicate from ground-to-satellite when a limited number of transmitter frequencies are available. (Figure 13.)

The “Vision” is the synergistic combination of a global, multi-sensor, near realtime data base providing inputs to a suite of operational, specification and forecast models which, in turn, provide realtime space weather information to the myriad of DOD and civilian Navigation and Communication customers. (Figure 14.)

USAF OPERATIONAL MODELS

PROVIDING SPACE WEATHER INFORMATION



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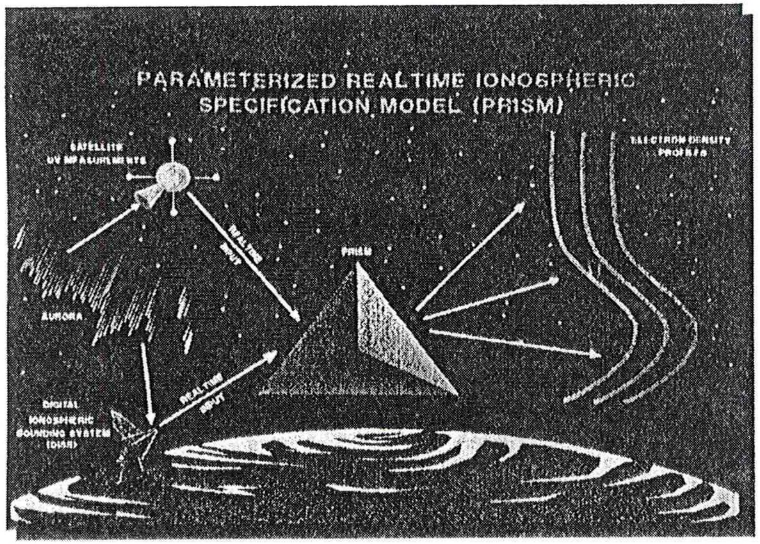
PARAMETERIZED REALTIME IONOSPHERIC SPECIFICATION MODEL (PRISM)



PAYOFFS

- Increased Operational Performance and Reliability of C3I, Navigation and SPACETRACK Systems
- Simulation of Operational Environments for Planning of Future Systems Acquisitions

GOALS/OBJECTIVES

- Reliable Global, Real-Time, Neutral Atmosphere Density and Ionospheric Specification and Forecast Techniques and Models
- Transition Specification and Forecast Models to AFSPC, DMSP and Others for Operational Use

APPROACH

- Develop and Validate Parameterized Models (Derived From First Principles), Simulation Codes, and Forecasting Techniques That Are Driven With Real-Time Sensor Data

BRIEF DESCRIPTION OF PRISM

PHILOSOPHY

- Theoretical rather than empirical climatology
- Pre-adjusted ionospheres are analytical representations based on state-of-the-art physics-based numerical models
- Use as much ground-based and space-based real-time data as possible to characterize current "weather" as differences from theoretical climatology

Theoretical vs. Empirical Climatology

Theoretical Climatology	Empirical Climatology
Relevant physics	Historical data
Dependent on knowledge of physical processes in the ionosphere	Dependent on quality and completeness of data
Tends to reproduce spatial structure and variability	Tends to smooth spatial structure and variability
Examples: PRISM models, PIM, FAIM	Examples: IRI, ICED

NEAR REALTIME DATA

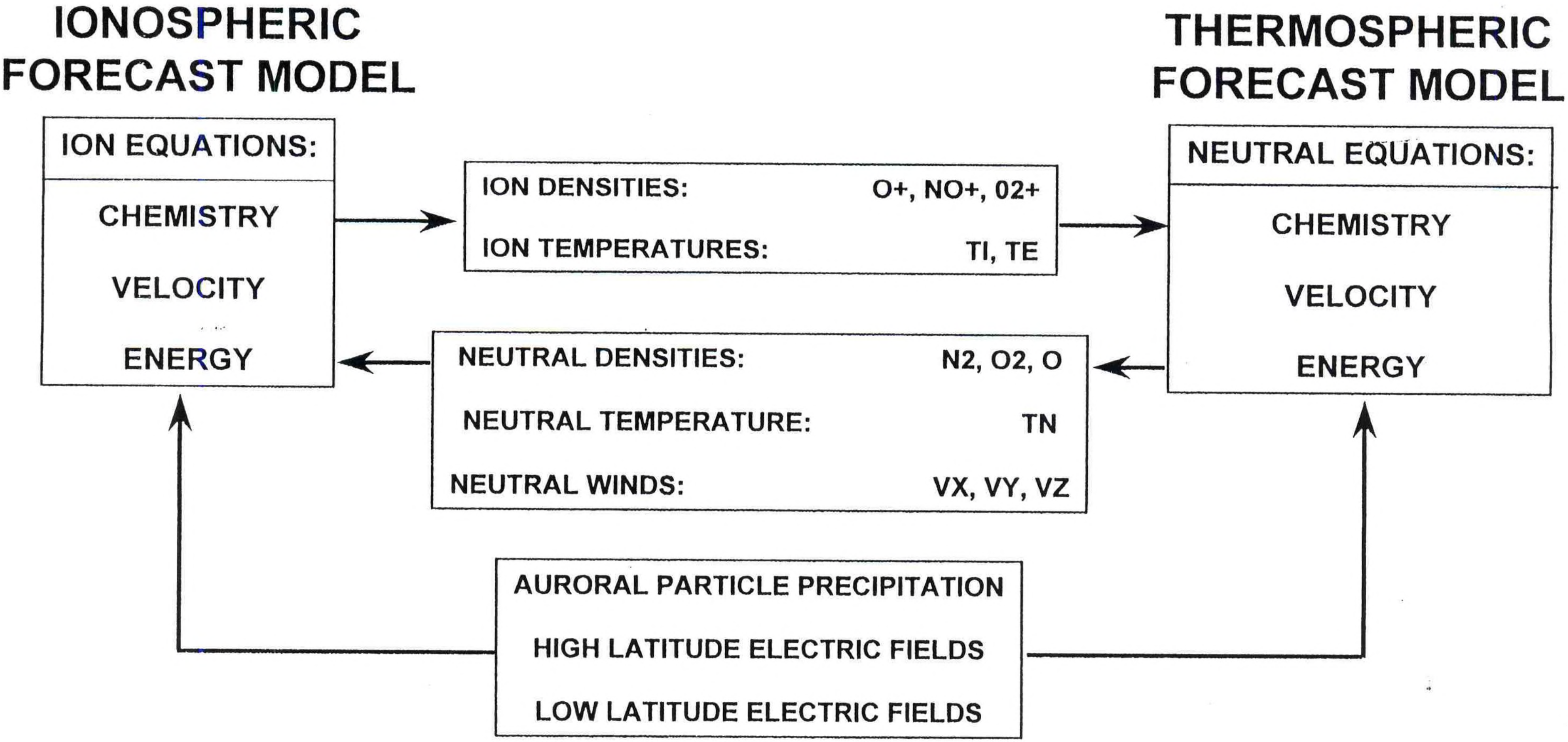
Data ingestion:

- **Ground-based data:**
  - –foF2, hmF2, foE, hmE, from digital ionosondes, TEC data from dual-frequency GPS receivers
- **Space-based data:**
  - –Electron density, ion composition, electron and ion temperature (e.g., DMSP SSIES)
  - –Electron and ion precipitation (e.g., DMSP SSJ/4, SSJ5)
  - –UV imagers (e.g. DMSP, SSUSI, SSULI)

Summary of PRISM and ICED Validation Results

Quantity	RMS Error		Improvement over ICED (%)
	ICED	PRISM 1.7c	PRISM 1.7c
f_oF_2 (MHz)	1.5	0.6	58
N_mF_2 (%)	40	19	54
h_mF_2 (km)	25	8	69

COUPLED IONOSPHERIC THERMOSPHERIC FORECAST MODEL



IONOSPHERIC FORECAST MODEL

ION EQUATIONS:

CHEMISTRY

VELOCITY

ENERGY

ION DENSITIES: O+, NO+, 02+

ION TEMPERATURES: TI, TE

NEUTRAL DENSITIES: N2, O2, O

NEUTRAL TEMPERATURE: TN

NEUTRAL WINDS: VX, VY, VZ

THERMOSPHERIC FORECAST MODEL

NEUTRAL EQUATIONS:

CHEMISTRY

VELOCITY

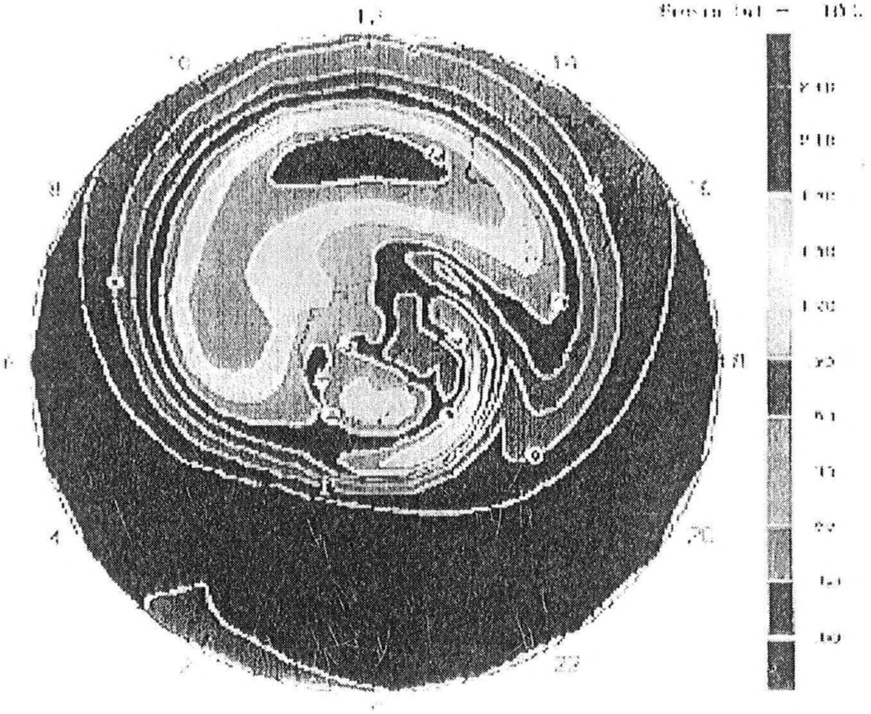
ENERGY

AURORAL PARTICLE PRECIPITATION

HIGH LATITUDE ELECTRIC FIELDS

LOW LATITUDE ELECTRIC FIELDS

NEUTRAL ATMOSPHERE/IONOSPHERE COUPLING



Local Time

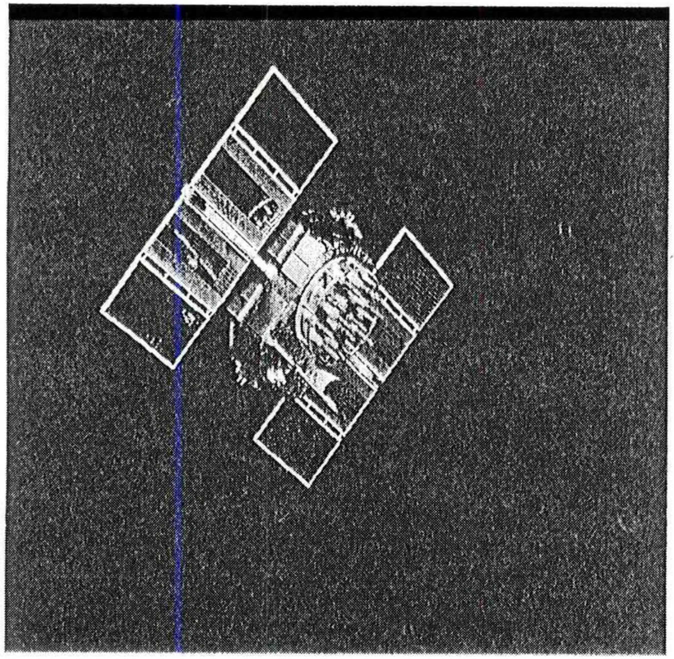
Local Time

Change in Neutral Composition → **Change in Electron Density**

SPACE WEATHER WORKSHOP (5WW)

IONOSPHERIC EFFECTS ON C3I SYSTEMS AND OPERATIONS:

The GPS Solution



Global Positioning System

- PL/GP Two-Frequency Concept Provides Ionospheric Corrections for Achieving High Precision
- Single-Frequency GPS Receivers Employ PL/GP Algorithms for Ionospheric Corrections; Algorithms for Next Generation Receivers Under Development

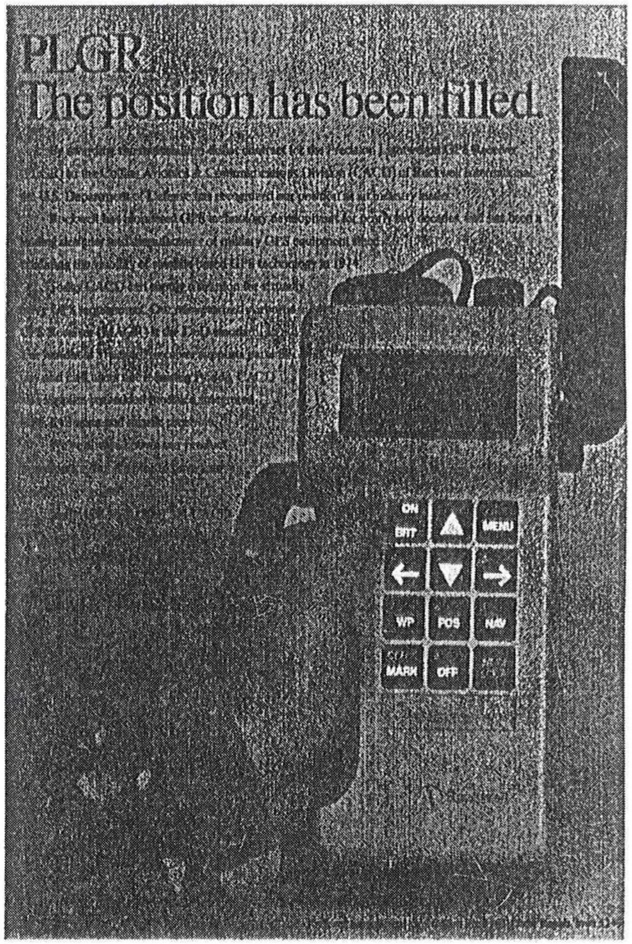
UPGRADE OF GLOBAL POSITIONING SYSTEM'S IONOSPHERIC CORRECTION ALGORITHM PLAN

STATUS

- Old Algorithm Does not Meet Position Accuracy Requirement

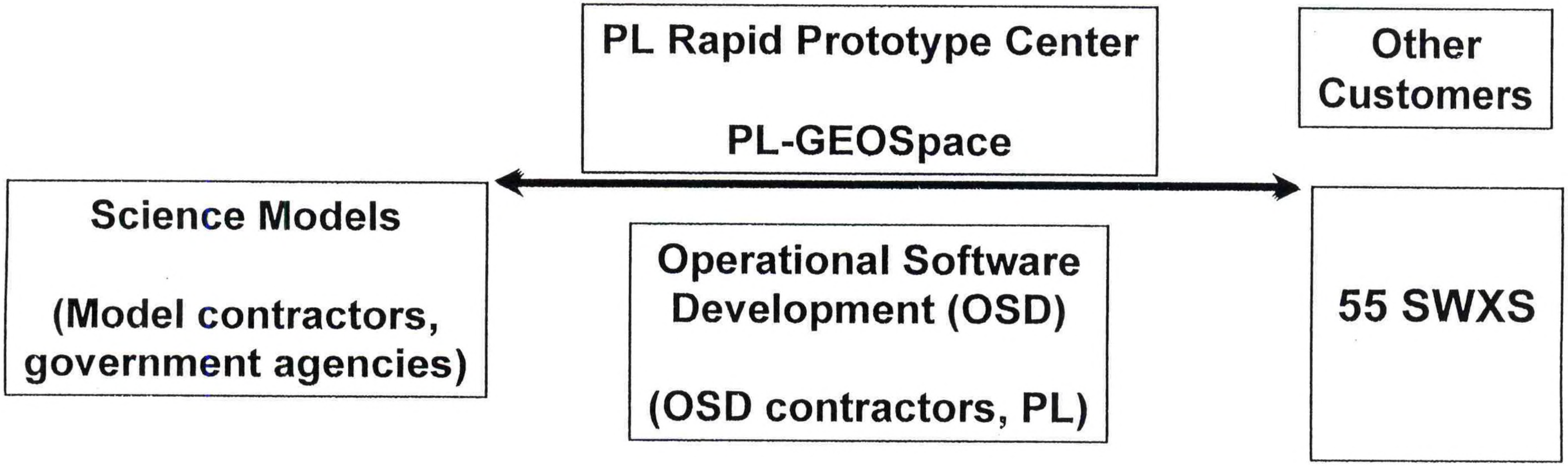
PLANNED UPGRADE:

- Develop/Install New Algorithm at GPS Master Control, Falcon AFB
- Base Algorithm on Tested Ionospheric Model
- Validate New Algorithm With GPS Data



Military Single-Frequency GPS Receiver

A NEW WAY



PL Rapid Prototype Center

PL-GEOSpace

Other Customers

Science Models

(Model contractors, government agencies)

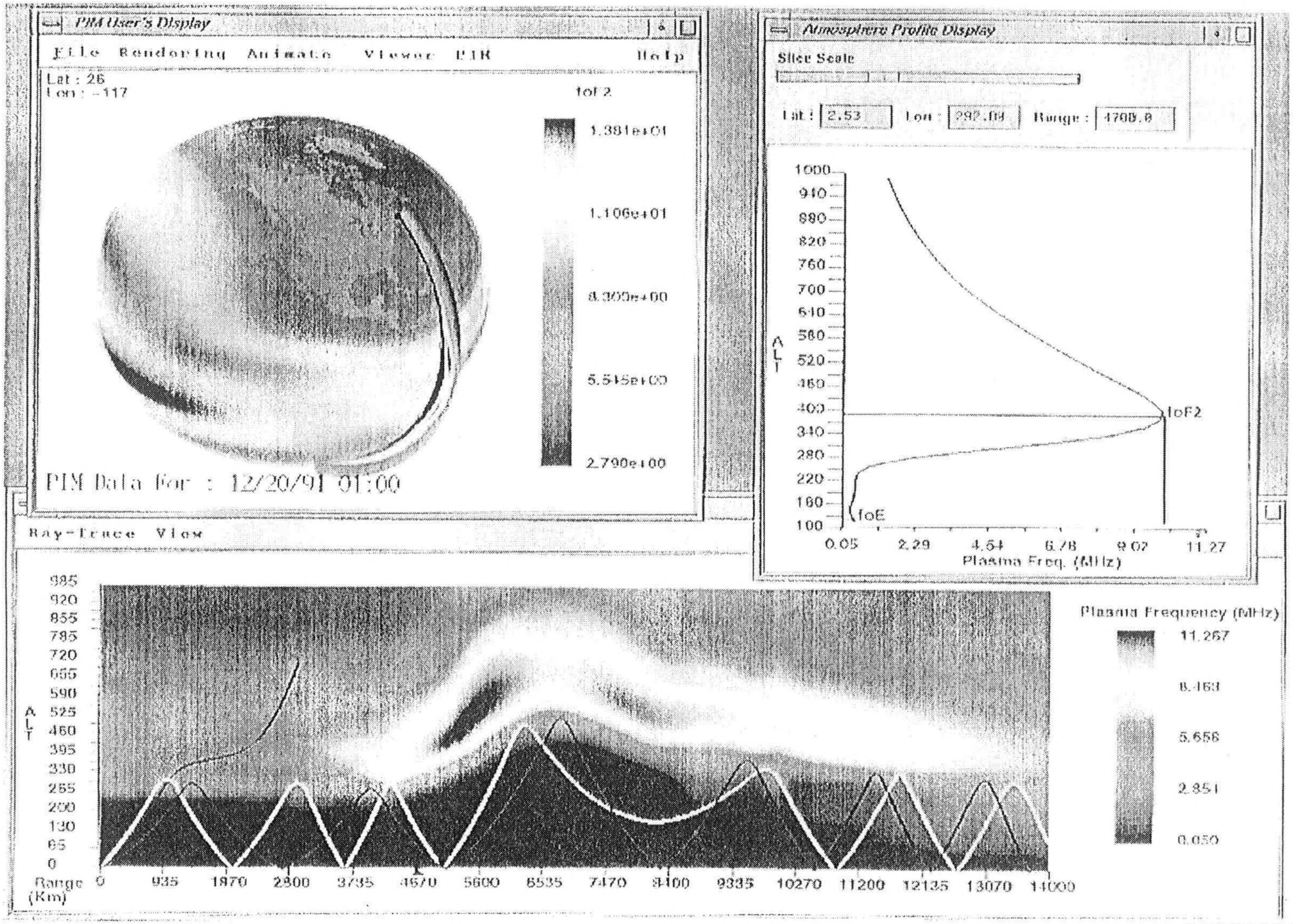
Operational Software Development (OSD)

(OSD contractors, PL)

55 SWXS

Operators have continuous feedback to model developers
RPC emulates 55 SWXS input databases and processing system
RPC develops operator - oriented displays and products
RPC performs extensive validation and verification
OSD is not done until model and derived products have proven useful

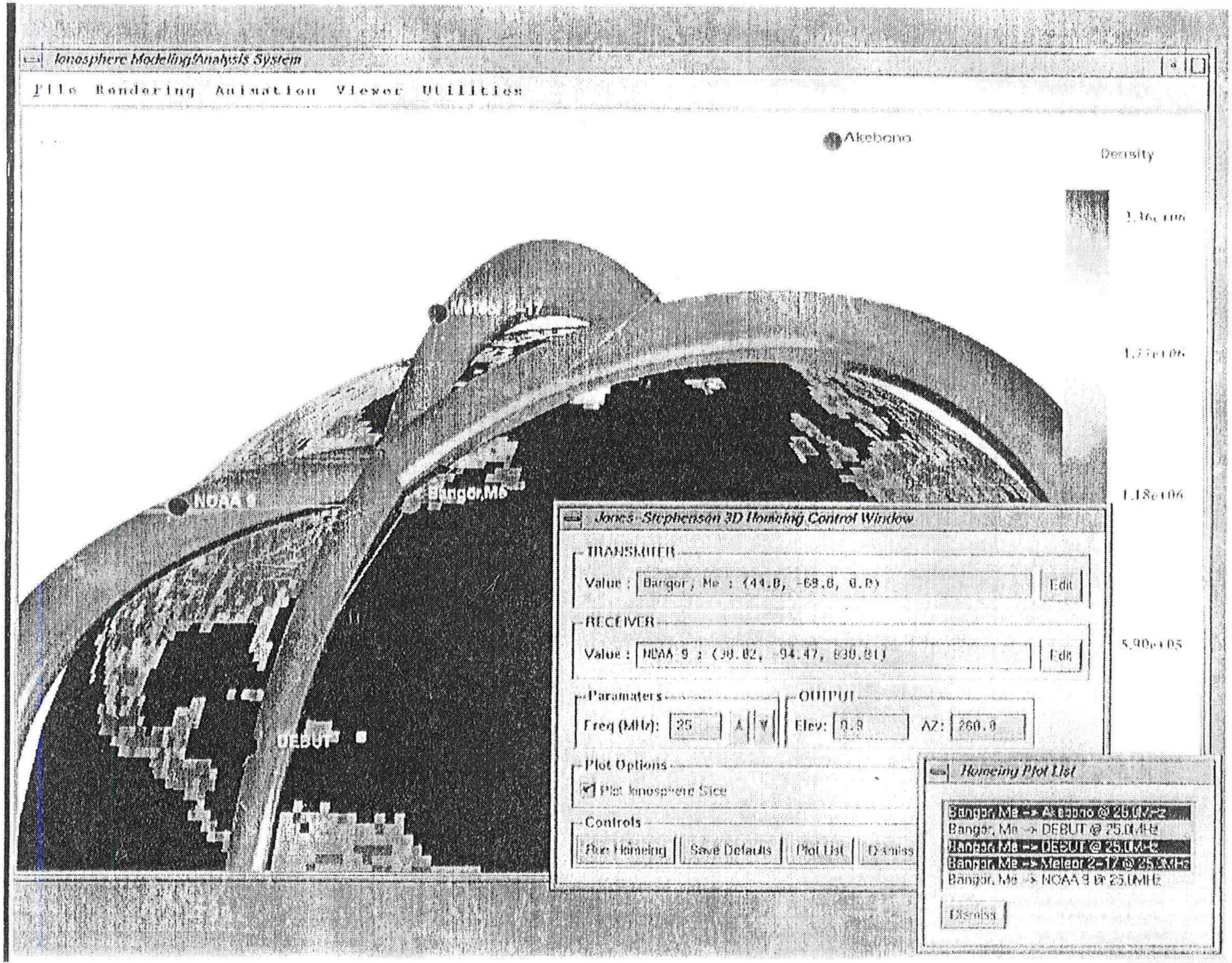
PL-GEOSPACE
PRISM FOR HF COMM



Lat : 26
Lon : -117

PIM Data For : 12/20/91 01:00

Lat : 2.53 Lon : 292.04 Range : 4708.0



Jones-Stephenson 3D Homeing Control Window

TRANSMITTER

Value : Bangor, Me : (44.8, -68.8, 0.0) Edit

RECEIVER

Value : NOAA 9 : (30.82, -94.47, 830.81) Edit

Paramaters

Freq (MHz): 25 ▲ ▼

OUTPUT

Elev: 0.9 AZ: 260.0

Plot Options

☑ Plot Ionosphere Slice

Controls

Run Homeing | Save Defaults | Plot List | Dismiss

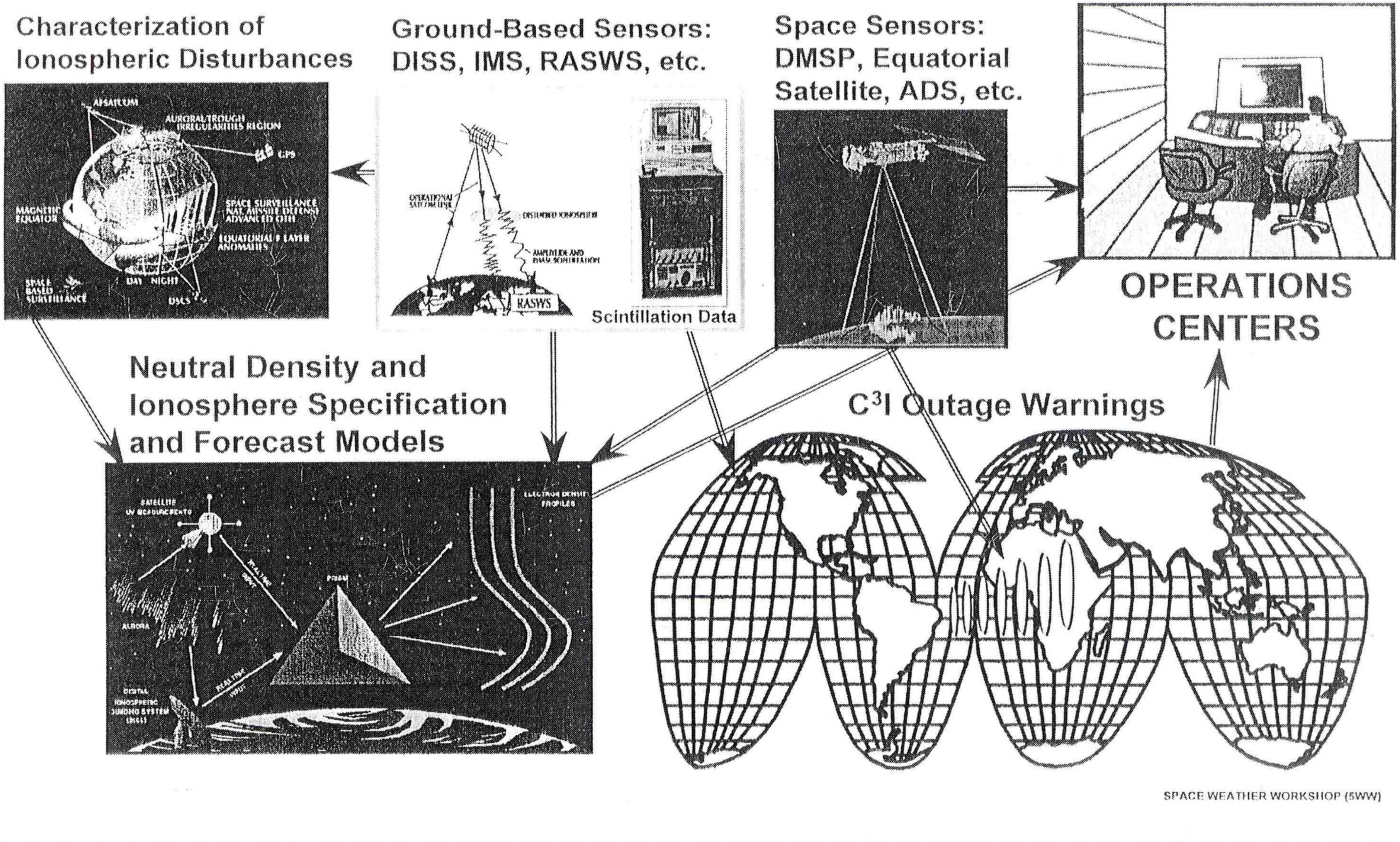
Homeing Plot List

Bangor, Me -> Akebono @ 25.0MHz
Bangor, Me -> DEBUT @ 25.0MHz
Bangor, Me -> DEBUT @ 25.0MHz
Bangor, Me -> Meteor 2-17 @ 25.0MHz
Bangor, Me -> NOAA 9 @ 25.0MHz

Dismiss

VISION

Near Instantaneous Global Monitoring, Specification, and Forecasts of the Battlespace Environment and its Impact on the Warfighter



Characterization of Ionospheric Disturbances

Ground-Based Sensors: DISS, IMS, RASWS, etc.

Space Sensors: DMSP, Equatorial Satellite, ADS, etc.

OPERATIONS CENTERS

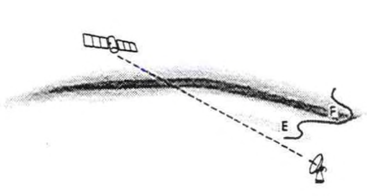
Scintillation Data

Neutral Density and Ionosphere Specification and Forecast Models

C^{3}I Outage Warnings

2.12 Civilian Space-Weather Services

Joseph M. Kunches



Civilian Space Weather Services

Joseph M. Kunches
Space Environment Center
NOAA
Boulder, Colorado

Space Weather Effects on Propagation
of Navigation & Communication Signals
COMSAT
Bethesda, Maryland
October 23, 1997

Abstract

CIVILIAN SPACE-WEATHER SERVICES

Joseph M. Kunches
Space Environment Center, NOAA
Boulder, Colorado

Predictions of disturbances in the near-earth space environment are useful to operators of navigation and communications systems. There are 10 international centers that supply space weather data to the scientific and user communities locally. In the United States, the Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA) is the responsible agency for services related to the space environment SEC's Space Weather Operations (SWO) team works 24 hours a day, having access to more than 1400 data streams that include solar, solar wind, magnetospheric, and ionospheric measurements. The SWO initiates immediate action to issue alerts when predetermined threshold levels are surpassed. SWO also predicts conditions to be seen in the environment three days into the future. As new navigation and communication systems mature over the next few years, it seems likely that information on the environment will become increasingly more important to them. The Federal Aviation Administration's (FAA) GPS Wide Area Augmentation System (WAAS) and the partially-deployed Iridium satellite system, are but two examples of the exciting new applications now being born. Solar cycle 23 is now in its earliest stages, but already has shown an increase in the types of events that may impact these fledgling systems. In anticipation of ever-increasing activity, SEC plans to work with the users to provide them the information they need to operate under the demands of solar maximum.

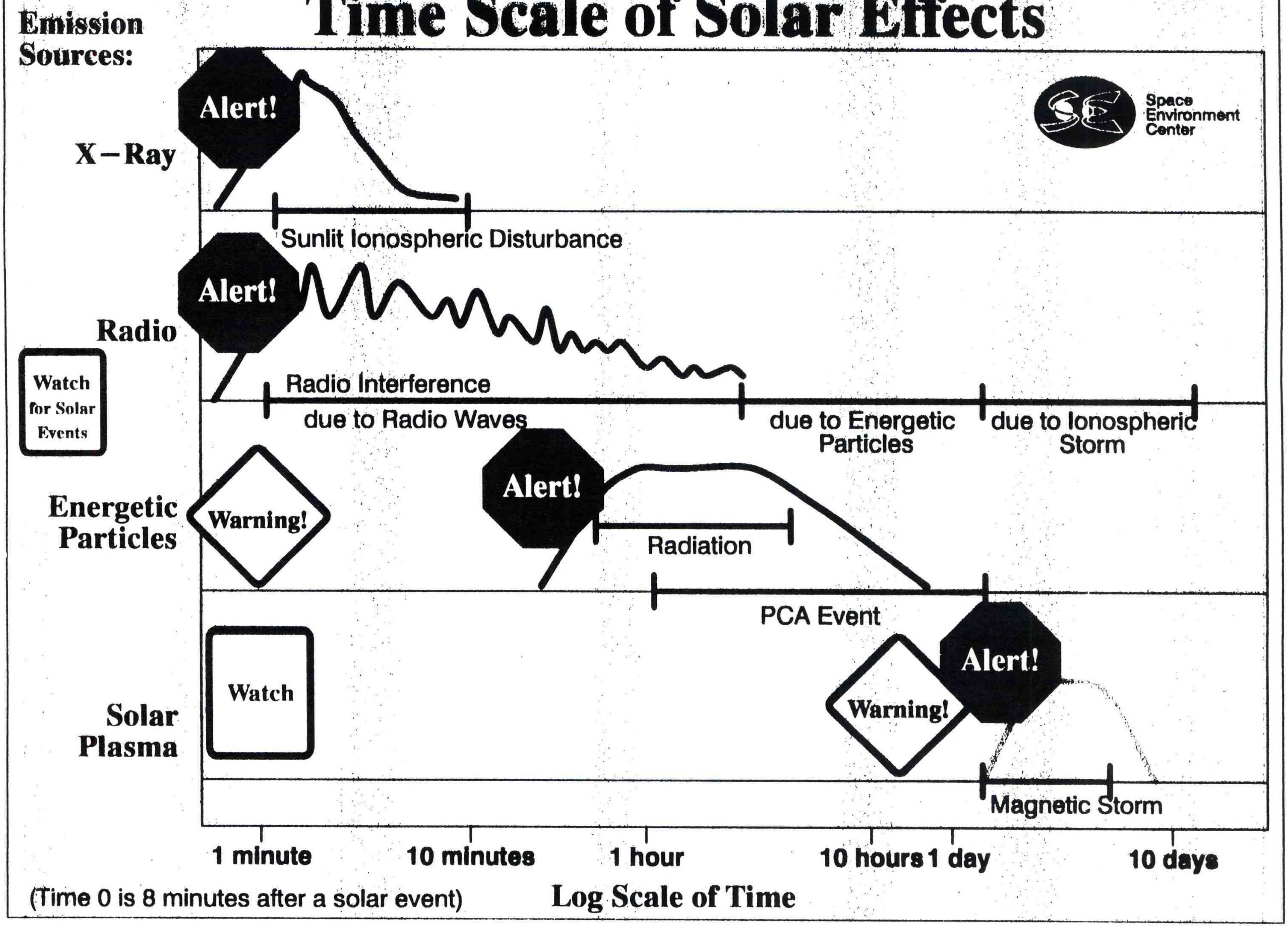
Summary

The Space Environment Center (SEC) will continue to play a central role in providing Space Weather Services to the public sector. It serves as the single point of issuance for official alerts, warnings and watches of significant conditions in the space environment. It provides a continuous flow of quality, real-time space environment data. It routinely issues both text and graphical depictions of space environment conditions, for both the present and for future times. It provides verification data on the quality of the products it issues. It maintains facilities for the implementation of new data and models in its Rapid Prototyping Center (RPC), allowing for the further improvement to its now-existing products and services.

SEC's Role

- Provide alerts, warnings, and watches
- Provide continuous, quality data
- Provide general characterizations and predictions of the space environment
- Provide verification data on forecasts and models
- Provide a testbed (Rapid Prototyping Center) for development and implementation of new data streams and models

Time Scale of Solar Effects

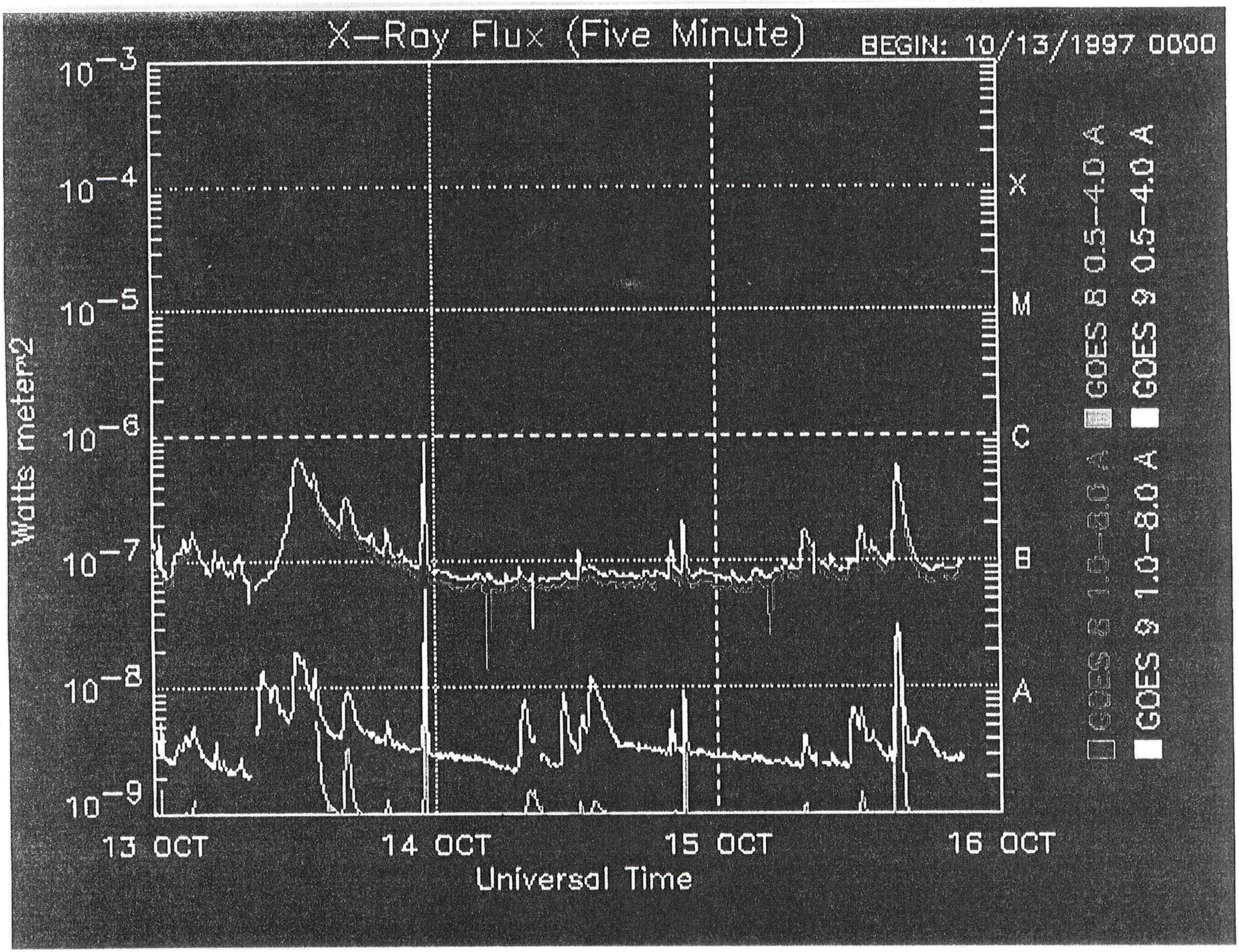


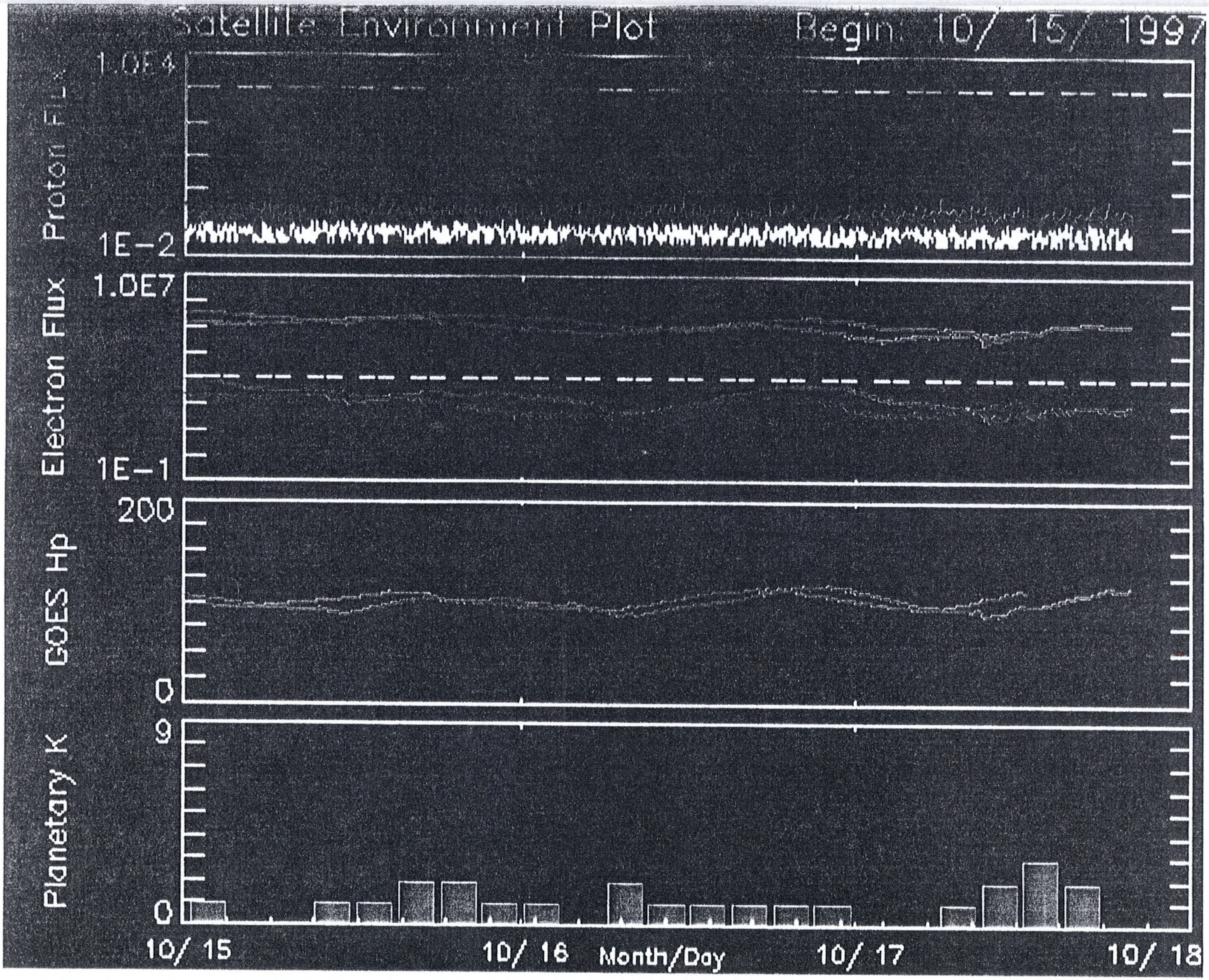
(Time 0 is 8 minutes after a solar event)

Timescale

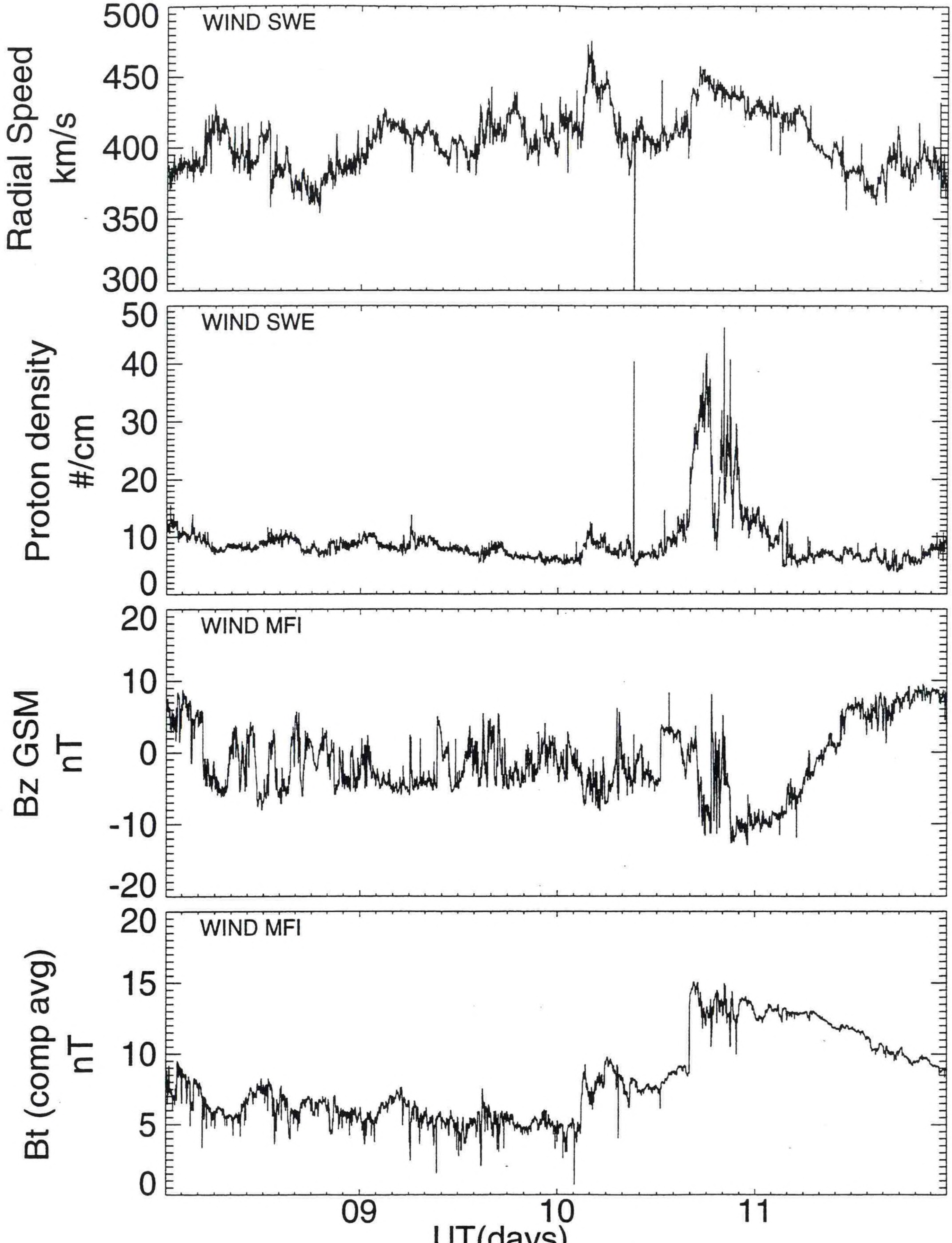
Figure Captions

Figure 1 (Time Scale of Solar Effects)	Solar events and the times scales relevant to issuing alerts warnings and watches.
Figure 2 (X-Ray Flux)	Three days of solar x-ray flux at two wavelengths from GOES.
Figure 3 (Satellite Environment Plot)	GOES Proton and Electron flux, GOES magnetic field, and pseudo Kp for three successive days.
Figure 4 ((DOY 281/1997) Oct....)	Solar wind velocity, density, Bz and Btotal from the WIND spacecraft.
Figure 5 (Statistical Auroral Oval)	Location of the auroral oval is determined statistically from NOAA/TIROS.
Figure 6 (NOAA-12 SEM)	>30 keV electron flux from NOAA/TIROS, plotted relative to climatology.
Figure 7 (Day = 121.8438)	Equatorial cut of the modeled electron flux at 35 keV from Rice University.
Figure 8 (Conditional Quantile Plot)	Verification data of F10.7 forecasts from SEC, plotting predicted (abscissa) vs. observed (ordinate).
Figure 9 (Pseudo Ap Storm/ No-Storm....)	Forecasts of Ap categorized as either storm (Ap>30) or no-storm, for cycle 22 (July 1986-March 1997).
Figure 10 (Growth of SEC Services....)	Time-line showing how the SEC user community has grown over time, identifying specific classes of users.
Figure 11 (The Process of Service....)	A schematic showing the traditional way in which users were served by SEC.
Figure 12 (Custom Interfaces vs....)	Two types of data delivery methods, custom and framework-based.
Figure 13 (SEC's Information....)	Schematic of SEC's three-layered data system, illustrating the framework-based design character.


X–Ray Flux (Five Minute)
BEGIN: 10/13/1997 0000
Watts meter^2
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
X
M
C
B
A
13 OCT
14 OCT
15 OCT
16 OCT
Universal Time
GOES 8 1.0–8.0 A
GOES 8 0.5–4.0 A
GOES 9 1.0–8.0 A
GOES 9 0.5–4.0 A

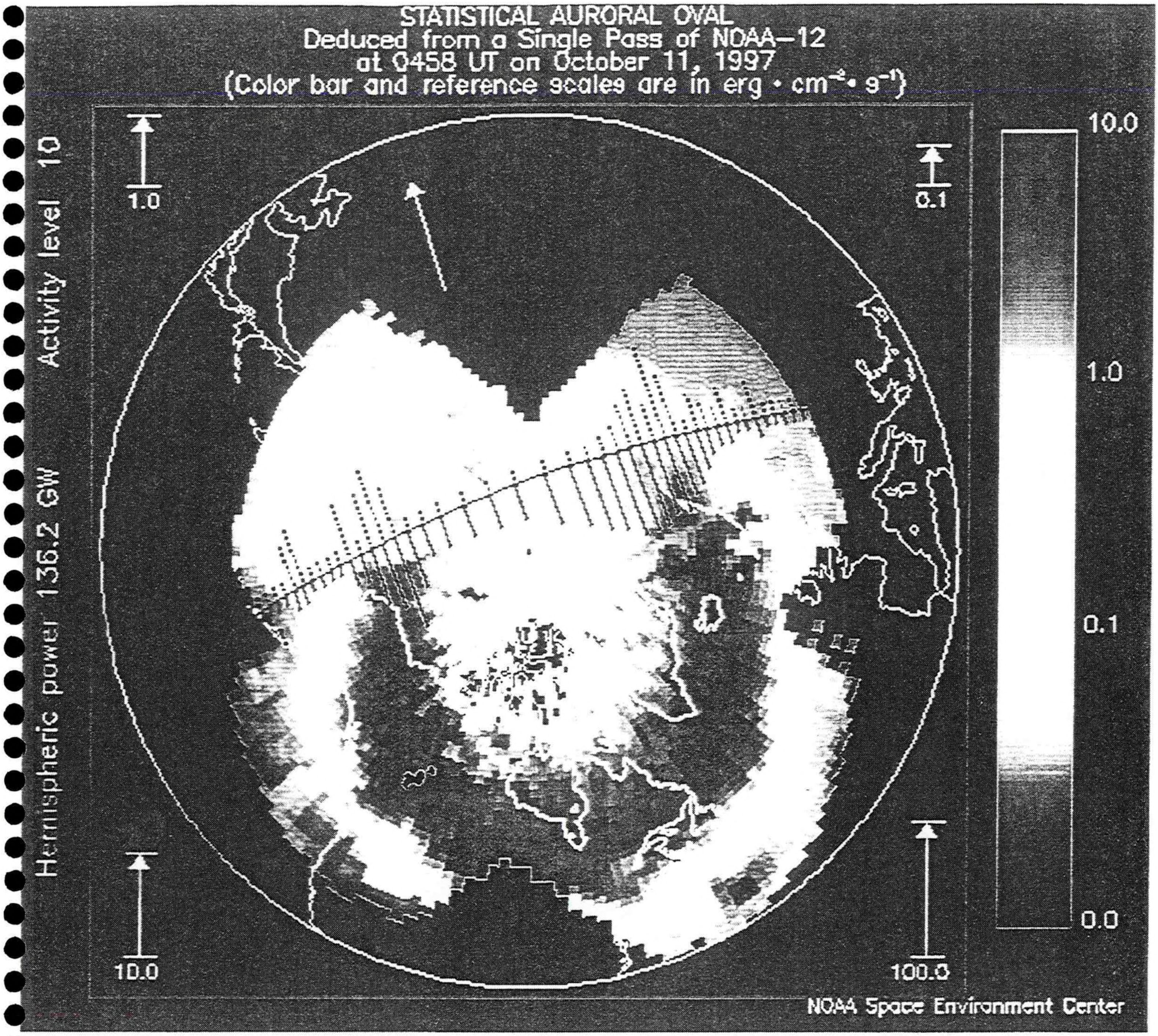

Satellite Environment Plot
Begin: 10/ 15/ 1997
Proton Flux
1.0E4
1E-2
Electron Flux
1.0E7
1E-1
GOES Hp
200
0
Planetary K
9
0
10/ 15
10/ 16
Month/Day
10/ 17
10/ 18

DOY 281/1997 OCT 8 00:00:35 UT

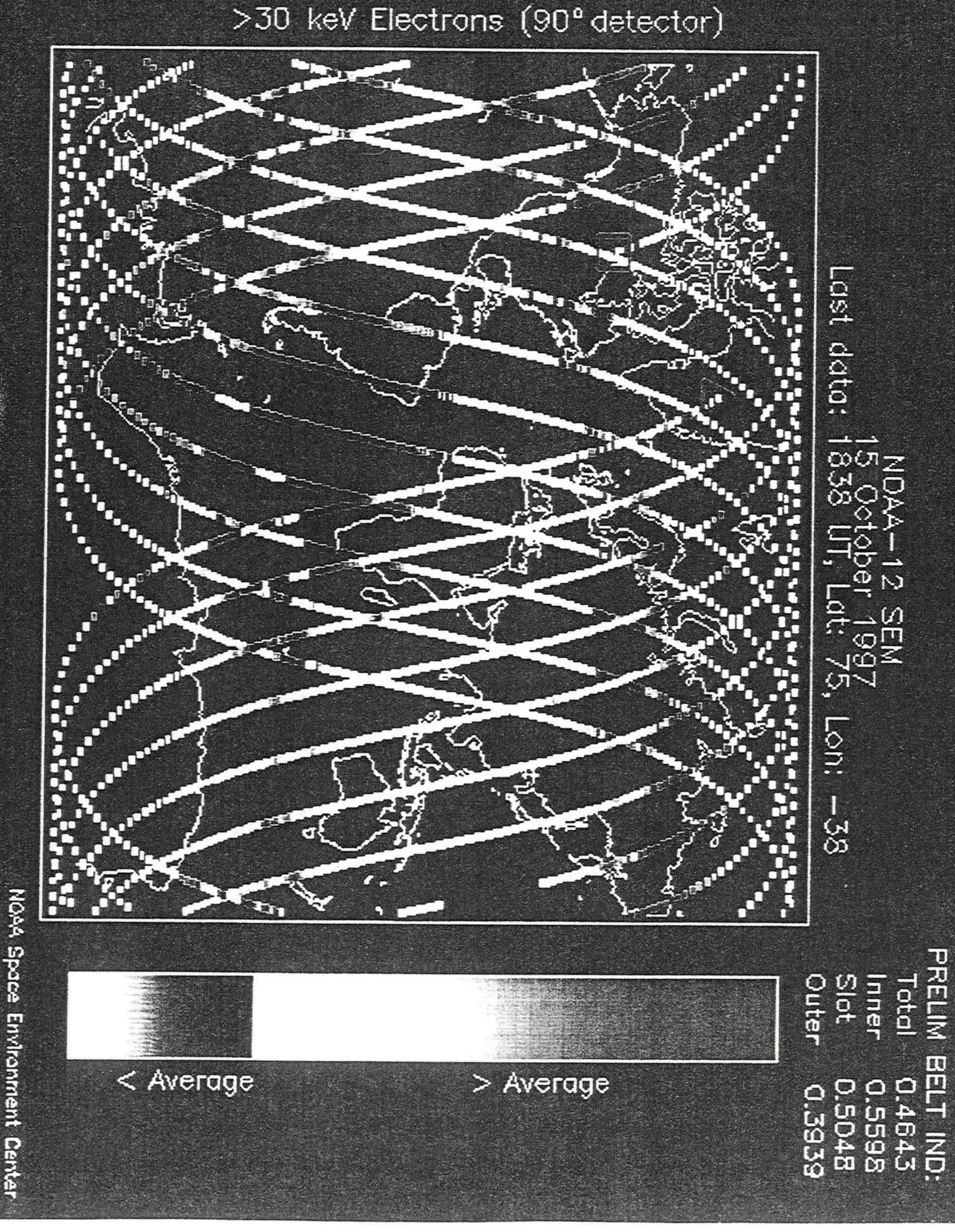


Plot date: Thu Oct 16 14:50:00 1997

298

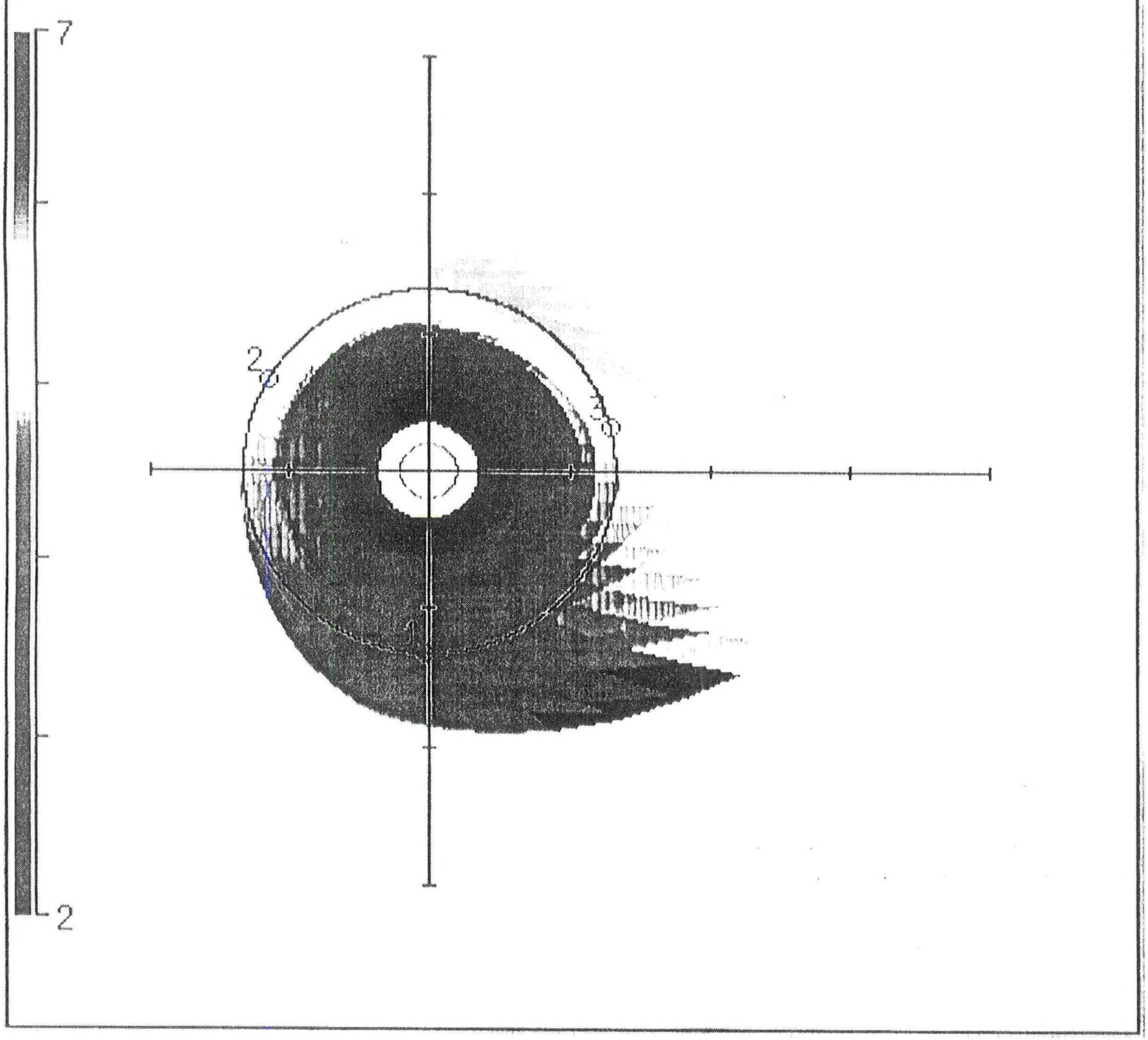


STATISTICAL AURORAL OVAL
Deduced from a Single Pass of NOAA-12
at 0458 UT on October 11, 1997
(Color bar and reference scales are in erg • cm^{-2}• s^{-1})



>30 keV Electrons (90° detector)

Day=121.8438 (20:15), it=10, Prefix=b, K=5/21
Flux, Species:e-, Ek=35.0keV @GEO, Scale:(log10)+3



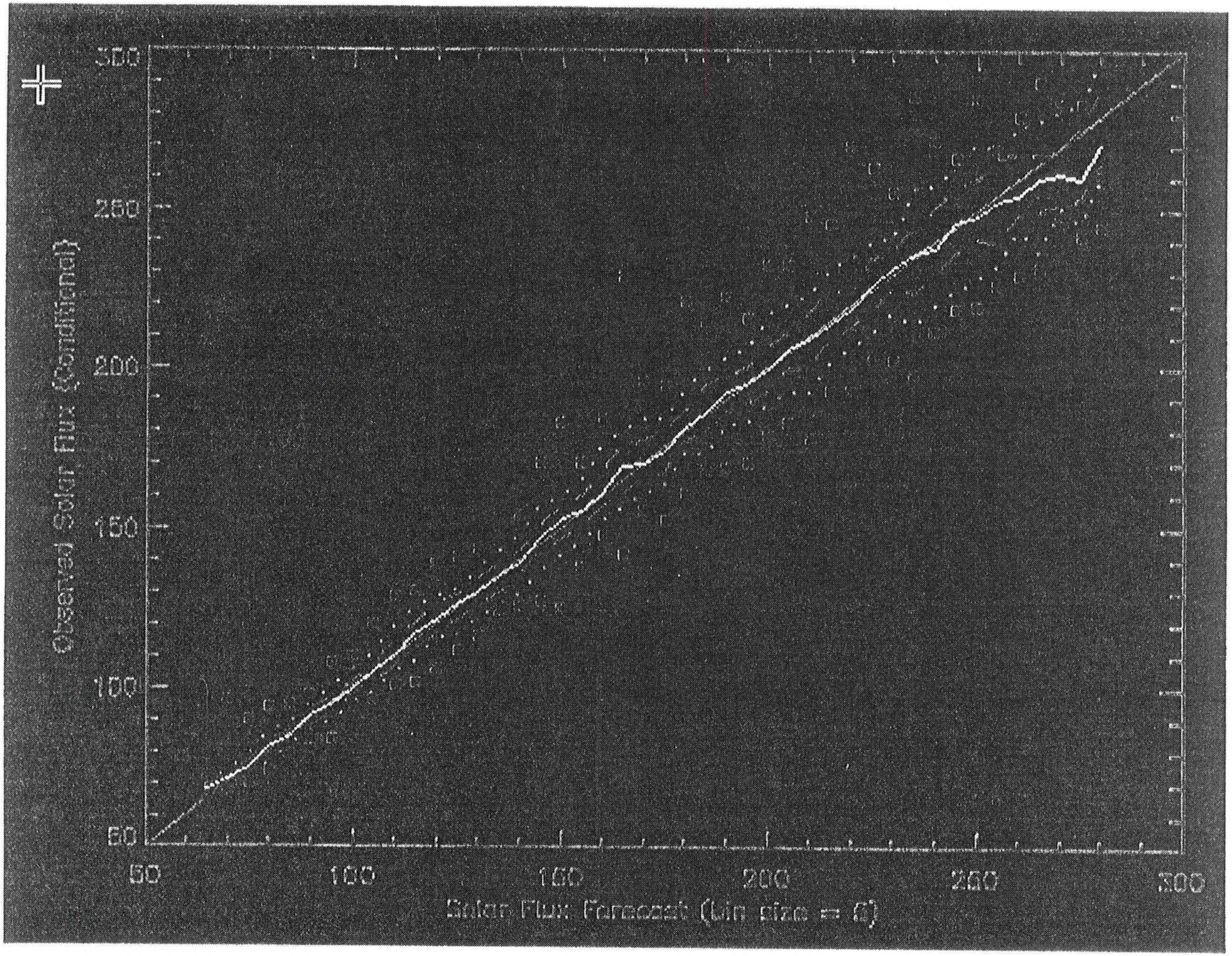


Figure 1. Conditional quantile plot for 10.7 cm Solar Flux forecasts (1989-1996). The following quantiles are plotted: 0.90th (upper dot), 0.75th (upper dash), 0.50th (solid), 0.25th (lower dash), and 0.10th (lower dot). The observed maximum and minimum in each forecast bin are indicated by asterisks. The spread in the quantiles is related to the accuracy of the forecasts and the deviation from the diagonal is related to their bias.

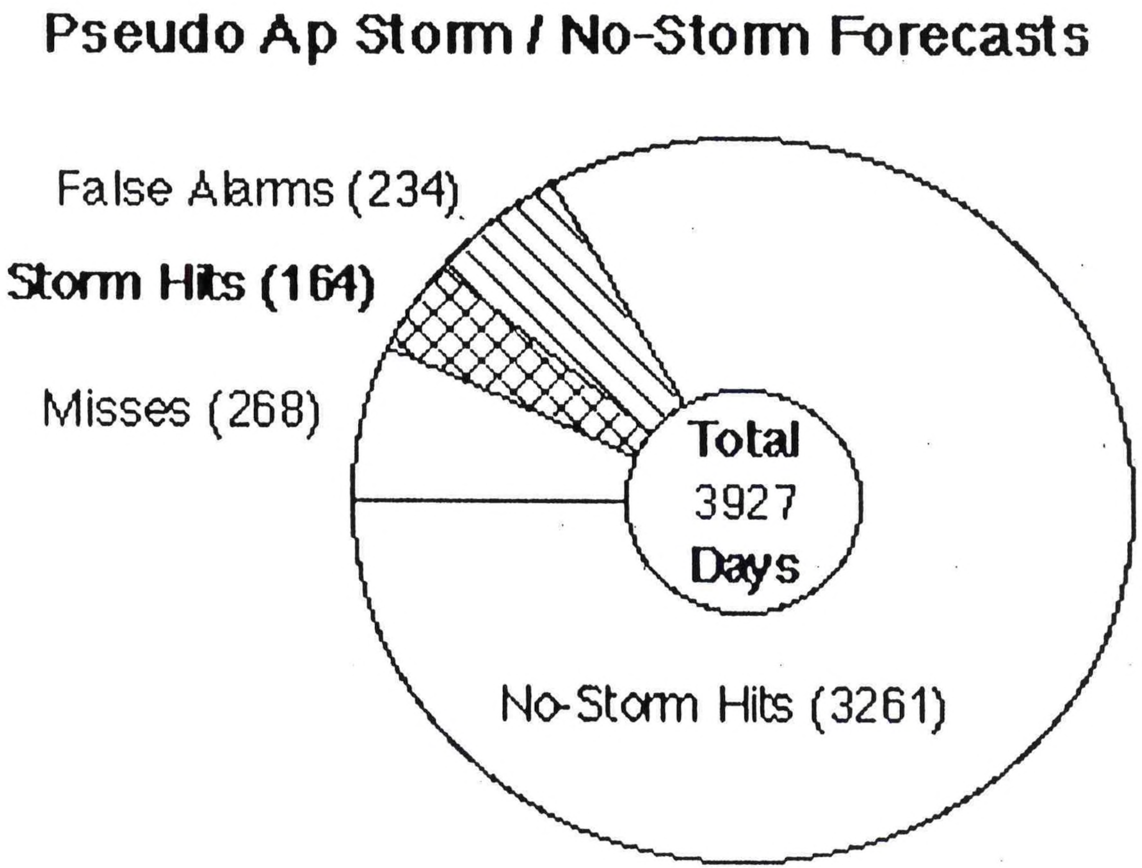
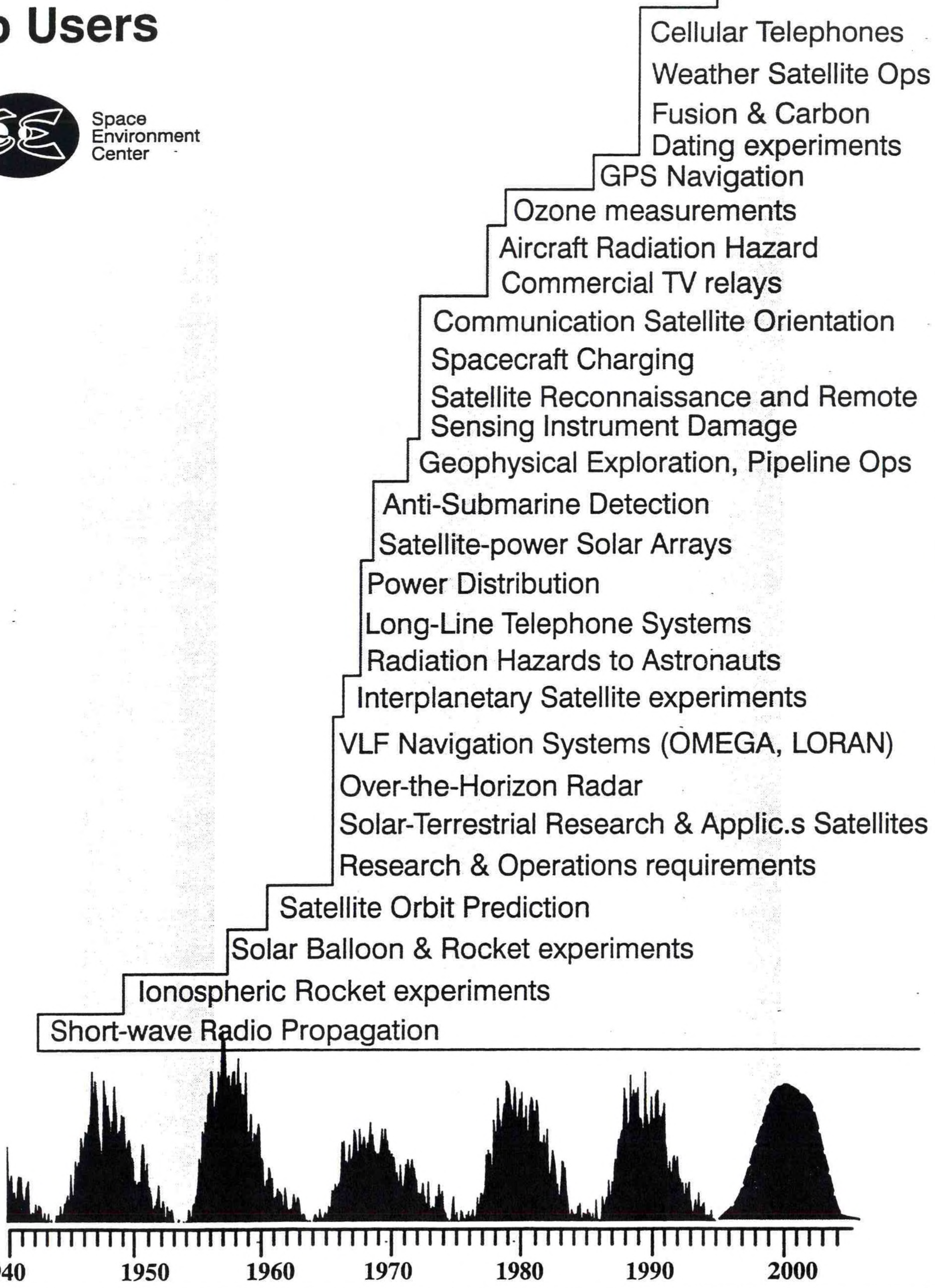


Figure 1. Forecasts of pseudo (estimated) Ap categorized as either storm (Ap>30) or no-storm (Ap<30) forecasts covering Solar Cycle 22 (July 1986-March 1997). Note that storm hits plus false alarms is equal to the number of storm forecasts and that storm hits plus misses is equal to the number of storms observed.

Growth of SEC Services to Users

Space
Environment
Center



Cellular Telephones

Weather Satellite Ops

Fusion & Carbon Dating experiments

GPS Navigation

Ozone measurements

Aircraft Radiation Hazard

Commercial TV relays

Communication Satellite Orientation

Spacecraft Charging

Satellite Reconnaissance and Remote Sensing Instrument Damage

Geophysical Exploration, Pipeline Ops

Anti-Submarine Detection

Satellite-power Solar Arrays

Power Distribution

Long-Line Telephone Systems

Radiation Hazards to Astronauts

Interplanetary Satellite experiments

VLF Navigation Systems (OMEGA, LORAN)

Over-the-Horizon Radar

Solar-Terrestrial Research & Applic.s Satellites

Research & Operations requirements

Satellite Orbit Prediction

Solar Balloon & Rocket experiments

Ionospheric Rocket experiments

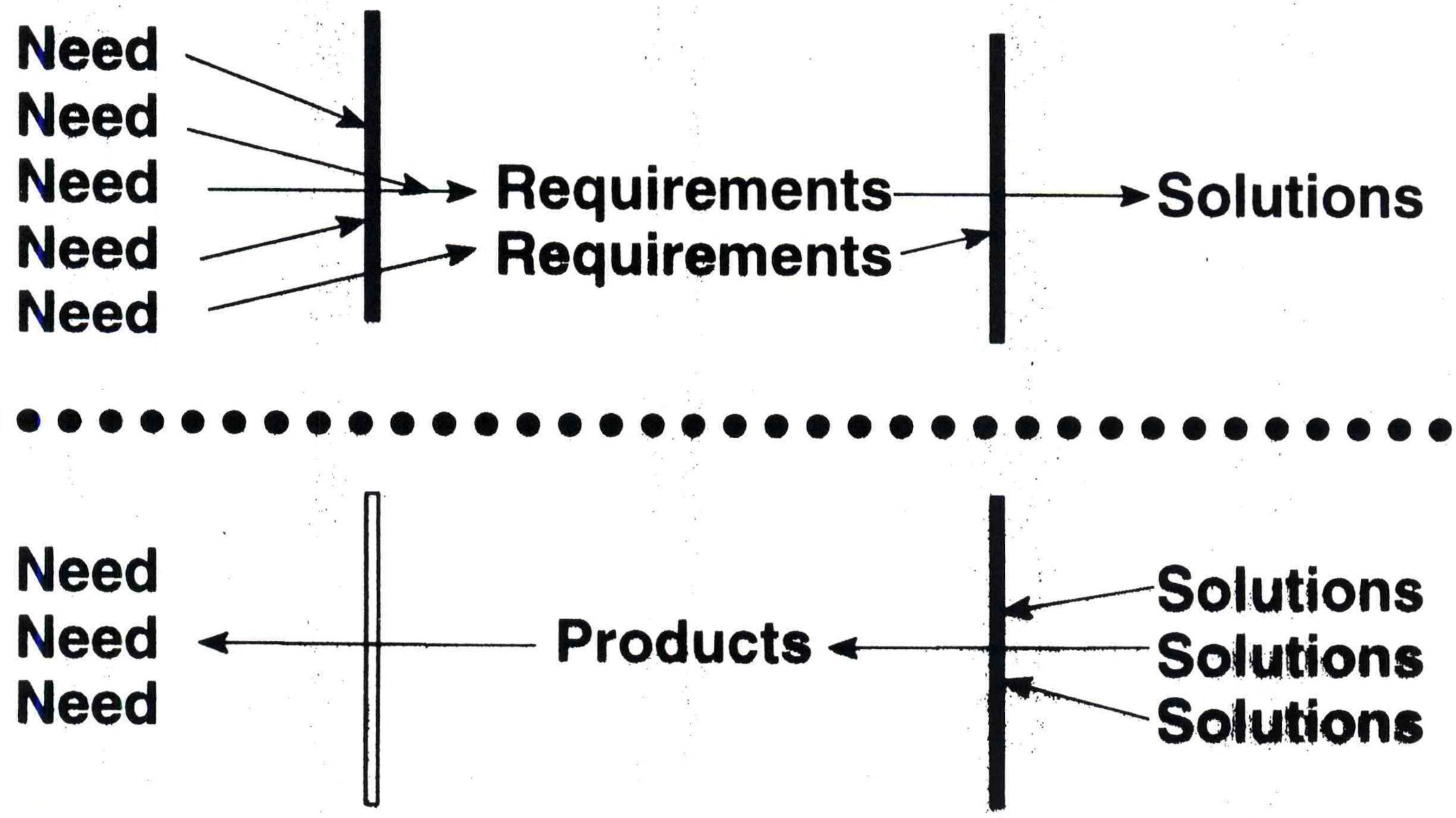
Short-wave Radio Propagation

The Process of Service Development

User

[redacted]

[redacted]



Need
Need
Need
Need
Need

Requirements
Requirements

Solutions

Need
Need
Need

Products

Solutions
Solutions
Solutions

Joe's Vus-L
2/95 BP

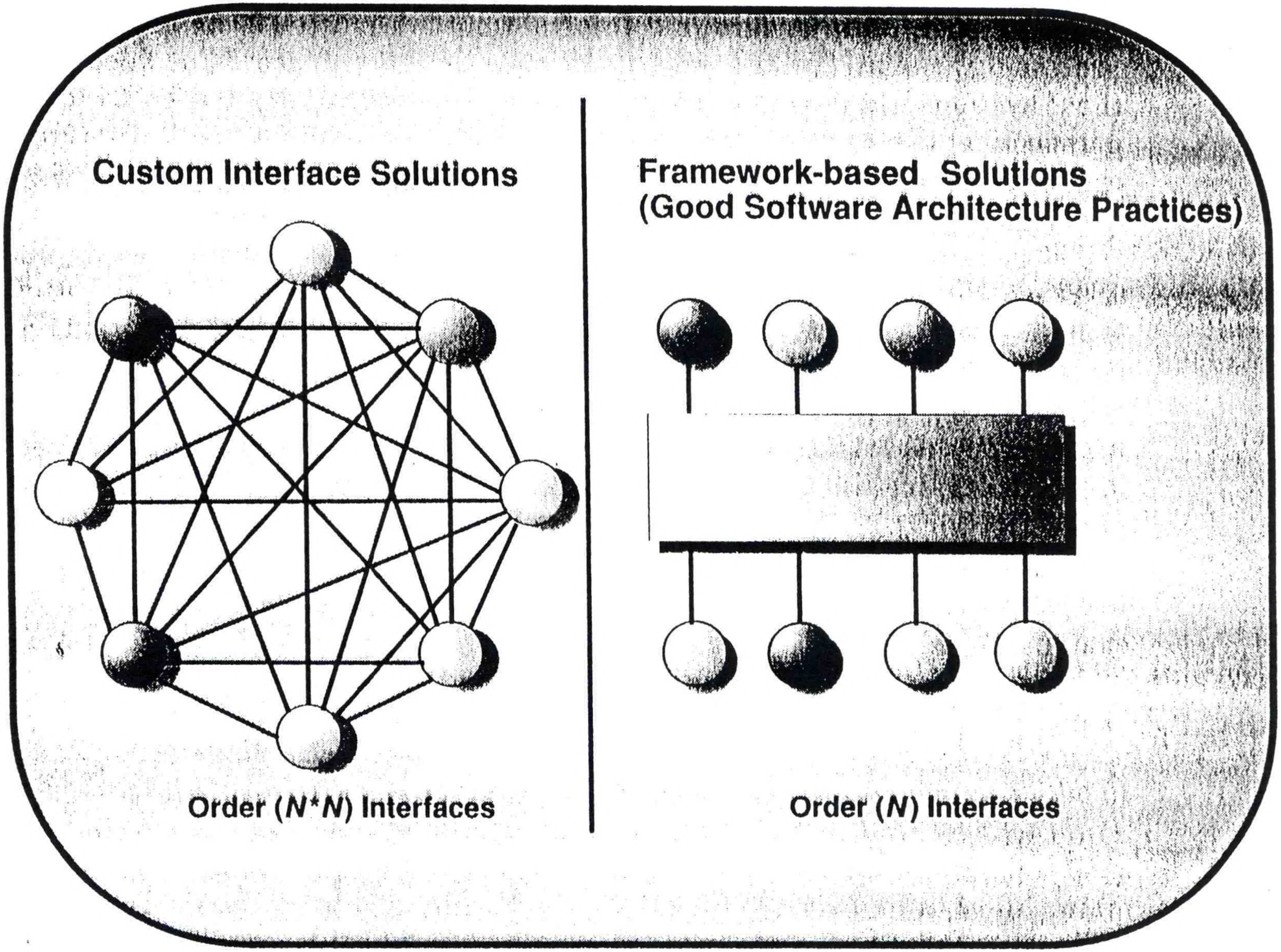
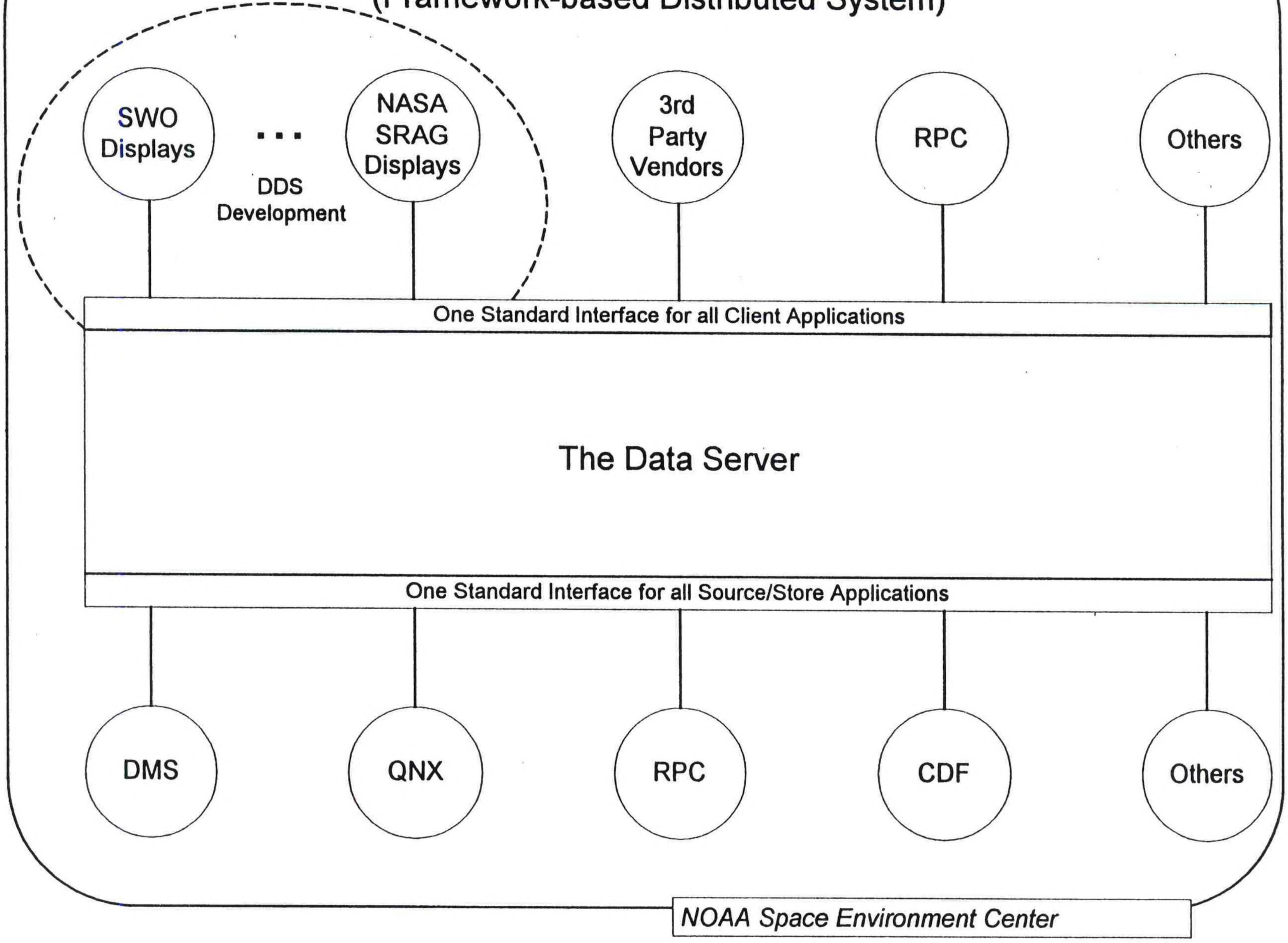


Figure 1.3. Custom interfaces vs. framework based.

SEC's Information Distribution System

(Framework-based Distributed System)



SWO Displays

. . .

DDS Development

NASA SRAG Displays

3rd Party Vendors

RPC

Others

One Standard Interface for all Client Applications

The Data Server

One Standard Interface for all Source/Store Applications

DMS

QNX

RPC

CDF

Others

NOAA Space Environment Center

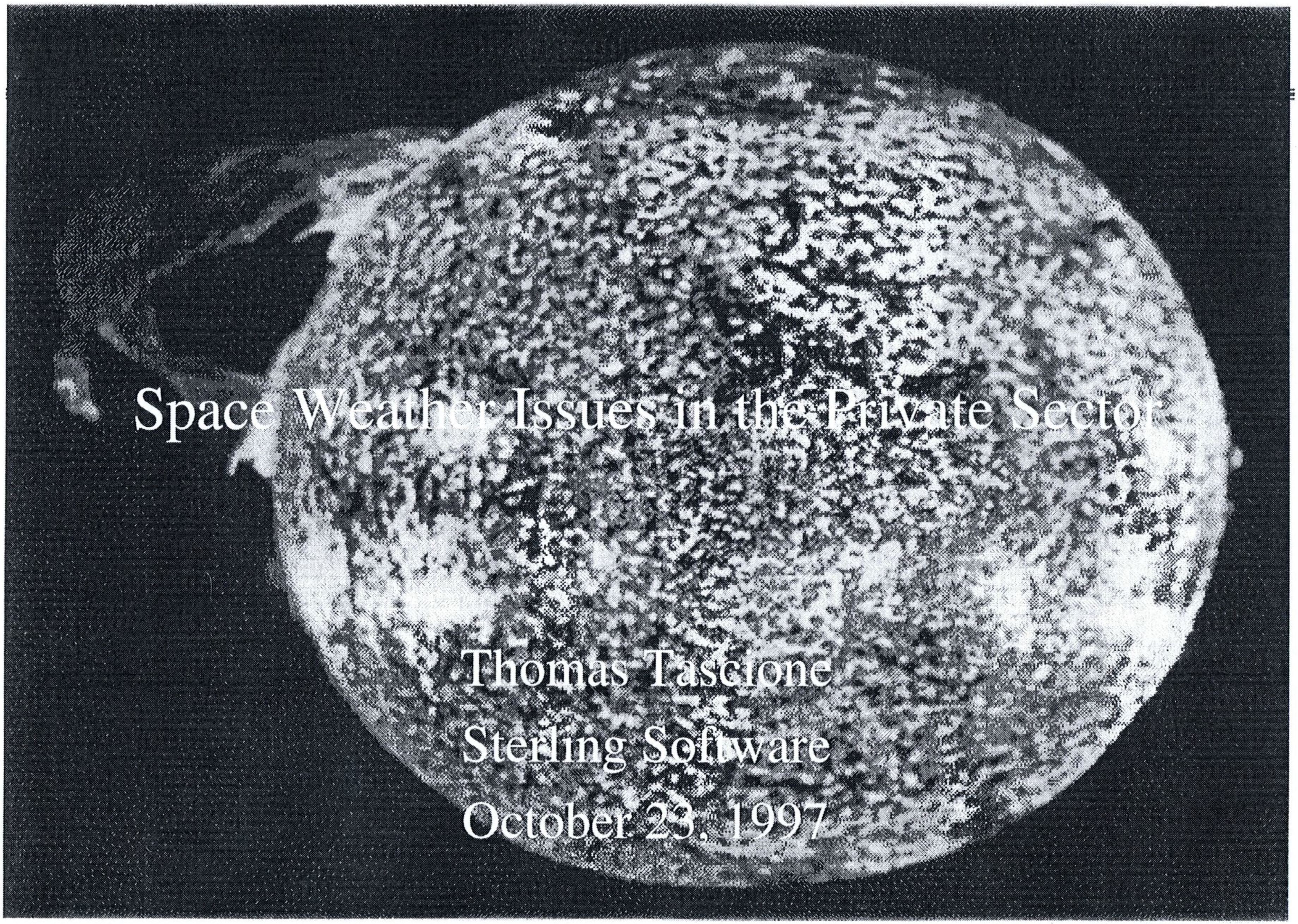
Summary

SEC is an important participant in the mix of providers of space environment services. As such it will:

- Issue official alerts, warnings and watches;
- Provide continuous, quality data;
- Produce general characterizations of the environment, text and graphical;
- Maintain and distribute verification statistics;
- Nurture new data and models in its Rapid Prototyping Center.

2.13 Space-Weather Issues in the Private Sector

Thomas F. Tascione



Space Weather Issues in the Private Sector

Thomas Tascione
Sterling Software
October 23, 1997

Abstract

SPACE-WEATHER ISSUES IN THE PRIVATE SECTOR

Thomas F. Tascione
Sterling Software
Bellevue, NE

The civilian space weather community is divided into two groups: space weather information providers and space weather consumers. This paper will concentrate on the issues affecting the "providers" community. For the purposes of this paper, the consumer community of interest is for-profit companies. However, these issues cannot be discussed in isolation of the consumer community because it is this community which provides the demand, and income, for the civilian space weather providers.

The consumer community has three sectors: system builders, system operators, and system users. In some commercial endeavors, the same company may span more than one sector; in other cases, different companies operate only within the bounds of a given sector. In all cases, a given sector has specific needs for space weather products, which can be quite different from the needs of another sector. Most times, these needs require tailored information unavailable from government providers. The hope is this void will be filled in by civilian space weather providers.

Even if the demand exists for services, the challenges facing any fledgling space weather provider can be daunting, if not overwhelming. First and foremost is the lack of accurate gridded forecast models from the government. This problem is not a deliberate government action, but rather a reflection of the maturity of the science and the result of historically poor levels of funding for government operated space weather facilities. Nevertheless, tailored, system specific forecasts are what the consumer wants and such forecasts require an unprecedented level of sophistication in environmental models. Thus the commercial space weather providers have a choice of either repackaging the qualitative government forecasts into some type of quantitative forecast, or taking the more daring approach of generating their own forecasts which is wrought with legal perils.

Another significant issue for the space weather provider is the often-impenetrable secrecy surrounding some space weather consumer's business practices. Compound this problem with the widely held myth among consumers that their systems are immune to the space environment, and you set the stage for significant uphill challenges facing any civilian provider. This myth can result from one (or more) of the following factors: a very competitive business environment which fosters a 'blind-eye' to environmental sensitivities; unawareness of how the environment can disrupt systems; a belief in engineering invulnerability; or an acceptance of the inevitability of environmental disruptions for which nothing can be done.

This paper will discuss all these issues and provide a roadmap that the author believes can provide the framework for a healthy and vibrant space weather provider community in the near future.

Overview

- Private Sector Constituents
- Private Sector Issues
- Government Partnership

Space Weather Private Sector Constituents

- Service Providers
- Consumers -- three sectors
  - Builders
  - Operators
  - Users
- Each consumer sector has unique space weather service needs

Service providers customize, or tailor, space weather products to meet specific needs of the consumer community

Private Sector Issues

- Legal
- Consumer Operational Business Practices
- Consumer Myths
- Shortfalls
  - Science
  - Observations
  - Funding
- Time

Private Sector Issues: Legal

- Indemnification (liability)
  - No case law
  - Legal precedent
- "Tailor" is the issue
  - Apply government provided information -- liability remains with government
  - Apply only in-house technology -- liability belongs to service provider
  - Fact-of-life: service provider is usually somewhere in-between but must demonstrate "clear" linkage to government information

Keep deviations from government provided information to a minimum

Private Sector Issues: Consumer Operations

- Secrecy about space weather sensitivities
  - Especially important for builders and operators
  - Small market -- high costs/high profits
  - Competitiveness downplays system sensitivities
- End users interested in private sector services
  - Depends on cooperation from operators/builder
  - Level of interest is directly proportional to cost/savings

Private Sector Issues: Consumer Myth

- Myth: “System immune to environmental hazards”
- Fostered by four factors:
  - Competitive market place
  - Engineering invulnerability
  - There is no such thing as “weather” in space
  - Can’t do anything about it anyway
- Demonstrate capability?

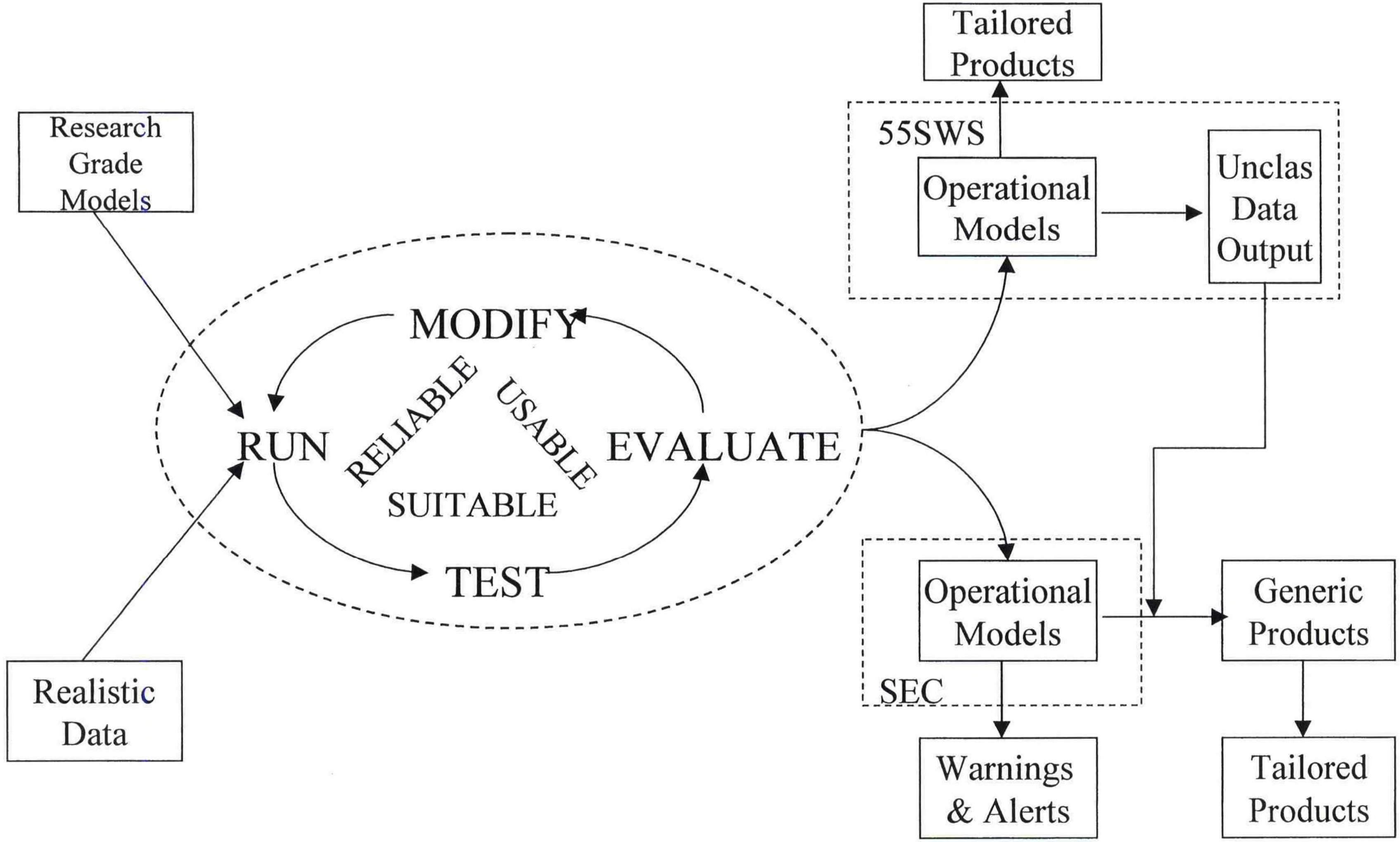
Private Sector Issues: Shortfalls

- Science
  - Limited numerical capability
- Observations
  - Too few
- Funding
  - Too little
  - Funding drives the other two

Private Sector Issues: Science

- Need “high-resolution” accurate, gridded analysis and forecast fields
  - Basis for tailored products
  - Timely and reliable
- Transition to operations takes too long
  - Requires model and input data
  - Rapid Prototyping Center

Private Sector Issues: RPC



Research Grade Models

Realistic Data

RUN

MODIFY

TEST

EVALUATE

RELIABLE

USABLE

SUITABLE

55SWS

Operational Models

Unclas Data Output

Tailored Products

SEC

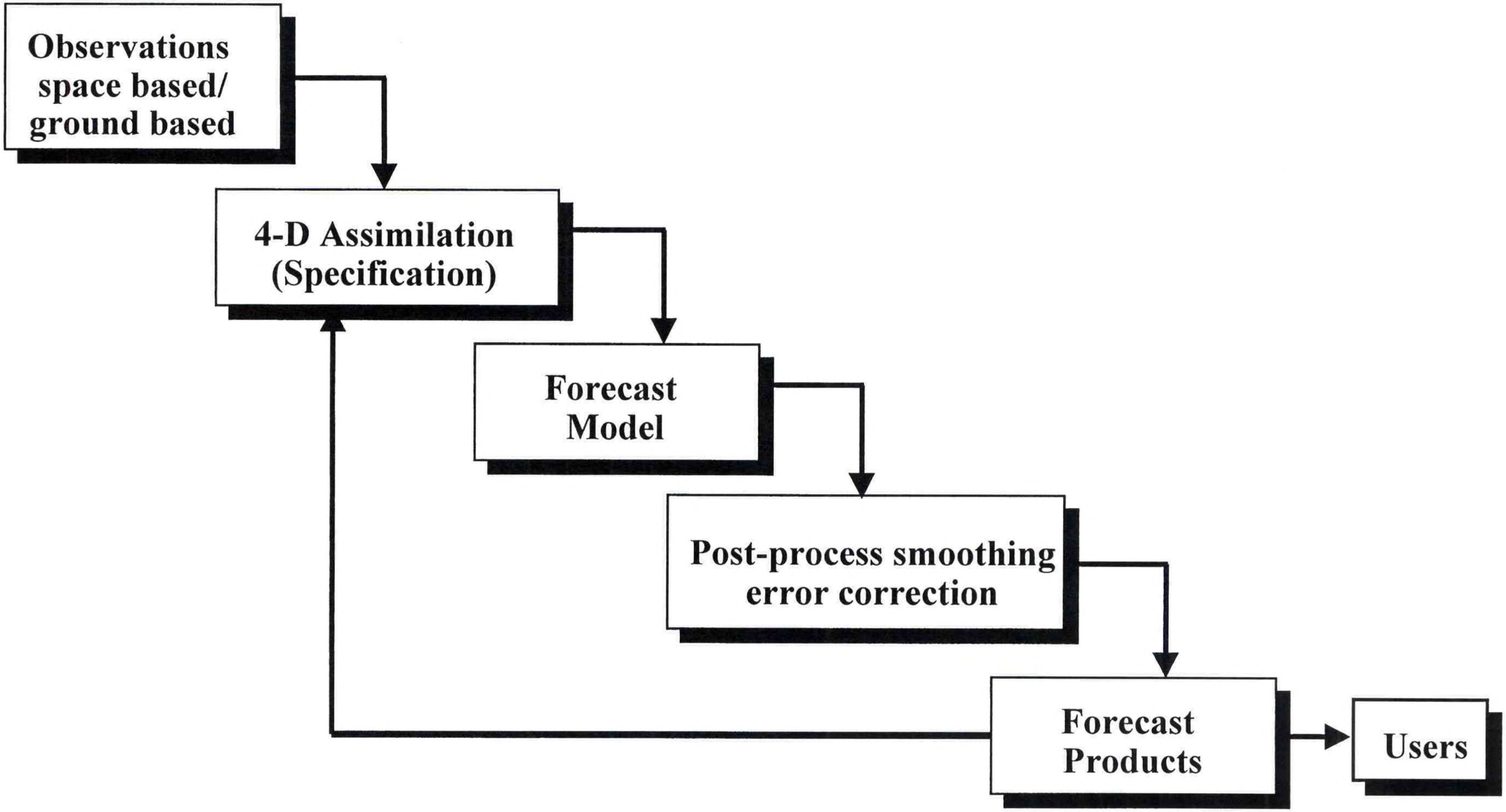
Operational Models

Warnings & Alerts

Generic Products

Tailored Products

Private Sector Issues: Forecast Process



Observations space based/ ground based

4-D Assimilation (Specification)

Forecast Model

Post-process smoothing error correction

Forecast Products

Users

Private Sector Issues: RPC

- Testing
  - Focus University/Government Lab R&D
  - Funding
- Exit criteria - role of private sector?
  - Private sector needs
  - Schedule (urgency)

Private Sector Issues: Observations

- Space-based
  - Limited spatial distribution
  - Timeliness
- Ground-based networks
  - Geographic limitations
  - Limited measurement types
- Funding
  - Networks expensive to maintain
  - Upgrades postponed
  - Interagency and International cooperation a must

Private Sector Issues: Funding

- Space Weather Agencies (especially operations) historically underfunded
- Interagency cooperation has helped flatten rate of descent (but still falling)
- Space weather providers are a “silent” constituency
- Congress responds to vocal communities
  - Must be unified and “reasonable”

Private Sector Issues: Time

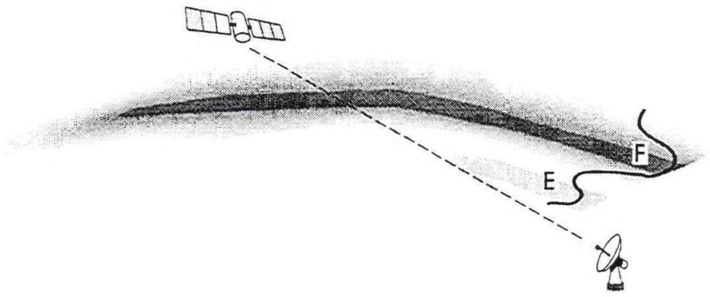
- Window for establishing services limited by solar cycle
- Start-up costs have to be capitalized over shorter period
- Consumers are finding work arounds
  - Once integrated into operations hard to change
  - Secrecy harder to overcome

Private Sector Issues: Government Partnership

- Private sector can’t go it alone
  - Worldwide data collection infrastructure
  - Large computing base
  - R&D pipeline
- Commercial weather services as model
  - Close partnership with NWS
  - Issues worked as a community
  - Set course for future development
    - Weighed against needs of general public
  - Vocal constituency

Conclusion

- Need for private sector services
- Issues: legal, business practices, observations, science, funding, and time
- Overcoming issues will take:
  - Private sector cooperation/commitment
  - Partnership with government



3 Summaries of Contributed Posters

Space Weather Impacts on DoD Communications

J.C. Baker, R. E. Turner, K. H. Wong
ANSER, Suite 800, 1215 Jefferson Davis Hwy, Arlington, Virginia 22202

Abstract: The authors place space weather impacts on DoD communications in perspective.

DoD has a wide range of communications missions to support military effectiveness. These missions range from hard core, high priority tasks to lower priority general purpose functions.

Hard core missions include tasks with very high timeliness requirements, such as control of nuclear forces, tactical warning and attack assessment, and selected intelligence information. Core missions include support with modest timeliness requirements such as support to theater and contingency operations, force projection, and intelligence operations. General purpose missions have the lowest timeliness requirements, such as logistics and administrative operations.

Space Weather interference is one threat of many facing DoD communications

The susceptibility of some communications channels to various types of space weather degradation (including fade, disruption, and scintillation) is well known. However, from a systems perspective space-weather-induced disruption must be compared with other sources of degradation and interference, including terrestrial weather, electronic jamming, and interception and exploitation.

DoD relies on multiple, redundant systems (space and terrestrial) to meet its communications requirements and to counter these varied threats.

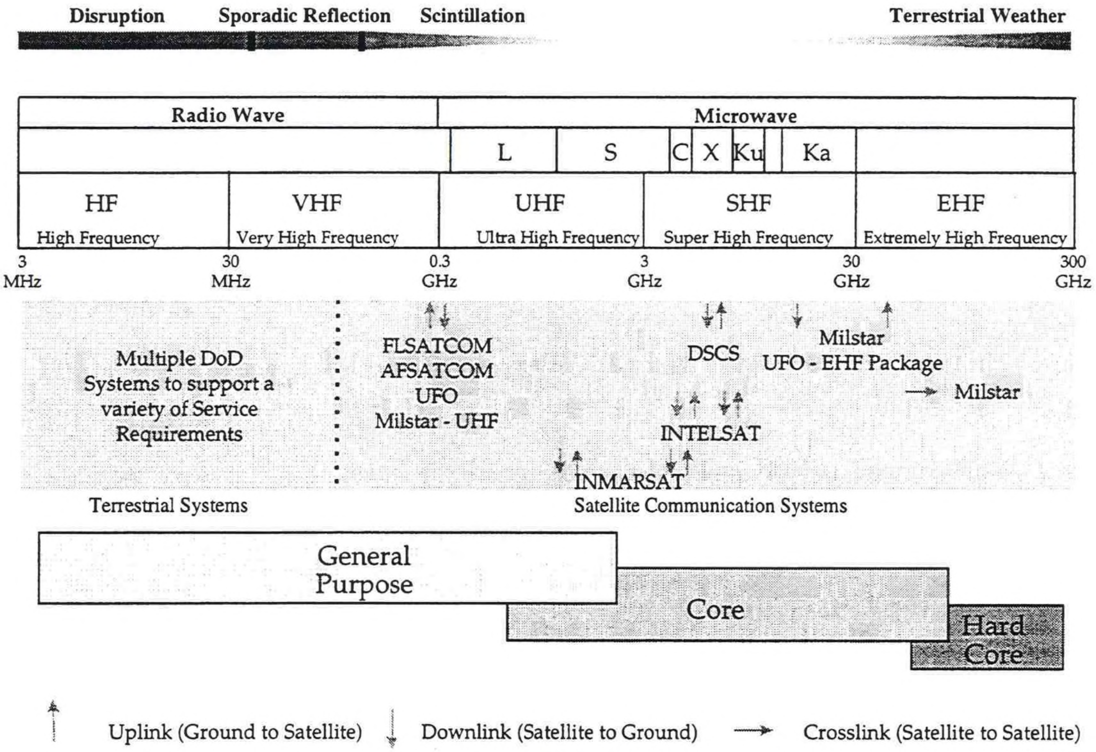
In general, higher priority messages travel on more robust channels. The highest priority channels are designed to be secure against interception, jamming, and nuclear effects, and as a side benefit are also immune to space weather interference. Hence, prediction of space weather could make improvements on optimization of lower priority channels. These lower priority channels are subject to diverse sources of interference. As a result, military operations are designed to accommodate periodic loss of these communications channels.

What is the military benefit to moving from a position of "Cope and Avoid" to a position of "Anticipate and Exploit" space weather effects?

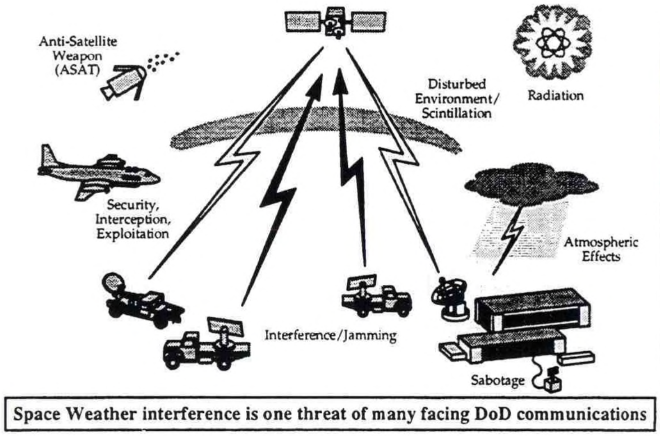
The "bombs-on-target" community is generally skeptical of claims that space weather has a significant impact on military operations. They argue that the U.S. has successfully constructed communications systems that can either operate through disturbances or can wait until conditions have cleared. The challenge for the space weather community is to move away from anecdotal examples and instead to identify ways to measure the impact of space weather interference.

There is a need for quantitative measures of merit to judge the marginal impact of space weather on military effectiveness.

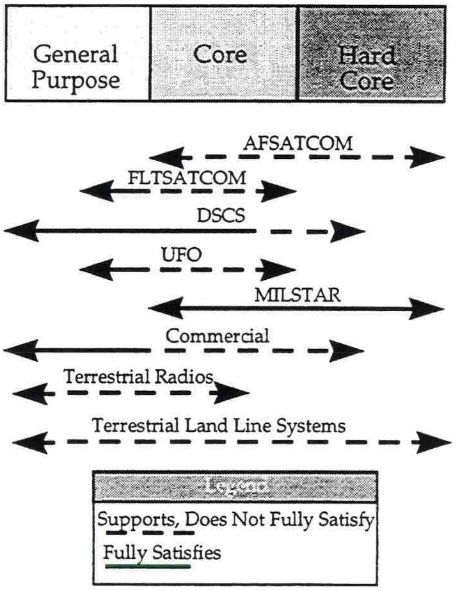
Unsubstantiated claims make it difficult, if not impossible, to prepare a risk/benefit assessment of costs associated with proposed improvements to space weather monitoring and forecasting. The operational community must be involved in identifying these impacts.



DoD Communication Frequencies



DoD Communication Challenges



DoD Communication Systems

DYNACAST™: PERFORMANCE ASSESSMENT FOR GLOBAL COMMUNICATION SYSTEMS

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ABSTRACT

Dynacast™ is an advanced resource management system, designed to provide real time radiowave propagation information for use by adaptive radiowave systems. The system concept is applicable in a wide range of applications, and its advantage over alternative approaches is embodied in features which are currently employed in the Chirpsounder® line of equipment, along with some unique mapping procedures, propagation algorithms, and user interfaces. Acceptance of the concept for frequency management of adaptive HF networks is growing, and several important systems are now engaged in the incorporation of the Dynacast methodology.

Conventional methods for predicting the performance of C^3I systems rely upon the information that may be extracted from historical data, and this information typically takes the form of a climatological or median representation of the propagation channel; and the system performance results are based upon scenarios which may be artificial and static. Such methods are quite useful in system planning, since they allow the system architect to develop a top level system design which can be in a position to cope with a wide range of system impairments, including those which derive from propagation effects. In actual operations, it is necessary to involve a form of real-time channel evaluation to handle the propagation effects for C3I systems. This is especially true in the case of communication networks and individual links. Dynacast™ is a technology, currently developed as a tool for management of resources associated with ionospherically-dependent systems. The first application has been at HF, thought to be the band most vulnerable to , and dependent upon, the propagation channel. This paper will outline the distinct advantages which real-time assessment plays in handling the channel disturbances which impact HF communications and which present significant challenges to the architects of HF systems and networks. The Dynacast approach has been realized in the context of HF through the generation of real-time maps of the ionosphere and relevant associated propagation parameters. The system which has been used for the development of the real time data base is an FMCW swept-frequency sounder

[Note: Chirpsounder® and Chirpcomm® are registered trademarks of TCI/BR Communications, and a patent application for Dynacast™ has been filed with the USPTO (April 1, 1997)].

DYNACAST™

Why Dynacast?

Like the weather, the ionosphere is notoriously fickle.

As with communications systems influenced by atmospheric weather, an ionospherically dependent system must account for various regimes of propagation impairment. To achieve specified high performance, adaptivity is the key. Dynacast provides the information you need to understand the dynamic ionospheric personality. It exploits proven modeling technologies to improve upon climatogical predictions, even those incorporating current solar flux information.

How it works

The Dynacast engine consists of a real-time sensor system, the Chirpsounder®, and application-specific software algorithms. Each Chirpsounder receiver can recover oblique-incidence ionograms from many transmitters, which vastly improves spatial sampling and makes Dynacast much more precise than systems relying exclusively on vertical incidence sounding. For unsampled points, propagation nowcasts are extrapolated by employing proprietary spatial and temporal algorithms that improve upon models such as VOACAP. Exploiting an FMCW Chirp waveform, which does not interfere with other users, means that Dynacast sounding is unobtrusive.

Not Just A Theory

Dynacast accuracy is supported by several years of precise observations.

- The Northern and Midlatitude Experiments, original research conducted by TCI from 1994 - 1996, confirm the efficacy of dynamic resource management principles in ionospheric support for HF communication.
- ITU-R Initiatives affirm Chirpsounding as a useful method for out-of-band frequency management for adaptive HF links and networks.
- The ITU-R has recently approved Rec. F. 1337 which finds..."the FMCW chirp sounding method is preferred to other methods..."
- Technical reports and scientific articles published by more than 20 organizations attest to Dynacast efficiency in spectrum management. These include the ITU, ICAO, FAA, US Department of Defense, AGU, IEEE, RTCA, AEEC, and URSI.

Dynacast HF Communication Applications

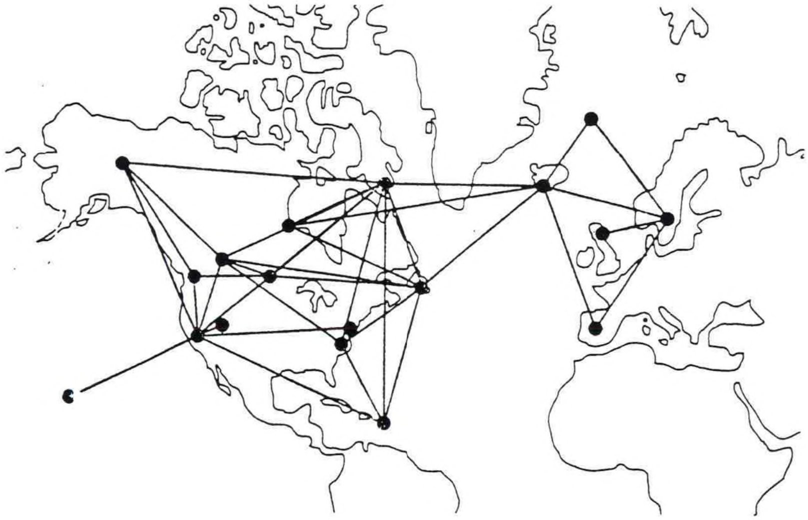
Dynacast provides the basis for:

- Improved ALE operation
- Enhanced operation of adaptive HF systems
- Optimization of frequency reuse
- Efficient dynamic resource management

Other Dynacast Applications

Dynacast also offers enhanced:

- Ionospheric mapping
- Power management for HF broadcasting
- Target registration for OTH radar
- Direction finding accuracy



Northern and mid-latitude experiments were conducted by TCI for two years to evaluate the ability of the ionosphere to support a network of HF communication links in the North Atlantic and Pacific routes.

To explore what Dynacast can do for you, we invite you to contact TCI/BR.

Ionospheric Predictions for Communication and Satellite Navigation using IRI and GPS data

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The International Reference Ionosphere (IRI) is the de facto international standard model for the specification of ionospheric electron and ion densities and temperatures. It was developed and is being improved by a team of experts under the joint sponsorship of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). By charter IRI is an empirical model being based on all available ground and space data sources. The IRI model has been used for a wide range of applications including many in telecommunications and satellite navigation (e.g. Bilitza et al. 1988). Recent progress in improving the IRI model and information about IRI application can be found in several issues of Advances in Space Research: Vol. 15, No. 2, 1995; Vol. 16, No. 1, 1995; Vol. 18, No. 6, 1996. These issues include selected papers presented at the 1993, 1994, and 1995 IRI Workshops, respectively. Papers from the 1996 IRI Workshop will be published in an upcoming issue of Advances in Space Research. Several teams are involved in IRI improvement efforts. Table 1 lists the most important ongoing IRI activities.

TABLE 1. IRI Projects

	Electron Density	**Ion Composition**	**Electron/Ion Temperatures**
Upper Ionosphere	FUTURE: New Topside Model -more than double BENT data dase - more segements than BENT - dynamical segment boundaries	FUTURE: O^+ /light ion transition height	FUTURE: T_e at 600km from HINOTORI data
Middle Ionosphere	NEXT VERSION: - B_0 Table with good low latitude and high solar activity coverage - New B_1 Table - Include F1 occurence probability	NEXT VERSION: Danilov & Smirnova (1995) FUTURE: O^+/molecular ions transition height	
Lower Ionosphere	NEXT VERSION: New Options: - Friedrich & Torkar (1992, 1995) dependence on neutral density - Danilov et al. (1995) no solar activity variation; includes Winter Anomaly and Stratospheric Warmings	NEXT VERSION: Danilov & Smirnova (1995) includes Cluster ions FUTURE: - moleciular/cluster ion transition height - cluster/molecular ion ratio (f^+) - negative ions/electron ratio (\ )	$T_e = T_i = T_n$

Additions: Plasmasphere, Ion Drift, Spread-F

Like other data-based models (e.g. CIRA, IGRF), IRI provides parameter values that are averages over a certain time period. In the case of IRI these are monthly averages for magnetically quiet conditions. IRI therefore can not be expected to represent the actual day-to-day variations observed in the ionosphere, which are important for many space weather related applications. To include such variations, the IRI profiles need to be updated with measured parameters. IRI has always allowed users to update the electron density profile with measured values of the F peak density (or critical frequency) and/or F peak height (or the propagation factor M3000F2) if such measurements are available for the specified time and location. Another updating option concerns the electron temperatures where IRI temperatures can be updated with measured electron densities based on the strong anti-correlation between electron density and temperature. All of these updating procedures require the availability of simultaneous measurements at the location of interest. If measurements are available from one or several stations close bye the user has to apply a weighting procedure based on the effective correlation distances.

Ionospheric data obtained by the more than two dozen GPS satellites have become a interesting data source for the updating of ionospheric models, because of their easy accessibility and their steadily expanding worldwide network of receiver stations. Komjathy et al. (1997) have presented a method for updating IRI with the GPS maps produced at the University of New Brunswick (UNB). The GPS-deduced UNB maps provide the ionospheric vertical electron content (IVEC) on an hourly basis on a 5 degree by 5 degree latitude longitude grid. IRI is updated at each grid point by varying the internally-used global effective solar index (IG) until the IRI-computed IVEC agrees with the GPS-deduced IVEC; the IG index is used in IRI to describe the solar cycle variation of the critical frequency and the F peak density. IVEC data obtained by the TOPEX dual frequency altimeter were used to verify the reliability of the updating process. Data from two three-day time periods were used for this test, one in 1993 (medium solar activity) and one in 1995 (low solar activity). The results are shown in Table 2. Updating with GPS data provides a significant improvement reducing the mean difference between the TOPEX measurements and the IRI-95 predictions to the 1-3 TECU level (1 TECU = 10^{16} m^{-2}).

TABLE 2. Average mean and standard deviation of the difference between the total electron content (in TECU) measured by the TOPEX altimeter and predicted by the IRI-95 model with and without updating with GPS data.

Date	Updated IRI-95 Average Mean	Updated IRI-95 Average SD	IRI-95 Average Mean	IRI-95 Average SD
13-Mar-93	1.7	7.7	10.8	8.7
14-Mar-93	0.5	8.8	9.1	9.5
15-Mar-93	-1.2	8.5	6.5	9.2
6-Apr-95	2.8	3.2	1.4	3.6
7-Apr-95	1.8	4.0	3.3	4.9
8-Apr-95	0.8	3.7	1.2	4.4

The IRI program can be run interactively on the WWW at http://nssdc.gsfc.nasa.gov/space/ models/iri.html. These WWW pages also include more information about the IRI project and membership and about the results of past IRI Workshops.

References:

Bilitza, D., K. Rawer, and S. Pallaschke, Study of ionospheric models for satellite orbit determination, Radio Sci. 23, 223-232, 1988.
Komjathy, A., R.B. Langley, and D. Bilitza, Ingesting GPS-derived TEC Data into the IRI for Single Frequency Radar Altimeter Ionospheric Delay Corrections, Adv. Space Res. in press, 1997.

New Methods for Monitoring the Protonosphere

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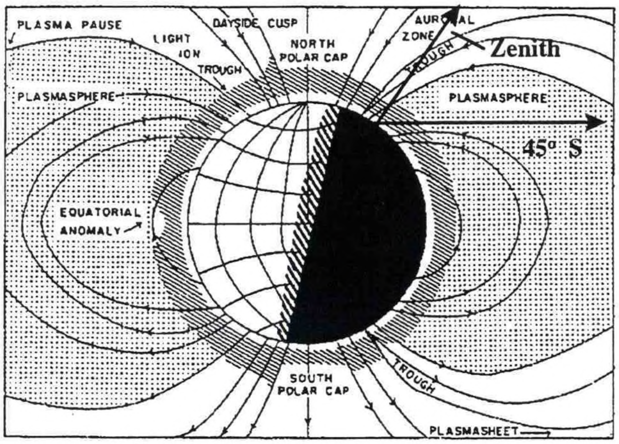

Figure 1. Representation showing topside ionosphere, and plasmasphere bounded by the geomagnetic field line that maps down to 60° magnetic latitude, [1].

Protonospheric (or plasmaspheric) electron content is included in GPS measurements of ionospheric total electron content (TEC), since the GPS satellites' altitude is 20,000 km and most of the ionospheric TEC lies below 1000 km., Figure 1. Measuring protonospheric content is a significant issue in the use of GPS TEC data for space weather modeling or for providing ionospheric TEC data to aid other systems. Recent advances in controlling errors in GPS TEC measurement [2] have achieved accuracies of better than 2 TEC units (1 TECu = $1x10^{16}$ electrons/m^2 integrated along the raypath, 2 TECu ≈ 1 ns delay at L1), which will support new protonosphere measurement techniques, and two new techniques have been introduced [3].

The first technique involves differencing GPS TEC and TEC derived from the Navy Navigation Satellite System (NNSS, now called the Navy Ionospheric Measuring System, NIMS). In one case, UW collected GPS data using a two-frequency GPS receiver at Aberystwyth (52.4°N, 4.1°W) and calibrated it using the SCORE method [2]. The NIMS data were collected at two sites, one collocated with the GPS receiver, the other at Hawick (55.4°N, 2.8°W). UW collected NIMS measurements using the two-station method described in Leitinger et al. [4]. Comparisons between the GPS and NIMS values were performed by converting both sets of values to equivalent vertical TEC, based on the simple shell model ionosphere at an altitude of 350 km. The same 35 degree elevation threshold utilized in SCORE was used to restrict the NIMS data selected for the comparisons of GPS to NIMS. The GPS data were averaged over bins spanning one hour in local time at the Ionospheric Penetration Point (IPP) and one degree in IPP latitude, on a daily basis, for comparison to NIMS measurements made closest to the center of each such latitude bin. The coverage of these bins around the observing station was limited to about 4 degrees of latitude and plus or minus half an hour of local time relative to that at the observing station, because of the elevation cutoff imposed. The excess of the GPS equivalent vertical TEC over the NIMS equivalent vertical TEC was calculated for each of the NIMS measurements and averaged over each calendar month A sample of the results is presented in Figure 2, comparing the average of the two latitude bands

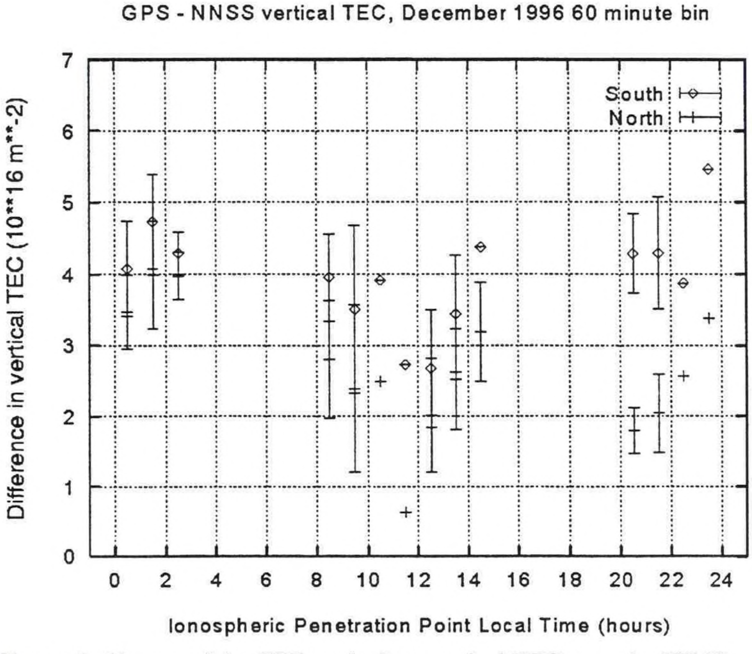

Figure 2. Excess of the GPS equivalent vertical TEC over the NIMS equivalent vertical TEC averaged over one month, December, 1996, southerly data consistently exceeds northerly [3].

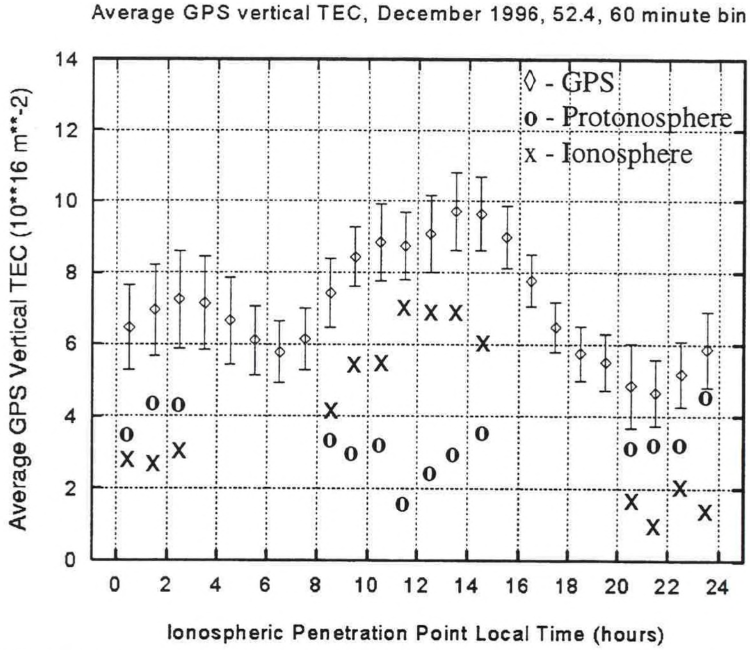

Figure 3. Average diurnal variation in GPS, 'excess', and GPS-excess TEC for December 1996, observed at Aberystwyth, 52° N, U.K. [3].

to the South of the observing station (centered on 50.4°N and 51.4°N), and the average of the two latitude intervals centered on 52.4°N and 53.4°N (referred to as North in the plot). Ths southerly (equatorward) measurements were all greater than northerly, consistent with protonospheric observation. Figure 3 shows the overhead data from Figure 2 subtracted from the average total GPS measurement, yielding a more expected ionosphere profile that is flatter at night. It appears that the high nighttime GPS values are due to protonosphere contributions.

The second technique involves differencing only GPS measurements. This technique is based on a simple insight from the geometry of the protonosphere: that (from mid-latitudes) overhead or poleward-looking GPS measurements should contain little or no protonosphere content (i.e. contain only ionosphere), whereas, equatorward-looking observations will have increasing protonosphere contributions as elevation angle increases. One approach is to difference observations from two GPS stations on the same longitude, both looking (at a relatively high elevation angle) through the same point in the ionosphere, one looking poleward and the other equatorward [3]. An example of a single-station approach would be to match an ionosphere model to the poleward observations, use the model to specify the equatorward ionosphere, and subtract that projection from the equatorward GPS observations. In Figure 4 an example of this approach is shown. ARL:UT calculated a difference between GPS and the PIM model for northerly data from Austin, TX, and subtracted this from southerly GPS-PIM data to obtain a protonosphere measurement.

[1] Rich, F. J., et al. "Structure of the Ionosphere",in *Handbook of Geophysics and the Space Environment*, A.S. Jursa, ed., Section 9.1, Air Force Geophysics Laboratory, 1985, NTIS accession number ADA 167000.

[2] Bishop, G., A. Mazzella, S. Rao, A. Batchelor, P. Fleming, N. Lunt and L. Kersley, "Validations of the SCORE Process", *Proceedings of ION NTM-97*, The Institute of Navigation, Washington, D.C., January 1997.

[3] Bishop, G. J., D. S. Coco, N. Lunt, C.Coker, A. J. Mazzella, and L. Kersley., "Application of SCORE to Extract Protonospheric Electron Content from GPS/NNSS Observations", *Proceedings of ION GPS '97,* Institute of Navigation, Washington, D.C., Sept. 1997.

[4] Leitinger, R., G. Schmidt, A. Tauriainen, "An Evaluation Method Combining the Differential Doppler Measurements from Two Stations that Enables the Calculation of the Electron Content of the Ionosphere" *J Geophys.* 41, 201, 1975.

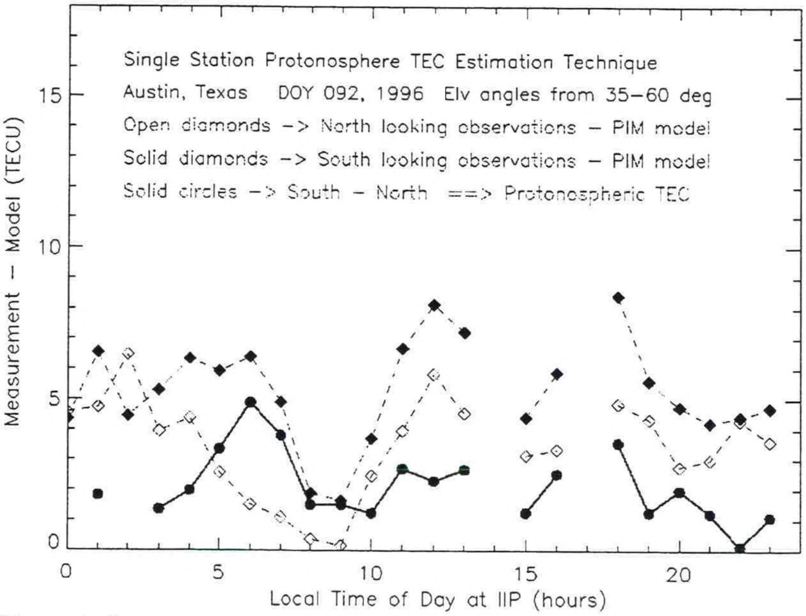

Figure 4. Protonospheric TEC obtained from single-station GPS measurements, using poleward-looking data to reference the PIM model, which is then used to specify the equatorward ionosphere, which is sub-tracted from the equatorward GPS data to yield protonospheric content.

Development of a Coupled Ionospheric Thermospheric Forecast Model for Operational Use

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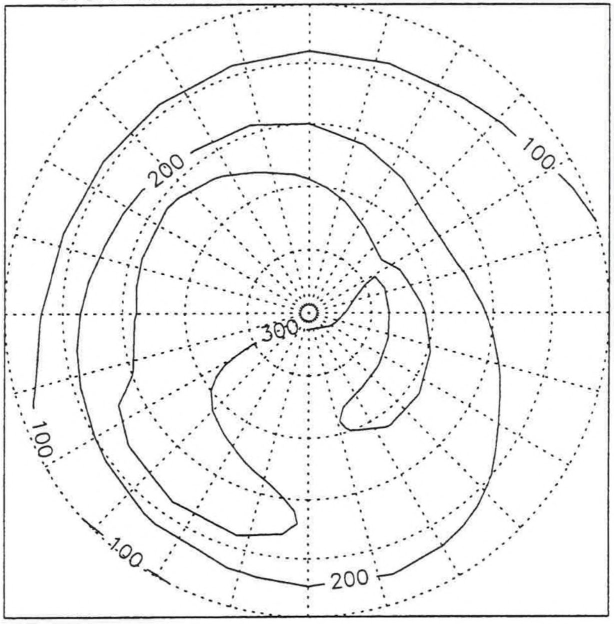
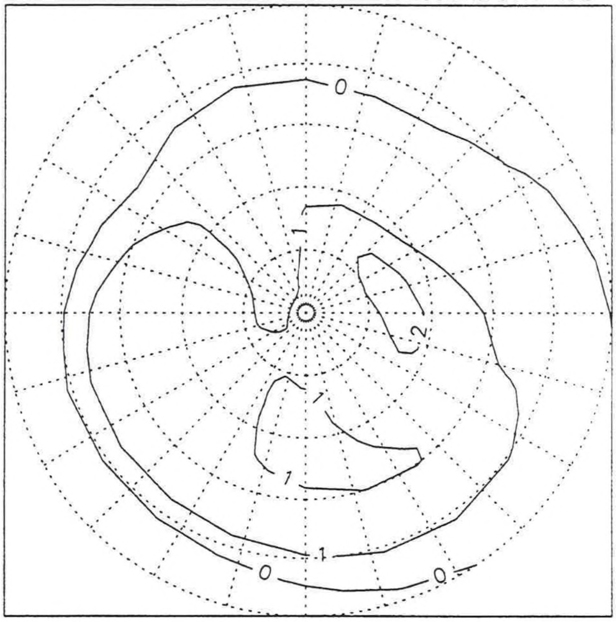
For approximately seven years Phillips Laboratory and contractors have been pursuing a program to develop physical models of the ionosphere for operational use. This program recently produced an Ionospheric Forecast Model (IFM) that is currently undergoing transition to the 55th Space Weather Squadron. IFM is now being enhanced by coupling, at the first principles level, its algorithms for charged particle densities, momentum and energy, to algorithms for corresponding observables of the neutral atmosphere. This is being achieved by modifying and combining its computer code with that of the NOAA Space Environment Center Physical Thermosphere Model so that charged particle properties as well as those of the neutral thermosphere are computed self-consistently by simultaneously solving a representative set of partial differential equations. This new Coupled Ionospheric Thermospheric Forecast Model (CITFM) simulates many of the short time scale and highly variable density and temperature structures that characterize space weather and involve physical processes that couple the charged and neutral particle populations. This is being demonstrated in a validation program that analyses its output and compares with observations made during disturbed as well as quiet conditions.

Representative output from the model is shown here from two model runs: The first being a simulation of a geomagnetically quiet equinox day with high solar activity (Kp=2.0, f10.7=180). The second run used the state defined at the end of this quiet day as the starting point for a geomagnetically disturbed period of 12 hours duration followed by another 12 hours of quiet activity. In this storm run the Kp was raised to 7.5 at 12UT and kept elevated until 0UT when it was lowered back down to 2.0. Both runs began and ended at the same times of 12UT. The first figure shows the difference in neutral temperatures between the two runs at 0UT and an altitude of 350 km in geographic coordinates north of 40 degrees N with local noon at the top and dawn at the right . Neutral temperature enhancements of more than 350K are the result of strong Joule and particle heating during the time of elevated geomagnetic activity. The next figure shows the difference in mean molecular mass (mmm) on a constant pressure surface of 0.000173 millibars, near 350 km, at the same time and again in geographic coordinates. The enhancements in mmm are evidence of upwelling in the neutral population through surfaces of constant pressure as the high latitude heating drives a horizontally divergent wind system. The last two figures show the decadic logarithm of peak electron densities (nmf2) exactly halfway through each simulation in geomagnetic coordinates north of 40 degrees. Depletion of peak electron densities is due to the increase in the fraction of molecular constituents at those pressures. Not shown here are longitude dependent wind surges triggered by the strong high latitude heating. This transient wind behavior causes changes in ion density at all latitudes.

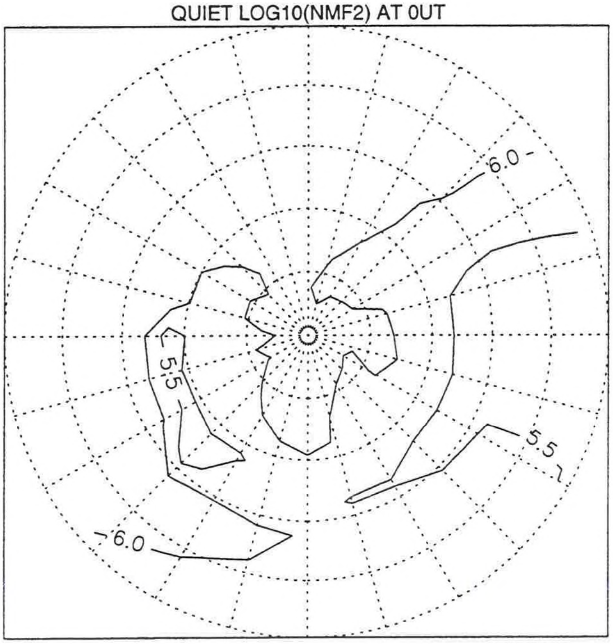
STORM-QUIET NEUTRAL TEMPERATURE AT 350 KM



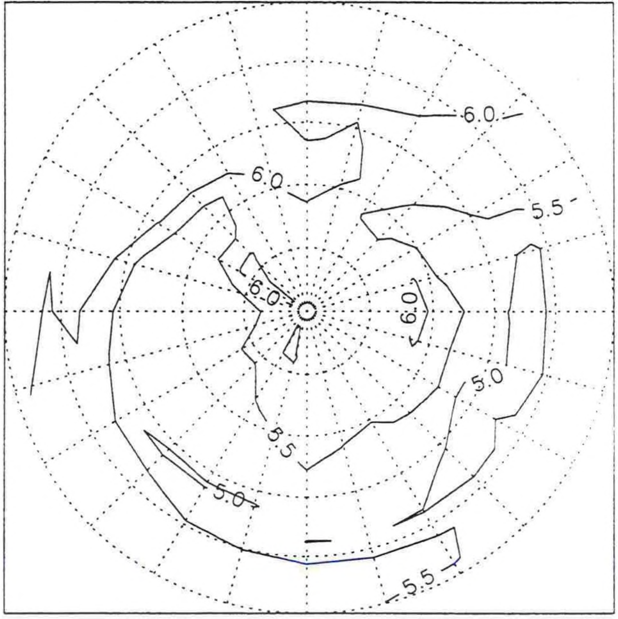
STORM-QUIET MMM ON CONSTANT PRESSURE SURFACE



QUIET LOG10(NMF2) AT 0UT



STORM LOG10(NMF2) AT 0UT



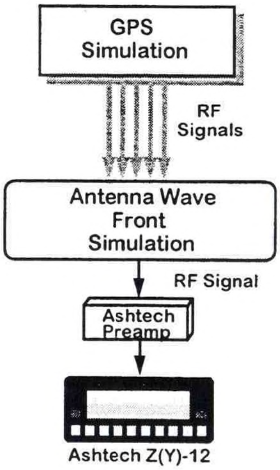
How Bad Are The Effects of Ionospheric Scintillation on GPS?
An Initial Bench-Test

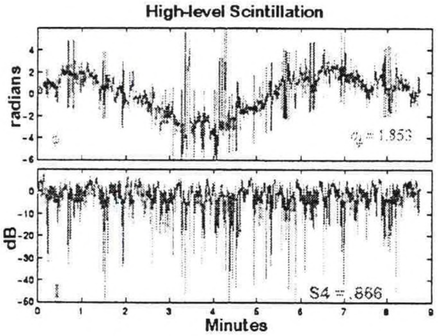
Clayton Coker and David S Coco
Applied Research Laboratories, University of Texas at Austin
Gregory J Bishop, *Phillips Laboratory, Hanscom AFB, MA*
Andy Mazzella, *Northwest Research Associates, Bellevue, WA*

The new generation GPS receivers have yet to experience solar maximum conditions. How will they respond to the next solar maximum period in 2000-2004. In June of 1997, a test was conducted to obtain some initial answers to this question. Several GPS receivers were exposed to realistic levels of ionospheric scintillation conditions. Scintillation scripts representing realistic levels of signal phase and amplitude scintillation were provided by the Air Force Phillips Laboratory and Northwest Research Associates. These data were applied, at a 250Hz resolution, to simulated GPS signals using the Antenna Wave Front Simulator at Wright Laboratory. This test represents the first time that modern GPS receivers have been systematically tested under simulated ionospheric scintillation conditions. The performance of a two-frequency commercial receiver under scintillating conditions is presented. Pseudorange and phase noise statistics are presented along with phase loss-of-lock rates for low, moderate and high levels of scintillation. The possible impact of solar maximum levels of scintillation on navigation and other GPS applications is discussed.

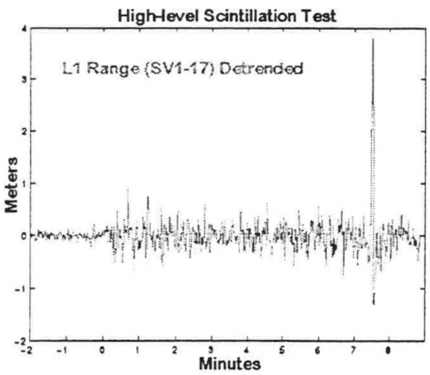
Synopsis

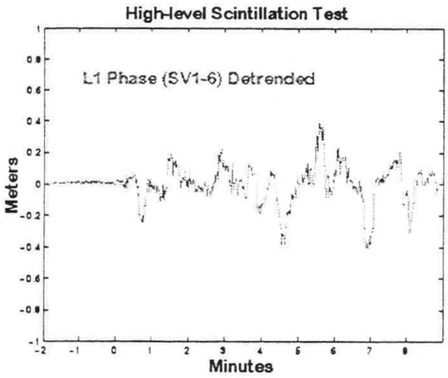
- Modern GPS Receivers Deployed During Solar Minimum
- 5 Receivers Tested with Realistic Scintillation at AFWL
- 250 Hz Phase and Amplitude Scintillation from AFPL



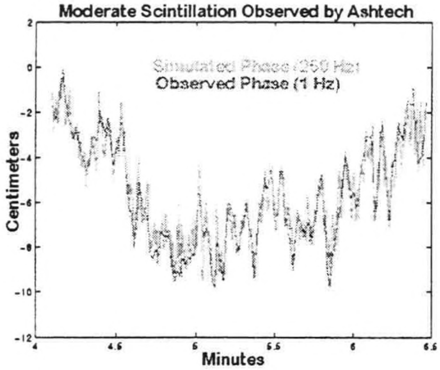


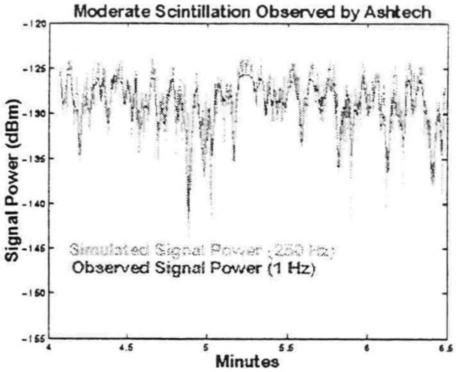
- Initial Results for Ashtech Z(Y)-12 under High-Level Scintillation
  - –Tracking Losses Not a Problem
  - –Pseudorange: 19 cm Noise, 2-5 m Spikes
  - –Phase: 100% of Minutes Affected with Loss-of-locks
- Other Receivers Not Reported Here





- Good Scintillation Monitor for Communications
  - –Amplitude Scintillation Agreement at All Levels
  - –Phase Scintillation Agreement at Low and Moderate Levels





- For the Equatorial Region at Solar Max, High-Level Scintillation Occurs in the Post-Sunset Period up to 50% of the Days.
- Impact on Navigation
  - –Minimal Effect for Autonomous Positioning (in the noise)
  - –Few Meters for WAAS Navigation
  - –Tracking Performance is a Concern for Less Robust Receivers
- Impact on Precise Positioning
  - –Ambiguity Resolution Fails if Enough SVs Affected
- Impact on Orbit Determination
  - –Loss of 15 min Smoothed Data in Affected Areas (or)
  - –Additional Error in 15 min Smoothed Data
  - –Degraded Ephemeris Production
- Unresolved Issues
  - –Response to Scintillation on L2
  - –Tracking Performance of Z-code vs. Y-code Modes
  - –Effects of Scintillation with Other Real World Variables
  - –Tracking Performance of Other Receivers

Proposed Signal Design for GNSS2: How to measure the Ionosphere with a Single Wideband Signal

Jock R. I. Christie, Per K. Enge, Bradford W. Parkinson
Stanford University

Abstract

The design of GNSS2 must incorporate the best aspects of both GPS and GLONASS, with allowance for technological advances. The design of this new robust, affordable, international, system must provide better accuracy, availability, continuity, and integrity than GPS and GLONASS currently provide. The foundation of GNSS2 must be a signal that can provide more accurate pseudoranging and ionospheric corrections than currently available. This paper will examine theoretical and experimental arguments for a high-bandwidth signal that would permit direct ionospheric measurements. By offering various signals for varying levels of accuracy, users can get accuracy appropriate for their needs.

GNSS2 may be loosely divided into five segments: the constellation, the ground monitors/ephemeris corrections, user segment, local signals, and the signal in space. While all five segments contribute to position accuracy, ultimately, a well designed signal will be essential for providing the basic measurements that serve as the foundation to this system. While deployment of GNSS2 is still 15-20 years from now, it is time to start examining various techniques that may provide improved navigational information.

Currently, GPS uses the large frequency difference between L1 and L2 (~350 MHz) for dual frequency measurements of the ionosphere, by exploiting its dispersive nature. This poster examines the possible use of a high bandwidth (~50 MHz), single frequency signal, as a means of measuring the ionosphere. This hypothesis has been verified with a computer simulation that examines the time domain effects of the ionosphere on a wideband (40- 80 Mbps) BPSK GNSS2 signal that uses longer (32-128 Kbits) acquisition codes.

Sample plots will demonstrate that the ionosphere introduces both amplitude and phase modulation, and that these effects grow according to the square of the bandwidth. Unfortunately these effects are negligible for current GPS and GLONASS signals (1-10 Mbps). This simulation shows that for faster codes, these perturbations should be measurable, and this would permit single frequency ionospheric measurement, by exploiting the dispersive nature of the ionosphere.

GNSS2 should use significantly faster (40-100 Mbps) and longer (32-128 Kbits) acquisition codes for the following five reasons:

1) reduced (code) pseudorange variance,
2) improved crosscorrelation,
3) more available codes for transmitters,
4) ability to reject narrow band jamming/interference, and
5) the potential for stand alone users to generate ionospheric corrections in near real-time.

While the signal is arguably the most important segment of GNSS2, it must be viewed in the context of the other segments, and the sum contribution to a precise, reliable navigation aid for the next century.

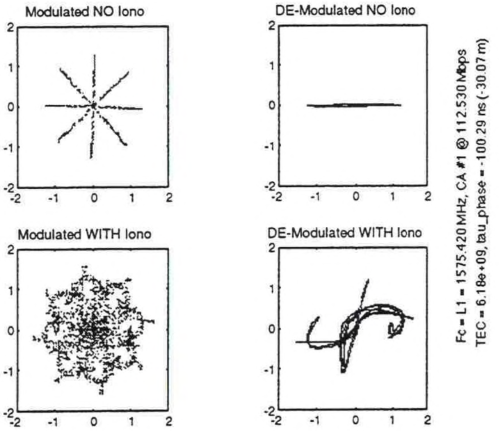


Figure 1. The upper left hand panel shows the RHCP signal in space. The spoke-like pattern is due to the simulation sampling at 8x the carrier. The upper right panel shows the signal after it was demodulated. The demodulated signal has a negligible quadrature component.

The lower panels show the effect of the ionosphere. The modulated carrier no longer exhibits a recognizable spoke pattern. The demodulated signal now has a larger quadrature component. This suggests that it would be more difficult to track the carrier. This implies a may to directly *measure* the ionosphere.

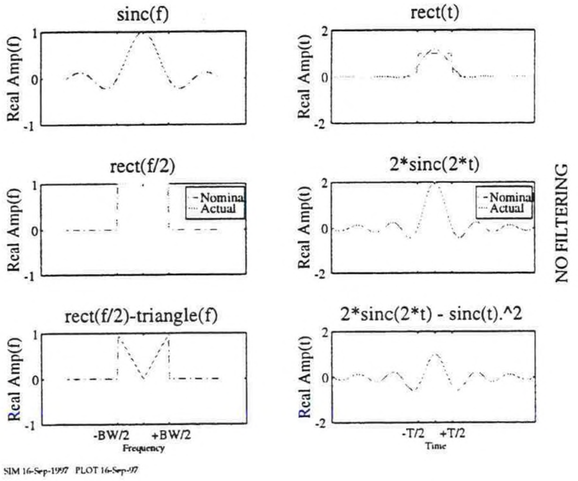


Figure 2. Code-carrier divergence does not depend on signal bandwidth, and it requires long observations. The dispersive effect of the ionosphere grows as the bandwidth squared. The square pulses in GPS/GLONASS do not utilize the full spectrum. GNSS2 should pursue a signal that is better distributed across the available bandwidth. This helps improve jam resistance and the ability to measure the ionosphere.

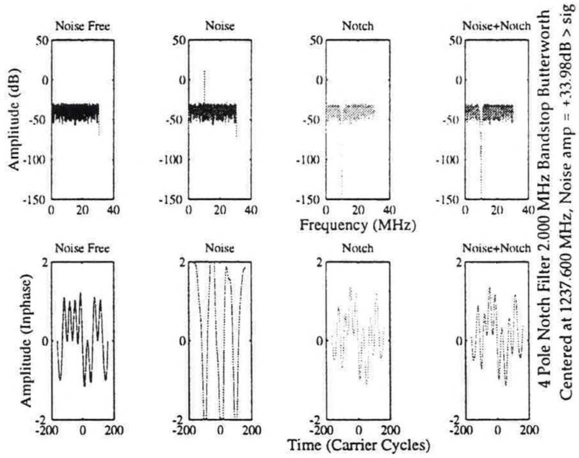


Figure 3. The upper panels show the signal in the frequency domain, and the time domain is plotted in the lower panels. The first column shows the nominal case. Noise is added in the second column, and an adjustable notch filter is added in the third column. Despite significant noise, it is possible to remove the narrowband interference and track the signal .

By using a faster code chipping rate for GNSS2, you get a significant improvement in raw pseudorange accuracy. Furthermore, the faster chipping rate also leads to a wider spectrum, which provides some jam resistance, and means of measuring the ionospheric group delay with a single wideband signal in near real time.

Ionospheric Weather for Ionospheric Specification for Single Frequency GPS Users and Other Applications

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Long term ionospheric variability ("climatology": months to years) is controlled by solar activity (variations in solar EUV emissions). Short term ionospheric variability ("weather": hours to days) is controlled by other factors: variability in thermospheric winds, low latitude electric fields, and geomagnetic activity. This paper focuses on the low latitude region and the equatorial anomaly. The equatorial anomaly is the result of a "fountain effect" produced by electric fields that drive plasma up at the equator, after which it "slides down" magnetic field lines to produce the density concentrations of the equatorial anomaly. Because the electric fields vary from day to day, so does the magnitude of the anomaly TEC.

The present GPS single frequency ionospheric correction algorithm (The "Klobuchar model") was developed two decades ago under very severe constraints, and does not attempt to capture either the average equatorial anomaly or its day-to-day variability. This is illustrated in Figure 1. We are developing a new ionospheric correction algorithm that is based on a major extension of the concepts used in the development of PIM and PRISM. The major innovation is the incorporation of ionospheric weather parameters into the theoretical climatology. Specifically, parameters specifying the departure of the equatorial drift and the thermospheric wind from climatological averages have been introduced. These parameters are longitude dependent, and are to be determined from near real time measurements. Initially, the drift parameters will be determined from DMSP *in situ* electron and ion density measurements. Several techniques for monitoring the thermospheric winds have been developed, and others may be developed in the future, but no method is currently being developed for operation use at this time.

An example of the use of ionospheric weather information (specifically, equatorial vertical drift inferred from satellite measurements) is illustrated in Figures 2 and 3. The drift was inferred from vertical TEC measurements by the TOPEX satellite compared to theoretical predictions for various drift levels. The inferred drift was then used in a prototype of the algorithm to predict slant TEC along the lines-of-sight to GPS satellites. The true line-of-sight TEC was obtained from dual frequency measurements of IGS receivers. We expect to complete the GPS single frequency ionospheric correction algorithm by April of 1998, and the new versions of PIM and PRISM by the end of 1998.

[Note: The TOPEX data was supplied by the Physical Oceanography Distributed Active Archive Center of the Jet Propulsion Laboratory (JPL). The IGS data was also obtained from JPL and was processed by P. H. Doherty of Boston College, who also supplied the predictions of the Klobuchar model. The new GPS algorithm is being developed under an SBIR contract with the Space Vehicles Directorate of the Air Force Research Laboratory]

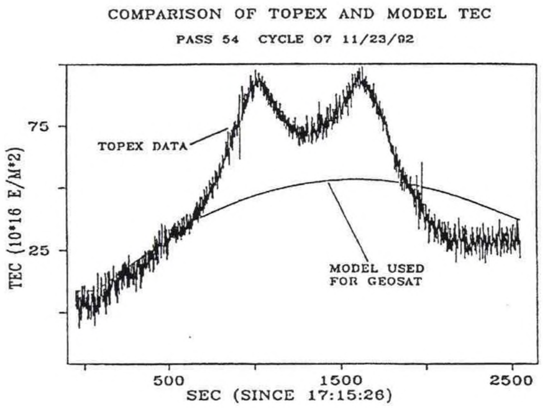

Figure 1. Comparison of the Klobuchar model (which was use for the GEOSAT mission) and actual TEC data taken by the TOPEX satellite as it passed over the equatorial anomaly.

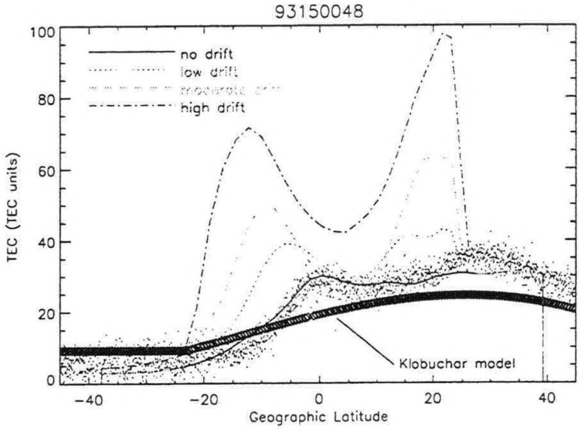

Figure 2. Estimation of equatorial vertical drift from satellite data. In this case, the satellite is TOPEX, and there was apparently no vertical drift on this day. The Klobuchar model is shown for comparison.

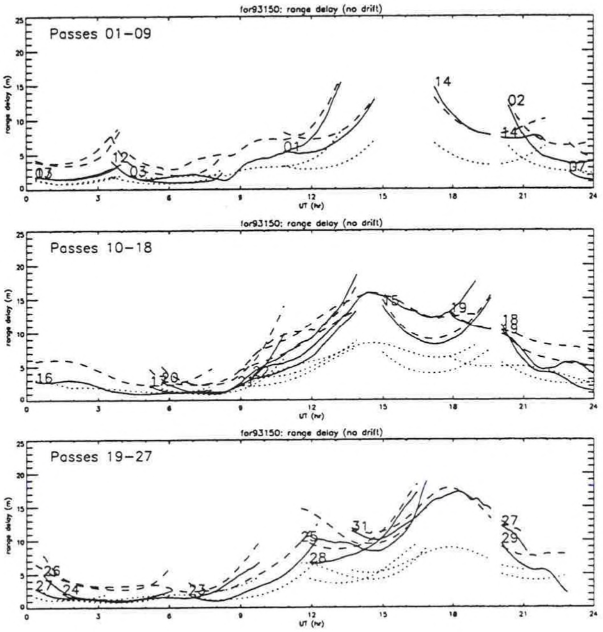

Figure 3. Prediction of line-of-sight TEC (converted to range delay) from a receiver in Fortaleza, Brazil to GPS satellites. The true TEC, determined from dual frequency measurements is shown as a solid line, while the CPI algorithm predictions are shown as dashed lines. The Klobuchar model predictions are shown as dotted lines. The GPS satellite passes were arbitrarily divided into three groups to reduce clutter in the figure.

The FAA's National Satellite Testbed (NSTB) Ionospheric Data Collection and Analysis

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Kristy Pham, FAA Technical Center

Poster Paper Submitted to the

Space Weather Effects on Propagation of Navigation & Communication Signals

Bethesda, Maryland
October 22-24, 1997

Abstract

The National Satellite Testbed (NSTB) has been used in the research, development, and test of concepts and algorithms supporting the Wide Area Augmentation System (WAAS). The effects of the ionosphere are a key factor in the performance of the WAAS, and so it is a prime area of research for the NSTB. This paper provides an overview of the NSTB and describes in detail the data collection and analysis efforts performed at the FAA Technical Center in support of the NSTB. Some examples of data collection and analysis are presented, including data from the May 15th, 1997 solar event which resulted in short bursts of apparent scintillation at NSTB sites in Grand Forks, North Dakota, and Winnipeg, Canada.

NSTB Overview

The NSTB is an FAA research and development oriented project which supports the Wide Area Augmentation System (WAAS). Previous NSTB efforts have focused on early prototype and flight test of the WAAS concepts and algorithms [1,2]. The NSTB has been used to test prototype software which demonstrate key WAAS requirements, including generation of corrections of GPS satellite errors (fast clock, slow clock, orbit) and generation of a grid to remove the error due to the ionosphere. Current efforts include providing a WAAS signal-in-space to support development of flight procedures, tests of international WAAS connectivity, and support of data collection and data reduction in preparation for the Operational Test and Evaluation (OT&E) of the operational WAAS.

NSTB Architecture

The NSTB currently operates with 18 US Testbed Reference Stations (TRSs) and 3 Canadian TRSs. By November, 1997, 5 TRSs are planned to be operational in Alaska and 2 are planned to be operational in Hawaii. The data collected by each TRS is forwarded to the Testbed Master Station (located at the FAA Technical Center) by dedicated 56 kB lines. In addition to the US and Canada sites, international agreements are being finalized to provide direct connection to similar reference stations in Iceland and Italy. Also, in addition to the FAATC Master Station, network data communications are provided to Master Stations at the NSTB software development sites (Stanford Telecommunications, Inc., and Stanford University). A network connection is also provided to the NSTB Maintenance contractor, SENTEL corporation.

Each TRS consists of at least one thread consisting of a commercially available GPS L1/L2 receiver, a workstation, a network router, and communications and power equipment. Most TRS also have a weather station which provides temperature, pressure, and humidity. Several TRS contain two threads of equipment, and also contain a GSV receiver which has modifications to permit reception of an off-L1 frequency to permit the NSTB to operate when an L1 geosynchronus satellite is not available to the NSTB.

TRS GPS Data Collection

Each TRS provides a formatted set of data to the Testbed Master Station. This data consists of GPS receiver measurements (both L1 and L2, every second), satellite ephemeris data, and weather data. All TRS data is received at the Master Station and archived on 4mm DAT. Current collection capacity is over 2 gigabytes per day. Data collection and archival has been continuous since January , 1997.

References

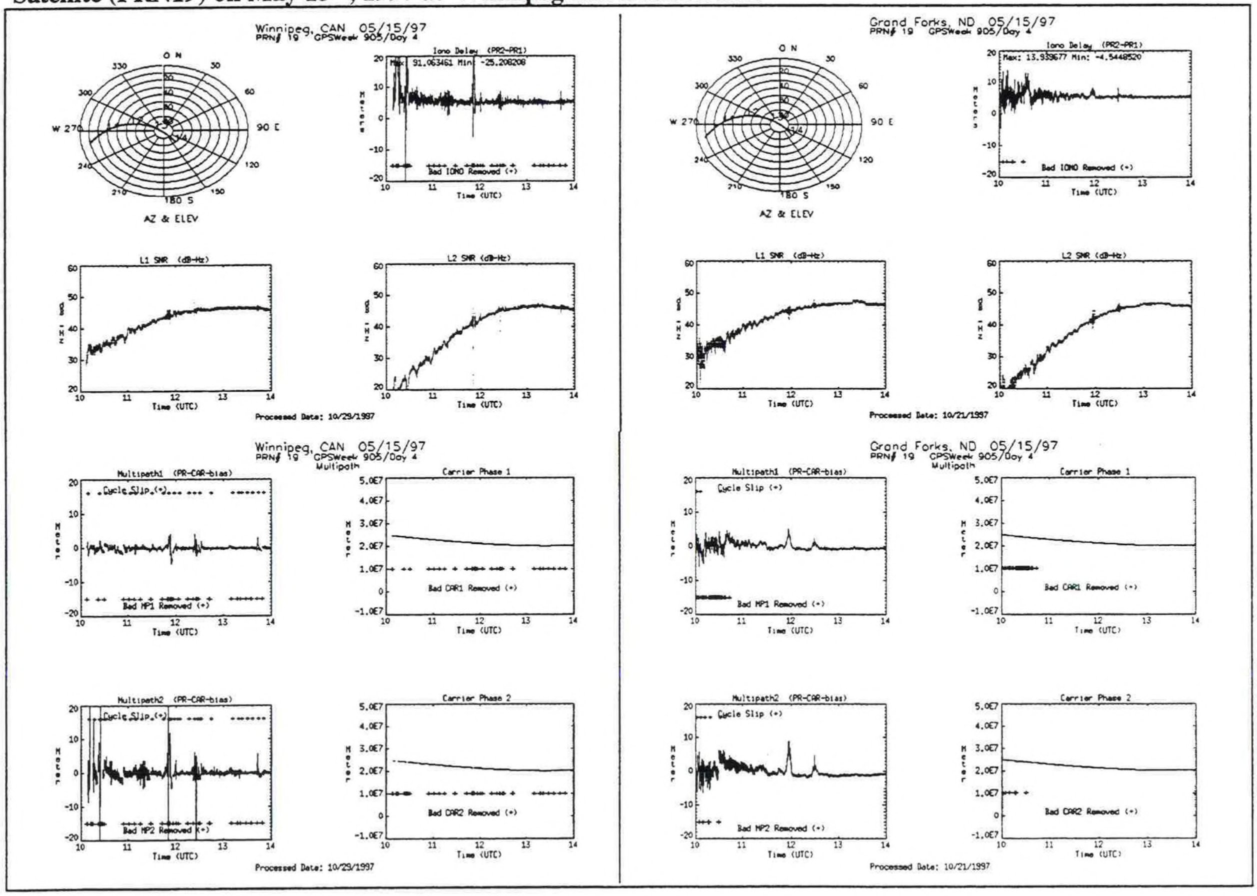
1. *Flight and Static Test Results for NSTB*, S. Pogorelc, D.Brown,; P. Enge, T. Walter, Stanford University; M. DiMeo, SRC; S. Kalinowski, ISI; T. Dehel, FAA Technical Center, Sept 17-20, 1996.

2. *FAA Flight Test Results for GPS Wide Area Augmentation System (WAAS) Cross Country Demonstration*, V.T. Wullschleger, D.G. O'Laughlin, F.M. Haas, Proceedings of the 50th Annual Meeting of the Institute of Navigation, June 6-8, 1994.

NSTB TRS Receiver Configuration List

#	Iden	Full Name	Receiver 0	Receiver 1	Receiver 2
1	Acy	FAATC	Trimble	GSV1012	Ashtech
10	And	Anderson, SC	Millenium 10-1	GSV1012	Ashtech
11	Rir	Riverside, CA	Millenium 12-2	GSV1012	Trimble
12	Sea	Seattle, WA	Millenium 10-1	GSV1012	Trimble
13	Gtf	Great Falls, MT	Trimble	GSV1012	Ashtech
14	Day	Dayton, OH	Millenium 10-1		Ashtech
15	Mia	Miami, FL	Millenium 10-1	GSV1012	Ashtech
16	Prs	Prescott, AZ	Trimble	GSV1012	Ashtech
17	Bgr	Bangor, ME	Millenium 10-1	GSV1012	Ashtech
18	Grb	Green Bay,			Ashtech
19	Acv	Arcata, CA	Trimble		Ashtech
20	Gwo	Greenwood, MS			Ashtech
21	Col	Columbus, NE			Ashtech
22	Den	Denver, CO			Ashtech
23	Gfk	Grand Forks, ND			Ashtech
24	Eko	Elko, NV	Millenium 12-2		Trimble
25	Okc	Oklahoma City, OK			Ashtech
26	Sag	San Angelo, TX			Ashtech
27	Hlu	Honolulu, HI			WAAS
28	Mnl	Mauna Loa			Trimble
30	Otw	Ottawa			Ashtech
31	Gdr	Gander	Millenium 10-1	GSV1012	Ashtech
32	Win	Winnipeg	Millenium 10-1	GSV1012	Ashtech
42	Stk	Sitka, AK			Millenium 12-2
43	Fbk	Fairbanks, AK			Trimble
44	Bth	Bethel, AK			Trimble
45	Ktz	Kotzebue, AK			Trimble
46	Cby	Cold Bay, AK			Trimble

Satellite (PRN19) on May 15th, 1997 at Winnipeg and Grand Forks



Ionospheric Effects on Single Frequency GPS Positioning

Patricia H. Doherty
Boston College

Capt. Matthew C. Smitham, David N. Anderson and Gregory J. Bishop
Air Force Research Laboratory

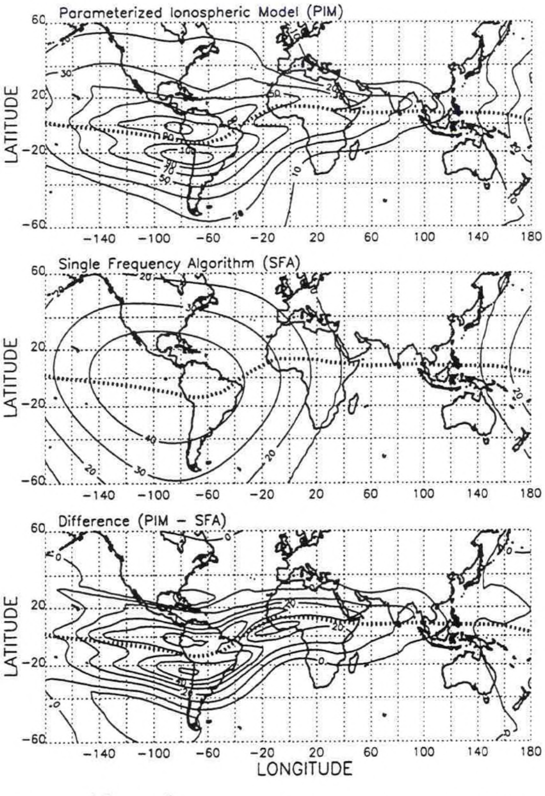
Andrew J. Mazzella
Northwest Research Associates

Abstract

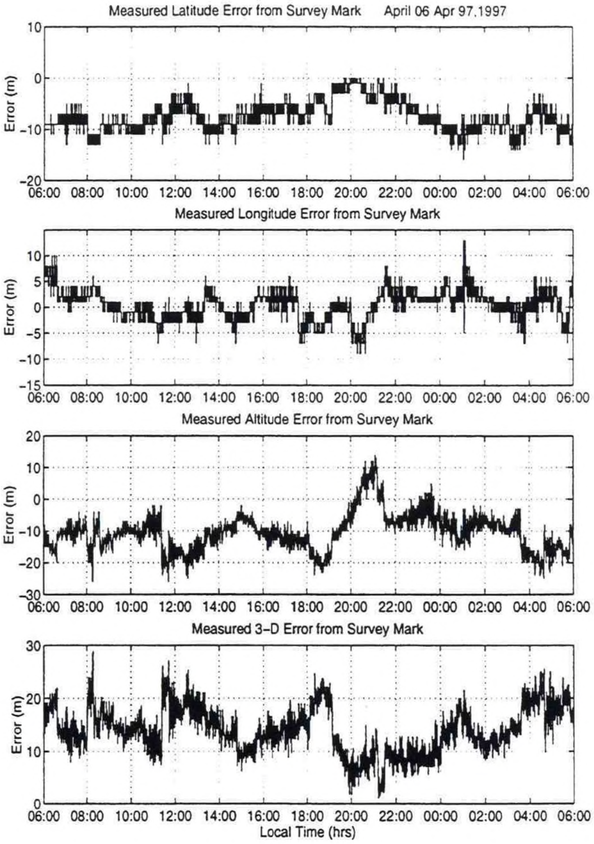
The ionosphere remains one of the largest and most variable sources of error for GPS positioning and navigation. Dual-frequency GPS users acquire highly accurate estimates of ionospheric range delay from the differential group delay and phase advance measurements made at the two GPS frequencies of 1.6 and 1.2 GHz. Single-frequency users, however, are limited to a less accurate ionospheric correction that is calculated with the current GPS ionospheric correction algorithm. This single-frequency user algorithm was developed in the mid-1970's to correct for approximately 50% of the total ionospheric range error. This level of correction may be acceptable to most users of single-frequency GPS; however it is not suitable for users who require a high degree of accuracy.

The U.S. Department of Defense (DoD) has procured over 100,000 Precision Lightweight GPS Receivers (PLGR) to provide precise time and positioning to troops in the field. The PLGR is a single-frequency receiver that is equipped with a cryptographic key to counteract the effects of selective availability (the intentional degradation of GPS signal accuracy). The largest remaining source of error for the PLGR is the ionosphere.

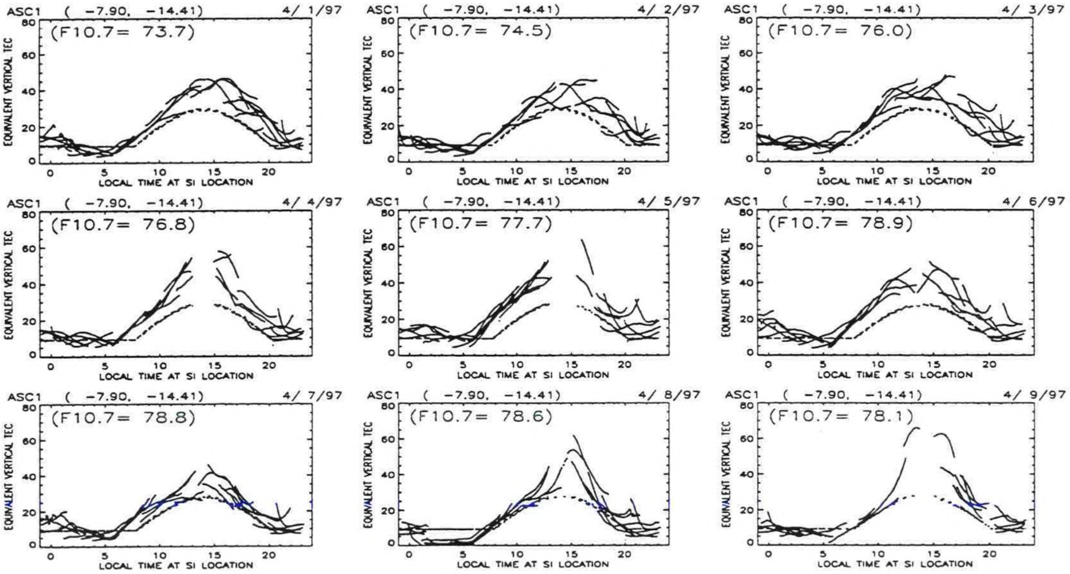
In this presentation, we will discuss a research task that is intended to satisfy a DoD request to provide near real-time information on the magnitude of the positioning errors which the single-frequency PLGR GPS receiver experiences due to uncorrected ionospheric effects. The ultimate goal of this task is to provide the capability to generate regional and global maps of these positional errors in near real-time. This product will utilize the near real-time measurements of TEC that are currently provided to the 55th Space Weather Squadron by the Ionospheric Measuring System (IMS) and the Jet Propulsion Laboratory. The maps generated by the final product will be a useful measure of when and where the ionosphere is the limiting factor to navigation and positioning for both DoD and non-DoD single-frequency GPS users.



Contours of modeled Equivalent Vertical TEC for a typical solar moderate/equinox period at 2000 hours UT. The top contour is based on calculations of the Parameterized Ionospheric Model (PIM). The middle contour is based on calculations of the GPS single-frequency user algorithm. The contour on the bottom represents the differences between the two models in TEC units. In general, the single-frequency user algorithm produces similar results as PIM in the mid-latitudes but does not capture the features of the equatorial anomaly region (~+/- 15° of the magnetic equator).



Errors in PLGR positioning for 1 day in April 1997. Errors are based on the difference between the PLGR position estimates and a co-located surveyed location. The four figures depict errors in latitude, longitude, altitude and overall distance from the survey mark.



Dual-frequency ionospheric measurements made at Ascension Island together with predicted single frequency ionospheric corrections made during a nine day period in April 1997. The differences seen in the dual-frequency data at common local times are primarily the result of measurements made along different lines of sight. Lines of sight from Ascension will propagate through the highly variable anomaly region.

Poster 3.11

Ionospheric Radio Tomography Using Maximum Entropy
3. A Film Showing Maxent Results, PIM Results And Mean Vertical Profiles

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Near the end of the Russian American Tomography Experiment (RATE), Nov 3 and 4, 1993, the index of magnetic activity (Kp) climbed rapidly from 0 to 7- in a little under one day. During the course of this magnetic storm, the ionospheric response was studied using data collected and analyzed in many passes. The results of this intensive study, using contour charts of electron density as well as the three important parameters of the average Chapman profile: the maximum density, the altitude of maximum and the scale height are presented.

We had dual-frequency receivers set up at four locations on the Eastern edge of North America: Block Island, Rhode Island; Hanscom AFB, Massachusetts; Jay, Vermont; and Roberval, Quebec, Canada. Using the dual-frequency (150 and 400 Mhz) beacon on the Navy Navigation Satellite System (NNSS), with a nominal altitude of 1100 km, a tomography pass would typically last about 20 minutes from horizon to horizon. From a total of 88 passes, 86 passes possessed sufficiently accurate data, and have been analyzed using the MaxEnt method described by Fougere[1995], which determines the average vertical profile in the form of an analytical Chapman profile, as well as a set of electron density contours.

The 86 contour charts were interpolated in time using cubic splines, producing a contour chart every 15 minutes from Oct 29 to Nov 3, 1993, for a total of 700 frames. Three movies were produced: MaxEnt results, PIM results, and mean vertical profile from both MaxEnt and PIM. In addition a film of the Haystack Incoherent Scatter Radar contour plots will be shown.

Utilization of Sky-wave Backscatter Sounders for Realtime Monitoring of Ionospheric Structure Over Extended Geographic Regions[1]

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Abstract. Backscatter ionograms (BI) and quasi vertical incidence (QVI) ionograms are routinely collected at over-the-horizon radar (OTHR) installations operated by the U.S. Navy. The BI provides information about the downrange ionosphere up to several thousand km from the sounder. In this paper, a method for the quantitative extraction of this information by means of a leading edge inversion technique is described and applied to data acquired by the BI sounder operating at the Chesapeake, VA OTHR facility. Because this sounder is used to sample 8 azimuthal sectors, maps of plasma frequency at a constant altitude can be derived over a geographic region that covers a 64° angular sector out to distances of ~2000 km. The unique capability of the OTHR BI sounders to provide realtime monitoring of the ionosphere over a large geographical area is demonstrated.

The method of sky-wave backscatter sounding, in which obliquely transmitted HF energy is received from distant ground backscatter, was developed several decades ago. The received "clutter" consists of radiowaves that propagate from the sounder, experience refraction by the ionosphere, then undergo backscattering from the Earth's surface, and finally return to the receiving site after a second ionospheric refraction. To facilitate the OTHR coordinate registration process, bistatic backscatter sounders are routinely operated along with QVI sounders at the two operational DoD facilities in Virginia and Texas. These sounders have azimuthal receive antenna beam steering capability, so that a BI can be measured for a set of beam directions within the azimuthal coverage sector of each backscatter sounder.

The leading edge of the BI contains information about ionospheric regions located thousands of kilometers away from the sounder and the inverse problem of backscatter sounding, as addressed here, is the problem of extraction of the plasma density distribution in the ionosphere from the measured leading edge. This inverse problem is rather cumbersome, because even the solution of the direct problem (the relationship between the plasma density distribution and the leading edge) can not be expressed explicitly. A rigorous approach that addresses the numerical solution of this problem was developed recently by the first author of this paper.

The accompanying contour map is a representation of the distribution of plasma frequency at the altitude h=235 km (ie. the altitude of the F-layer maximum as obtained by the QVI at the OTHR site) as a function of geographic coordinates. Isolines on this figure correspond to integer values of the plasma frequency (in MHz). The range extent of the area for which the reconstruction is valid is restricted because, at sufficiently large distances, there are no leading edge related rays that pass through the F-region. This restriction was taken into account in determining the greatest range extent of the ionospheric map presented here. In this example, which was acquired near 18h LT, the day-night transition pattern is clearly evident with a relative difference of a factor of two in plasma density across the terminator region.

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[1] Submitted for publication to *Geophysical Research Letters*

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Implementation of the BI inversion technique at the existing OTHR sites can provide real-time monitoring of ionospheric irregularity structures over a very large geographic area. In addition to direct utilization in the OTHR coordinate registration process, this unique information is of potential use to other users of ionospheric propagation information, as well as providing a valuable input to the National Space Weather Program.

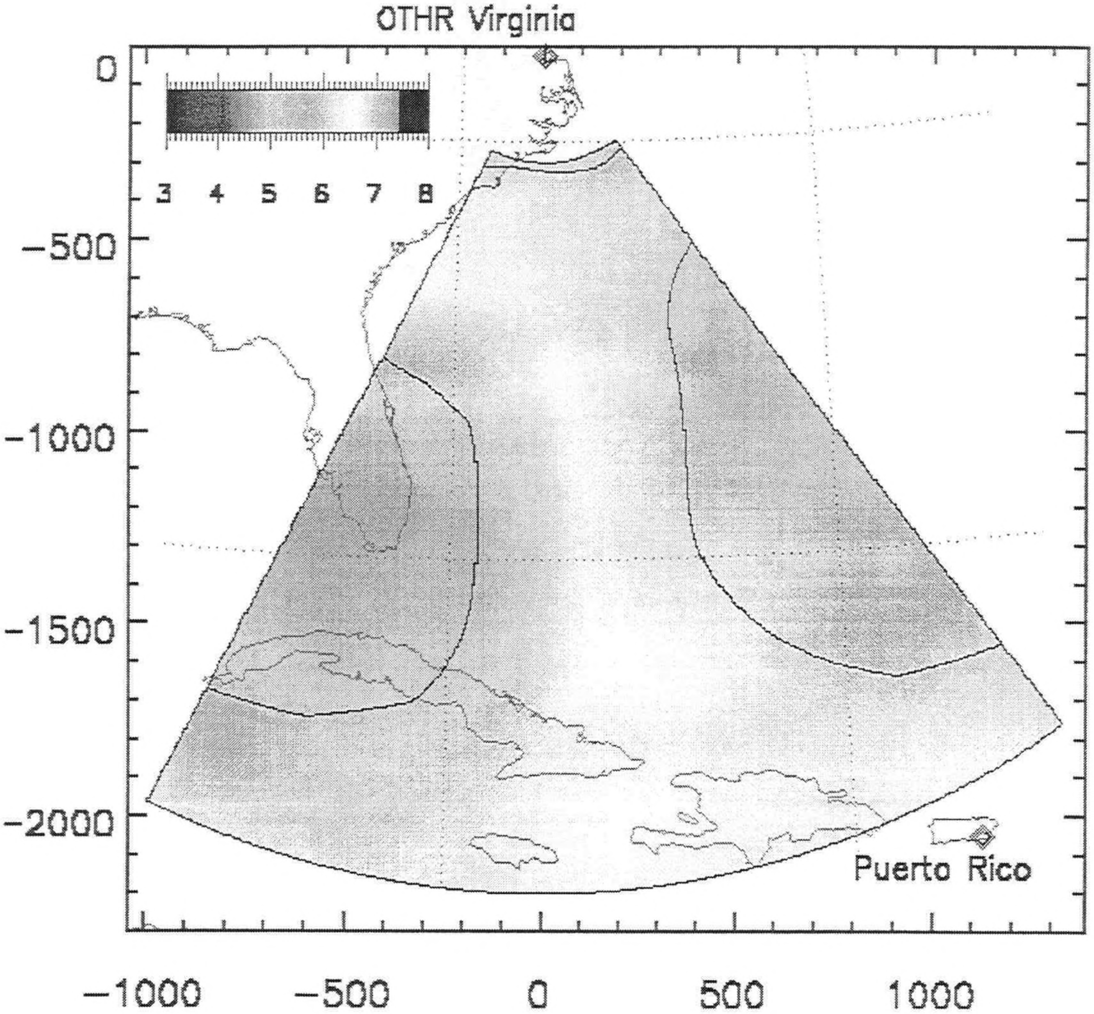

Figure 1. A contour map showing the plasma frequency (in MHz) at the altitude 235 km as a function of geographic coordinates. These data were derived from OTHR backscatter ionograms acquired on December 8, 1994, at 2244UT and show the day-night transition region very distinctly.

Storm-Time Ionospheric Predictions: Physically-Based and Empirical Modeling

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One of the challenges of the National Space Weather Program is to understand and predict the effects of geomagnetic storms on the near-Earth environment. Ionospheric changes at Earth during geomagnetic storms cause disruption of communication and navigation systems. Recent advances in simulating the response of the ionosphere to storms with a Coupled Thermosphere Ionosphere Model (CTIM) have shown that the local-time, seasonal, and regional dependences of the ionospheric response are controlled by interactions between the neutral and plasma environment. The clearest signatures are the large plasma depletions that occur at midlatitude, particularly in summer. These "negative phases" are driven by changes in the neutral atmosphere composition. The regional dependence is controlled by the location of "composition bulges" generated by the storm forcing, and depends on onset time, duration, and spatial distribution of the magnetospheric sources. The seasonal and local time dependences are controlled by thermospheric winds moving the composition bulge. To capture and predict these ionospheric storm effects one approach is to simulate the system using a physically-based model, and let the ionospheric changes follow naturally from the changes in the neutral atmosphere. A second approach is to harness the knowledge from the numerical simulations and capture the "physics" with empirical algorithms. Either method can benefit the goals of the Space Weather Program, by improving ionospheric predictions during disturbed intervals for radio propagation and navigation users.

For the second approach, the key index parameter is the weighted integral of the auroral hemispheric power over the preceding 30 hours. The optimum shape of the filter weighting function was determined by linear regression; the filter showed power values have equal weight for the first 24 hours prior to the time of interest, and linearly reduce to zero between 24 and 30 hours. The figure shows the relationship between this “integral of the power” index and the ratio of the storm-time NmF2 to the monthly median, as a function of latitude and season. The fit of the ionospheric data are shown for four levels of the integral of the power, <800, 800-1200, 1200-1600, and >1600 GWhours, at each ionospheric station, and sorted by three seasons, May-June-July, November-December-January, and the equinox months. In summer the ionospheric ratios become successively more depressed (“negative phases”) at all latitudes as the storm intensity increases. In winter, poleward of 40° geomagnetic latitude, the ratios decrease in the same way as in summer. Equatorward of 40°, the ionospheric ratios show a “positive phase”. Scatter plots show clearly that the ionospheric ratios have a non-linear dependence on the integral of the power. In the northern summer the fit to the data makes a significant reduction in the root-mean-square-error of the prediction compared with the monthly median. The results imply that much of the increase in variance during storms can be captured by the algorithm. The improvement in winter and equinox have yet to be quantified.

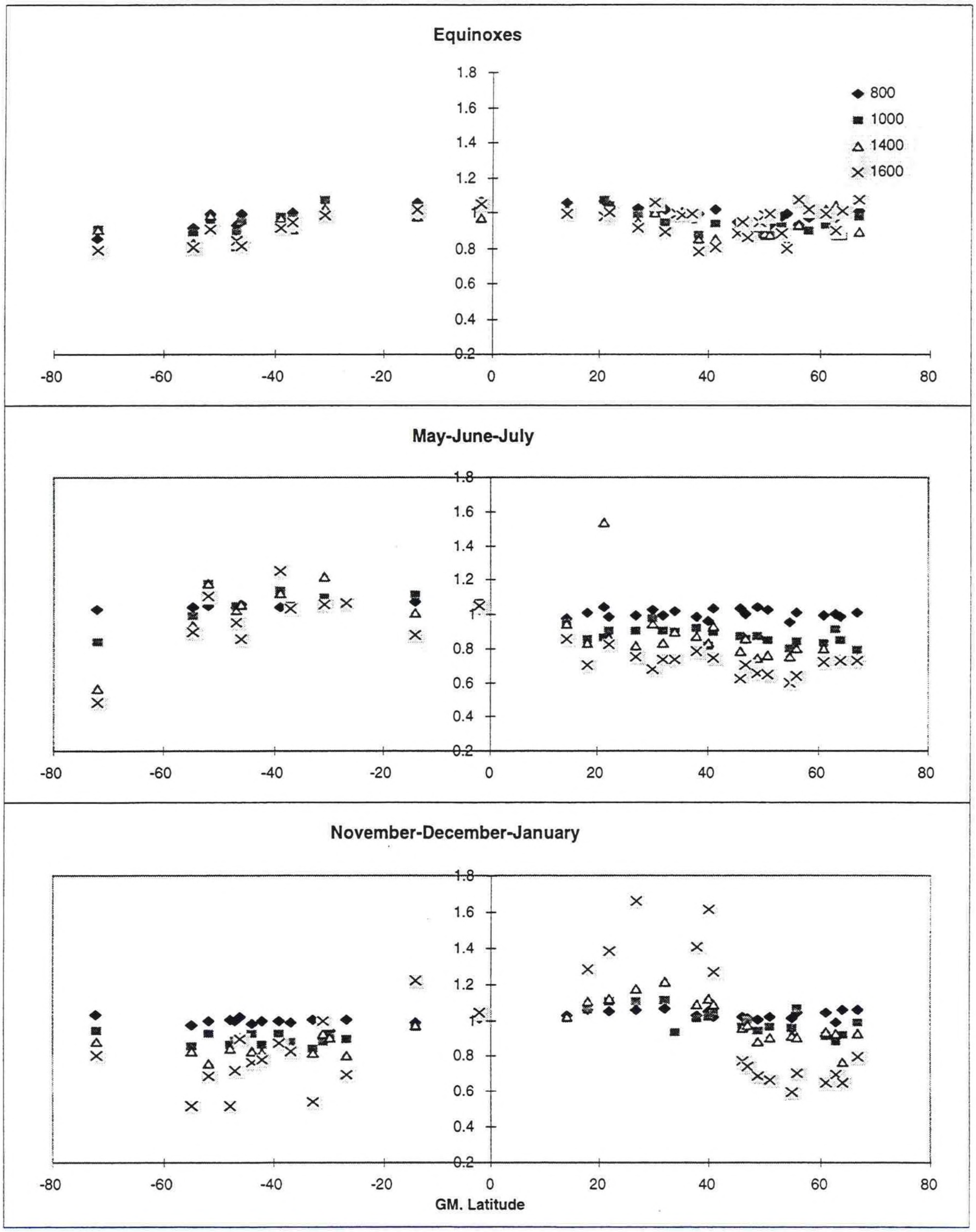

Figure showing the dependence of the ratio of storm-time NmF2 to the monthly median, for four levels of the integral of the power, as a function of latitude and season.

Poster 3.14

Specification and Nowcasting of Equatorial Ionospheric Scintillation in Near Real-time

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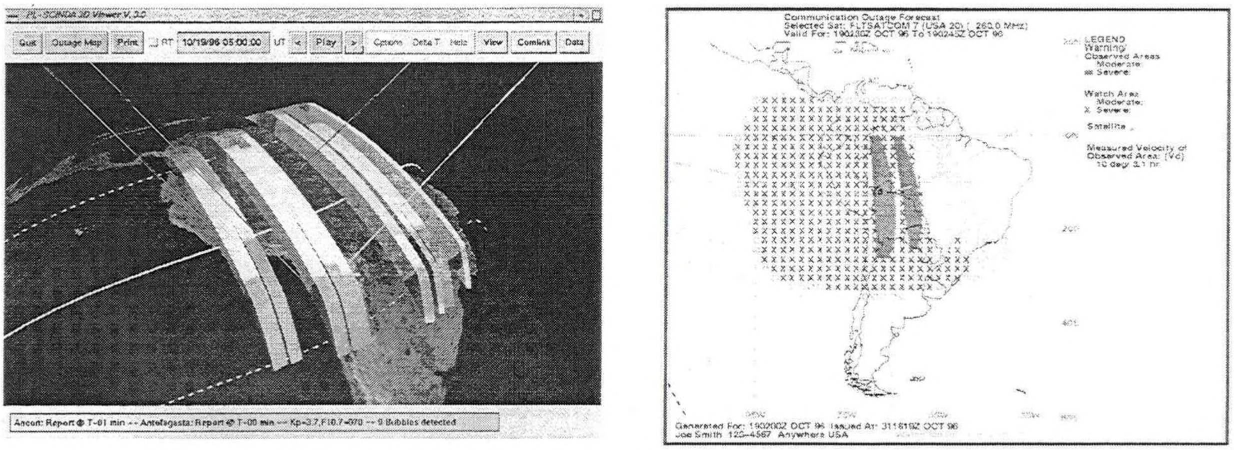
Electron density variations in the ionosphere can cause rapid amplitude and phase fluctuations, known as scintillation, of radio frequency (RF) waves which propagate through these regions. While scintillation effects are usually not significant at mid-latitudes, ionospheric disturbances in the polar and equatorial regions can severely modulate signals at UHF and lower frequency bands, resulting in the performance degradation and disruption of many satellite-based communications and navigation systems. At high latitudes, scintillation is closely linked to magnetic and solar activity levels, and is correspondingly highly variable and unpredictable. Equatorial scintillation, by comparison, follows a regular diurnal and seasonal variation from which a meaningful climatology can be derived. The diurnal behavior is driven by the formation of large-scale equatorial depletions which form post-sunset via the Rayleigh-Taylor instability near the magnetic equator. The highly-structured depletions map poleward along the magnetic field lines to approximately 20° latitude, causing scintillation over a large geographic region as they drift eastward and slowly decay prior to sunrise. Seasonal variation is a function of geographic longitude and magnetic declination angle. Understanding the climatology and behavior of these depletions, however, provides only weak guidance for forecasting their occurrence on a daily basis, just as a knowledge of monthly precipitation amounts for a given location says little about whether rain will fall on a specific day. To provide information on scintillation weather, two receiver sites have been established in the equatorial region of South America.

The sites were chosen to 1) detect the formation of the large-scale scintillation structures very close to the magnetic equator (Ancon, Peru, 12° S, 77° W) and 2) monitor the latitudinal extent of the structures and the scintillation intensity near the equatorial anomaly (Antofagasta, Chile, 22° S, 71° W). Signal power from 250 MHz geostationary satellite beacons located at 100° W and 23° W, respectively, is sampled at a 50 Hz rate at both sites; the use of spaced antennas facilitates drift velocity measurements as well. Scintillation parameters, such as S4, sigma phi and spectral indices, are derived from the raw data every 87 sec and stored on a local server. L-band signals from a single geostationary satellite and available GPS satellites are similarly processed. At fifteen minute intervals the data are retrieved via internet from the remote sites to Phillips Laboratory, Hanscom AFB, to drive a near-real-time model which generates dynamic graphic displays of the large-scale three dimensional scintillation regions for both 250 MHz (UHF SATCOM) and L-band (GPS) frequencies, (see Fig 1a). This system is known as the Scintillation Network Decision Aid (SCINDA).

The wedges displayed in Fig 1a represent the 3D location of large-scale equatorial depletions associated with scintillation. The features are propagated eastward in time at the observed velocity and thus, in time, specification of scintillation structures over a limited region is possible. Measurements from near the equator and the anomaly are used to obtain meridional variations. The structures are imaged using a simple red-yellow-green color code which corresponds to scintillation intensity. While the 3D views provide a good description of scintillation activity, SCINDA can also be used to generate 2D "outage maps" to support satellite communication users. Outage maps are essentially the projections (i.e., shadows) of the 3D structures from a selected satellite to the earth's surface. Scintillation intensity is adjusted for propagation geometry and frequency and mapped over the



10/19/96 05:00:00

Ancon: Report @ T-01 min -- Antofagasta: Report @ T-00 min -- Kp-3.7,F10.7-070 -- 9 Bubbles detected

Communication Outage Forecast
Selected Sat: FLTSATCOM 7 (USA 20) (260.0 MHz)
Valid For: 190230Z OCT 96 To 190245Z OCT 96

Generated For: 1902002 OCT 96 Issued At: 311619Z OCT 96
Joe Smith 123-4567 Anywhere USA

Figure 1. a) 3D representation of 250 MHz scintillation structures observed by SCINDA in OCT96; links from ground-stations to the geostationary satellites are color-coded green if clear of scintillation, red if disturbed;
b) 2D Outage Map from earlier the same night showing the projection of the features from the satellite at 23° W; the "watch" area, denoted by x- and o-symbols, indicates the probability for scintillation upstream based on climatology adjusted for current conditions.

satellite footprint, as shown in Fig 1b. "Warning" areas, plotted in solid colors, are based on the current location of observed disturbances, while "Watch" areas, delineated by x- and o-symbols, are derived by adjusting climatological activity levels, based on WBMOD, to be consistent with current observed levels. This provides a powerful tool for expanding specification beyond the region of actual observations, particularly to the west of ground-based sensors where meaningful predictions would be otherwise impossible due to the eastward drift of observed scintillation features. Scintillation intensity in both the Watch and Warning areas is displayed using the same simple three-color mapping scheme employed in the three-dimensional view. If the operator sets the color map thresholds properly for a given user, the red-yellow-clear areas can be immediately interpreted as regions of severe, moderate and little effect on his specific system, respectively. Information regarding the scintillation structures' evolution is employed by the model to generate "nowcast" projections of scintillation activity up to three hours in advance. Hardcopy and electronic image format outputs are supported to facilitate getting the information to the user as soon as possible.

Work on the L-band model is currently in progress as a number of issues not important to the 250 MHz specification model are being addressed. L-band scintillation occurs in smaller, discrete regions and decays more rapidly than its 250 MHz counterpart, imposing more demanding spatial-temporal specification requirements. Scintillation parameters based on GPS measurements require careful calibration. Additionally, a lack of consistent L-band scintillation due to current low solar activity provides a limited number of case studies and hampers overall validation efforts. Historically, L-band will experience severe scintillation effects as solar activity increases, and the goal of the SCINDA L-band component is to provide GPS users with the navigation equivalent of the current communication outage maps in a timely fashion. That is, to provide "navigation error" maps for GPS users during the approaching solar maximum.

In addition to meaningful GPS error maps, future releases of SCINDA will ingest DMSP electron density data to provide short-term prediction of scintillation occurrence based on an algorithm developed at Phillips Laboratory by Peter Sultan [private comm., 1997]. These data are available at 55 SWXS, Falcon AFB, where SCINDA is installed for prototype operational support and evaluation. Based on this evaluation and the desire to improve our understanding of equatorial scintillation physics, current plans call for the expansion of the network to include coverage to other longitude sectors. Under an agreement with the Australian Defence Science Technology Organization, stations in SE Asia will be established in FY98. Potential sites in other regions, such as the Middle-East, are also being explored. The expansion and continued development of SCINDA is designed to provide immediate real-time support to communication and navigation users while collecting information that will facilitate the development of improved scintillation forecast models for the space weather community.

Poster 3.15

Real Time Estimation of Ionospheric Electron Density

Andrew J. Hansen, Todd Walter, and Per Enge
Stanford University

A full realization of the Federal Aviation Administration's Wide Area Augmentation System (WAAS) is intended to provide aircraft guidance throughout the en route, terminal, non-precision and precision approach phases of flight. The most demanding phase is precision approach where vertical positioning accuracy of ones of meters is necessary. Integrity requirements ensuring safety of life specify that any vertical position errors greater than the Vertical Protection Limit be enunciated to the flight crew within six seconds. The ionosphere is the foremost impediment to such a guarantee.

Stanford, as a member of the National Satellite Test Bed (NSTB), has developed techniques for estimating the ionosphere in real-time. Previous research has established a connection between ionospheric error and vertical positioning error within the framework of modal decomposition. Ionospheric tomography is a natural extension of modal decomposition to the estimation of the ionosphere's three-dimensional electron density.

We present a 3D tomographic estimation algorithm and its implementation over the NSTB network (Figure 1). This estimator supplies not only corrections to the user but also appropriate confidence information for predicting the accuracy of those corrections in the aircraft. The tomographic approach to ionospheric correction obviates the troublesome obliquity factor associated with typical 2D gridded vertical delay algorithms.

At the core of the tomographic estimator is a predefined set of spectral basis functions spanning latitude, longitude, and altitude. Here we have constructed empirical orthogonal functions (EOFs) in altitude from the International Reference Ionosphere (IRI) and invoked spherical harmonics in solar-magnetic latitude/longitude. The instantaneous observation of the NSTB reference network (Figure 1) will typically resolve 3 EOFs and 5th order spherical harmonics.

Using a weighted damped least-squares inversion (Kalman gain matrix) coefficients for each spectra are estimated from the instantaneous reference station measurements. Likewise, covariance estimates on each coefficient are generated from the linear estimator and serve as the input for generating position domain confidence intervals.

The primary task of the ionospheric model in WAAS is to take dual-frequency TEC measurements at fixed reference stations and combine them in real time to estimate the current state of the ionosphere and a confidence on that estimate. The state and confidence are then transmitted to the user's receiver over a geosynchronous satellite channel. The ionospheric model is then combined with GPS satellite clock and ephemeris models to form a wide area (vector) differential position solution and associated confidence interval.

The three dimensional estimator has been applied on live NSTB observations to generate time series of 3D electron density reconstructions over the Coterminous United States (CONUS). Wide area ionospheric delay correction is demonstrated on independent live data in the pseudo-range domain (Figure 2). The accuracy, integrity, and availability of the complete navigation solution afforded the user by this approach may also be quantified. The accuracy of 1 Hz position solutions over ~26 hours at the Columbus, NE monitor station was compiled for 29 July 1997 (Figure 3). In addition the true-to-predicted error ratio which is a measure of the integrity of the differential correction for the same data are compared against the unit Gaussian. That is, the area under the Gaussian is equivalent to the area under the ratio histogram and demonstrates that the residual errors are short tailed.

Supported by FAA Grant 95-6-005.

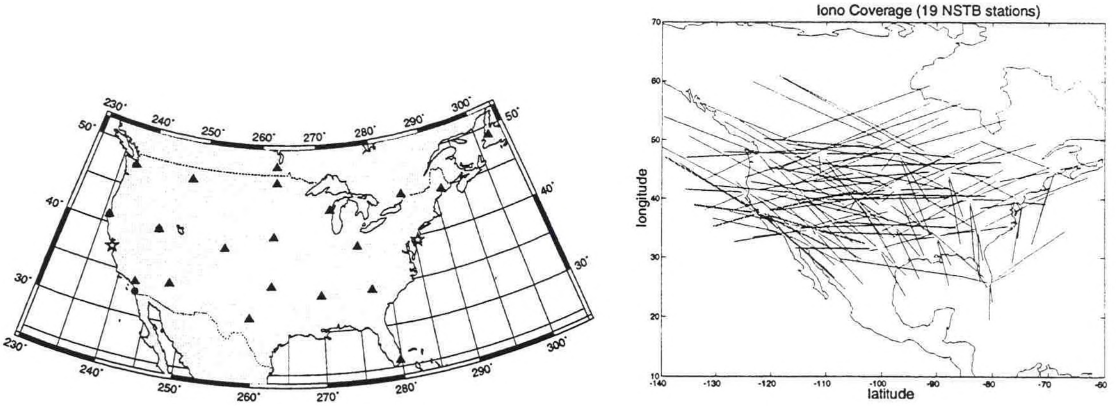


Figure 1: The left figure shows the NSTB reference network and on the right is its instantaneous sampling of the ionosphere with the altitude 100-1000 (km) projected onto the lat/lon plane.

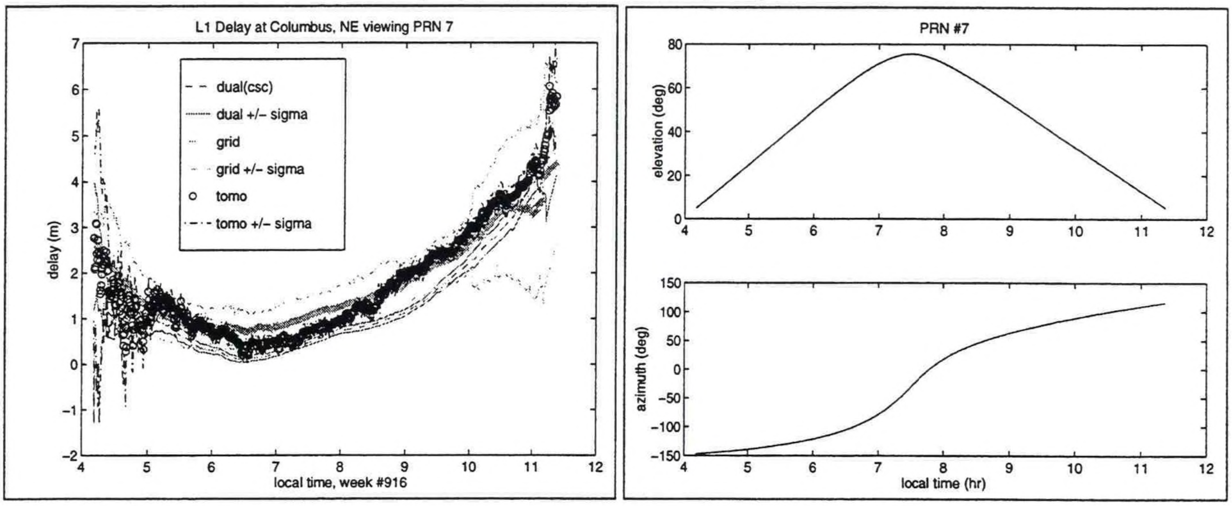


Figure 2: Dual frequency carrier smoothed delay measurements from a static user at Columbus, NE on PRN #6 are compared against predictions from 2D grid and 3D tomographic estimators in the left graphic. The right plot shows the local elevation and azimuth of the seven hour pass.

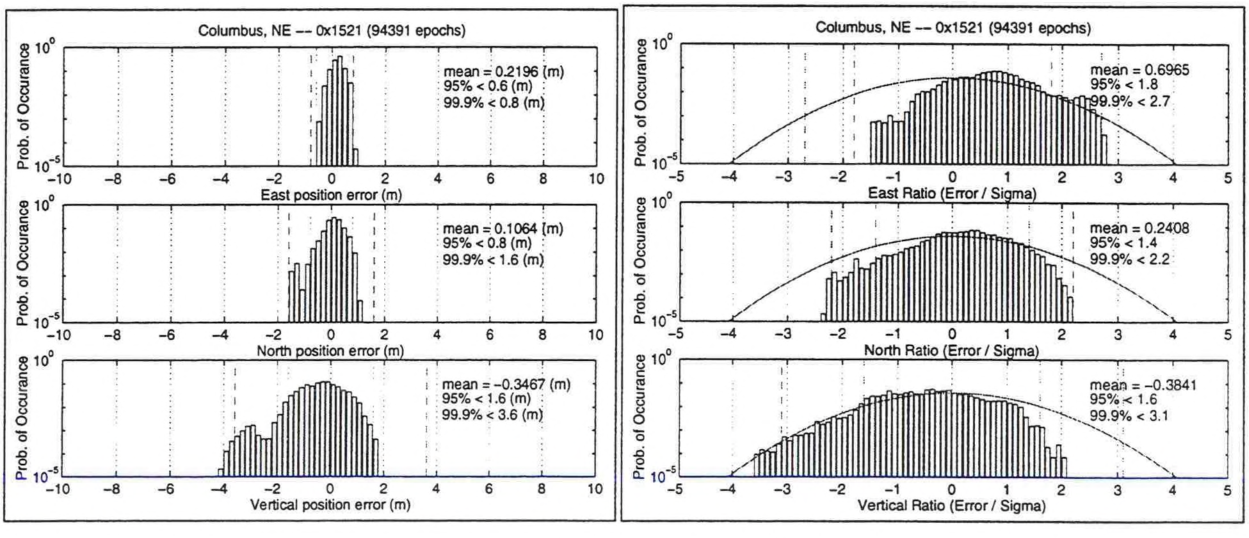


Figure 3: The left histogram shows the real-time WAAS position error (East/North/UP) for 26 hours in July. That on the right reports the ratio, overbounded by the (red) unit Gaussian, of the true error to the predicted 1-σ error .

Specific Space Weather Effects on High Latitude Communication and Navigation Systems

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The effects of Space Weather disturbances are especially severe on Communication and Navigation systems operating at high latitudes. Data describing these effects for the last four sunspot cycles has been analyzed and published in various journals (see Hunsucker, 1967; Hunsucker and Bates, 1969; Hunsucker, 1992; and Hunsucker et al, 1996). In this poster paper we will show representative electron density profiles obtained with the Chatanika incoherent scatter radar (ISR) [Bates and Hunsucker, 1974] and riometer absorption events, as well as examples of specific effects upon VLF transpolar navigation signals, medium frequency (MF) skywave paths, HF transpolar and cispolar communications circuits, HF backscatter sounders and low VHF propagation paths. Some of these examples represent near worst-case scenarios. In addition to the profound effects upon the performance of certain systems, i.e. - blackouts on transpolar HF circuits; more subtle effects, such as doppler shifts and spread, multipath delay, etc. will also be illustrated. It has also been demonstrated that one can use GPS/TEC data to characterize the most severe disturbances (Coker et al,1995; Hunsucker et al, 1995). It is also possible that a degradation of signal-to-noise ratio (S/N) at LF/MF/HF frequencies near ground level may occur during substorms (Benson, R.F. et al (1988) and LaBelle et al (1994).

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LaBelle, J. A.T. Weatherwax, M.L. Trimpi, R. Brittan, R.D. Hunsucker and J.V. Olson (1994), *Geophys. Res. Lett.*, 2749-2752.

Some Conclusions:

Abrupt phase and amplitude changes occur on ELF/VLF propagation paths which transit the auroral oval.

At MF (the US Standard AM Broadcast Band), Skywave interference can occur on high latitude paths.

Blackouts lasting for well over one week have been observed on HF Transpolar paths during sunspot maximum years.

High Doppler shifts and spreads often occur on HF Auroral paths.

During Sunspot Maximum, the VHF propagation can be significantly enhanced.

Anomalies have been observed at high latitudes on GPS systems.

The signal-to-noise (S/N) ratio may be degraded at LF, MF and HF frequencies by auroral radio emissions.

Multi-point In Situ Measurements of Ionospheric Effects

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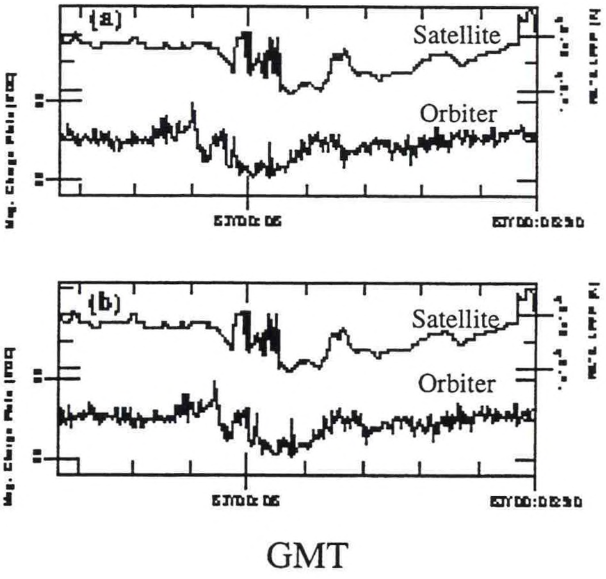
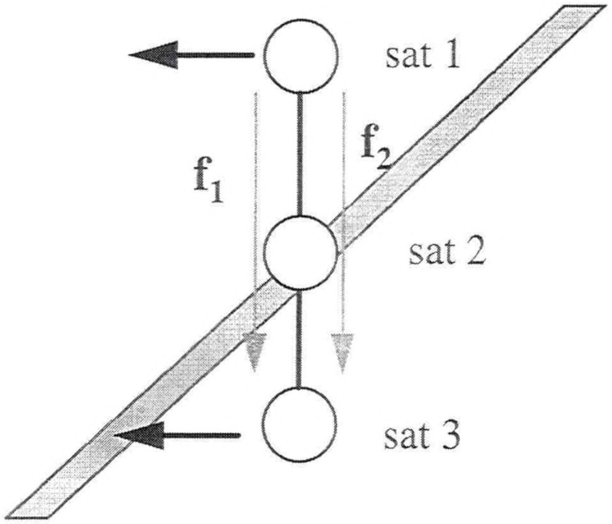
Plasma instability phenomena occurring in the F region ionosphere can vary in spatial scales ranging over seven orders of magnitude (10^5m -- 0.1m) and temporal scales of a few minutes to several hours. In order to understand the physics of irregularities like equatorial spread F (ESF), auroral regions and ionospheric layers, improved sampling in the spatial and temporal scales is required. The above instabilities vary rapidly in the horizontal and vertical spatial scales, and therefore, measurement techniques like single satellites, rockets, balloons and ground-based instruments are limited in their spatial and/or temporal resolution. This presentation outlines the advantages of using multi-point, in-situ, sensor techniques to better understand the morphology and dynamics of these ionospheric instabilities.

Preliminary results from the reflight of the Tether Satellite System (TSS-1R) mission are also presented. During this mission the first ever simultaneous, in-situ measurements of irregularity features at two different altitudes were obtained, giving an opportunity to determine the altitudinal variation of the irregularity. In future missions, radiowave signal propagation between satellite/sensor platforms can be used to increase the knowledge of spatial variation and character of the plasma between platforms. One specific quantity that can be measured is total electron content (TEC) and its time variability along the signal ray path between the satellites as they move together through their orbit. Two-frequency techniques, similar to those used by the Global Positioning System, represent one possible approach to providing TEC measurements. Such information would improve the ability of the multi-point system to identify and characterize ESF irregularities and their variation over time. Theoretical measurements of such a system passing through modeled plasma structures are shown to demonstrate the concept.

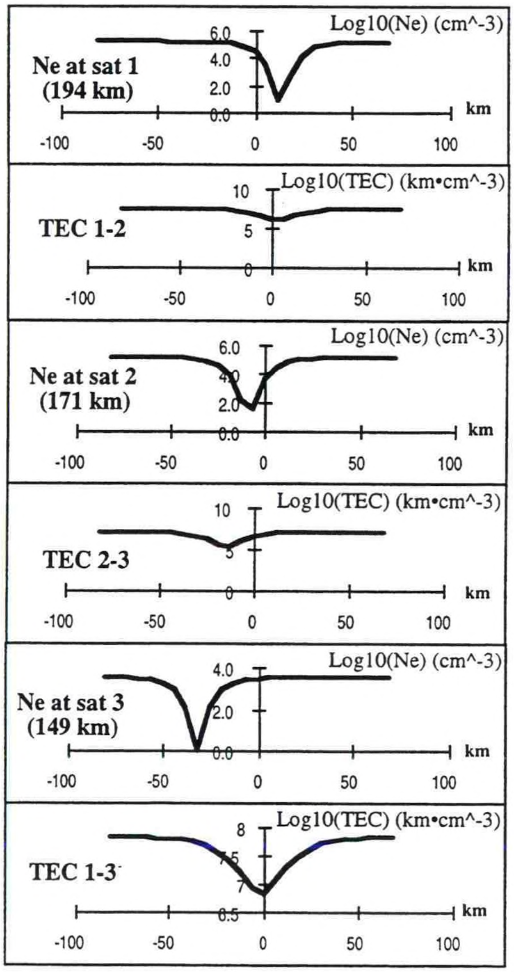
Hence, multi-point in-situ measurements, in coordination with ground-based measurements, can be used to distinguish between various ESF irregularities as well as to study their initiation and subsequent growth (e.g., understand questions like the relation of the irregularity with respect to the F-peak, bifurcation in bubbles, relation between small and large scale features, etc.).



Preliminary observations from the TSS 1R mission which flew in 1996, deploying a satellite spacewards on a tether, is shown to the right. The correlation between the measurements made at the satellite end and the Orbiter end depicts the first simultaneous, dual-point, *in situ* measurements of ionospheric irregularites. The delay in the measurements made at the satellite end (panel a) of the tether suggests a possible eastward tilt to the structure, assuming that the measurements are with respect to the same irregularity feature. Panel b applies a time shift to align most of the irregualrity features at the two ends, thus accounting for the tilt. From the geographic position (equatorial-low latitude), time of observation (2000LT), and the density depletions (25-100%) it appears that these irregularities could be density depletions such as plasma bubbles.



With a multi-point and TEC measurement system, structures are easily identified as continuous rather than separate phenomena. As the plots to the right show, measurements from the satellites alone could indicate separate structures. The TEC measurements between, however, clearly indicate that a continuous structure is being observed. Furthermore, slopes and gradients of the edges of structures are easily found via simultaneous solution with the rates of change of TEC and Ne.



Nowcasting and Short-Term Forecasting of Communications and Navigation Outages Using a Data-Driven Model-Based Approach

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Charged Particles Physics Branch
Plasma Physics Division
Naval Research Laboratory
Washington, DC 20375

M.H. Reilly and M. Singh
Geoloc Corp.
Arlington, VA

Space weather can adversely affect a variety of military and civilian communication and navigation systems, e.g., GPS, UHF satcom, tactical HF, OTH radars, and WAAS. Currently, there is a need to develop a nowcasting and forecasting capability for global and regional ionospheric climatology and weather. Conventional global ionospheric climatological models represent explicitly only the large scale structure typically on the order of a thousand kilometers and larger. Mesoscale ionospheric weather models can describe features on smaller scales on the order of kilometers. Real-time data-driven global ionospheric models which are coupled to an appropriate mesoscale model can address nowcasting and forecasting needs over a range of spatial scales. We have developed an approach and associated fast, compact, model to address aspects of these needs. The formal procedure is as follows [1]. We invert ground-based GPS TEC data using a global ionospheric climatological model to specify local ionospheric characteristics, i.e., the vertical electron density profile (EDP) at and near the GPS receiver. The EDP's are then used as input to drive a mesoscale ionospheric weather model to specify mesoscale structures. We have applied this methodology to the low latitude and equatorial ionosphere using a GPS receiver located at Arequipa, Peru for the night of October 18, 1996. Fig. 1 shows the EDP derived from the global model and from the Jicamarca radar nearby to the northwest. This vertical EDP is then input into a mesoscale equatorial ionospheric model which computes the evolution of scintillation-causing equatorial spread-F rising bubbles in the F-region ionosphere as shown in Fig. 2. The model output is validated using Jicamarca radar observations as shown in Fig. 3.

Work supported by the Office of Naval Research. We gratefully acknowledge useful discussions with D. Hysell.

1. M.J. Keskinen, M.H. Reilly, and M. Singh, *Radio Sci.*, submitted, 1997.

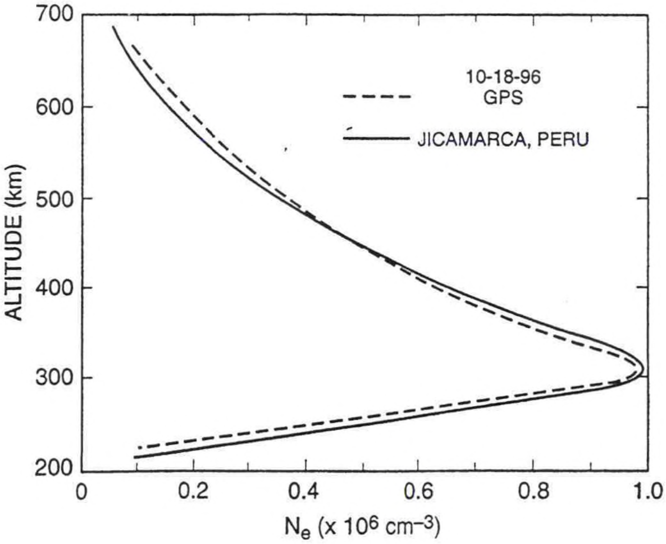


Fig.1

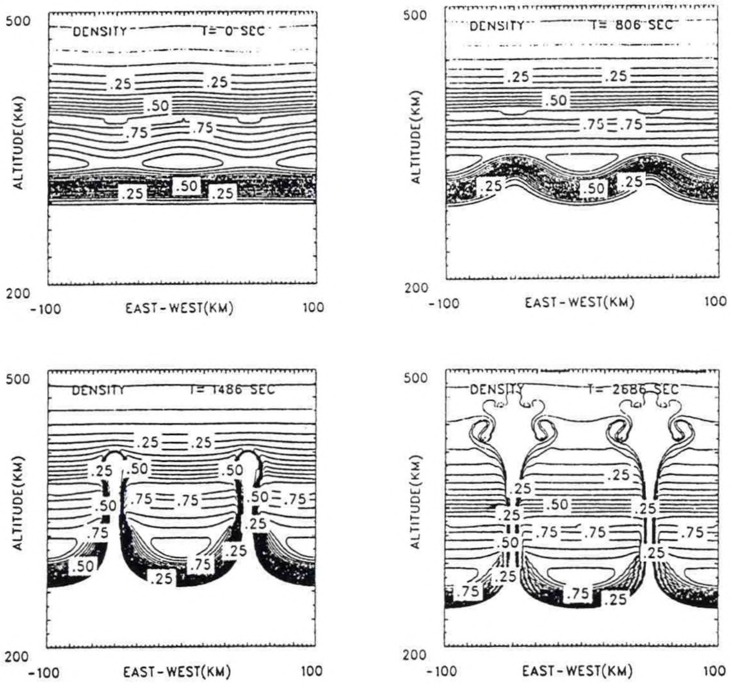


Fig.2

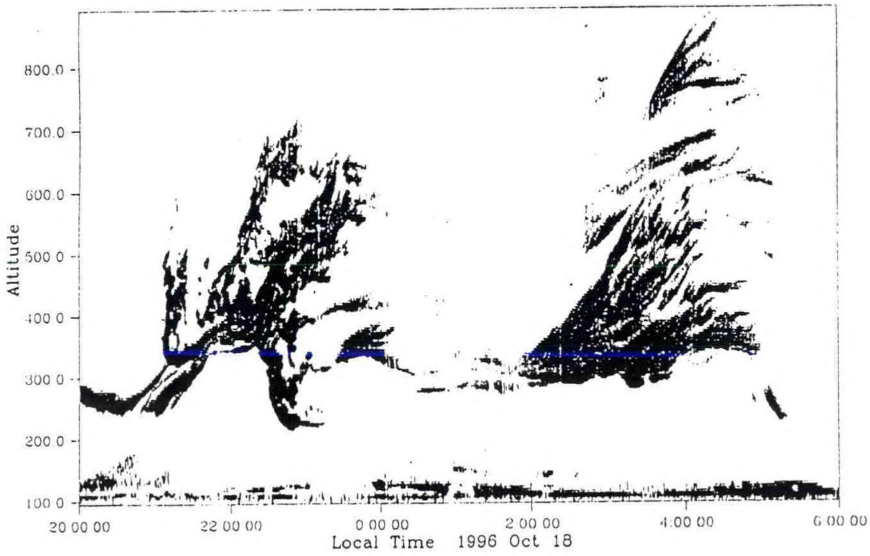


Fig.3

GPS Scintillation Fade Period Lengthening by Velocity Matching

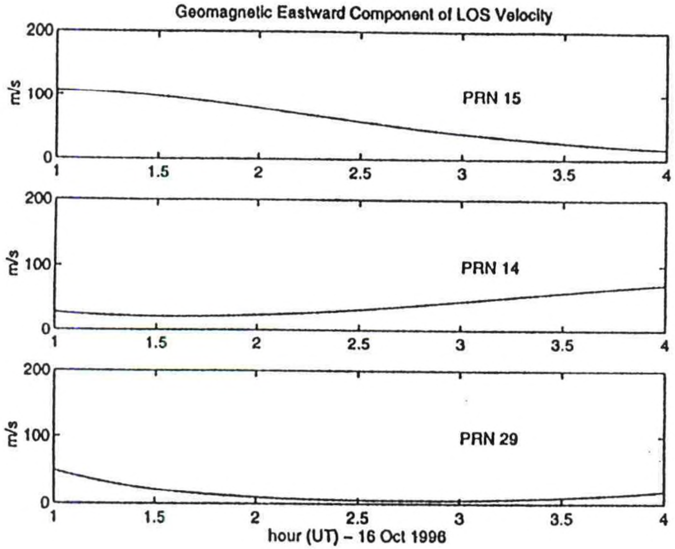
Paul M. Kintner and Theodore L. Beach
School of Electrical Engineering
Cornell University

Global Positioning System signal scintillations were measured from Ancon, Peru during Fall 1996 using the Cornell GPS scintillation receiver. Although during a time of low solar activity scintillations associated with equatorial spread-F were frequently observed with amplitudes of up to 6 dB. The Cornell GPS scintillation receiver produced signal strength estimates at a maximum rate of 50 samples per sec. This fast sample rate allowed the measurement of scintillation drift between two receivers whose antenna were separated 100 m apart in the East-West direction and from which we inferred ionospheric irregularity drifts. A key difference between GPS signals and signals from geostationary satellites is that the GPS signal ionospheric penetration point moves at E-W speeds of up to 100 m/s or more toward the East. Since the equatorial ionosphere typically drifts with an Eastward velocity of about 100 m/s there is the potential for the ionospheric irregularities and the GPS signal penetration point to match velocities. Under these resonance conditions we observe the scintillation fade times to greatly lengthen. Longer fades have design implications for GPS receivers specifically for tracking, signal acquisition and receiver clock drift rates.

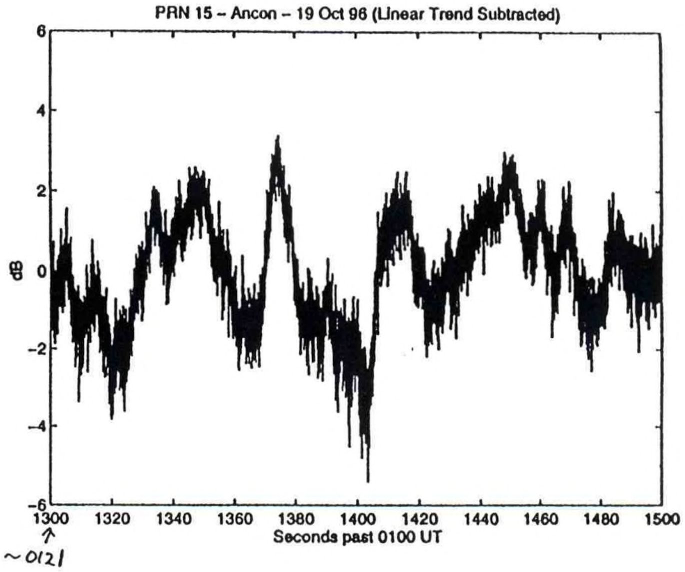
- GPS scintillation fade times will vary from fractions of a second to several tens of seconds and on rare occasions even longer within regions of equatorial spread-F.
- GPS signal acquisition times will lengthen. Different receiver acquisition strategies will be affected differently.
- GPS signal tracking is at risk. C/A code sideband amplitudes are -20 dB corresponding to scintillation amplitude expected at solar maximum. Loss of correlation is to be expected. Successful tracking through loss of correlation depends on ability of receiver to “flywheel”.
- Velocity matching criteria will be modified on moving platforms (airplanes) and will likely *increase* the probability of lengthening scintillation fade periods. (100 m/s = 225 mph).
- **Conclusion - Reduced integrity**

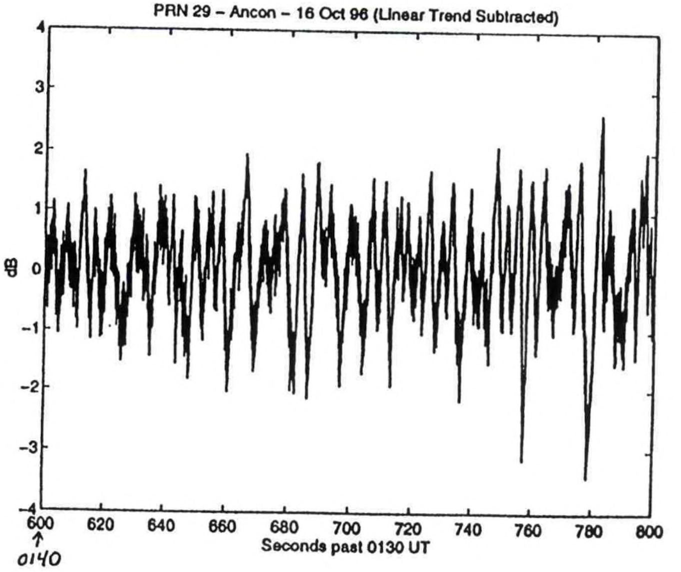
We gratefully acknowledge the support of the Office of Naval Research which funded the development of the Cornell GPS scintillation receiver and field campaigns. We also acknowledge the support of the Department of the Air Force through the Palace Knight Program and the Air Force Research Laboratory (AFRL, Phillips Lab) Hanscom AFB.

Effect of Ionospheric Penetration Point Velocity on Fading Rate



Satellite with larger geomagnetic eastward velocity shows longer fade time due to velocity matching.





The Upper Atmosphere Research Collaboratory

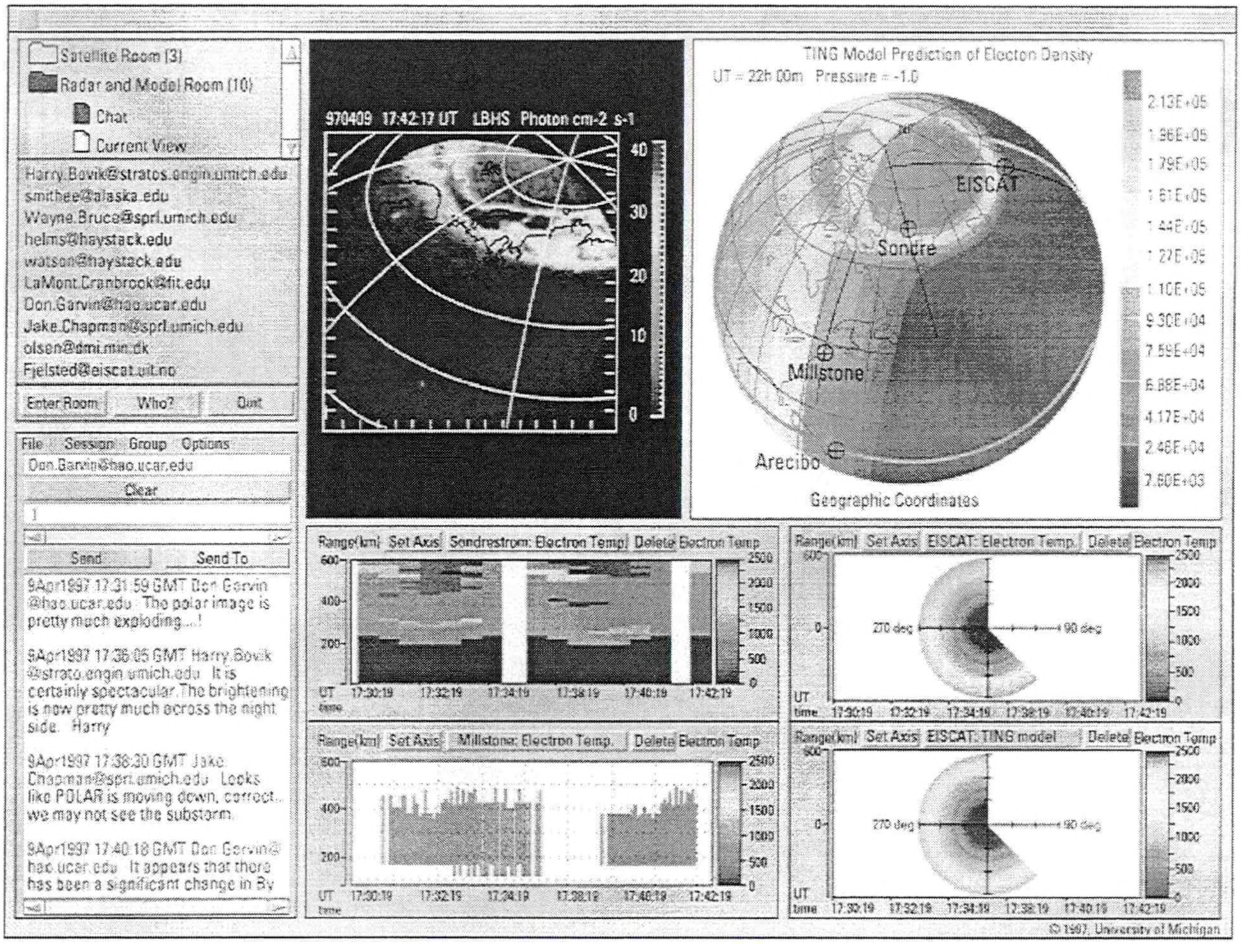
Peter Knoop
University of Michigan
Department of Geological Sciences

The Upper Atmosphere Research Collaboratory (UARC) has developed a WWW-Based capability to support real-time campaigns that can be undertaken by a number of investigators at a number of different sites. Recent developments have allowed several new data sources and theoretical models to be incorporated into the UARC Testbed. Up to this time, two global-scale campaigns have been conducted using these WWW tools, one in October 1996 and one in April 1997. The latter campaign used data streams from four incoherent scatter radar sites, the SuperDARN radar network, ground magnetometers, and optical instruments. In addition, real-time data streams from the ISTP, POLAR and WIND satellites were included. Furthermore, theoretical models, including a nested grid general circulation model based on codes developed at NCAR, were used to provide real-time or near-real-time nowcasts and forecasts.

Figure 1 is a screen dump which serves to illustrate a typical UARC collaborative science session. In the upper left corner is the "Session Manager" applet for organizing campaing activities and applications. Directly beneath it in the lower left corner is one of the "Chat" applets for communication between participants; all chat messages are logged so that you can leave and rejoin a chat session, and view what transpired while you were away. The upper left data display is a Polar UVI image, and next to it is a correlative diplsay from a near-real-time general circulation model. The lower displays contain data from incoherent scatter radars (Sondrestrom, Millstone Hill, and EISCAT), as well as a prediction of EISCAT data from the near-real-time general circulation model.

The UARC-supported network provides for a fairly comprehensive space weather system that can be used for validation and verification of theoretical models. It also has the potential to provide an immediate, useful space weather prototyping testbed. A new UARC campaign is being run this October to compare TEC data with model output, incoherent scatter radars, digisondes and other instrumentation. As well as doing TEC validation, the campaign also aims to study variability in the global ionosphere over normal geomagnetic activity and to provide a better understanding of the ways that space weather investigations can be carried out. The campaign will run from October 15 to 29, with a core period between October 20 and 24, coinciding with a World Day campaign; and, in addition, overlaping with this conference and demonstration.

For more information please visit our web site: *http://www.si.umich.edu/UARC/.*



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Fjelsted@eiscat.uit.no

Don.Garvin@hao.ucar.edu

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9Apr1997 17:31:59 GMT Don.Garvin@hao.ucar.edu The polar image is pretty much exploding....!

9Apr1997 17:36:05 GMT Harry.Bovik@strato.engin.umich.edu It is certainly spectacular. The brightening is now pretty much across the night side. Harry

9Apr1997 17:38:30 GMT Jake.Chapman@sprl.umich.edu Looks like POLAR is moving down, correct.. we may not see the substorm.

9Apr1997 17:40:18 GMT Don.Garvin@hao.ucar.edu It appears that there has been a significant change in By

Poster 3.22

Using TRAITS to Specify Scintillation and Propagation Error Over Large Regions

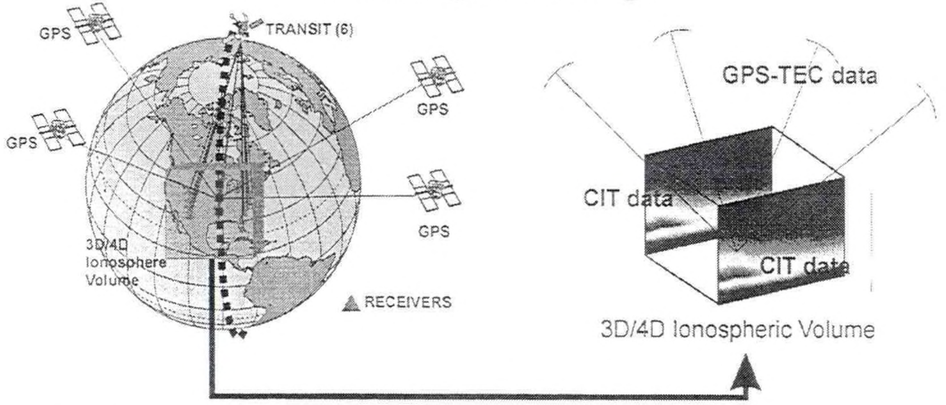
Glenn Kronschnabl, Clayton Coker, Thomas L Gaussiran II, Gary S Bust,
and David S Coco
Applied Research Laboratories, The University of Texas at Austin

The Applied Research Laboratories, The University of Texas at Austin (ARL:UT), is currently conducting a US Navy sponsored ionospheric specification campaign in the Caribbean using the Tactical Regional Area Ionospheric Tomography System (TRAITS). By combing computerized ionospheric tomography (CIT) from Transit with total electron content (TEC) data from GPS, a time varying 3D ionosphere is specified over a area which extends from -10N to 40N and is 50 degrees wide in longitude. The goal of the campaign is to provide opportunities for scientific studies of space weather and to develop the real-time capabilities of providing 3D ionospheric specification to applications which employ transionospheric satellite signals, e.g. GPS navigation and satellite communication. Adding Transit/CIT to GPS improves the specification of the shape and structure of the ionosphere which is a major source of error in the FAA Wide Area Augmentation System. Transit/CIT at 150 MHz and 400 MHz provides information about the strength, density, height, thickness, and latitudinal extent of scintillation. GPS at 1.2 GHz and 1.6 GHz, while less sensitive to scintillation, provides the needed longitudinal distribution and temporal evolution of scintillation. By combining the two systems, scintillation can be specified in real-time over a large region of the globe for communication applications and provide information necessary for an operator to determine whether to deploy alternative communication options.

Synopsis

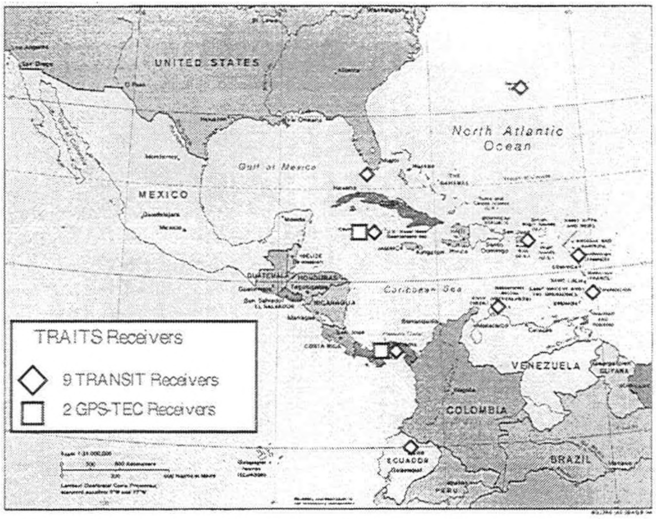
- Tactical Regional Area Ionospheric Tomography System (TRAITS) provides real-time 4-D ionospheric specification: N_e*(latitude, longitude, altitude, time)*

TRAITS System Concept



Utilizes LEO dual-frequency beacons (e.g. TRANSIT) for computerized ionospheric tomography (CIT) ⇒ Combines CIT with GPS-TEC systems to provide real-time 4D ionospheric specification

- Recent Accomplishments
  - –TRAITS currently deployed in Caribbean region
  - –Developed prototype real-time reconstruction software
  - –Developed algorithms to ingest GPS data



- TRAITS provides a 4D database for ionospheric corrections over a regional area
  - –Ideal for WAAS Validation
  - –Real-time WAAS Improvement
- Potential for Scintillation Monitoring by Exploiting Caribbean network
  - –Latitudinal and height snapshots
  - –Continuous spatial coverage
- TRAITS can be used to improve performance of many RF Systems
  - –HF Direction Finding
  - –BLOS Time Difference of Arrival
  - –Over-the-Horizon Radar
  - –SSL (Single Site Location)
  - –Transionospheric Applications
- Provide Real-Time Regional Ionospheric Measurements
  - –Geomagnetic storms
  - –Space weather
- Mission planning/assessment in near real-time
  - –Example scenario: optimal use of satellite transmitters and placement of ground receivers
- TRAITS is the Perfect Marriage
  - –Combines two ionospheric measurements (CIT & GPS-TEC) which provide complimentary insight into the ionosphere and implements them into a simple database with well a defined API
  - –"Open" design allows for inclusion of additional ionospheric sensors and observation types, such as UV limb scanning, optical sensors, and GPS-MET like systems

TRAITS

MEASURING THE IONOSPHERE

An Algorithm for Simulating Scintillation

A.J. Mazzella, Jr., E.J. Fremouw, J.A. Secan

NorthWest Research Associates

C.H. Curtis, Jr., G.J. Bishop

Air Force Research Laboratory

With the approach of the solar sunspot maximum in the year 2000, there is concern about the impacts on systems developed since the previous sunspot maximum in 1989. For solar-max conditions, there is a paucity of representative scintillation datasets, especially for systems operating at frequencies above UHF. To overcome this deficiency, methods for simulating scintillation effects are being developed.

The method presented here employs the two-component model of scintillation put forth by Fremouw et al (1980). This model characterizes a scintillation signal in terms of a high-frequency diffractive-scatter component and a low-frequency geometric-optics component. With separate standard deviations and correlation coefficients for each component, six parameters specify the first-order signal statistics. Second-order statistics are characterized by means of the power-law spectral indices for amplitude and phase, the Fresnel frequency, and a sampling interval.

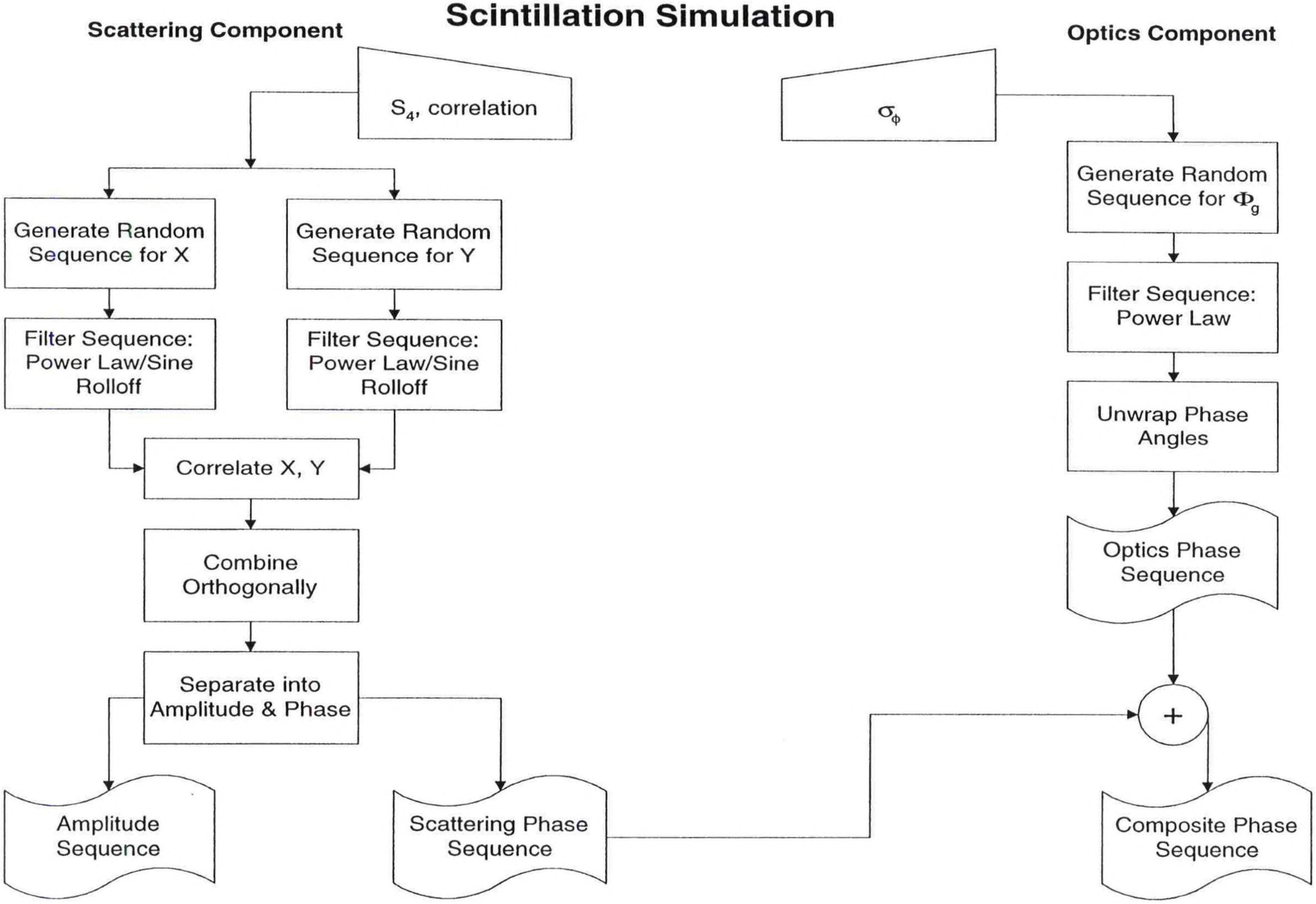
An algorithm has been developed for generating amplitude and phase time series for a scintillating signal from specification of the two-component model parameters. In this poster presentation, simulation examples are compared with scintillation data recorded in the Wideband Satellite experiment. Simulations at the GPS L1 frequency are also presented. These latter simulations were used to test the response of GPS receivers to strong scintillation using the Antenna WaveFront Simulator at Wright Laboratory, Wright-Patterson AFB. Test results from a single-frequency GPS receiver are presented.

Reference:

Fremouw, E.J., R.C. Livingston, and Deborah A. Miller, "On the Statistics of Scintillating Signals", *J. Atmos. and Terr. Physics*, *42*, pp. 717-731, 1980.

The Simulation Algorithm

Scintillation Simulation



Scattering Component

S_4, correlation

Generate Random Sequence for X

Filter Sequence: Power Law/Sine Rolloff

Generate Random Sequence for Y

Filter Sequence: Power Law/Sine Rolloff

Correlate X, Y

Combine Orthogonally

Separate into Amplitude & Phase

Amplitude Sequence

Scattering Phase Sequence

Optics Component

σ_ϕ

Generate Random Sequence for Φ_g

Filter Sequence: Power Law

Unwrap Phase Angles

Optics Phase Sequence

+

Composite Phase Sequence

Using the CORS Network of GPS Receivers to Produce Detailed Maps of the TEC over the Continental United States

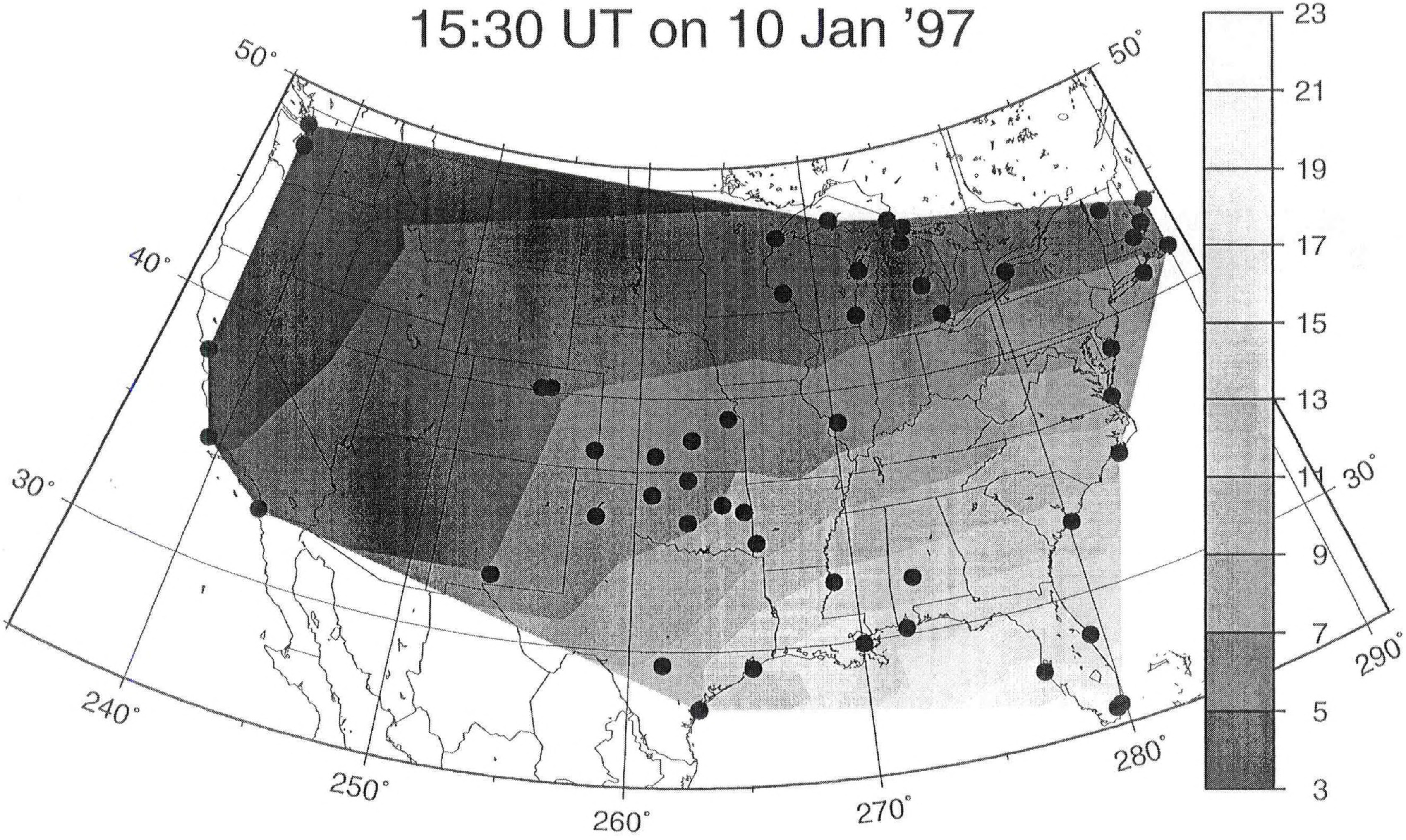
Steven Musman
Gerry Mader
C. Everett Dutton
Geosciences Research Division
NOAA
Silver Spring, Maryland

The Continuously Operating Reference System (CORS), administered by the National Geodetic Survey, is a network of Global Positioning System receivers used for a geodetic reference and other applications. At present there are over ninety receivers in the continental United States and new ones are being continuously added. We use the carrier phase of the two broadcast frequencies to estimate Total Electron Content (TEC) independently at each receiver site. Values since January 1, 1997 have been archived. We regularly monitor changes in TEC. During ionospheric storms the basic diurnal pattern is altered. The January 10, 1997 disturbance arrived when the network was in the predawn darkness. The major consequence was an increase of a factor of 1.5 to 2.0 in the daytime values of TEC several hours later. The accompanying figure shows this disturbance in the early daylight hours when the gradients were strongest. Local time is 10:30 am on the east coast and 7:30am on the west coast. In contrast during the May 15, 1997 disturbance, daytime values of TEC generally decreased. These changes are consistent with current ideas of seasonal differences in the response of neutral winds and chemical composition.

We plan to make available maps at half hour intervals on the internet. Also display of sequences of maps in movie form is under development.

TEC from the CORS Network

15:30 UT on 10 Jan '97

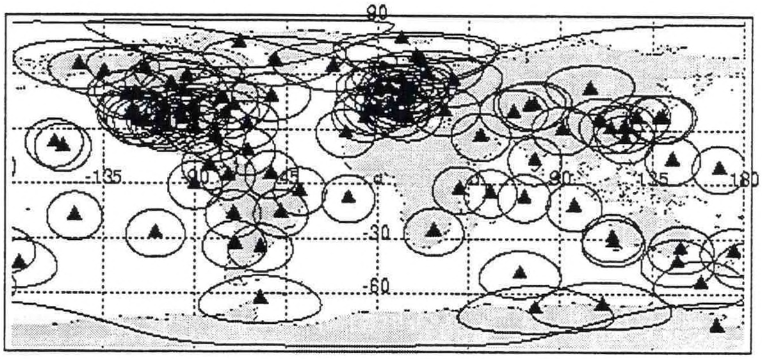


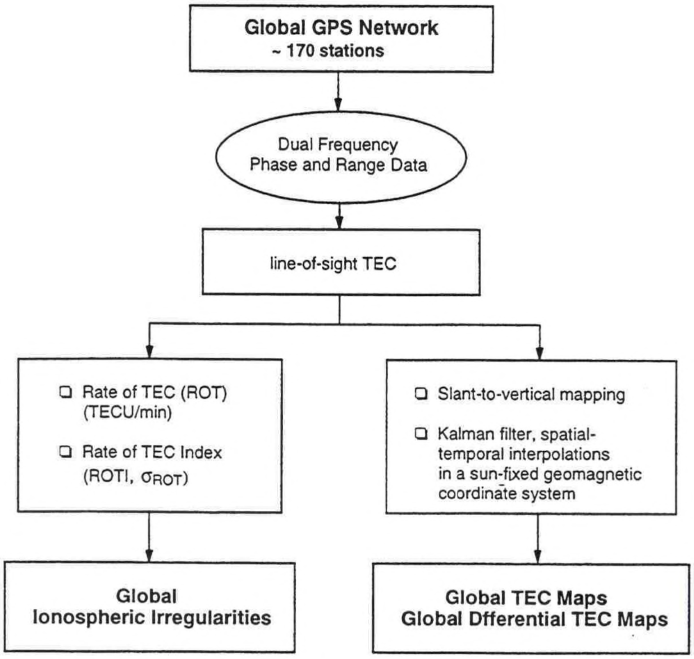
Poster 3.25

Monitoring of the global weather of ionospheric irregularities using the worldwide GPS network

X. Pi, C. M. Ho, U. J. Lindqwister, A. J. Mannucci, L. C. Sparks, and B. D. Wilson
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Continuous operations of the global GPS network, containing about 170 ground stations, make it possible to monitor the global weather of ionospheric irregularities. Such an effort is being made at the Jet Propulsion Laboratory using a technique that characterizes the differential phase fluctuations of GPS signals. In this presentation, cases of receiver loss of lock and phase cycle slip will be shown that are associated with strong GPS phase fluctuations in the presence of ionospheric irregularities. Besides low-and high-latitude activities, significant mid-latitude irregularity events have also been captured using the global GPS network, which occurred across the U.S. and adjacent regions during a major geomagnetic storm. This should bring our attention to the space weather effects on propagation of navigation and communication signals even at middle latitudes. The global differential maps (disturbed vs quiet) of ionospheric TEC, also obtained from the global GPS measurements, provide another diagnostic of ionospheric storm conditions under which irregularities develop. The combination of global maps of ionospheric irregularities and TEC will provide a powerful tool that can potentially contribute to the nowcasting of the irregularities and ionospheric storms.





Global GPS Network
~ 170 stations

Dual Frequency
Phase and Range Data

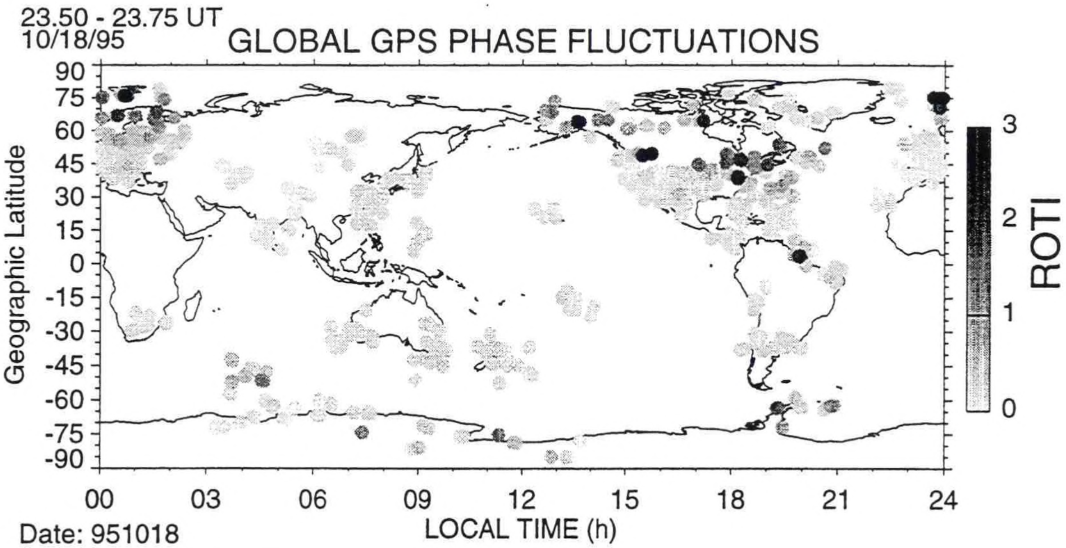
line-of-sight TEC

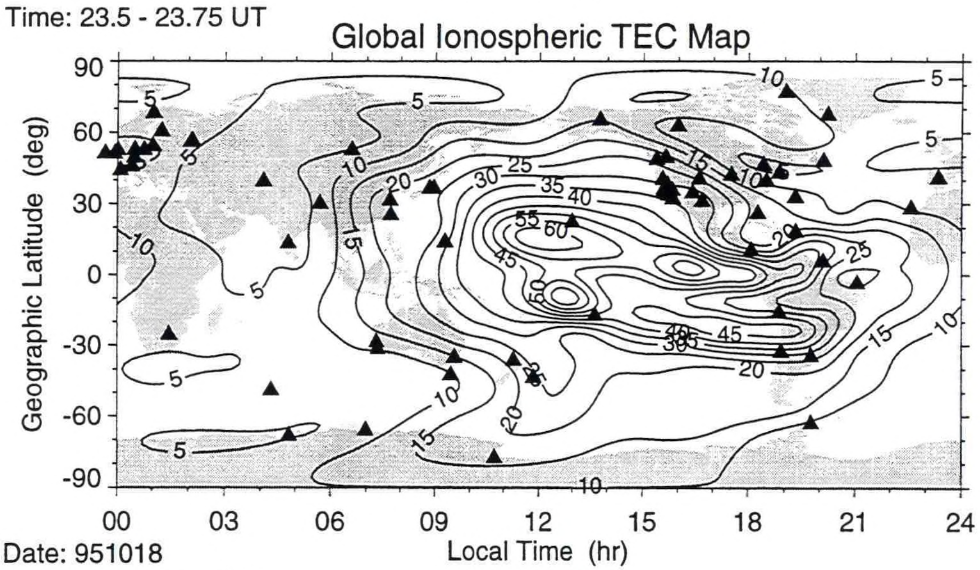
- ☐ Rate of TEC (ROT) (TECU/min)
- ☐ Rate of TEC Index (ROTI, σ_{ROT})

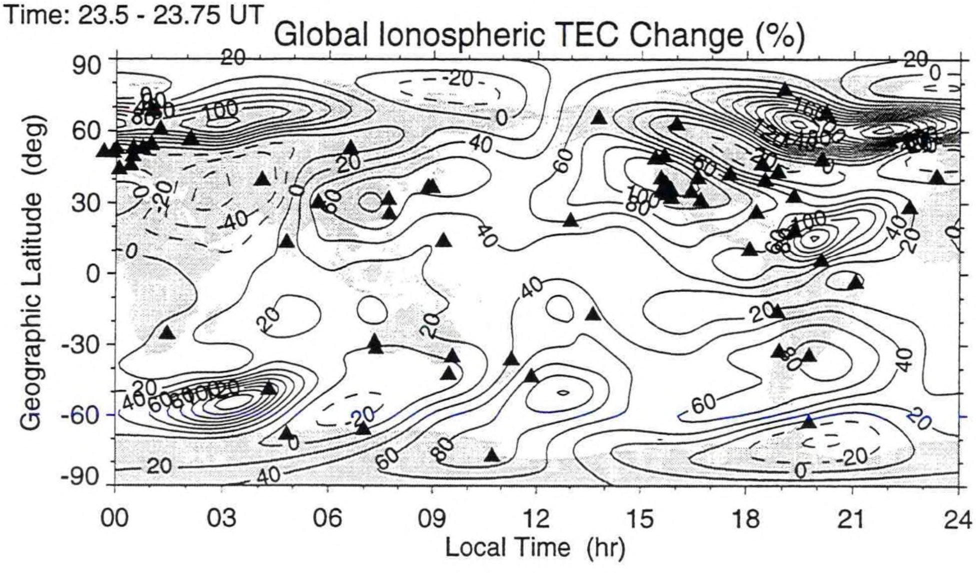
- ☐ Slant-to-vertical mapping
- ☐ Kalman filter, spatial-temporal interpolations in a sun-fixed geomagnetic coordinate system

Global Ionospheric Irregularities

Global TEC Maps
Global Dfferential TEC Maps


23.50 - 23.75 UT
10/18/95
GLOBAL GPS PHASE FLUCTUATIONS
Geographic Latitude
90 75 60 45 30 15 0 -15 -30 -45 -60 -75 -90
00 03 06 09 12 15 18 21 24
LOCAL TIME (h)
ROTI
0 1 2 3
Date: 951018


Time: 23.5 - 23.75 UT
Global Ionospheric TEC Map
Geographic Latitude (deg)
90 60 30 0 -30 -60 -90
00 03 06 09 12 15 18 21 24
Local Time (hr)
5 10 15 20 25 30 35 40 45 55 60
Date: 951018


Time: 23.5 - 23.75 UT
Global Ionospheric TEC Change (%)
Geographic Latitude (deg)
90 60 30 0 -30 -60 -90
00 03 06 09 12 15 18 21 24
Local Time (hr)
-20 0 20 40 60 80 100

Poster 3.26

Forecasting Solar Activity and Cycle 23 Outlook

Kenneth Schatten
Atmospheric Division, NSF; code 926, GSFC/NASA

Solar activity, although virtually impossible to forecast a month in advance, has succumbed to scientific methods on long time scales, much as climate or seasonal weather predictions are simpler than weekly weather forecasting. Moderately accurate solar activity forecasts on decadal time scales now seem possible. The methods that work fall into a class of prediction techniques called "precursor methods," and although other techniques, such as Fourier analyses do not appear to work, the precursor methods have worked for two solar cycles!

We will discuss 1) the historical origin for precursor indices; 2) the physical basis for the solar and geomagnetic precursor techniques and ; 3) how big the next cycle will be, based upon a NASA supported, NOAA SEC panel of experts findings that the next solar cycle would peak in early 2000 at a sunspot number near 160 +/- 30 based upon these techniques.

Poster 3.27

AURORAL ZONE LIMITATIONS FOR WADGPS

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Department of Geomatics Engineering
The University of Calgary

ABSTRACT

Ionospheric delays can be the largest source of GPS positioning error (up to tens of meters), outside of Selective Availability. Current GPS research is focused on developing differential networks capable of reducing these positioning errors, such that GPS can support precise positioning applications requiring meter-level accuracies. Such accuracies may be achieved through the use of differential GPS (DGPS) positioning techniques - the calculation of ranging errors by a monitor station, with errors broadcast to a user's remote receiver. An extension of the DGPS concept is a sparse array of GPS monitor stations, each equipped with a dual frequency receiver, referred to as a Wide Area Differential GPS (WADGPS) network. Estimates of ionospheric effects are computed using observations from each station in the wide area network and a grid of ionospheric corrections (vertical TEC) is formed and transmitted to remote receivers for correction of local positioning results.

An application of the WADGPS network is the wide area augmentation system (WAAS), a safety-critical system designed to support precision approach air navigation. FAA specifications for the WAAS include a grid ionosphere vertical error (GIVE) of 2m 99.9% of the time (3.29σ). This corresponds to an accuracy of approximately 60cm rms for grid point ionospheric vertical delay values. WAAS specifications include an update interval of 2-5 minutes. The grid accuracies, and estimates of the grid ionosphere vertical error (GIVE), generally depend on the estimated temporal/spatial correlations of TEC. Ionospheric grid models can suffer degraded performance in regions, such as the auroral zone, where spatial gradients and temporal variations of electron density may differ significantly from assumptions.

The auroral zone is characterized by particle precipitation events (i.e. auroral E-ionization and magnetospheric substorms) which cause significant variations in both the vertical and horizontal electron density gradients. The auroral oval is generally located between 65 and 72 degrees magnetic latitude, and can extend several degrees southward under significantly disturbed levels of ionospheric activity. Variations of auroral zone TEC are therefore significant concerns for WADGPS systems operating in Canada, Europe, and Alaska. In order to determine the effects of auroral activity on WADGPS grid performance, ionospheric disturbances must be identified and correlated with variations in ionosphere electron densities or TEC.

In the past, performance evaluations of wide area grid algorithms have relied on planetary indices to identify disturbed ionospheric conditions. The use of such indices (i.e. Kp, AE) to infer levels of ionospheric activity is ambiguous, however, since these indices are based on magnetometer measurements made at various stations distributed around the globe. A large planetary index may not necessarily indicate enhanced ionospheric activity in the wide area network region. In this paper, an alternative approach, not previously investigated, is employed to identify the level and magnitude of local ionospheric activity. Magnetic field measurements from twelve Canadian auroral zone magnetometer stations (the CANOPUS MARIA array) are used to identify the magnitude and location of localised particle precipitation events, during the period April - October 1996. Corresponding TEC values are then calculated, using simultaneous GPS data from ten stations in the Natural Resources Canada (NRCan) wide area network. Statistics representing the spatial correlation of TEC, under varying levels of localised ionospheric activity, are determined for the NRCan data set. The corresponding temporal variations of TEC, and the spatial extent of ionospheric disturbances, are also presented. Implications, with respect to wide area ionosphere grid models, are then analysed. In particular, the following considerations are discussed: grid spacing requirement for adequate resolution of localised activity, modeling of temporal correlations, and accuracies of wide area corrections.

FIGURES

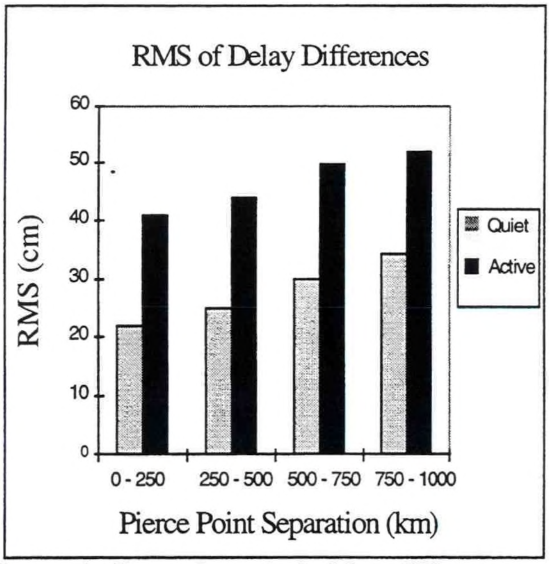


Figure 1. Rms of vertical delay differences, as calculated for various pierce point separations on the ionospheric shell at 350km altitude. "Quiet" statistics represent low levels of ionospheric activity, while "active" statistics represent geomagnetic disturbances in the northern auroral zone.

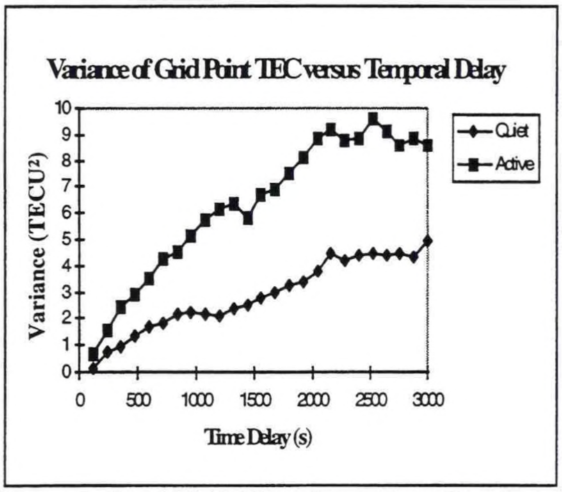


Figure 2. Vertical TEC variance, as a function of temporal delay. Slopes of the two plots correspond to process noise values of approximately 0.04 (0.08) TECU/√s for the quiet (active) data set.

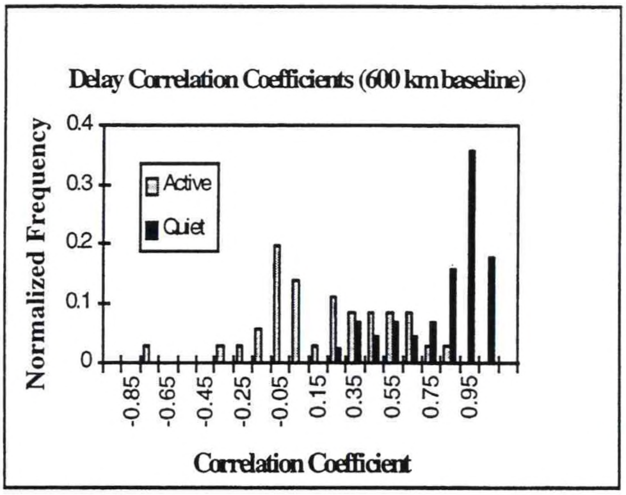


Figure 3. Correlation statistics for both active and quiet ionospheric delays, over a 600 km baseline. Statistics calculated using time series of simultaneous observations for the same SV, from two different stations.

TABLES

Table 1. Ionospheric grid vertical delay errors (m) for the active data set: grid spacing 3°×3°

PROCESS NOISE (TECU/√s)	MAXIMUM	MINIMUM	MEAN	RMS
0.04	.65	-.73	-.03	.32
0.08	.68	-.64	-.06	.28

Table 2. Ionospheric grid vertical delay errors (m) for the active data set: grid spacing 6°×6°

PROCESS NOISE (TECU/√s)	MAXIMUM	MINIMUM	MEAN	RMS
0.04	.72	-.75	.03	.36
0.08	.74	-.79	-.02	.35

CONCLUSIONS

- larger spatial gradients and temporal variations for the active, versus quiet, data set.

- results of tables 1 and 2, and figure 3, suggest grid spacing of < 6° preferable, for optimal results.

- higher accuracies for "active" data set using higher (lower) values of process noise (grid spacing).

A Two-Tier Educational Approach to Space-Weather Modelling Via Computer Graphics

Bryan Talbot
TASC, Inc., 4801 Stonecroft Blvd., Chantilly, VA 20151, (703) 633-8300 x4111

One of the important yet lesser-studied propagation problems associated with the space weather community is that of ''propagating" new modelling capabilities from the researchers to the users. The space weather community encompasses a diverse set of individuals and activities. The gap between science-oriented researchers and application-oriented users is sometimes very large, as measured by the effort required to inject new models and capabilities into the system. It is often true that the effort required to educate the community regarding new capabilities may equal or exceed the effort to develop the capabilities in the first place. In this light, this presentation focuses upon computer graphics as an education mechanism. Graphics generation often represents the final stage of the model development process, as viewed from a science perspective. At the same time, computer graphics often represent the first stage of the educational process, as viewed from an applied perspective.

This presentation asserts that computer graphics can function in a pivotal position by linking the final stages of model development to the initial stages of model education and application. The effective application and advancement of computer graphics is important to many fields in addition to the ionospheric community [1]. Here, a two-tier graphics approach is demonstrated for educating the community regarding new advances in the field using a single pivotal element: interactive visualization software.

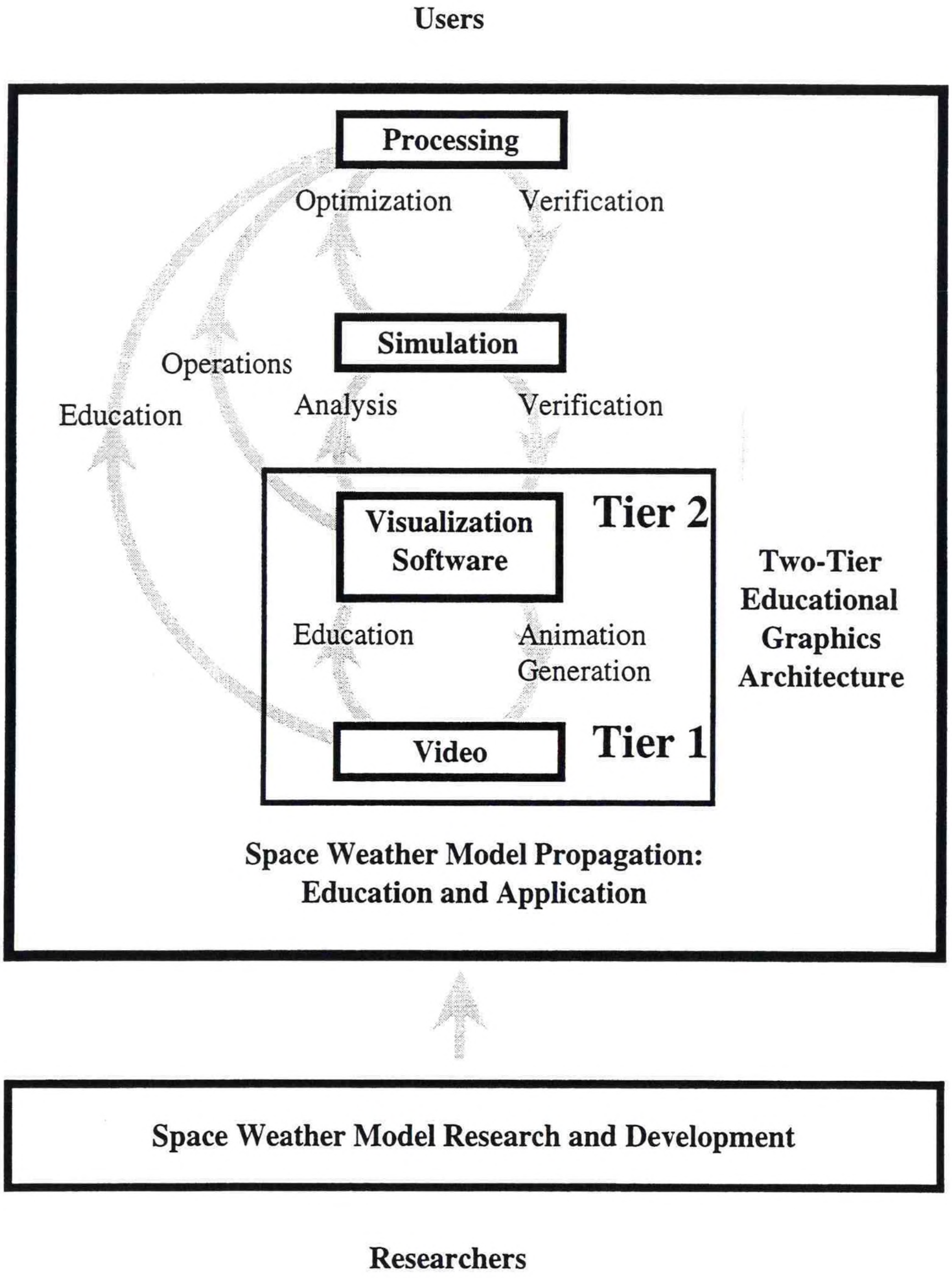
The first tier, targeted at decision makers and new users, employs graphics using a video tape medium to educate regarding general system characteristics in conjunction with model solutions. This tier provides a simplified representation of model potential and capabilities.

The second tier, targeted at users and analysts, employs graphics in the context of a simple interactive visualization application which provides direct access to the models. This tier provides additional in-depth information regarding model capabilities.

Here, we illustrate the two-tier graphics approach using SWEET (Space Weather Extensible Environment Tool), a prototype visualization tool derived from SEAT (Space Environment Analysis Tool). The first tier educational process is exemplified by a new video-tape produced using SWEET, "Ionospheric Scintillation Effects: A Visual Demonstration using WBMOD and SWEET", designed to help individuals understand scintillation activity and application of scintillation models. The second tier educational process is exemplified by interactive windows in SWEET and SEAT which provide access to modelling capabilities. The tiers are linked by visualization software design which supports video animation production.

We are finding this two tier graphics approach to be successful in educating decision makers and analysts about space weather effects and models. Thus, it is providing a useful mechanism by which new modelling capabilities can be introduced and propagated to the community with greater speed and assurance.

Talbot, B.G. and Peterson R.E, ''A polygon reduction algorithm for enhancing graphics performance with application to fast rendering of geophysical and ionospheric model data", To appear in the *International Journal of Geographical Information Science*, 1997.



Computer Graphics: The Pivotal Link Between Model Development And Application Stages

Measuring Ionospheric Scintillation Using GPS Receivers

A. J. Van Dierendonck & Quyen D. Hua, GPS Silicon Valley, Los Altos, CA, USA
Jack Klobuchar, Total Electronic Concepts, Lincoln, MA, USA

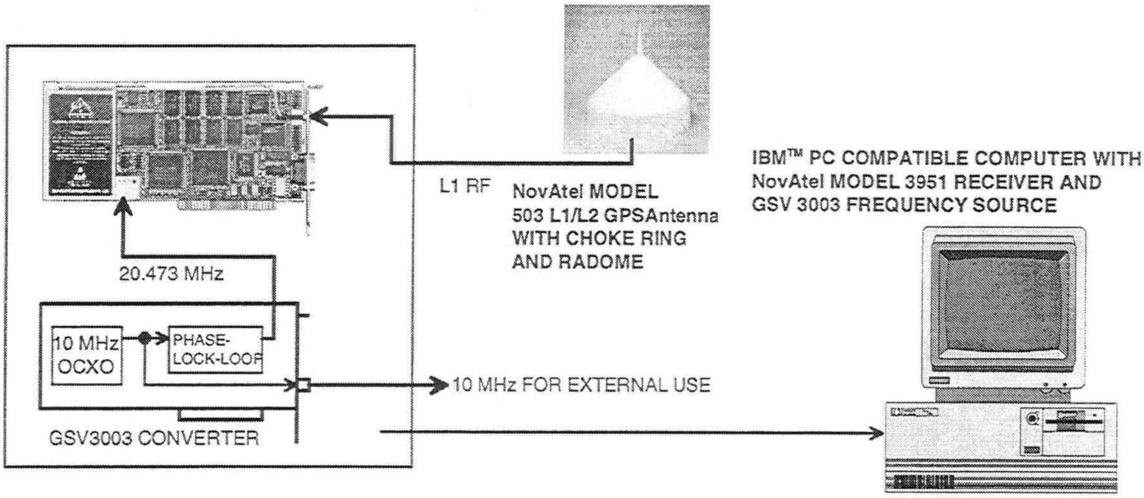
GPS signals provide an excellent means for measuring ionospheric scintillation effects on a disperse global basis because they are continuously available and can be measured through many points of the ionosphere simultaneously. GPS signals are themselves affected, but because of the spread spectrum properties of the signal, tracking through disturbances with a GPS receiver is usually possible with reasonably wide bandwidth tracking loops, and scintillation parameters can be extracted. Thus, GPS provides an excellent means for monitoring both amplitude and phase ionospheric scintillation as well as total electron content (TEC).

This paper presents the algorithms required to perform scintillation measurements and the results of testing a software and hardware-modified commercial GPS C/A code receiver to perform this function. The development of this receiver resulted in a low-cost GPS Ionospheric Scintillation Monitor (GISM) that has been transformed into a commercial product (GSV4000). Development is underway to extend this capability to a dual frequency version that will also measure TEC. Although the non-availability of actual scintillation has prevented testing in that environment, results of extensive testing in a benign noise environment, but in a somewhat moderate multipath environment, is presented.

GPS IONOSPHERIC SCINTILLATION MONITOR

GPS Silicon Valley is pleased to offer the GSV 4000 ionospheric scintillation receiver which comprises the major component of a GPS signal monitor, specifically configured to measure amplitude and phase scintillation from the L1 frequency GPS signals. This scintillation monitoring receiver fits into two slots in a personal computer, and provides true amplitude and single frequency carrier phase measurements of all GPS satellites in view. The unit comes with complete software which allows the automatic measurement and computation of all the major scintillation parameters, and an antenna with a choke ring ground plane to minimize multipath effects, and a radome for protection from snow, ice and birds.

BLOCK DIAGRAM OF THE GSV 4000 GPS IONOSPHERIC SCINTILLATION MONITOR



GPS IONOSPHERIC SCINTILLATION MONITOR (GISM) FEATURES:

- Tracks and reports scintillation measurements from all GPS satellites in view.
- A 12.5 Hertz raw signal intensity noise bandwidth and a 15 Hertz phase noise bandwidth insures that all the spectral components of both amplitude and phase scintillations are measured. Phase data is sampled at a 50 Hz rate, and amplitude data is sampled at a 25 Hz rate.
- Actual, single frequency satellite carrier phase is compared against a stable ovenized crystal oscillator to insure that all phase scintillation effects are recorded, not merely the 1/f refractive component measured by dual-frequency differential systems.
- Software is included in the GISM to automatically compute the following scintillation parameters: amplitude scintillation index, S_4, phase scintillation index, σ_ϕ, and the computed power spectral intensity and spectral slope of both the amplitude and the phase spectra. In addition, the amplitude scintillation rate parameter, ν_c, can be computed from recorded amplitude spectra parameters.
- Scintillation measurements from the GISM can easily be scaled to the frequencies of the new, L-band and C-band low-orbit personal telecommunications satellites, such as Iridium and others presently under construction, to predict the magnitude of scintillation effects on those commercial systems. These measurements can also be scaled to lower frequencies typical of older military and commercial systems.
- The GISM is available as plug-in cards for a Personal Computer. Only two slots are used. The receiver is powered directly from the PC.

4 Results from Communication Discussion Sessions

Facilitator: Dr. Louis Lanzerotti, Bell Labs, Lucent Technologies

Recorders: Dr. John Goodman, TCI/BR Communications (TCI)

Dr. Keith Groves, Air Force Research Laboratory (AFRL)

4.1 Notes from Wednesday

As facilitator, Louis Lanzerotti set the stage for fruitful discussion by affirming that this workshop was focused specifically on propagation of communication and navigation signals via and through the ionosphere. While Space Weather is a substantially broader topic, we should strive to maintain the propagation focus in order to meet the workshop goals. The facilitator noted the presence of three identifiable groups of participants: (1) end users of space-weather services, (2) providers of such services; and (3) ionospheric modelers and developers of space-weather tools. He then invited participants from those three communities to identify themselves and state their space-weather interests.

Several from the DoD user community stressed the need to know operational impacts of space weather. The phenomena may be interesting, but the important question operationally is "So what?" For example, what are the impairment possibilities for aircraft communication systems. A participant from Aerospace Corporation pointed out the possible utility of coding and other approaches to mitigating impairments.

Gus Lott (Naval Postgraduate School) identified several points of Navy interest. When a problem with UHF communications via satellite occurs, it is important to know whether it is due to attack, equipment malfunction, or ionospheric disturbance. Gus pointed out that geopositioning at HF is to become clandestine in operations, so the accuracy of passive geopositioning is of interest. A member of a Coast Guard communications assistance team also described communication needs.

From the private sector, a representative of General Electric identified space-weather effects as a component of setting link budgets in satellite communications systems, specifically the emerging systems in low-earth orbit (LEO). It was pointed out that some small entrepreneurial companies are users as well, but they are reticent to acknowledge potential vulnerability to space-weather effects.

The discussion then turned to categorizing space-weather effects on communications by frequency band, as follows:

1. ELF:
    - Lower frequency limited set by Navy use.
    - Space weather has little impact on existing ELF operations, with tropospheric weather being more pertinent.
    - The High-frequency Active Auroral Research Program (HAARP) could lead to enhanced use of ELF for naval operations.
    - For HAARP, geomagnetic and auroral aspects of space weather are important.

2. VLF:
   - There are DoD applications of VLF.
   - Space weather has little impact on them.
3. MF:
   - Space weather has little relevance.
4. HF:
   - Battleforce e-mail is an important HF activity [groundwave and skywave]. Phase disturbances on modems may be a problem.
   - In addition to communications, space weather is very relevant to operation of over-the-horizon (OTH) radars.
   - OTH radars also can serve as sensors of ionospheric conditions (e.g., detection and location of spread-F conditions).
   - There is interest in development of nowcasting products and services.
   - Automatic Link Establishment systems are intended to mitigate the effects of ionospheric variability.
   - The Center for Remote Sensing (CRS) is developing a high data-rate HF modem; Suman Ganguly stated CRS' expectation that, under some conditions, such devices can provide information rates competitive with those provided by operational satellite communication systems.
   - Gus Lott reported that 55 different models of "mean" ionospheric conditions that he surveyed were based on essentially five "algorithms." He pointed out the need to transition to a real-time model. He doesn't see a DoD need for additional models.
   - Bodo Reinisch (Univ. of Mass. at Lowel) asserted that models will never do as well as observation-based nowcasting.
5. VHF/UHF:
   - These are the primary bands in which transionospheric scintillation can present operational problems.
   - Several "Little LEO" systems may operate transionospheric uplinks and/or downlinks at VHF and/or UHF. The Little LEO system most likely to be launched first is "Orbcomm," planned by Orbital Sciences Corp. (See talk by J. Evans in these workshop proceedings.) It will employ transionospheric links at 138 MHz, 149 MHz, and 400 MHz, all of which have been employed for direct observations of scintillation over several solar cycles.
   - Gus Lott stated that the Navy will continue to employ 250 MHz for communications throughout the foreseeable future because of its substantial

investment in equipment at that frequency and because of tropospheric effects at higher ones.

6. L Band and above:

    - In addition to ionospheric effects on GPS, one may expect effects on "Big LEO" systems that include transionospheric links at L Band (such as Iridium Globalstar, and ICO-Global).
    - Both the GOES downlink and Seasat operate at L Band.
    - In the equatorial region, substantial scintillation has been measured at S Band during post-sunset hours of years near solar maximum, and weak scintillation has been measured at S Band in the auroral region.
    - Above S Band, little ionospheric effect is likely.

During ensuing discussion, David Anderson (AFRL) pointed out several organizations that are very cognizant of the importance of HF as a communications asset. The High Frequency (Radio) Industries Association (HFIA), for example, is an industry association involved with promotion of HF products in the U.S. and elsewhere.

John Goodman (TCI) described the High Frequency Data Link (HFDL), which is an internationally sanctioned com link being developed by Aeronautical Radio Incorporated for aeronautical-mobile use. Ultimately, HFDL may plan a role in communications for air traffic services and control, and it's likely to replace HF voice on a number of maritime links. It can be important for some over-the-pole routes, where current satellite coverage is relatively sparse. It is also being examined as a companion to satellite communications for transequatorial flights, where scintillation at L Band could lead to some communications outages. John suggests that a useful synergy could be developed between HF and satellite communications because their ionospherically induced failure mechanisms are different. He points out that combining a satellite system with a reliability of 0.999 with an independent HF system with a reliability of 0.9 would produced a combined reliability of 0.9999.

Specific research and monitoring needs identified included the following:

- quantification of coherence bandwidth on transionospheric links;
- metrics to quantify the accuracy and reliability of models;
- metrics to quantify the utility of improving model accuracy; and
- continued operation of the Navy's Transit satellites as signal sources for ionospheric tomography and monitoring of VHF/UHF scintillation at all latitudes.

Also important is communicating space-weather behaviors to users. System designers often are looking for a single number to quantify link reliability. They need to be informed about climatology. Then the research community can characterize behaviors in best and worst times of day, best and worst months, etc. Nowcasting and forecasting then can be made relative to the climatological characterizations. Rapid deployment of regional models may then be feasible.

John Goodman pointed out the relevance of space-weather effects to regulatory matters. Approval of licenses and spectrum utilization depend on efficient use of the spectrum. Cognizance of space-weather effects and conditions can enhance the quality of a service, which should better its chances of being licensed.

This first session of the communications discussion group ended on a programmatic note. While this workshop is bringing together the three communities identified by the facilitator at the beginning of the session (users, providers, and developers of space-weather services and tools), technology transition often is "homeless." Agencies have defined missions: NSF is chartered to promote basic research and education; the DoD labs and extra-mural funding agencies must focus on defense applications; etc. NOAA, an element of the Dept. of Commerce, probably is in the best position to foster technology transition in the civilian sector, but its budgets always are very limited. Programs that cross agency boundaries, such as that for Small Business Innovative Research (SBIR), can help bridge existing gaps. The SBIR Program, established some years ago by an act of Congress, does provide opportunities to turn research into products.

4.2 Notes from Thursday

The second communication session began with a short but significant briefing by Willow Cliffswallow (AF Materiel Command). Emphasizing theater battle management, Willow stressed that space-weather products should be devised with a plan of operations in mind. She described the following four stages of planning:

- long-term (six months to a year), for which climatology is relevant;
- campaign (weeks to months), for which climatology and long-term forecasts are relevant;
- generation of Air Tasking Orders (24 to 72 hours in advance), with forecasts needed by Air Combat Command;
- next-day route and action planning at the unit level, for which forecasts and nowcasts are needed.

At least two levels of model were noted. For example, we need to go from a magnetospheric parameter like B_z (magnitude of the northward component of the interplanetary magnetic field) to S_4 (intensity scintillation index). Next we need to go from S_4 to its impact on a specific system – or even on troop deployment if the system impact leads to a deployment decision.

The entire process has to be automated. The operators don't need geophysical parameters (geomagnetic indices, plasma-densities, etc.); they need indicators that are virtually "binary" in nature: Go/No-Go, color codes (red, green), etc. The most important things to do are the following:

- Quantify sensitivity of systems to effects in operational terms;
- Quantify reliability of models, forecasts, and other products;
- Answer the "So what?" question by quantifying the mission improvement contributed by space-weather products. (That is, assess the benefits.)

Repeatable methods and standard metrics are needed for all of the above. It was noted also that the Air Force likes to develop what it calls All-Weather systems, which Willow prefers to think of as Adverse-Weather systems.

From the Navy perspective, Gus Lott affirmed the importance of quantifying the reliability of models, etc. Models must be statistically quantified before they are accepted. For example, a forecaster must answer questions such as, one day before a mission, "Are you 99% confident that satellite communications will not be interrupted by scintillation from midnight to 0700?" During ensuing discussion, the group repeatedly returned to the importance of quantifying probabilities and uncertainties, which are largely lacking in current space-weather products. Examples of this need include (a) the probability of a given frequency being useable and (b) the uncertainty range in a forecast of dB path loss on an HF link.

Gus Lott also posed a need for portable sensing systems that could be deployed for remote operations. He challenged the research community to identify, for example, what ionospheric information and associated uncertainties (δ) could be extracted from a dual-frequency GPS receiver (e.g., TEC $\pm \delta$, $f_of_2 \pm \delta$, $S_4 \pm \delta$, etc.). These comments were driven by a desire to utilize sensors available on every ship in the fleet and the Navy paradigm of generating products on-board vs. the Air Force approach of centralized product generation and dissemination via 55 SWXS.

Willow Cliffswallow suggested that there might be much Air Force interest also in doing "something small" – that is, developing a procedure that would be rather easy to implement, could be done quickly, and would make an immediate impact. She suggested, as an example, dropping sounders into a target environment to provide propagation information. She also suggested that there may be opportunities to exploit space-weather forecasting and prediction by considering impacts on hostile systems. That is, superior knowledge of effects on enemy nav & com may be an asset.

Returning to the question of assessing the validity and accuracy of models and other space-weather products, the group noted the need for some sort of organized approach with defined responsibilities. A relatively new development is Air Force emphasis on "tech. transition" of models via a rapid prototyping center. Validation should include comparison of various related or competing models to determine quantitatively which approach provides the best accuracy in a variety of applications.

Lou Lanzerotti pointed out the relevance of disparate applications. Even if a sunspot pattern repeated itself exactly in two solar cycles, the fact that the properties of deployed systems vary from cycle to cycle means that the influence of the storms will be different from one cycle to the next. Moreover, ionospheric disturbances associated with the solar cycle vary from cycle to cycle in terms of numbers and intensity.

A remark was made that two-thirds of all customers of the Air Force space-weather forecasting services are HF systems users. The workshop charter included HF as kind of afterthought (i.e., parenthetically) since it was viewed as not likely to be significant for future DoD and civilian use. The discussion group concluded that the attention paid by the Air Force forecasting community (i.e., 55th Weather Squadron) to HF is due to the disproportionate number of HF users who <u>currently</u> profess to need the products and are happy to get the forecasts and advisories. Space-weather services must address existing problems, as well as future ones, and there are a lot of HF systems in use.

A discussion followed about whether or not the discussion group should list all communication systems by band and evaluate the impact of space weather on each one. It was decided that doing so would take too long and that this group might not be able to provide an accurate assessment since each system is different. It was decided that a better approach would be to examine parameters such as fading depth, signal-to-noise ratio (SNR), coherence bandwidth, and related quantities as functions of frequency band.

Discussion continued about requirements for information about parameters that space-weather products need to quantify. It was felt that measures are needed to quantify the level of sensitivity by various system types to environmental parameters. Confidence limits also need to be established for those parameters. Gus Lott reiterated that Navy applications require path-loss information (such as might be provided by the Damboldt model) plus its variability. The following table (in which LUF and MUF denote "lowest useable frequency" and "maximum useable frequency," respectively) contains consensus points about relevant parameters.

Frequency Regime	SystemType	Relevant Parameters
HF (3-30 MHz)	DoD & some civil com, OTH	LUF, MUF, fade level, SNR
VHF (30-300 MHz)	Little LEOs	Scintillation fading, SNR
UHF (300 MHz-3 GHz)	Big & Little LEOs, GOES, Inmarsat, Seasat, other	Scintillation fading, SNR, Coherence bandwidth

Discussion continued around the subject of 'So What?'. The question of what financial or other saving will a user realize from a particular space-weather product is an important issue.

A comment was made about Iridium. Motorola chose not to come to the workshop, even though early interest in scintillation impairments had been expressed to Santimay Basu (AFRL), Robert Schunk (Utah State Univ.), and James Secan (NWRA). Suman Ganguly suggested that if Iridium perceived a problem, it would take a small percentage of its capital investment and try to solve the problem directly; it probably would not involve the Space-Weather community. Lou Lanzerotti stated that issues of satellite drag (which is related to A_p, as suggested by Jacchia many years ago) is an issue with Iridium, but drag effects are not within the intended scope of this workshop.

It was remarked that, while an ionospheric perturbation (say, scintillation fade depth) may decrease with increasing radio frequency, the effect of a given perturbation may be larger at the higher frequencies. This applies to earth-space systems for which the system margin is critical.

There was more discussion on metrics for models. This topic will be addressed in a special session at the meeting of the American Geophysical Union in San Francisco in December 1997.

The final topic discussed was electromagnetic interference (EMI). The SNR is set by both signal **and** noise. Noise can be influenced by both space weather (e.g., by propagation of RF noise below the ionospheric layers) and tropospheric weather (e.g., vy noise sources such as thunder-storms). This is one area in which space weather and tropospheric weather both play a role.

5 Results from Navigation Discussion Sessions

Facilitator: Dr. Bakry El-Arini, MITRE Corporation

Recorders: Mr. Greg Bishop, Air Force Research Laboratory (AFRL)
Mrs. Patricia Doherty, Boston College

5.1 Notes from Wednesday

The session opened with a briefing on summary of the requirements and capabilities of the FAA navigation systems including Wide Area Augmentation System (WAAS) and Local-Area Augmentation System (LAAS). Bakry El-Arini, the session facilitator, presented the briefing. In response to the presentation, the scientists in the audience were concerned about several issues related to WAAS. The following questions/concerns were raised:

- What ionospheric conditions were present during flight-testing?
- Were they under ideal ionospheric conditions?
- At what times of day, season, solar activity, and magnetic activity levels were the flight tests conducted?
- Are spatial gradients accounted for in the WAAS grid algorithm?
- Can the grid miss spatial gradients?
- What are the scintillation effects for WAAS?

The discussion that followed indicated a need for the scientific community to provide advice to the FAA on locations and times for WAAS flight-testing into the next solar maximum. In addition, there is a need for the scientific community to provide the aviation community with a study on the spatial gradients of TEC. Wide Area Systems, such as WAAS, will provide single-frequency user aircraft with a 5°-by-5° geographic grid of vertical ionospheric delay corrections. Each ionospheric grid point will be accompanied by an error estimate of the ionospheric correction at that grid point. The concern is that the grid calculations could miss steep spatial ionospheric gradients such as those found at the boundaries of the mid-latitude trough, the equatorial anomaly region and those induced by magnetic activity.

Dean Miller (Boeing) said that he was more concerned with general navigation problems. In particular, he would like to initiate discussion related to understanding the ionospheric effects not just for WAAS but in satellite tracking. He would like to understand the ionospheric threats before attempting to understand an individual design. Dean also was concerned with how the receiver behaves, that is, the probability that the receiver will encounter severe conditions to cause deep fades.

In response, Greg Bishop (AFRL) and Clayton Coker (Univ. of Texas at Austin) talked about the joint AFRL/WRIGHT Patterson plan to test receiver performance at Wright Lab. The most stressful periods for the latest technology in GPS receivers will be during solar maximum. Unfortunately, solar maximum GPS measurements are not available for current receivers.

At the facilitator's request, A.J. Van Dierendonck talked to the group about GPS receivers in general. He suggested that short deep fades (~100 milliseconds) would not pose a problem, while longer fades (~5 seconds) would be a definite problem. He continued the discussion by saying that a receiver would recover quickly from short dropouts, but a long dropout or a series of shorter dropouts would make the receiver start the search again. He gave the depth-of-fade level of 15 dB as a margin for dropouts. He said that, under otherwise normal conditions, receivers can withstand 15 dB of fading. At 20dB, however, receivers lose lock. He also commented that receivers are very different and that a user must know its intended use. He specifically pointed to a study by Wanniger that indicated a high frequency of dropouts. A.J. emphasized that Wanniger used a survey receiver – one that is very sensitive to scintillation. It was not an aviation receiver.

Greg Bishop talked about data seen in his work with Santimay Basu (AFRL) in 1994. In these data, under disturbed conditions, most visible satellites were scintillated at some level. Greg was concerned about the results under more extreme conditions. He indicated that there would be a continued need to monitor receiver performance into the next solar maximum.

In closing this first meeting of the navigation discussion group, the facilitator asked Dean Miller to prepare a list of concerns to be presented on the following day. He also invited all participants to think about specific issues that they would like to have addressed in the next day's session.

5.2 Notes from Thursday

The scope of the second navigation discussion session was substantially broader than that of the first (shorter) session. The facilitator opened the second session with the following proposed agenda:

- Short briefings (10 minutes max for each presentation)
    - Listing of major space-weather problems to navigation systems by Dean Miller and by John Foster (Lincoln Lab)
    - Some questions from Steven Chavin (Illgen)
    - Summary of the statistics of scintillation by Santi Basu
    - Scintillation Simulation by Andrew Mazzella (Northwest Research Associates)
    - Testing of GPS receivers by Clayton Coker
    - Performance of single-frequency receivers by Patricia Doherty
- Group definition of open issues (60 minutes)
    - TEC: Mismodeling, leading to errors in pseudorange and, hence, position
        - Spatial gradients, rate of change
        - Where, when, how big?
        - Peak of solar cycle, storm effects
        - Probable impact on Nav?
        - What needs to be known?
    - Scintillation: Reduced signal quality, availability, and integrity

        - Will there be nav accuracy degradation and/or outages?
            - Anecdotal reports exist. Any hard data?
            - Hard data is essential.
        - Can we presently quantify effects/impacts? No!
            - Wait and measure at solar max?
            - Find a way to bench-test?
        - What does a bench-test require?
            - Can we macro/micro characterize structure/occurrence? (Data/Models)
            - Define nominal and extreme conditions: Mid lat., Equatorial, Polar, Auroral; Storms
            - Can we apply scintillation data "on-bench"?
    - NAV system field tests: What are shortfalls of existing tests?
    - Ionospheric data: What data are needed?
- Group recommendations (60 minutes)
    - TEC
    - Scintillation
    - NAV field tests
    - Ionospheric Measurements

Dean Miller's presentation provided a clear goal for the aviation community. That goal is to understand ionospheric effects well enough to assess whether or not they pose a threat to a GPS-based operating system. He described the need for a couple of products that would provide a clear link between solar/ionospheric observations and their impact on GPS reception. The needed products are (1) a statistical study and/or model that could be used for design and certification and (2) a prediction capability.

The statistical model should include statistics on the depth of fading in dB with power spectral densities; the phase rate change in radians/second with power spectral densities; the distribution of time that scintillation is present and not present; the total time duration of events for a stationary user; and the percent of sky affected or number of space vehicles affected. The study should include these statistics for different levels of solar activity; geographic variations (polar, equatorial latitudes, and different longitudes); and daily and seasonal variations. The aviation community would also benefit from a model with predictive capability – one that could answer the question "What will happen this evening?"

[Reproductions of Dean Miller's transparencies are included as Attachment A]

John Foster presented information on radar data measured from Millstone Hill in Massachusetts. He stated that, on approximately two days per month for the past 20 years, measurements of electron density and TEC over a 20-deg latitude range have been made with the Millstone Hill radar. He offered this database to researchers working to characterize the spatial gradients of the mid-latitude trough region. This presentation was made in response to issues raised yesterday on the ability of the WAAS grid algorithm to capture the apparent spatial gradients in the mid-latitude trough region.

Steve Chavin posed questions to the group on the status of TEC models and data. He said that he would benefit from a study that statistically defines the changes in TEC that occur during magnetic storm periods and in the equatorial anomaly and trough regions. He also wondered about the status of products to help predict ionospheric events and their effects. In particular, Steve would like to obtain a TEC storm model or TEC storm data to be used in testing WAAS algorithms.

Greg Bishop suggested that Steve Chavin investigate the potential to use the Space Forecast Model that was presented in this morning's briefing by David Anderson (AFRL). The model makes ionospheric predictions using the PRISM model with solar and magnetic input provided by NOAA and near real-time TEC provided by JPL and IMS. Mihail Codrescu (NOAA) suggested that Steve also consider the ionospheric correction maps using updated calculations from the International Reference Ionosphere (IRI) that are available on the World Wide Web. These maps are generated using GPS-measured data as updates to IRI. Calculations are made with 2° latitude and 18° longitude spacings at 1-minute time intervals.

Steve Chavin wondered about the accuracy of these models in predicting ionospheric storm effects.

Greg Bishop stressed the importance of understanding the goals articulated by Dean Miller, who wants us to describe dB fading and phase rate correctly. Unfortunately, GPS measurements of amplitude and phase are not available from the last solar maximum. We should take what few data there are and use them for receiver testing at Wright Laboratory. Greg asked about the possibility of getting the structure of a new GPS receiver to be used in testing to see if it cares about scintillation at all.

Santi Basu discussed some details of measuring scintillation. He defined an intensely disturbed period as one in which the standard deviation of the signal intensity equals the average signal intensity (i.e., S_4 is unity) over a five-minute time interval. He has found that, in the 20-24 hour local-time period, intensely disturbed periods of scintillation occur 20% of the time in the equatorial region. In a static environment, where both the satellite and the measurement system are fixed, a 20-dB fade may appear for approximately .5 seconds. In a dynamic environment, for example where the measurement system moves east while the ionosphere moves east, the fades will be of shorter duration.

In response to a question on how long bubbles last, Santi Basu responded that they could last up to a period of hours. A.J. Van Dierendonck added that a bubble would not affect all satellites in view of a site. Dean Miller asked about patches of irregularity – how they will affect the user and how many satellites will be affected. Santi proposed that a test be performed to provide answers to these questions. He closed his presentation by noting that his scintillation results for GPS have been mostly extrapolated from other measurements. At this point, he doesn't know for sure how the GPS signals will be affected.

Greg Bishop added that this problem has a lot of interesting features and that there is a need to test receivers on an individual basis. He cited early GPS measurements made at Ascension Island that failed. However, he noted that they used old GPS receivers that were not aviation receivers. He suggested that interested participants look at the poster by Coker et al. The poster describes bench testing of GPS receivers for effects of ionospheric scintillation.

Andy Mazzella presented a discussion on a technique to simulate scintillation for GPS. The simulations are based on a two-component model of scintillation, derived directly from actual measurements employing the Wideband research satellite. He described the complex-scintillation equations used in the model and included a description of scintillation levels for the model in terms of S_4, as follows:

$S_4 = 0.18$ for low scintillation

$S_4 = 0.50$ for medium scintillation

$S_4 = 0.86$ for high scintillation

This method was used to simulate scintillation at the GPS L1 frequency. These simulations were used in initial bench testing for GPS receivers at Wright Lab. More detailed information on the technique can be obtained at the poster by Mazzella et al. James Clynch (Naval Postgraduate School) wondered if the model was more extreme than the real world. The statistical model itself is neither more nor less extreme than the real world; it must be parameterized (S_4 levels chosen) for consistency with observations characteristic of a given set of geophysical conditions.

Clayton Coker described the Wright Lab receiver testing for scintillation and jamming. He mentioned that bench testing of ionospheric scintillation on GPS would address questions on reacquisition time and jamming effects. He said that the length of fades depends on the speed of the aircraft. He showed an initial bench test of ionospheric scintillation on GPS. Details of the test are included in the poster paper by Coker et al. He indicated that Wright Lab would be open to sharing the results with the user and research communities. Jim Clynch provided advice on the patches and drift rates of patches to be used in the simulator.

Pat Doherty presented information on the accuracy of ionospheric TEC correction for single-frequency users. She showed dual-frequency TEC from GPS in comparison with single-frequency GPS corrections at five sites characteristic of different ionospheric behaviors. The results illustrated that the single-frequency ionospheric algorithm provides adequate correction in the mid-latitude region but fails to model the equatorial anomaly region. She discussed a proposal to provide 55th Space Weather with a product that quantifies the magnitude of positioning errors that a single-frequency military user would experience due to uncorrected ionospheric effects. Pat further illustrated some of the spatial gradients observed along the East Coast of the United States during a magnetically disturbed period in January 1997. She discussed plans to study spatial gradients in ionospheric TEC, measured with GPS, which occur during disturbed periods and also in the trough and equatorial anomaly regions. This information would be important in a Wide Area navigation system.

Anthony Mannucci (JPL) asked the general audience if anyone has observed localized depletions (characteristic of a hole or vortex) in TEC measurements. He wondered if depletions like this could be undetected by the WAAS and as a result not be reflected in its 5°-by-5° grid. An audience member suggested that optical images could be used to detect this feature. Optical images have shown round dots in the mid-latitudes that represent small scale size features approximately 50 to 100 km across. Nelson Maynard (Mission Research Corp.) suggested that sub-storm effects at the lower edge of the auroral oval should also be investigated for this feature. Other audience members suggested that TID's (traveling ionospheric disturbances) and narrow trough depletions could impact a GPS line of sight. Note that the mid-latitude trough varies night-to-night with magnetic activity. In addition, if such a feature was undetected in the Wide Area scheme, poor position solutions could result because a nearly overhead satellite measurement is heavily weighted in the position calculation.

There was some concern that the FAA's WAAS system would only be viable if the whole world uses it. Others were not convinced that this is the case.

As the meeting approached its time limit, the audience was asked for recommendations related to scintillation and wide-area navigation concerns. On scintillation, the general request was for a statistical description of scintillation that includes:

a) fade intervals at different fade depths;

b) rates of change in phase and acceleration of phase;

c) spatial problems (number of satellites affected);

d) S_4, σ_φ, psd's - only for very extreme cases.

Dean Miller asked if a program is in place to begin providing these scintillation statistics for the aviation community. Santi Basu was asked if there is enough equipment to collect and test for scintillation into the next solar maximum. He replied that he never has enough equipment.

In addition, a realistic scintillation model has been suggested. Jim Clynch recommended that a group be assembled to recommend and critique a scintillation model. He recommended that the model be based on real scintillation measurements. The model could then be used to test the levels of stress that current GPS receivers can withstand. The results would then provide receiver manufacturers with information to aid in the design of better equipment.

For Wide Area Systems in the mid-latitude sector, participants in the Navigation discussion sessions saw a need for studies that characterize ionospheric behavior during storm activity and in the presence of steep gradients, such as those found near the mid-latitude trough. The audience was also concerned with small disturbances such as blobs that would not be characterized in the 5°-by-5° grid. In addition, a request was made for information on large ionospheric height variations, which would cause errors in slant-to-vertical and vertical-to-slant conversion. It was noted that a relationship should be established between the scientific community and the FAA so that the scientific community can advise on locations and times for flight testing for WAAS. There was concern that the initial flight tests were conducted under ideal ionospheric conditions.

5.3 Issues Identified

- TEC mismodeling, leading to errors in pseudoranges and resulting positions
    - Steep gradients in restricted regions may be overlooked in coarse sampling used in wide-area modeling. Special concern: troughs, depletions, patches, or 'holes' will tend to

impact high-elevation satellites and have a disproportionate negative impact on vertical accuracy. Solar eclipses and TIDs produce effects on limited regions.

    - Issue: what are the impacts on system nav accuracy?
    - Issue: what is adequate sampling (space/time) to achieve a given level of TEC modeling accuracy in the differing ionospheric regions?
    - Applies to GNSS WADGPS aircraft precision approach navigation
        - It was suggested that WAAS would need to be accepted world-wide in order to be usable in a practical sense by commercial aviation.
        - It was suggested by Boeing that WAAS would also need a world-wide precision-approach capability in order to 'close the business case' for WAAS.
        - WAAS-type monitor stations in the equatorial region may be knocked off the air by scintillation at exactly the time they are most needed to model steep TEC gradients.
  - Applies to GNSS WADGPS in-harbor application for very large ships.
  - Broad-scale mismodeling is issue for determining real-time accuracy bounds of single-frequency GPS receivers.
- Scintillation: Reduced signal quality/availability/integrity.
  - Issue for potential outage or out-of spec condition in GNSS WADGPS.
- Nav-system field tests:
  - Issue: existing tests represent optimum (solar min, mid-latitude) conditions.
- Ionospheric data:
  - Issue: only limited GPS or L-band data available from solar-max conditions.

5.4 Opportunities for Cooperation

- FAA working on establishing a "Sat Nav Center," which will study (among other things) new products and parameters to predict ionosphere conditions one to three hours ahead.
- 55 SWXS, AFRL and NOAA SEC opportunity to use ACE satellite data, IFM and other model products.
- AFRL cooperation with the FAA in bench-test certification of GPS receivers' capabilities in ionospheric scintillation conditions, using NWRA scintillation simulation from Hanscom and GPS simulator equipment at Wright.
- AFRL-FAA collaboration to maximize value of field/flight tests of WAAS.

5.5 Recommendations

- TEC:
  - Determine impact of regional steep gradients (troughs, depletions, patches, or 'holes', etc.) on navigation accuracy.
  - Determine adequate sampling (space/time) to achieve a given level of TEC modeling accuracy in the differing ionospheric regions.
- Scintillation:
  - The research community should develop a statistical/morphological description of scintillation that includes
    - fade intervals at different fade depths;
    - rates of change in phase and acceleration of phase; and
    - spatial extent (number of satellites affected).
  - AFRL should continue to pursue capability for bench-testing scintillation effects on GPS receivers, modeling real satellite signals, and using realistic ionospheric scintillation models for simulation.
    - FAA certification people should use the AFRL facility to certify receivers for scintillation.
    - A group should be set up to cross-critique AFRL scintillation simulation algorithms.
    - AFRL may develop a worst-case conservative test, which would result in a receiver being certified as fully robust, if it passed the test.
    - AFRL should enhance simulation to include capabilities such as velocities and all-sky mapping.
      - Relative velocities of ionosphere penetration point and drift can speed or slow the observed scintillation (Poster, Kintner, this meeting).
      - Nulls can become almost continuous, when observed from an aircraft travelling in the same direction as the ionospheric structure is drifting, (observation by Weber et al. 20 years ago).
- Nav field tests:
  - AFRL-FAA collaboration to maximize value of field/flight tests of WAAS. The ionospheric-scintillation research community is able to advise on locations and times where ionospheric conditions would be most appropriate to test needs. AFRL is able to supply ionospheric measurement instruments to assure actual conditions are recorded. Opportunities exist to access AF aircraft to support wide-ranging tests.
- Ionospheric measurements of interest:
  1. Detailed TEC data during magnetic storms.

2. Data characterizing troughs, depletions, and other small-region steep gradient features.
    - Millstone Hill (John Foster) has >20 years of radar data that could be used to characterize regional TEC gradients throughout two solar cycles.
    - IGS data archives also can be accessed to address this issue.
3. Variations in altitude of peak ionization from its normal daytime levels.
    - Ionosonde databases contain such information.
4. Morphology of poleward extension of anomaly regions.
5. Morphology of equatorward motion of trough regions.
6. Characterization of scintillation boundaries.

Attachment A: Transparencies presented by Dean Miller (Boeing).

Commercial Aviation-GNSS/Ionospheric Effects

Goal = Understanding the effect well enough to assess whether it poses a threat.

If so - Two capabilities needed:

Statistical model - used for design and certification (similar to FAA and JAA wind models)
Predictive capability - useful for the airlines operational community (What will happen this afternoon?)

Must have a clear link between solar/ionospheric observations and impact to GPS reception.

Background

Large % of commercial jet transports delivered with GPS
Used for oceanic/en-route/terminal area/non-precision approach
GPS integrated with IRS - loose or tightly coupled
Systems introduced near solar minimum (1994/1995)

First Application was for Pacific FANS-1 routes.

No commitment to offer GNSS Landing Systems (GLS)

Ionospheric Effects assumed detectable. As such will have impact on availability, not integrity.

Specific Model Parameters

Micro Level

X dB (y% or 1_σ with power spectral density.
Z rad/sec (y% or 1_σ with power spectral density.
Duty cycle per event - averaged.
Distribution of "on" and "off" times with durations of each.
Total duration of events for a stationary user.
% of sky or number of satellites affected.

Macro Level

Solar cycle variations - 1/2/3 years at peak level.
Geographic variations - Polar vs equatorial, longitude
Dimensions of disturbed regions
Velocity of disturbed regions 500kts ~ 250 m/sec
Duration of disturbed regions - distribution, histogram, 1_σ
Lower priority - Daily, monthly, yearly (i.e. seasonal) variations

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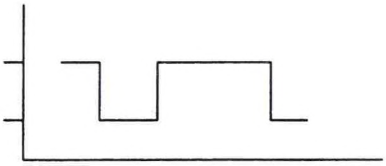
DUTY CYCLE



- Are t_1 and t_2 measured in msec/sec/minutes
- What is the distribution of t_1? Of t_2?

Example: ARINC 743A requires reacquisition within 5 seconds if 1 sv lost for 1 minute.

Attachment B

Preliminary Results of Using GPS to Observe Ionospheric Scintillation at Vanimo, Papua New Guinea

Yue-Jin Wang and Phil Wilkinson
IPS Radio and Space Services
Sydney, Australia

Abstract

In order to monitor the equatorial ionospheric effects on GPS signals, IPS Radio and Space Services (IPS) has set up a dual-frequency Novatel MiLLenium receiver at its ionosonde station in Vanimo (latitude = 2.70°S, longitude = 141.36°E), Papua New Guinea (PNG). This dual-frequency receiver has collected GPS data since April 1997 and provides GPS raw data at a sampling rate of 1 Hz. Beside the GPS receiver, IPS also has an ionosonde deployed at the same station.

In this paper we present preliminary results of ionospheric scintillation observations using GPS data collected at Vanimo. The effects of equatorial scintillation are analysed by examining the local night variations of the GPS signal strength and the total electron content (TEC) during magnetic storm and quiet conditions. The following analyses have been carried out:

(1) Amplitude scintillation observations

The top panel of Fig 1 illustrates the comparison of C/No (C/No = 10 $\log_{10}$ (S/N)) values of L2 channel for individual satellites during two successive days, 14 -15 May 1997. It shows that during a geomagnetically disturbed local night, the signal amplitude fluctuation is around 5 dB-Hz. In the panel there is an offset for clarity. The elevation angles of the line of sight to the satellite are also listed. This ionospheric disturbance on GPS signals is consistent with the presence of equatorial spread F detected using the IPS ionosonde data.

(2) Analysis of rapid TEC variations

High precision TEC values can be derived from the dual-frequency carrier phase measurements. The bottom panel of Figure 1 show the TEC variations for the individual satellite paths during four successive days, 12-15 May 1997. During the magnetically disturbed night, almost all satellites experienced phase fluctuations. The level of the effects varies with the profile of the line of sight to the satellite, with the sharp change of TEC values in a north-south direction during the period 1300-1500UT (PRN 26, PRN 10, PRN 5, PRN 24, and PRN 4). During local midnight to dawn, the ionospheric electron density appears to decrease in the north-south direction, and then increase (PRN 5, PRN 30, PRN 6, PRN 10). The irregular variations of TEC may be attributed to the dynamics of the local-night equatorial ionosphere structure.

(3) Loss of L2 data

The equatorial structure can cause GPS data loss, especially on the L2 channel. Loss of L2 data from a satellite means a loss of the receiver's ionospheric correction for the raypath from this satellite. This would result in a limitation for differential GPS applications. The recorded data show that data loss rate (percentage) during the disturbed period is as high as 3.9% comparing 2.0% of that for the same period of the quiet day.

In general, the data analysis results show that the GPS performance may be degraded by the severe ionospheric conditions in the equatorial region. The disturbed satellite pass can affect the strength of satellite signals and result in data loss, especially on the L2 channel. The rapid change of TEC may result in larger range-rate errors and degrade the accuracy of real-time differential GPS applications. GPS signals provide a useful means for monitoring ionospheric scintillation. Further work will include development of processing methods for calculating scintillation parameters and regional real-time scintillation modelling.

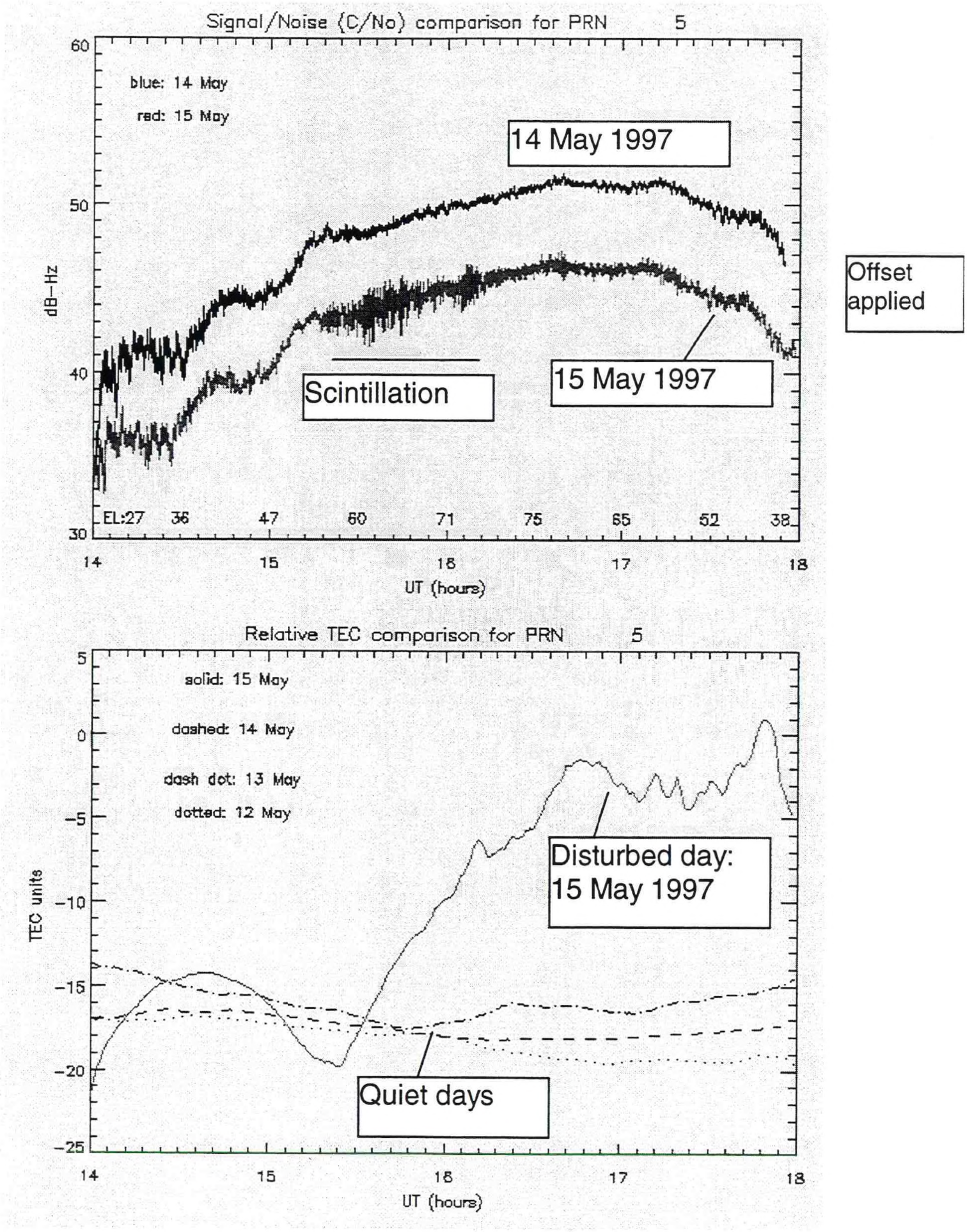


Figure 1: Comparison of GPS scintillation and relative TEC at Vanimo, 12-15 May 1997

6 Results from Discussion Session on Commercial Space Weather Services

Facilitator: Dr. Thomas Tascione, Sterling Software

Recorders: Mr. James Secan, Northwest Research Associates (NWRA)

Dr. Lee Snyder, NWRA

Approximately 20 interested participants attended a two-hour panel meeting on 23 October 1997 concerning the newly developing market for vendors of space-weather services. Participants included representatives from the private sector, the National Oceanographic and Atmospheric Administration Space (NOAA), and the NOAA Space Environment Center (SEC), as well as government and university engineers and scientists. There were no formal presentations during the session.

To initiate discussion, the facilitator summarized the following five developments that have promoted emerging opportunities for private-sector vendors of space-weather services:

- breakthroughs in understanding space weather and space-based or space-impacted technologies;
- organizational changes within NOAA that recognize the role of third-party vendors;
- decreases in cost of computational hardware;
- ease of communications via the Internet; and
- growth of a user base, which includes system developers, system operators, and end users.

He asserted that time is the worst enemy of private-sector vendor success in the space-weather field, stemming from the 11-year periodicity in solar activity and the approaching solar maximum predicted for late 2000. The best opportunity for private-sector vendors is to provide support during the solar-maximum period. This means the vendors must develop capabilities and establish a customer base quickly or opportunities may be lost.

Following the facilitator's introduction, a number of topics were discussed. A summary follows for each topic.

6.1 Relationship with the Government

It was proposed and generally accepted that commercial vendors of space-weather services would depend upon data and products developed and maintained by the government, especially those of NOAA/SEC. Thus a cooperative relationship with the government is essential. The cooperation between the commercial sector and the government in tropospheric weather was cited as a useful model for the space-weather community. Several examples were discussed.

In the field of tropospheric weather, the commercial-sector vendors don't change National Weather Service (NWS) alerts and warnings; rather, they tailor NWS products to meet specific end-user needs. SSI provides road-freeze forecasts for Indianapolis, IN. The Weather Channel and Weather Services International repackage and interpret NWS products for public dissemination. Similar relationships are envisaged between space-weather vendors in the commercial sector and the NOAA/SEC. Such a relationship depends upon an effective NOAA/SEC information-dissemination system. NOAA/SEC is conducting commercial-sector vendor meetings to foster a relationship with the government. The third NOAA/vendor meeting is planned for April 1998.

6.2 Quality of Government Products

If commercial space-weather vendors are to rely on government data sources, forecasts, alerts and warnings, it is important that the quality of these government data sets and products be known. The NOAA/SEC Web page summarizes an initiative to verify certain products. The Panel concluded that understanding how well NOAA/SEC does in forecasting major disturbances would be helpful, as would the ability to predict changes of a lesser magnitude. It was also concluded that it is important to understand the measurement accuracy of in-situ space-weather data. Another element of concern to the commercial vendors is understanding the government's planned response time to repair problems that may arise in the generation and dissemination of NOAA/SEC products.

6.3 Prioritized Needs of Commercial-Sector Space Weather Services Vendors

The private-sector vendors and the NOAA representatives agreed that it would be useful for the private-sector needs to be prioritized and offered to NOAA. This would provide NOAA insight as to which products the private vendors depend upon and would be useful in establishing priorities for the use of limited NOAA resources. The prioritization may also be useful to NOAA in planning their fiscal year (FY) 2000 budget submissions as it may be too late to affect the FY99 budget process.

Without significant discussion, the following strawman list of data needed was presented:

- solar-wind and interplanetary magnetic-field data;
- cross polar-cap potential;
- coronal structure;
- energetic-particle data;
- real-time estimates of geomagnetic indices AE and Dst.

It was noted that space-weather data are perishable, with the value decreasing as dissemination delays increase. While space-weather data can be computer-retrieved from the NOAA/SEC, the database is not organized by user need. It was noted that the Advanced Composition Explorer (ACE) satellite is designed for a five-year lifetime; yet, support funding is assured for only two years. The ACE satellite will monitor the solar wind and the interplanetary magnetic field at the earth-sun libration point and is considered an essential space-weather data source. The panel unanimously supported an expression of need for full five-year support funding to ensure continuous ACE data availability through the solar-maximum period.

Panel participants from NOAA noted that the SEC has an established information-dissemination policy. The policy statement was made available to panel participants and is included as an attachment. It was concluded that a prioritized list of needed government space-weather products would be developed by several interested parties and then distributed for broader coordination. While not discussed in detail, a statement was made that the private-sector vendors are also dependent upon results and continued progress from the research community. One panel participant noted that private-sector vendors must at times invest to acquire government-generated data or products, e.g., tropospheric doppler weather-radar data.

6.4 Legal Considerations

Concern was expressed for commercial-sector vendor liability in providing space-weather support. It was noted that there is no case law or legal precedent in space-weather support, i.e., new ground is being broken. One panel participant noted that this issue "can get dicey."

6.5 Private Sector Customer Needs

Considerable curiosity and interest was expressed about understanding the base of customers and their needs. In response to a participant query, the facilitator noted that, over the past year, the number of commercial-sector vendors of space-weather services "has increased from one or two to a dozen or more." However, a shroud of secrecy covers the specifics of commercial space-weather vendors as they must protect their business plans from exploitation by established or emerging competitors. On the other side, system developers, operators, and end users often publicly deny space-weather impacts. For these two reasons, it is unlikely that specific private-sector support needs be discussed publicly.

Several general statements were made by panel participants, such as "Navigation is a big customer;" and "you can't sell Kp." It was also pointed out a need exists for support of HF communications outside the United States. Private-sector customers' problems generally are centered on individual space-weather events, and these customers need forecasts of when impacts will occur and how severe they will be. While some private-sector customers may understand space weather and have their own in-house expertise, there still may be a need for third-party support. For example, the in-house tropospheric weather capability of United Airlines is coupled with third-party support. The use of a private-sector vendor often depends upon a perceived cost/benefit ratio. Support modes were viewed as falling in two general categories: "push" and "pull." In the push mode, the private-sector vendor generates a product and delivers it to the customer. In the pull mode, the vendor establishes a fully open database from which the customer may pull products.

6.6 Commercial Vendor Association

Panel participants discussed the possibility of forming a space-weather vendor association. Areas in which an association could work include the following:

- helping to ensure that NOAA/SEC needs are understood;
- promoting vendor-community growth; and
- providing a unified voice for vendor needs.

Thomas Tascione (Sterling Software) summarized a recent Congressional staffer's comment regarding space weather – "Who cares? You are the first outside the government to express a need." Tom volunteered to draft a vendor-association charter and distribute it for review and comment.

Attachment:

Space Environment Center — Policies on Information Dissemination

NOAA Space Environment Center is the Nation's official source of space weather alerts and warnings. The Center continually monitors and forecasts Earth's space environment; provides accurate, reliable, and useful solar-terrestrial information; and leads programs to improve services.

- SEC establishes its policies on information distribution and vendor partnerships, consistent with Department of Commerce, NOAA, and National Weather Service policies.*
- SEC must ensure that members of the public have timely and equitable access to SEC's public information.
- SEC participates fully in interagency sharing and international exchange of information and data.
- SEC allows access to information by research and academic institutions at no cost for non-commercial applications so as to support NOAA's mission by stimulating space weather research in the academic sector.
- SEC continually reviews their information dissemination to ensure that its products and services are necessary to fulfill its statutory mission and are consistent with that mission.
- SEC recognizes an obligation to disseminate information in such a manner so as to maximize the usefulness of the information while minimizing the cost to the government and the taxpayer.
- SEC provides in a timely and reliable way information and data in standardized formats.
- SEC recognizes that the creation and dissemination of specifically customized information to meet the needs of particular users is an appropriate role for the private sector.
- SEC may recover its cost to disseminate its products or services from the users of its products and services. However, SEC will balance the requirement to establish user fees with the need to ensure that information products and services reach the public, for whom they are intended.
- SEC provides links from World Wide Web pages to national centers, government agencies, international governmental partners, and some universities with information relating to space weather. It does not provide, on its Web pages, lists of, nor links to, private individuals, commercial vendors, or other organizations, nor does it make their products available via SEC's Website.
- SEC makes available through its customer newsletter vendors' announcements of products and services. It will not include advertisements for such products and services in its

newsletter. Periodically presenting a non-endorsed listing is viewed as a service to its customers to inform them of available products and services.

* References: The Paperwork Reduction Act of 1995 and OMB Circular A-130

May 22, 1997

7 Results from Plenary Discussion Session

Facilitator:	Dr. Edward Fremouw, Northwest Research Associates (NWRA)
Com Reporters:	Dr. John Goodman, TCI Dr. Keith Groves, Air Force Research Laboratory (AFRL)
Nav Reporters:	Mr. Greg Bishop, AFRL Mrs. Patricia Doherty, Boston College
Vendor Reporters:	Mr. James Secan, NWRA Dr. Lee Snyder, NWRA

7.1 Report from Communication Discussion Group

The Communications Discussion Group ordered its initial discussion by frequency band. It then addressed questions of what characteristics of space-weather products and services render them valuable for communication via or through the ionosphere.

7.1.1 Relevant Effects

Proceeding upward from the lowest operational frequency bands, the group found little deleterious impact of space weather at ELF, VLF, and MF, although the ionospheric electrojets obviously do produce ELF and VLF effects. The group noted the possibility, in fact, of enhancing the use of ELF for naval communications. Investigations of this possibility are planned in the High-frequency Active Auroral Research Program (HAARP) being developed jointly by AFRL and the Office of Naval Research (ONR). For HAARP, geomagnetic and auroral aspects of space weather and plasma physics in the ionosphere are important.

Communication at HF, as well as operation of over-the-horizon (OTH) radars, depends fundamentally on the ionosphere as a propagation medium. Mitigation of the effects of ionospheric variability is provided by automatic link-establishment (ALE) systems, but forecasts are still used. Indeed, in spite of ALE, two-thirds of all customers of the Air Force space-weather forecasting services are users of HF systems. Relevant parameters are LUF, MUF, fade level, and SNR.

For satellite communications (and for GPS) at VHF and UHF (including L Band), transionospheric scintillation can be a significant effect, especially at equatorial and auroral/polar latitudes. Varying from night to night (near the equator) and/or day to day as geomagnetic conditions change (at middle and, especially, high latitudes), it can produce fading of several tens of dB at VHF, decreasing with increasing frequency. The most severe scintillation occurs between sunset and approximately local midnight within about ±20° of the magnetic equator, where tens of dB of fading may be expected in years near solar maximum even at L Band. Moderate effects may be expected on frequencies as high as S Band, but not substantially higher. Signal phase also fluctuates rapidly, with reduction in coherence bandwidth possibly being an issue – but only for extremely broadband systems.

7.1.2 Important Needs

Regardless of the propagation effect at issue or of the type of system affected, application of space-weather models and other products must be based on quantification, in operational terms, of system sensitivity to the effects addressed. For example, how many dB of fading or how much decrease in SNR can be tolerated for acceptable reliability? In turn, the models and products must include quantification of their confidence limits. Thus model verification and metrics for specifying reliability and accuracy are crucial.

For operational utility, geophysical parameters must be converted to system-performance parameters. At high latitudes, a long series of interactions may need to be modeled before obtaining a forecast of operationally relevant parameters. Even at equatorial latitudes, where solar-wind dynamics is not a central issue, one needs to go from ionospheric parameters to signal characteristics to something akin to a "red/yellow/green" assessment. For instance, for scintillation fading, one might combine a measurement or forecast of plasma-density profiles with plasma-instability and radiowave-scattering theory to provide a nowcast or forecast of signal and system behavior. The following sequence would be necessary:

- forecast the height-integrated strength of ionospheric irregularity (C_kL);
- calculate the resulting rms phase fluctuation (σ_ϕ) and fractional fluctuation of signal intensity (S_4);
- convert S_4 to a dB fade level;
- compare with system sensitivity to fading in order to forecast whether a communication disruption or outage may be expected.

Moreover, the forecast must be accompanied by an assessment of its percent reliability.

7.2 Report from Navigation Discussion Group

There were two major topics of interest in the Navigation discussion sessions. One related to scintillation effects on GPS signals, and the other related to ionospheric behavior in TEC.

7.2.1 Scintillation

One of the most significant space-weather needs of the aviation community is a statistical characterization of scintillation, especially for extreme events. This characterization should include regional information on fading depths, duration of fades, and frequency of occurrence. Summary information in the form of S_4, σ_ϕ, and power spectral densities also would be useful.

Santimay Basu (AFRL) described how intense scintillation is detected, and he reported that 20-dB fades occur in the nighttime (between sunset and midnight) equatorial ionosphere approximately 20% of the time. He advised the audience that projected statistics of scintillation effects on GPS mostly have been extrapolated from measurements made with non-GPS technology. He noted that effects on GPS near solar maximum are uncertain for two reasons: (1) they will occur in a substantially more disturbed environment, and (2) the receivers that may be affected contain updated technology. With the increasing dependence of the aviation community on GPS, it is important to initiate programs to collect and characterize scintillation into the next solar maximum.

The navigation group devoted much discussion to the critical need to test the ability of modern receivers to withstand scintillation. Current receiver technology was not available during the earliest GPS measurements. It is not known how current receivers will react to scintillation with increasing solar activity. Greg Bishop (AFRL) and Clayton Coker (Univ. of Texas, Austin) described the receiver bench-test program that has been initiated at Wright Laboratory. The program will include testing for scintillation and jamming, and the results of bench-testing will be made available to interested users. Additional concerns related to receiver testing were focused on the need for a realistic scintillation model to provide test data. It was suggested that the model be based on scintillation measurements and that a group be established to review and critique the model.

7.2.2 TEC

Discussion related to TEC illustrated that the aviation community could benefit from studies related to ionospheric spatial gradients in TEC. Wide Area Systems, such as WAAS, will provide a 5°-by-5° geographic grid of vertical ionospheric corrections to single-frequency user aircraft. The concern is that the grid may not properly account for small ionospheric depletions and enhancements and for steep gradients, such as those that occur during periods of extreme geomagnetic activity and near the boundaries of the mid-latitude trough and equatorial anomaly. The scientific community was concerned that WAAS flight-testing may have been conducted under ideal ionospheric conditions. It was suggested that the FAA establish and maintain a formal agreement with a scientific group for recommendations on locations and times for flight-testing under various levels of ionospheric behavior.

Additional concerns were voiced about potential errors in aircraft position solutions due to unusual height variations. In the WAAS System, slant TEC measurements are converted to equivalent vertical and then interpolated onto a regular grid across the CONUS. Aircraft users interpolate the grid for an ionospheric correction at their location and then convert the local correction to slant TEC along the line of sight to the GPS satellites. Inaccuracies enter in the slant-to-vertical and vertical-to-slant conversions when large horizontal gradients are present. A study of height variations observed in the CONUS, together with efforts to improve slant-to-vertical and vertical-to-slant conversions, would be useful to the navigation community.

Discussion also included the position errors that result from inadequate ionospheric correction for users of single-frequency receivers. Single-frequency users rely on ionospheric corrections from the current GPS single-frequency ionospheric correction algorithm. The algorithm provides at least 50% rms correction in the mid-latitudes, but it fails to model the equatorial anomaly and high-latitude regions.

7.3 Report from Discussion Group on Commercial Space Weather Services

The discussion group on commercial services described potential roles for private-sector vendors and their necessary relationship with government agencies, including the Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA). Thereafter, it presented its views on critical issues and actions needed.

7.3.1 Vendor Roles

The group identified four general roles that could be played by commercial-sector vendors, as follows:

- repackaging NOAA/SEC products (e.g., translating them into specialized language understood by customers in the context of specific needs);
- passing SEC products to customers via specialized communication channels (providing easier access);

- developing tailored warnings or alerts based on SEC products; and
- selling space-weather data to the government.

7.3.2 Relation of Vendors to Government Organizations

Commercial-sector vendors need to work with the government organizations and agencies that will be providing information and services to the vendors to establish prioritized lists of needs. The vendor community also needs to lobby for financial and programmatic support both within Congress and within the government organizations and departments that have groups involved in space-weather activities (most notably the Departments of Commerce and Defense and the National Science Foundation). This lobbying must address needs for both operational support to the vendor community and results from more long-range basic research.

Commercial vendors need two basic types of information from the government: (1) products generated by the government (analyses, warning, alerts, and forecasts), and (2) observations from either government collection systems (such as the TIROS, GOES, and DMSP satellites) or purchased by the government from commercial-sector vendors. An example of the latter from the tropospheric-weather sector consists of the NEXRAD radar data, which is purchased by the National Weather Service from a commercial vendor.) The information needs to be both timely (space-weather data being even more perishable than most tropospheric data) and carefully quality-controlled. Whenever possible, all data made available to commercial vendors should be accompanied by data-quality information (uncertainty levels, warnings about potentially contaminated information, etc.).

It is essential that the government validate all products provided to the commercial sector, including data, products, analyses, and model outputs. The commercial sector must know how good (or bad) the government's products are before it can sell value-added products to potential customers. These validations must focus on how well these products perform when conditions are changing, not averaged over long periods of time. Good metrics need to be established that will demonstrate clearly how much better than simple climatology or persistence a particular forecast is, for example. Standard validation suites for models and techniques need to be established so that vendors can see whether new models are (1) good enough to employ for selling services to customers and (2) any better than old models. One solution may be establishment of a Rapid Prototyping Center (RPC). Validations should be conducted by organizations not involved in development of the model or technique being validated. Critical to utility of the RPC would be clear exit criteria for models and techniques so that the prototyping neither ends prematurely nor goes on forever.

The government forecast center (NOAA/SEC, located in Boulder, CO) must provide 24-hour service, seven days a week, and the service must be dependable. There must be clear procedures established for responding to system outages, and there need to be backups available during catastrophic failures (either via the government or perhaps a commercial vendor). SEC policies on recovering from outages (priorities on which data or products are re-established first, etc.) need to be established and published.

7.3.3 Vendor Association

Commercial-sector vendors of space-weather services need to begin working together on common issues such as developing a prioritized list of needs (data and products) to be provided to

NOAA/SEC and to use as a basis for lobbying efforts. The tropospheric-weather community has several such organizations, and they have met with some success in lobbying for needs in that area. Thomas Tascione (Sterling Software) has agreed to draft a charter for such an organization.

7.3.4 Critical Issues and Actions Needed

- The commercial-sector vendors support the Advanced Composition Explorer (ACE) satellite mission and ask that (1) the mission be funded for its full five-year life; (2) if possible, additional funding be found to expand the real-time coverage to 24 hours/day; and (3) planning be started now for the follow-on mission in order to avoid a gap in coverage when ACE ceases functioning.
- The commercial-sector vendor community needs to establish a prioritized list of needs for data, products, improvements to current products and models, and new products and models. This list would be provided to NOAA/SEC and would form the basis for lobbying efforts by the vendor community.

7.4 Notes from Open Discussion

Non-propagation aspects of space weather (e.g., spacecraft drag and charging, radiation effects, etc.) were excluded from the charter of this particular workshop, not because they were deemed irrelevant, but to provide focus. Within that discussion boundary, two days of consideration in breakout groups revealed broad consensus about what ionospheric characteristics and related propagation parameters are relevant to reliable operation of communication and navigation systems.

For HF applications (communications and OTH radar), the vertical and horizontal distribution of electron density is the fundamental ionospheric description needed. From it, operationally relevant parameters such as f_0F_2, MUF, and LUF may be calculated. From it and consideration of absorption, assessments and forecasts of signal strength also may be provided.

The pre-eminent navigation system of the day and for a considerable span of the future is GPS. Clearly TEC, either computed as the integral of electron density along operational lines of sight or measured directly, is the quantity required if pseudorange errors imposed on single-frequency GPS receivers are to be corrected. For WAAS and differential GPS systems, TEC gradients are pertinent.

For both communications and navigation (GPS), scintillation is the ionospheric effect of concern at VHF and above. Scintillation fading is pertinent for essentially all types of systems, and a few may be susceptible to phase fluctuations (doppler spread) and/or effects on the complex signal due the transionospheric channel's decreased coherence bandwidth.

Discussion ensued on the need for information on what scintillation will do to GPS in the future. In particular, information on the percent of time that one, two, or three satellites could be affected by an event is important to navigation systems. It was suggested that a study be undertaken to provide regional statistics of fade rate and duration at different fade depths on GPS frequencies. An additional request was made for testing of GPS receivers. Specifically, there is a requirement to define, verify, and implement a testing platform so that receivers can be tested for scintillation effects at known levels.

The ionospheric conditions present during flight testing of WAAS was called into question. Bakry El-Arini (MITRE) explained that initial tests were conducted near solar minimum using the

National Satellite Testbed. The WAAS will be tested from 1999 to 2001 under conditions of increased solar activity. It was strongly suggested that information on the best times and locations to test WAAS be recommended to the FAA by the ionospheric research community.

Just as the severity of ionospheric effects on propagation differ in different parts of the world, Dean Miller (Boeing) pointed out that needs also vary by region. For example, GPS is the main form of navigation in Fiji. He said that information on space-weather effects on GPS systems is of great interest to all navigation system users and designers and that space-weather information should be disseminated widely. It was suggested that an article be submitted to GPS World explaining the effects of scintillation and fading conditions on GPS receivers. It was also recommended that information on space weather and the impact on navigation systems, specifically WAAS, be presented to RTCA and RTCM. These groups would benefit from our results.

An issue was raised about the need for ionospheric monitoring tools. Santi Basu described a proposed Air Force satellite that would provide ionospheric measurements in the equatorial region. In low-inclination orbit, the satellite would pass the same location every 90 minutes, providing information on background features that would aid in nowcasting and forecasting equatorial propagation conditions.

Robert McCoy (ONR) described a UV ionospheric imager that the Navy has proposed for placement in geostationary under the Air Force Space Test Program. It would image night-time TEC at low and middle-to-high latitudes with sufficient resolution (10-by-10 km in fields of 1000-by-1000 km) to permit detection and tracking of regions prone to producing scintillation. On the limb, this same imagery would yield vertical profiles of electron density.

Anthony Mannucci (Jet Propulsion Lab) recommended that the ionospheric community consider supporting the IGS network by installing additional dual-frequency GPS receivers. That network can provide large volumes of TEC data. Edward Fremouw (NWRA) asked how useful the same measurements might be for monitoring scintillation. As facilitator, he asked for comments about the data rate from other scintillation observers. Santi Basu pointed out that the available data rate addresses only large-scale features. For instance, in a typical GPS observing geometry, a 60-sec Nyquist period captures only structures larger than about 20 km. This still can be useful, however, because such features often are associated with smaller scales. Larger-scale gradients (as in equatorial plasma depletions and high-latitude plasma "blobs") can serve as source regions for scintillation-scale (sub-kilometer) irregularities via plasma instabilities (Fremouw *post-facto* comment).

Gus Lott (Naval Postgraduate School) pointed out that the Navy continues to operate some of the Transit satellites from the decommissioned Navy Navigational Satellite System as the Navy Ionospheric Measurement System. The at-large discussion group endorsed continued Transit operation as a cost-effective use of existing assets. Transmitting a mutually coherent pair of signals at VHF (150 MHz) and UHF (400 MHz) from polar orbits at 1000 km altitude, the Transits are ideally suited for producing latitudinal scans of relative TEC. When recorded at a chain of coherent receivers, such data can be inverted tomographically to produce horizontal-vertical mappings (or images) of electron-density distribution. Such receiver chains are being operated by several (U.S. and other) research groups at locations from Scandinavia to Antarctica. If sampled rapidly (at 50 Hz, say), the Transit signals also are very suitable for measuring phase and intensity scintillation.

The general consensus was that the foregoing four suggestions all relate to useful trans-ionospheric monitoring tools (Air Force Equatorial Satellite, Navy Optical Imaging Satellite, the IGS network, and the Transit Satellites), operation of which near solar maximum would prove beneficial.

Beyond the types of effects that are pertinent and the need for monitoring as inputs to nowcasting and forecasting, clear consensus was reached on the need to quantify (a) system vulnerabilities, (b) channel effects, and (c) uncertainty levels in model outputs and other products. The latter led to a discussion of model validation and associated metrics, with the group recognizing lack of validation, leading to lack of credibility, as a serious issue. A question was raised as to what organization(s) should define validation responsibilities, specify metrics, and pay for the validation process.

Based on twenty years experience with technical transition in the Air Force, Lee Snyder (NWRA) pointed out the following needs for transitioning models and other space-weather tools into useful products:

- establishment, in writing, of a baseline plan for use by both developers and users, without which users will levy additional performance requirements and developers will accrue additional costs;
- development of a test plan, with defined metrics, for quantifying performance.

He cautioned modelers against wanting to continue development indefinitely, pointing out that "Better often is the enemy of good enough." To users and agencies that sponsor research, he pointed out that developers need funding (and/or a market) to develop products, challenging the sponsors of this workshop (NSF and NOAA, in cooperation with AFRL and ONR) to “step up to the plate” and support validation efforts.

In response, Louis Lanzerotti (Bell Labs, Lucent Technology) stressed the need for flexibility in the baseline process to avoid the inefficiency of rigid, slow development – traditionally viewed as the “government” paradigm. He lauded the “industry” approach of changing the development baseline in response to changing needs, feedback received, etc. Willow Cliffswallow (USAF) concurred about the need for flexibility. She stressed keeping users involved in all phases of operational testing.

It was recognized that flexible baselines imply effective and on-going interaction between developers and users at all stages, not just that of operational testing. The session facilitator asked about the “vertical integration” being advanced in the Navy, and Bob McCoy responded that, by means of this restructuring, the Navy is attempting to improve communication between organizational levels, from 6.1 through 6.4.

It was pointed out that validation is less complicated within a given organization – a company producing a limited line of products, or even the Dept. of Defense (DoD), which has well defined mission objectives – than in the broader civilian community. The RPC foreseen by NOAA was viewed as a very useful step toward developing an industry for producing space-weather tools. An association of vendors in that fledgling industry also is to be encouraged.

After the open discussion, Michael Feen (Johns Hopkins Applied Physics Lab) suggested to a recorder that a set of standard scenarios or benchmarks, analogous to Whetstone tests in the computer industry, might be useful for community evaluation of model/product performance. It could be a web-based utility and might be as simple as links that point users to appropriate data sets. Lewis Duncan (Univ. of Tulsa) suggested organizing "Space-Weather Days," analogous to the scientific communities "World Days," to facilitate interaction between developers and users. Products from research and operational models could be made available on selected days for users to compare with their experience in operations.

Tony Mannucci cautioned that, whatever the organizational approach and structure, researchers and developers should not have sole responsibility for validation. Leaving that responsibility to them can lead to incomplete validation (testing of only a few cases, etc.), thereby limiting credibility. It was pointed out that the topic of metrics for validating models will be the subject of a special session at the meeting of the American Geophysical Union (AGU) in San Francisco in December 1997. Lou Lanzerotti cautioned that space-weather applications and tools need to be presented to forums other than AGU meetings.

Generally, the group recognized a need for both "research" validation and operational validation. Tony Mannucci stressed the need for field testing. Others pointed out that field testing is only one component of the validation process. For cost reasons, it may not be feasible to perform tests in the field for the full range of operational conditions to be encountered. Simulations can help, especially when trying to test in advance of anticipated conditions (e.g., solar max).

James Secan (NWRA) suggested that, for both field tests and simulations, "suites" of validation tests are needed. The developer/user baseline should be developed from a careful choice of metrics designed to validate the product in terms of parameters truly useful in application. John Goodman (TCI/BR Communications) concurred that "certifiable validation schemes" are needed, and he cautioned that industry may tend to develop standards favorable to their products. He concurred, however, with the "industry" approach of maintaining flexibility by avoiding rigidly standardized methods.

Consistent with the latter point, John Evans (COMSAT) questioned use of the term "validation." He pointed out that numerical weather models are not truly "validated," but rather they undergo progressive improvement. "Validation" implies a degree of truthfulness that cannot be delivered in forecasting space weather, just as perfect predictions of tropospheric weather are not achieved. John prefers the term "verification" and suggested the following as relevant verification questions:

- Does a forecast improve upon climatology?
- Can additional information reduce the spread in a probability distribution that quantifies uncertainty?

Keith Groves (AFRL) pointed out that, whether we call the process "validation" or "verification," tropospheric weather models do undergo extensive testing. New models generated by the NWS first are tested in-house and then released to the community in parallel with existing weather-model outputs. The entire community provides quantitative feedback on model shortcomings, and these are then addressed in future releases. In the case of tropospheric weather, the broader community largely seeks a common set of parameters supplied by a very few models run and distributed from a central location – primarily because real-time data and extensive cpu capacity are required. Keith pointed out that the space community has no such common set of models at present.

In providing space-weather services, the Air Force traditionally has operated from a central location (currently, 55 SWXS). Greg Bishop pointed out that even this is moving toward some dispersion of the type noted by Keith Groves, specifically providing some monitoring and forecasting capability at surveillance radar facilities. Bob McCoy described a similar situation in the Navy. Since modern Navy ships have great on-board processing capability, they can generate in-theater forecast products using data downloaded from DMSP, Fleet Numeric, etc.

A short briefing was presented by David Bosley (Stellar Solutions) and Jerry Picantine (Science Applications International Corp.) on forthcoming activities of DoD's Office of the Space Architect (OSA), including its Space Weather Architecture Study. In February of 1998, OSA will begin addressing space-architecture issues for the 2010-2025 time frame, including those of space weather. It struck Lou Lanzerotti that 2025 is a long time away, asking how one could hope to capture the thrust of technical innovation that far in advance. He suggested that the group consider commercial plans, although they might be hard to track due to secrecy of the industrial activities and the fast pace of commercial development.

Richard Behnke (NSF) expressed support for the commercialization by private-sector vendors of space-weather products and services. Regarding their relationship to the National Space Weather Program (NSWP) formulated by NSF and other agencies, he stated, "They are stepping into the gap, and they must succeed if the NSWP is to succeed." Lou Lanzerotti noted that "competition will exist between the government and the private-sector vendors, and the government needs to respond to this conflict of interest." Amy Holman (NOAA) stated that NOAA and SEC recognize the government/private-sector tension and have established official Policies on Information Dissemination to define clearly the NOAA/SEC roles. A summary of these policies is included as an Attachment to Section 6 of these Proceedings.

There was widespread support expressed for the RPC envisioned by NOAA/SEC as a means to test and demonstrate research-community models and results that may be useful for space-weather environmental analyses and forecasting. Tom Tascione stated that it would be useful to establish guidelines for how scientists are to enter and exit the RPC and what operation and maintenance contributions are to be made by the government and the RPC users.

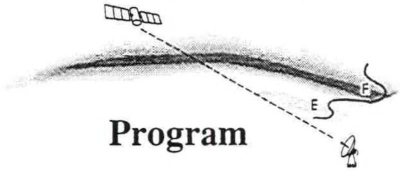
Jim Secan asked that all government organizations establish guidelines similar to those developed by NOAA to define clearly what commercial-sector space-weather activities the agencies may or may not engage in. This would extend to both operational (SEC, USAF 55th Space Weather Squadron) and research (government laboratories) organizations within the government. Such guidelines are necessary so that vendors know that they will not develop a capability only to be pre-empted by a government agency. The possibility was suggested for joint ventures between DoD and private-sector vendors, e.g., cooperative research and development agreements.

At this point, the facilitator asked the assembled participants to identify one or a few key **recommendations** from the workshop. Putting aside the semantic question, Jim Secan nominated **model "validation"** as having **top priority**, even though (or, in part, because) a comprehensive definition and assignment of roles and responsibilities are lacking.

Based on inputs from the workshop recorders, the facilitator of the Plenary Session believes that broad consensus was reached in favor of the foregoing recommendation. Discussion of it was consistent with emphasis throughout the workshop on quantifying uncertainties in space-weather products so that they can be factored into operational planning and decision-making quantitatively. Products should be simple and tailored to address specific user objectives so their impact can be quantified clearly as well. Users must participate in defining meaningful validation metrics and determining system sensitivities to space-weather effects in operational terms. Researchers and developers also must participate, however, and this workshop should be only one step in bridging the gap.

A final recommendation, initiated by David Anderson (AFRL), was made to hold a follow-up workshop in one to two years.

Space Weather Effects on Propagation of Navigation & Communication Signals



Program

Wednesday morning, 22 Oct

- Call to Order and Statement of Workshop Objective 0830
  Edward J. Fremouw, NorthWest Research Associates (NWRA)
- Welcome and Logistical Announcements
  John V. Evans, COMSAT
- The National Space Weather Program
  Richard A. Behnke, National Science Foundation
- An Introduction to Space Weather in the Ionosphere
  Michael C. Kelley, Cornell University
- An Overview of GPS
  Keith McDonald, Sat Tech Systems
- Wide Area Augmentation System
  Richard R. Domikis, Federal Aviation Administration
- Group Delay and Phase Advance due to Ionospheric Total Electron Content
  Anthony J. Mannucci, Jet Propulsion Laboratory
- Communication Satellite Systems and the Ionosphere
  John V. Evans, COMSAT

Lunch Break 1130

Wednesday afternoon, 22 Oct

- Signal Statistics of Transionospheric Scintillation 1230
  Edward J. Fremouw, NWRA
- Climatology of Transionospheric Scintillation
  Santimay Basu, AF Research Laboratory (AFRL)
- Refinement of Workshop Goals0
  Edward J. Fremouw, NWRA
  All Participants

Break to Reconfigure Room

- Open Discussion Session on Communications (including HF) 1330
  Facilitator: Louis J. Lanzerotti, Bell Labs, Lucent Technologies
  Recorders: John M. Goodman, TCI
  Keith M. Groves, AFRL
- Open Discussion Session on Navigation Systems 1330
  Facilitator: Bakry El-Arini, MITRE
  Recorders Patricia H. Doherty, Boston College
  Edward J. Weber, AFRL
- Poster Session 1530
  James A. Secan, NWRA
  All Participants

Wednesday evening, 22 Oct

- Banquet at Bethesda Marriott Hotel (Pooks Hill) 1830
  After-dinner Speaker: E.W. (Joe) Friday, Assistant Administrator of NOAA

Thursday morning, 23 Oct

- Air Force Space Environmental Requirements in Support of Communication and Navigation 0830
  Russell A. Kutzman, Air Force Space Command (AFSPC)
- Navy Requirements for Space Weather Information 0900
  Gus K. Lott, Naval Postgraduate School
- DoD Space Weather Services 0930
  Michael S. Christie, AFSPC
  David N. Anderson, AFRL

Break 1000

- Civilian Space Weather Services 1030
  Joseph M. Kunches, NOAA Space Environment Center
- Space Weather Issues in the Private Sector 1100
  Thomas F. Tascione, Sterling Software

Lunch Break 1130

Thursday afternoon, 23 Oct

- Open Discussion Session on Communications (including HF) 1300
  Facilitator: Louis J. Lanzerotti, Bell Labs, Lucent Technologies
  Recorders: John M. Goodman, TCI
  Keith M. Groves, AFRL
- Open Discussion Session on Navigation Systems 1300
  Facilitator: Bakry El-Arini, MITRE
  Recorders Patricia H. Doherty, Boston College
  Edward J. Weber, AFRL
- Open Discussion Session on Commercial Space Weather Services 1300
  Facilitator: Thomas F. Tascione, Sterling Software
  Recorders: James A. Secan, NWRA
  A. Lee Snyder, NWRA
- Informal discussions, with refreshments (posters available) 1600

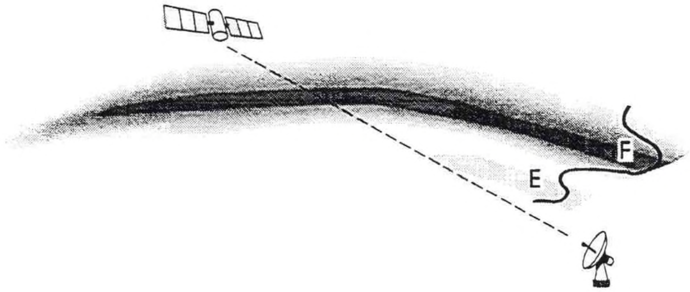
Friday morning, 24 Oct

- Report from Open Discussion Sessions 0830
  Facilitators and Recorders
  All Participants

Break 1030

- Summary and preliminary statement of conclusions 1100
  Members of Program Committee
  Open discussion by all

Adjourn 1200



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