The National Plan for Stratospheric Ozone Monitoring and Early Detection of Change

1981-1986

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METEOROLOGICAL SERVICES
AND SUPPORTING RESEARCH**

U.S. DEPARTMENT OF COMMERCE/National Oceanic and Atmospheric Administration

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PREFACE

The Federal Committee for Meteorological Services and Supporting Research in January 1976 charged the Federal Coordinator with the responsibility to develop and coordinate a national program for stratospheric ozone monitoring. Monitoring is needed to detect changes and to understand the processes involved if emissions of manufactured halocarbons and other pollutants, as predicted by numerical models, are depleting the global concentration of stratospheric ozone, the earth's ultraviolet shield. In August 1977, Congress enacted a program for Ozone Protection (Public Law 95-95, Amendments to the Clean Air Act of 1977, Section 126). The National Plan for Stratospheric Ozone Monitoring and Early Detection of Change has been developed both to respond to the action of the Federal Committee and to support the provisions of Public Law 95-95.

In PL 95-95 Congress authorized some new programs while affirming the objectives of many existing programs in eight Federal agencies. The Federal agencies involved are the following:

(1) Environmental Protection Agency

(2) Department of Commerce, National Oceanic and Atmospheric Administration

(3) National Aeronautics and Space Administration

(4) Federal Aviation Administration

(5) Department of Agriculture

(6) National Cancer Institute

(7) National Institute of Environmental Health Sciences

(8) National Science Foundation

The purpose of Public Law 95-95 is to provide (1) a better understanding of the effects of human actions on the stratosphere, (2) understanding of the effects of changes in the stratospheric ozone on public health and welfare, (3) information to Congress on the progress of regulation, and (4) information to Congress on the need for additional legislation in this area. The Administrator of the Environmental Protection Agency (EPA), in accordance with PL 95-95, has established a coordinating committee, known as the Interagency Committee for Stratospheric Ozone Protection (ICSOP), to coordinate the long-term research, monitoring, and study programs necessary to achieve those objectives.

The national plan will be reviewed annually by the Interagency Committee for Stratospheric Ozone Protection. In addition, the biennial agency reports to Congress will be reviewed by an independent group of experts (funded by

EPA). The plan will be revised and updated as necessary by the Federal Coordinator for Meteorological Services and Supporting Research, based on the findings and recommendations of the ICSOP and the group of experts.

Due to current budgetary uncertainties in all participating agencies, this Plan is being published without the customary section on agency resources over the planning period of FY 1981-FY 1986.

Special recognition is due to A. J. Miller of NOAA, who carried out the responsibility of integrating and writing the major portion of this document, especially the appendices on verification and calibration, with grace and dedication; and to Donald H. Hunt, Chairman of the Working Group, who shared in the writing and editing, and without whose leadership and perseverance this Plan could not have been prepared.

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EXECUTIVE SUMMARY

This initial National Plan for Stratospheric Ozone Monitoring and Early Detection of Change calls for a transition from reliance on a ground-based, geographically-biased ozone observing network operated by cooperating nations to a combined satellite and ground-based monitoring program that will provide global coverage of the vertical distribution of stratospheric ozone, as well as total ozone overburden.

The plan discusses the strategy, instrumentation, and monitoring products to be prepared during this transition period, and while it focuses attention on the planning period of 1981-86, recognizes that global atmospheric monitoring for protection of the ultraviolet shielding properties of atmospheric ozone will be required to continue over several decades.

The operational satellite ozone vertical profile monitoring system will be flown on the NOAA Tiros N operational satellite series beginning in 1984 to carry on ozone measurements initiated on the NASA R&D satellites.

The Dobson ozone network, which has been improved already through upgrading, improved calibration, and periodic international intercomparisons, will be expanded in 1982 through the addition by NOAA of a new station on the west coast of the United States.

The goals of the combined satellite and ground-based monitoring program are to:

(1) Acquire, process, and evaluate various atmospheric data necessary to detect how and why parameters are changing that may impact atmospheric ozone that shields the earth from damaging ultraviolet radiation;

(2) Improve understanding of the natural global variability of atmospheric ozone and its vertical distribution, information which is essential to detect any trend change exceeding, in a statistically significant sense, the limits of natural variability;

(3) Provide sufficient information and data in standardized form to numerical modelers to test and validate the models that predict potentially harmful impacts from such changes;

(4) Provide information and validated data to national and international agencies, such that requirements for remedial action can be established where necessary for the protection of the public health and welfare.

Toward these goals, this Plan sets forth a requirement to monitor the following parameters during the 1981-86 period:

(1) Total ozone overburden and the vertical distribution of ozone;

(2) Stratospheric vertical distribution of the meteorological parameters of temperature, pressure-height, and wind;

(3) Solar ultraviolet flux variability in the spectral region of 175 to 320 nm;

(4) Content and vertical distribution of stratospheric water vapor;

(5) Chlorofluoromethanes in the troposphere.

Less well-defined, at this time, are the requirements for monitoring specific trace constituents in the atmosphere that influence the ozone amounts. This is the subject of considerable on-going research, which will be addressed in future revisions of this plan based on the results of such research studies.

It is important to note that changes in stratospheric ozone cannot be understood unless the change in the entire ozone profile is known. Effects of chlorofluorocarbons, for example, cannot be separated from the effects of oxides of nitrogen. These interactions lead to a combined effect which is different at various altitudes.

Operational monitoring products and services will be prepared by NOAA and distributed to interested agencies, researchers, and other users, after suitable calibration corrections, as follows:

(1) Daily global meteorological charts at standard pressure levels of 100, 70, 50, 30, 10, 5, 2, 1, and 0.4 mb (corresponding approximately to 16, 18, 20, 24, 30, 35, 42, 48, and 55 km).

(2) Daily global synoptic charts of ozone mixing ratio at standard pressure levels of 30, 10, 5, 2, 1, and 0.4 mb [based on resolution capabilities of the Solar Backscatter Ultraviolet (SBUV) satellite ozone measurement system].

(3) Daily global synoptic charts of total zone overburden.

(4) Monthly averages of daily chart products above.

(5) Daily, monthly, seasonal, and annual spatial averages of hemispheric and global ozone values.

(6) Total ozone and vertical ozone profile data from individual stations in the ground-based network used in calibration of satellite instruments.

(7) Ozone trend analysis (using both satellite and ground-based information) for determination of changes exceeding natural variability. (Updated annually).

All products and services will begin with the historical data record, where practical, which includes the NASA R&D satellite systems, the NOAA operational satellite program, and the ground-based observing systems. In this manner, the monitoring data record will be extended backwards in time to about 1970 for the satellite data. The ground-based Dobson network data exists back to the late 1950's, with one station, Arosa, Switzerland, operational since 1926.

These products will be used by the Federal agencies, researchers, industry, and other users to undertake studies of atmospheric processes and interactions, trends in stratospheric ozone and the causes thereof, and assessments of the impacts of stratospheric change on health and public welfare.

I. INTRODUCTION

Considerable concern has been expressed about the effects of anthropogenic influences on the stratospheric ozone layer's ability to shield the earth from the sun's ultraviolet radiation with possible deleterious effects on the biota and climate. The National Academy of Sciences has estimated (NAS 1979a) that if the atmospheric release of chlorofluorocarbons continues at the 1977 rate, the result will be, in the steady state, depletion of global total ozone that will range somewhere between 5 and 28 percent. The effect of such a depletion would be a percentage increase in damaging ultraviolet radiation larger by a factor of two than the percentage of ozone depletion.

The National Academy of Sciences in a companion study (NAS 1979b) states:

> "All human life depends on satisfactory growth of the plants and animals used for food. We know that the release of CFCs (chlorofluorocarbons) -- mainly CFMs (chlorofluoromethanes) -- into the atmosphere acts to deplete ozone in the stratosphere, although we can only estimate approximately by how much. We know that stratospheric ozone depletion will increase the amount of DUV (damaging ultraviolet radiation) reaching the ground from the sun, and by how much. We know that increased DUV can have unfavorable effects on plant growth and on life near the surface of our seas, although our information is incomplete and qualitative. We do not know at what annual release of CFCs the consequences for the world's food would be intolerable, but we know there is such a level ...."

Other effects from the CFC releases, the NAS study states, include an increase in skin cancer in the countries of Western Europe and North America and in Australia and New Zealand, where the skin types of significant fractions of the population make them susceptible to skin cancer caused by overexposure to sunlight.

The NAS study cautions:

> "A reasonable projection for the 'wait and see' policy, with decision triggered by a crucial depletion, involves exposure about 20 years later to at least twice that depletion as well as continuing exposure to at least the crucial depletion for several decades more. This is clearly not a prudent strategy."

In response to these concerns, Congress has required, under Public Law 95-95, Amendment to the Clean Air Act of 1977, Section 126 (See Appendix) that eight Federal agencies undertake continuing studies of the cumulative effect of all substances, practices, processes, and activities that may affect the stratosphere, especially ozone in the stratosphere, including specifically halocarbons, other sources of chlorine, bromine compounds, and emissions of aircraft propulsion systems. These studies shall also include such physical, chemical, atmospheric, biomedical, or other research and monitoring as may be necessary to ascertain (a) any direct or indirect effects upon the public health and welfare of changes in the stratosphere, especially ozone in the stratosphere, and (b) the probable causes of changes in the stratosphere, especially the ozone in the stratosphere.

In addition, large aircraft fleets could affect the environment adversely. In response, the Federal Aviation Administration (FAA) has assumed the responsibility "to quantitatively determine the requirements for reduced cruise-altitude emission and, in conjunction with the Environmental Protection Agency and the International Civil Aviation Organization, to ensure that, if necessary, appropriate regulatory action is taken to avoid environmental degradation."

The rationale for this encompassing approach is presented in Figure 1, which illustrates the basic physical parameters of the stratospheric region and their internal readjustments. Initially, the constituent distribution is governed by the incoming solar UV radiation and the natural sources of the constituents interacting through atmospheric photochemistry. The atmospheric heating associated with the effect of radiation on these constituents influences the temperature and wind fields which, in turn, influence the constituent distribution through the temperature dependence of the reaction rates and the redistribution of material by the winds. In order to understand the cause of observed changes in the constituents, then, we need information on all the other aspects as well. Of further importance in terms of the climate of the atmosphere are the tropospheric interactions with the stratosphere. While it is well-recognized that such interactions are very important forcing functions of the stratosphere (e.g., Miller, 1970, Wallace, 1978), recent studies (Bates, 1977, Ramanathan, 1977) have indicated that the dynamic interactions and radiational influences may well have significant impacts on the tropospheric circulation and regional climate.

From the above, then, it is clear that stratospheric monitoring cannot be limited to any single parameter, such as ozone. Within this plan we considered the various parameters outlined above and their interactions. After due consideration of cost, available instrumentation, both that qualified for monitoring and that still experimental, and the scientific requirements for monitoring as currently recognized (e.g., WMO, 1977), it has been determined that for the planning period 1981-1986 the following parameters should be monitored:

(1) total ozone and its vertical distribution,

(2) vertical distribution of such meteorological parameters as pressure-height, temperature, and winds,

(3) solar ultra-violet radiation in the range from 175 to 320 nm,

(4) content and vertical distribution of water vapor,

(5) chlorofluoromethanes in the troposphere.

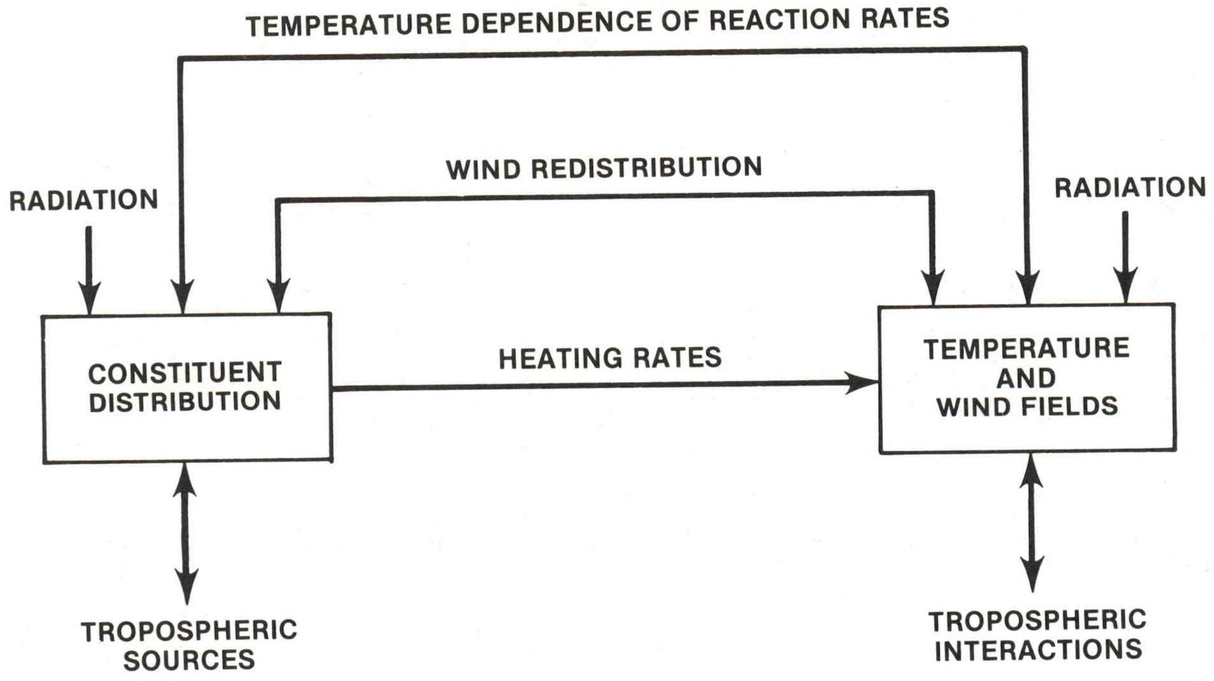

Figure 1 — Schematic of Stratospheric Forcing and Internal Readjustment Mechanisms

Monitoring of trace constituents that significantly influence ozone concentrations, such as the oxides of hydrogen, chlorine, and nitrogen (key parameters in processes of stratospheric change), may be needed in order to determine unambiguously the causative factors in any detected trend. As the requirements are further refined through basic research and observation, the plan will be modified accordingly.

II. MONITORING PARAMETERS

A. Total Ozone and Its Vertical Distribution

1. Horizontal Resolution Requirements. The World Meteorological Organization (WMO) Report of the Meeting of Experts on Measurements of Rare Species Relevant to the Ozone Budget (WMO, 1977) states that the minimum monitoring requirements for ozone are:

	Long-term Reproducibility	Minimum Measurement Frequency
O_3 total overburden	± 1%	Daily
O_3 vertical distribution	± 3-5%	Daily

where long-term reproducibility refers to the capability of two or more of the same instrument systems to conduct comparable measurements of a given variable at different times and locations.

The recommended minimum measurement frequency is daily for both total ozone and the vertical distribution. With respect to the horizonal spatial sampling of total ozone, it has been shown that the minimum spatial requirement is on the order of 1000 km (13° longitude at 45° latitude) and about 2.5° latitude (e.g., Bojkov, 1969, Prabhakara, et al., 1976). For the vertical ozone profiles, however, it appears that above about 10 mb (30 km) in the photochemical domain, the horizontal spatial scales of motion are effectively filtered such that the planetary waves in the pressure-height and temperature fields account for over 95 percent of the variance (Quiroz, Mahlman, private communications). The minimum spatial requirement within this region, then, is on the order of 2000 km (26° longitude at 45° latitude) and 5° latitude. In the lower stratosphere, the dynamic domain, it is not clear what the actual minimum horizontal spatial requirement is, but it would seem that it must be at least as good as that for total ozone, on the order of 1000 km and 2.5° latitude.

2. Vertical Resolution Requirements. With respect to the vertical resolution, the standard meteorological pressure levels for analysis in the stratosphere are 100-, 70-, 50-, 30-, 10-, 5-, 2-, 1-, and 0.4-mb (16, 18, 20, 24, 30, 35, 42, 48, and 55 km) (staff, UAB, NASA SP-3102, 1976), which represent an approximate 5-km height resolution over the range 16-55 km. As one aspect of the monitoring program is to relate the ozone and the meteorological information, the ozone profile resolution should be at least on the same order. At the same time, the results of Chandra, et al., (1978) show that a 5-km vertical resolution is satisfactory to delineate the anthropogenic influences.

3. Ground-based Instrumentation Qualified for Monitoring.

(a) Total Ozone Overburden. The most widely used tool for monitoring total ozone is the Dobson ozone spectrophotometer (Dobson, 1931). This instrument is a quartz-prism double-monochromator, which measures the differential attenuation of sunlight in adjacent spectral bands in the UV Huggins bands of ozone. By use of a double wavelength pair method with direct sunlight, measurements precise to ± 2% are possible. Empirical relationships between measurements on direct sunlight and zenith skylight have been derived. This allows a less accurate estimation of total ozone on partly cloudy and cloudy days.

In the U.S.S.R., a filter photometer system, the M-83, is used for total ozone measurements. In a direct comparison with the Dobson spectrophotometer, Bojkov (1969) had found differences as large as 40 percent. These differences, which depend on the solar zenith angle and the season, apparently arise from the use of broadband filters and the assumption of constant ozone absorption coefficients. The U.S.S.R. has about 35 M-83 instrument reporting stations.

The Dobson total ozone measurements have been successfully coordinated by WMO to provide meaningful results on a global basis. For the United States, the National Oceanic and Atmospheric Administration (NOAA), in addition to operating the U.S. Dobson sites, contributes to the WMO global monitoring program by maintaining the world primary standard instrument for these measurements (No. 83) and by participating in international and regional intercomparisons.

The differential absorption technique for measuring total ozone from the surface is potentially very accurate, but calibration and maintenance of a Dobson spectrophotometer are difficult (Dobson, 1957). It is a continuing effort of the WMO to maintain data quality, and the maintenance at the different stations does vary. Calibration drifts can be falsely interpreted as real ozone changes, and biases between stations can exist.

The current (1980) contiguous U.S. Dobson network consists of stations at Caribou, ME; Bismarck, ND; Boulder, CO; and Nashville, TN (all operated by NOAA); Wallops Island, VA (cooperative between NOAA and NASA); Tallahassee, FL (operated by Florida State University), and White Sands, NM (operated by the U.S. Army). Current plans are for total ozone measurements to be added at one site on the west coast of the United States. This will expand the longitudinal coverage over the contiguous United States and make the real averages more representative of the true value. In addition, there are Dobson instruments at the four NOAA Geophysical Monitoring for Climatic Change (GMCC) stations at Mauna Loa, HI; Point Barrow, AK; American Samoa; and Amundsen-Scott Base, South Pole. There is also a U.S. Dobson instrument at Huancayo, Peru, operated in cooperation with the Peruvian government. Currently, there are about 60 other Dobson stations reporting throughout the world under the aegis of the World Meteorological Organization (WMO) Global Ozone Research and Monitoring Program. Ozone data are archived at the World Ozone Data Center, Toronto, Canada.

It should be noted here that Dobson spectrophotometers are no longer being produced. Two groups have developed possible replacement instruments. W. A. Mathews and R. D. Basher of New Zealand have developed an interference filter ozone photometer, which is currently undergoing evaluation at Wallops Island, Virginia. A. W. Brewer has developed a grating ozone spectrophotometer, which is now available commercially. Preliminary evaluation indicates that the Brewer instrument provides direct sun total ozone observations of precision comparable to the Dobson (Kerr et al., 1976). Further evaluation is continuing at Toronto and Wallops Island. The extent to which either or both of these instruments can serve as successors to the Dobson instrument (without adversely affecting the historical total ozone series) remains to be seen. Completion of these evaluations may take several years.

(b) Vertical Distribution of Ozone. Estimates of the vertical distribution have been made with the Dobson instrument using the "Umkehr" effect (Gotz et al., 1934). The United States does not now conduct routine "Umkehr" observations using the Dobson instrument, partly because there was considerable doubt as to whether the vertical profiles of ozone obtained in this way had much validity. Recently, evidence has been adduced indicating that the "Umkehr" measurements are not as bad as previously thought (Mateer, 1965, and DeLuisi, 1979).

Recently, a new method for obtaining ozone profiles, known as the "short Umkehr," has been tested and accepted. The short Umkehr method requires zenith sky measurements on the A, C, and D wavelength pairs of the Dobson ozone spectrophotometer while the solar zenith angle is between 80 and 89 degrees. It has been shown by DeLuisi (1970) in a theoretical-numerical study that such measurements should contain at least as much information about the ozone profile as do the conventional Umkehr observations taken on the C wavelength pair while the solar zenith angle is between 60 and 90 degrees. The short Umkehr requires about one-third of the observing time needed for the conventional Umkehr.

This reduced observing time gives the short Umkehr at least three distinct advantages over the conventional Umkehr. First, there is less chance that significant changes in the ozone profile will occur during the course of the observation; second, there is a better chance that the zenith sky will remain clear; and third, it costs less per Umkehr observation in terms of observer time.

The development of the short Umkehr computer evaluation program (a cooperative Canadian-U.S. effort) for ozone profile information builds upon the earlier work done on the conventional C-pair evaluation program (Mateer and Dutsch, 1964). To this has been added the optimum or maximum likelihood inversion method which uses *a priori* ozone profile information obtained from rocket and balloon ozonesondes. The short Umkehr computer evaluation program has been completed and preliminarily tested using ozonesonde observations taken concurrently with a short Umkehr observation (Mateer and DeLuisi, 1980). It is available for routine reduction of Umkehr measurements submitted to the World Ozone Data Center at Toronto.

With respect to the long-term trend of stratospheric ozone as depicted by the Umkehr observations, a significant problem arises in that the observations are sensitive to the stratospheric aerosol loading. Angell (1980), for example, has shown that the Umkehr values in the region 32-46 km were strongly influenced by the volcanic eruptions of Mt. Agung (1963) and Tierra del Fuego (1974). There has been little or no effect from the Mt. St. Helens (1980) eruption (Angell, private communication).

Errors on short Umkehr ozone profiles caused by aerosol scattering and absorption are most strongly related to optical depth and, to a much lesser extent, to aerosol refractive index, size distribution, and vertical profile in the troposphere. Stratospheric aerosols cause considerably greater error than tropospheric aerosols (for ozone concentration at 45 km, 10% for stratospheric optical depth of 0.017 and 3% for tropospheric optical depth of 0.17). Because the aerosol error in ozone profiles is mainly related to aerosol optical depth and in a systematic and linear way, it becomes feasible to make a reasonable correction to the ozone profile if tropospheric and stratospheric optical depth are known.

Tropospheric optical depth is commonly obtained by sunphotometer measurements, but stratospheric aerosol optical depth requires more sophisticated means for its measurement; methods include lidar and satellite (SAGE) measurements or transmission measurements from a remote nountaintop observatory much as Mauna Loa. Finally, the short Umkehr method seems to be less sensitive to atmospheric aerosols, as compared to the standard method. Moreover, the difference is nearly a factor of 2. Corrections to longterm series of Umkehr observations affected by stratospheric aerosol have been estimated by DeLuisi (1979). These corrections show that the sudden decrease in upper stratospheric ozone following the eruption of Mt. Agung was most likely fictitious.

For determinations of the vertical ozone distribution with good vertical resolution, direct soundings are required. Optical balloonsondes, using differential absorption techniques analogous to the Dobson method, were designed by Kulcke and Paetzold (1957), Vassy (1958), and Kobayashi et al., (1966). Above the ozone maximum, these methods have limited vertical resolution but potentially good absolute accuracy.

Electrochemicalsondes, using the reaction of ozone with an aqueous solution of potassium iodide, were later developed by Brewer and Milford (1966), Komhyr (1965), and Kobayashi and Toyama (1966). These can be flown day or night and have better vertical resolution than the opticalsondes below 25 km. In practice, data from the electrochemicalsondes must be adjusted by coincident independent total ozone observations, and all such sondes require air pump efficiency corrections. Intercomparison between balloonsondes shows agreement within about two percent after corrections are applied.

A third type of balloonsonde, based on the chemiluminescence of a dye substance exposed to ozone (Regener, 1964), was used extensively for a relatively short period of time. This device, while capable of fast response, provides only relative concentration data, and was found to be subject to calibration changes in flight.

Although the United States funded balloon ozonesonde networks from 1964 through 1966, these measurements have been discontinued. The only station flying sondes routinely in the United States is Wallops Island, Virginia, on about a weekly basis. Other than this station, our information on the vertical ozone distribution in the lower stratosphere comes from approximately 10 stations in Canada, Japan, Europe, and Australia.

For altitudes above 30 km, optical and chemiluminescence techniques have been adapted for the sounding rocket. These methods can operate at altitudes up to approximately 70 km. The earliest successful rocket data were acquired by Johnson et al. (1952) using a spectrograph launched at sunrise. This technique has been more recently employed by Krueger (1965, 1969), Nagata et al. (1971), and Weeks and Smith (1968), using UV filter radiometers. Carver et al. (1966) have used the moon for nighttime measurements. Hilsenrath et al. (1969) have used the chemiluminescent method for day and night soundings. By use of preflight multipoint calibrations and inflight flow-rate measurements, they find agreement within 10 percent of optical results. Randhawa (1967) has used a similar method on small rockets; however, his measured ozone concentrations above 35 km are generally two to five times greater than those of the other investigators.

The United States is currently operating one rocket ozone station taking observations once a month at Wallops Island, Virginia, using the Krueger optical technique. In addition, the United States is involved in cooperative efforts with the Canadian and Brazilian governments. Monthly soundings are being taken with the Krueger technique from Fort Churchill, Canada. Monthly soundings from Natal, Brazil, will be initiated in the near future, again using the Krueger technique.

In September 1979, International Rocket Ozonesonde Intercomparisons were held under FAA, NASA, and WMO sponsorship at Wallops Island, Virginia. Results of this intercomparison should be available in late 1981.

Recently, it has been suggested that a modified electrochemical balloonsonde may be capable of reliable ozone measurements up to about 40 km. This instrument is currently under test by NOAA to determine instrument performance at high altitudes (30-40 km) and to test the reliability of balloon launch systems. Results should be available in late 1982.

4. Satellite Systems Qualified for Monitoring

(a) Total Ozone Overburden. Satellite remote sensing methods for determining total ozone are basically divided into two techniques, that using backscattered UV sunlight (Dave & Mateer, 1967) and that using 9.6 um radiation emitted by the atmospheric ozone (Prabhakara et al., 1970). Both require the use of prior statistical information on the ozone distribution. These techniques were evaluated with the backscatter UV spectrometer (BUV) and infrared interferometer spectrometer (IRIS) sensors flown on Nimbus satellites, and they were found to agree to about ± 6 percent with near simultaneous Dobson spectrophotometer data over a broad range of conditions (Mateer, et al., 1971; Prabhakara & Kunde, 1972; Heath et al., 1973; Prabhakara et al., 1973; Lovill, 1974; Miller et al., 1976). Table 1 indicates past and present satellite systems capable of determining total ozone and their major features.

TABLE 1. Total Ozone - Satellite Measurement Systems

Instrument	Type	Day/Night Sensing	Side Scan
IRIS	Atmospheric Emission	Day/Night	No
BUV	Solar Backscatter	Day Only	No
SBUV	Solar Backscatter	Day Only	No
TOMS	Solar Backscatter	Day Only	Yes
TOVS	Atmospheric Emission	Day/Night	Yes
MFR	Atmospheric Emission	Day/Night	Yes

Figure 2 shows a schedule of the total ozone satellite systems and their approximate (planned for future) lifetimes. A significant gap, from 1982-1984, may occur between the Nimbus 7 and NOAA F and G spacecraft, if only the lower limits of the planned lifetimes are achieved; however, NASA, as a matter of high priority, will attempt to extend operations of Nimbus 7 as long as possible.

Fortunately, the NOAA Tiros N Operational Vertical Sounder (TOVS) is equipped with channels whose measurements of atmospheric radiances can be used to derive total ozone overburden, precise to within about ± 10%, which NOAA is reducing, analyzing, and archiving. Absolute accuracies cannot yet be stated, as the satellite determinations are tied to ground-based Dobson measurements. The NOAA TOVS series is scheduled to overlap both the NASA Nimbus Solar Backscatter Ultraviolet and Total Ozone Mapping Systems (SBUV and TOMS) and the NOAA SBUV-2 satellites.

While the TOVS instrument was not designed originally to be an ozone-monitoring instrument, analysis of the data provides a significant source of satellite-derived global coverage. Also, during the time period 1977-1982, the similar USAF Multifilter Radiometer (MFR) with an infrared ozone channel at 9.8 μm provides global total ozone data. Both the FAA and NASA are supporting the reduction, analysis, and archiving of these data at the Lawrence Livermore Laboratory, California.

An objective comparison of total ozone data derived from the NASA SBUV, NOAA TOVS, and USAF MFR instruments with data from the Dobson network is being conducted under the leadership of the FAA.

(b) <u>Satellite Systems - Vertical Distribution of Ozone</u>. Table 2 summarizes the satellite techniques for vertical profile ozone measurements and provides altitude ranges for the profiles. Methods for remote sounding of the vertical ozone distribution (Singer and Wentworth, 1957) using backscattered UV radiation have been discussed by Mateer (1972). Instruments using the backscatter principle have been flown on satellites in several short-lived experiments (Iozenas et al., 1969, Rawcliffe and Elliott, 1966), while longer-lived experiments were flown on OGO-4, Nimbus 4 (Heath et al., 1973), and on Nimbus 7 (SBUV, TOMS, LIMS).

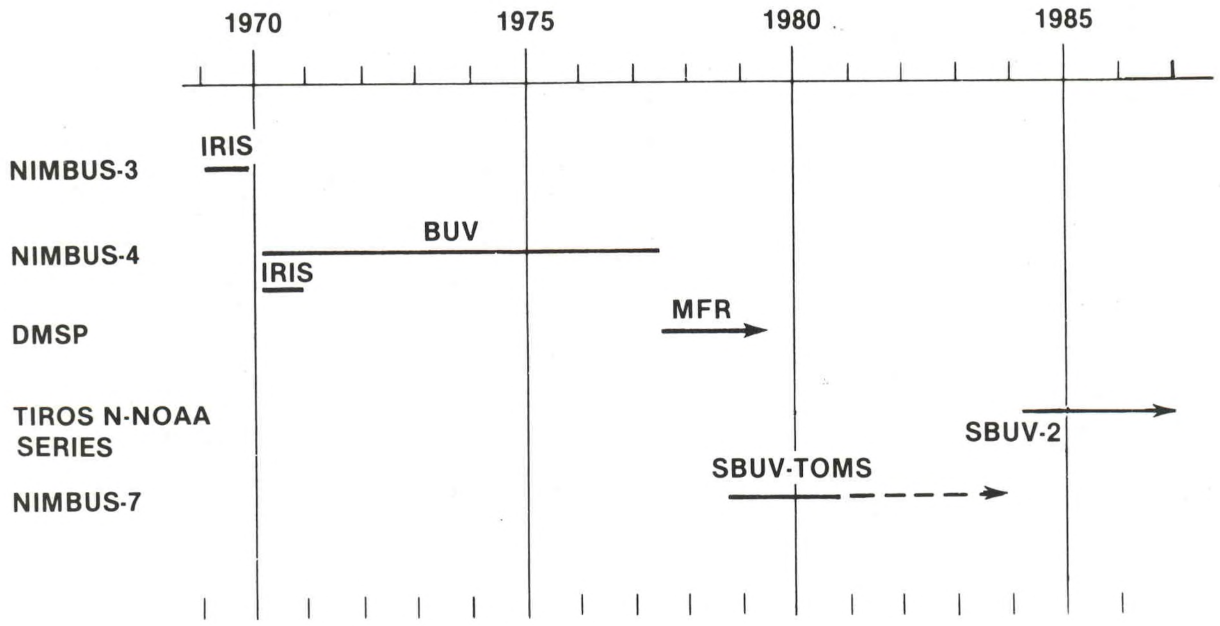

Figure 2 — Schedule of Satellites and Measurement Systems for Total Ozone

TABLE 2. Vertical Ozone Profile - Satellite Measurement Systems

Instrument	Type	Day/Night Sensing	Side Scan	Altitude Range
OGO 4	Solar Backscatter	Day Only	No	25-55 km
SAGE II	Solar Backscatter	Terminator Only	No	16-60 km
HALOE	Solar Backscatter	Terminator Only	No	10-65 km
BUV	Solar Backscatter	Day Only	No	25-55 km
SBUV	Solar Backscatter	Day Only	No	25-55 km
LRIR	Atmospheric Emission	Day/Night	No	15-16 km
LIMS	Atmospheric Emission	Day/Night	No	15-70 km
SAGE	Solar Occultation	Terminator Only	No	16-60 km

The Solar Backscatter Ultraviolet Ozone Measurement System (SBUV) launched on Nimbus 7 in late 1978, is an improved version of the BUV. NASA and NOAA have agreed to jointly fund procurement of SBUV systems to be configured for the NOAA TIROS-N series of spacecraft. These systems, designated SBUV-2, are planned for launch on NOAA, in FY 1984 to continue acquisition of vertical ozone profile data following the end of the Nimbus 7 SBUV lifetime. A gap in data acquisition between Nimbus 7 and NOAA F and G is possible if the Nimbus 7 systems fail before NOAA F and G are launched.

Gille and House (1971) and Russell and Drayson (1972) have discussed ozone profile determinations using the 9.6 μm radiance of the earth's limb from satellite measurements. The first satellite infrared limb scanner, the Limb Radiance Inversion Radiometer (LRIR), flew on the Nimbus satellite (Gille et al., 1975). The LRIR was a multi-channel filter radiometer, one channel of which sensed radiation in the spectral region 940-1160 cm^{-1}. It viewed the limb of the earth in emission and through angular scanning obtained measurements of radiances in the vertical, which allows the vertical distribution of ozone to be determined through appropriate inversion procedures. The results have been evaluated by Gille et al. (1980). The precision of the retrievals is approximately 0.2 ppmV over the 15-67 km altitude range of the retrievals. The mean agreement with rocket profiles is within about 0.2 ppmV, and differences are not statistically significant down to 10 mb. A second instrument, the Limb Infrared Monitor of the Stratosphere (LIMS), flew on the Nimbus 7. Its results are expected to be similar to those of the LRIR. An infrared limb scanner will fly on the Solar Mesosphere Explorer (SME), with launch scheduled for Fiscal Year 1982.

The Stratospheric Aerosol and Gas Experiment (SAGE) on Application Explorer Mission - B (AEM-B) was launched in early 1979. It is a four-channel grating spectrophotometer for deducing the physical properties of stratospheric aerosols. SAGE is a solar occultation experiment; i.e., it obtains its basic data by the absorption of solar radiation viewed through the earth's limb. An ozone channel provides a correction factor to the data of the other three channels which are used to deduce information on the stratospheric aerosol properties.

The SAGE II instrument scheduled to fly on the Earth Radiation Budget Satellite (ERBS) to be launched in 1983 is similar to the SAGE instrument. The primary difference is that SAGE II will have the capability to measure NO_2 in addition to ozone and aerosols.

The Halogen Occultation Experiment (HALOE) will also fly on the ERBS satellite to measure the concentration profiles of ozone (O$_3$) and selected species of the nitrogen (NO), hydrogen (H$_2$O, CH$_4$), and halogen (HCl, HF, CH$_2$Cl$_2$) families that can cause ozone depletion. Four channels use the gas filter correlation radiometer technique (HCl, HF, CH$_4$, NO), and four channels use conventional filter radiometers (O$_3$, H$_2$O, CF$_2$Cl$_2$, CO$_2$). The CO$_2$ measurements are used to relate the correlation profile measurements to the tangent height pressure. HALOE, like SAGE and SAGE II, is a solar occultation experiment that obtains data during satellite sunrise and sunset events. ERBS will have about a 2-year lifetime beginning in 1983. Thus, the SAGE II and HALOE ozone data should complement the SBUV-2 data from the NOAA satellites.

3. Problem Areas. The previous discussion leads to the conclusion that no one instrument or type of instrument can completely satisfy the WMO recommendations. In this section we will delineate the strengths and weaknesses of the available systems and in the next section will present our program strategy.

a. Total Ozone - Ground-Based Systems. With respect to the total ozone measurements, Figure 3 indicates the locations of the ground-based observations. They are mainly limited to the major continental areas in the Northern Hemisphere with extensive unsampled areas.

b. Total Ozone - Satellite Systems. While it is obviously true that the satellite systems offer more extensive spatial coverage than the ground-based systems, it is important to recognize that certain caveats must be considered. From Table 1 we see that the SBUV and BUV instruments are nadir-viewing daylight sensors only, which means that for a typical polar orbit the data are about 27° longitude apart. A single instrument, then, cannot meet the 13° longitude spatial requirement. Also, as a daylight sensor it does not obtain retrievable information in the wintertime polar night (i.e., poleward of about 60°N,S). In addition, uncertainties in O$_3$ cross-sections as a function of temperature will effect the absolute accuracies of the SBUV. The Total Ozone Mapping System (TOMS) has a side-scanning capability that resolves the longitudinal spatial sampling problem, but the winter polar limitation is still in effect.

For a 9.6 or 9.8 um instrument the spatial sampling limitations are not as great, with both day and night coverage. When side-scanning capability is included, as in the NOAA TOVS and USAF MFR instruments, flown on the Tiros N and DMSP satellites respectively, the coverage is excellent. The major difficulties with this technique are that the total ozone retrievals must include a correction to the observed radiances for cloud contamination and there is a limitation in the winter polar areas due to the lack of temperature discrimination.

If SBUV-2 is carried on each satellite of a two-satellite system, such as the NOAA TOVS, the longitude spacing will be about 13°, thus meeting the spatial sampling requirements. This means that there will be morning observations by one satellite, afternoon observations by the second.

In Appendix 2, the precision of the daily total ozone estimates, assuming unbiased measurements, is presented for the SBUV and the

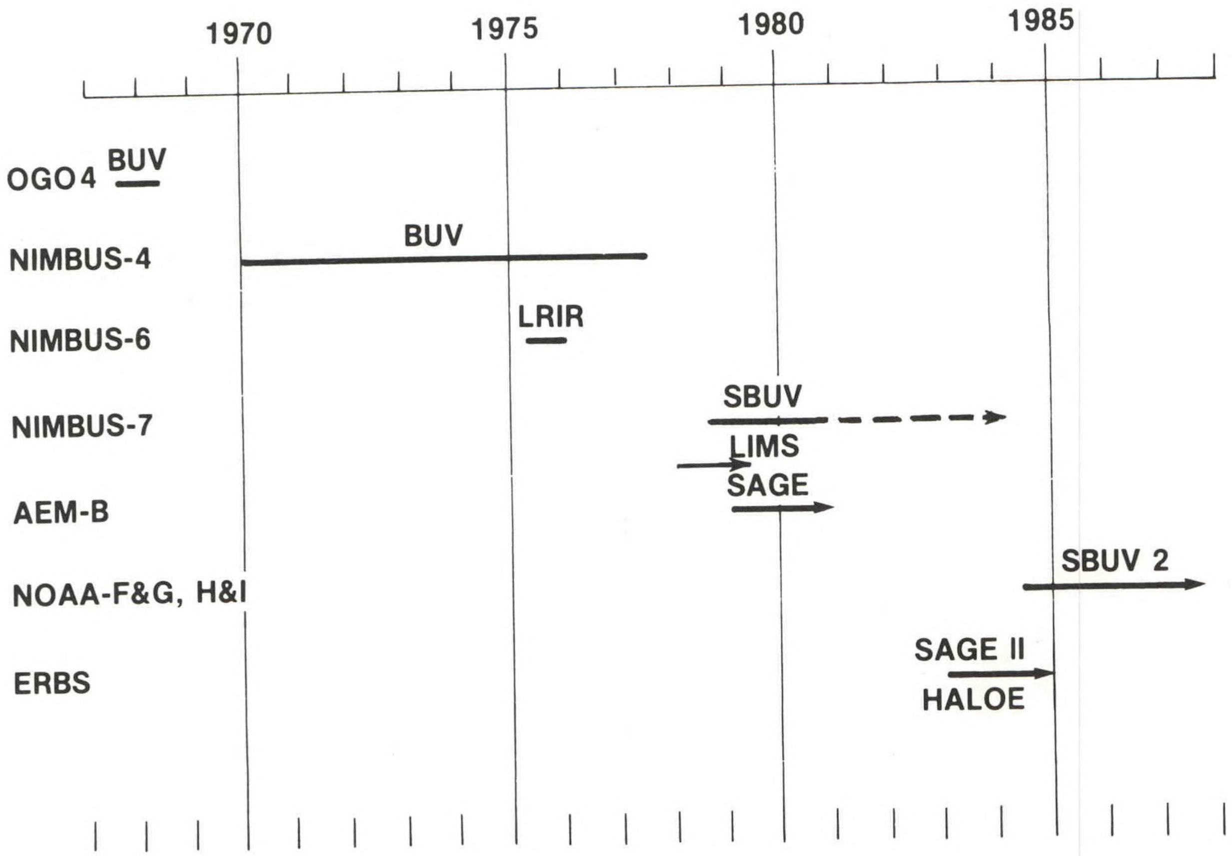

Figure 3 — Schedule of Satellites and Measurement Systems for Ozone Vertical Profiles

TOVS. The 95 percent confidence level of daily total ozone over the domain where data are obtained is shown to be on the order of ±0.90 percent and ±0.58 percent for the SBUV and TOVS, respectively. Also indicated in Appendix 3 is the uncertainty in estimating the average global ozone in mid-winter when the data loss in polar regions is a maximum. We see that the 2] (95 percent) level of uncertainty is about 1 percent, but that this error is most likely not random on a daily basis. The result is that for daily estimates of average global ozone the total 2] uncertainty including sampling is about ±1.34 percent, and this decreases to ±1.01 percent for a monthly average. The reason is, of course, that the sampling errors are random and, hence, for a monthly average are reduced to quite low levels.

With respect to the calibration of the satellite systems against the Dobson, a detailed discussion is presented in Appendix 2. It is shown that a 1 percent confidence level (95 percent) on the calibration can be achieved for the SBUV and TOVS utilizing the available Dobson network. The major difficulty with this approach is that the Dobson instruments would have to be routinely compared and cross-calibrated with the world standard instrument (No. 83) at Boulder, Colorado.

c. Vertical Ozone Profiling - Ground-Based Systems. The major difficulty associated with the ground-based systems is the lack of coverage, not only in terms of sampling the global ozone (Figure 4), but also with respect to the ability to delineate the dynamics of the ozone budget. The United States is currently operating only one routine balloon ozonesonde observing site, Wallops Island, on about a schedule of once per week. The rocket ozonesonde program is currently limited to three sites, Wallops Island, United States; Primrose Lake, Canada; and Natal, Brazil. The NASA rocket ozonesonde programs, however, are limited to about one observation per month. The advantages of shortened Umkehr measurements have been discussed previously. The Umkehr measurements should be instituted at all U.S. Dobson stations, using the short Umkehr method.

One of the major strengths of the ground-based systems is the ability to launch or make an observation in conjunction with satellite overpass. The statistics of such a verification procedure are discussed in Appendix 2 and an extensive program is recommended.

At the same time, it is recognized that the ground-based balloon ozonesondes provide information in the height domain (belowN25 km) where the SBUV information is very slight and the actual ozone amount is the greatest. Consequently, it is necessary that we supplement an SBUV type satellite system with a balloon program to provide data over the entire stratospheric region of interest. Within the U.S. national program, this should consist of once-per-week soundings at a low-, mid-, and high-latitude site with this schedule increasing at the latter two sites to about three-per-week during winter because of the increased synoptic variability of ozone. These data will be incorporated within the global observing system, depicted in Figure 5, to provide an initial data base for continued research and to help delineate the vertical structure of ozone variability.

d. Vertical Ozone Profiling - Satellite Systems. In terms of the spatial coverage, above about 10 mb the spatial scales of the pressure-heights and temperature fields appear to be effectively filtered such that the planetary waves account for over 95 percent of the variance. For such a cir-

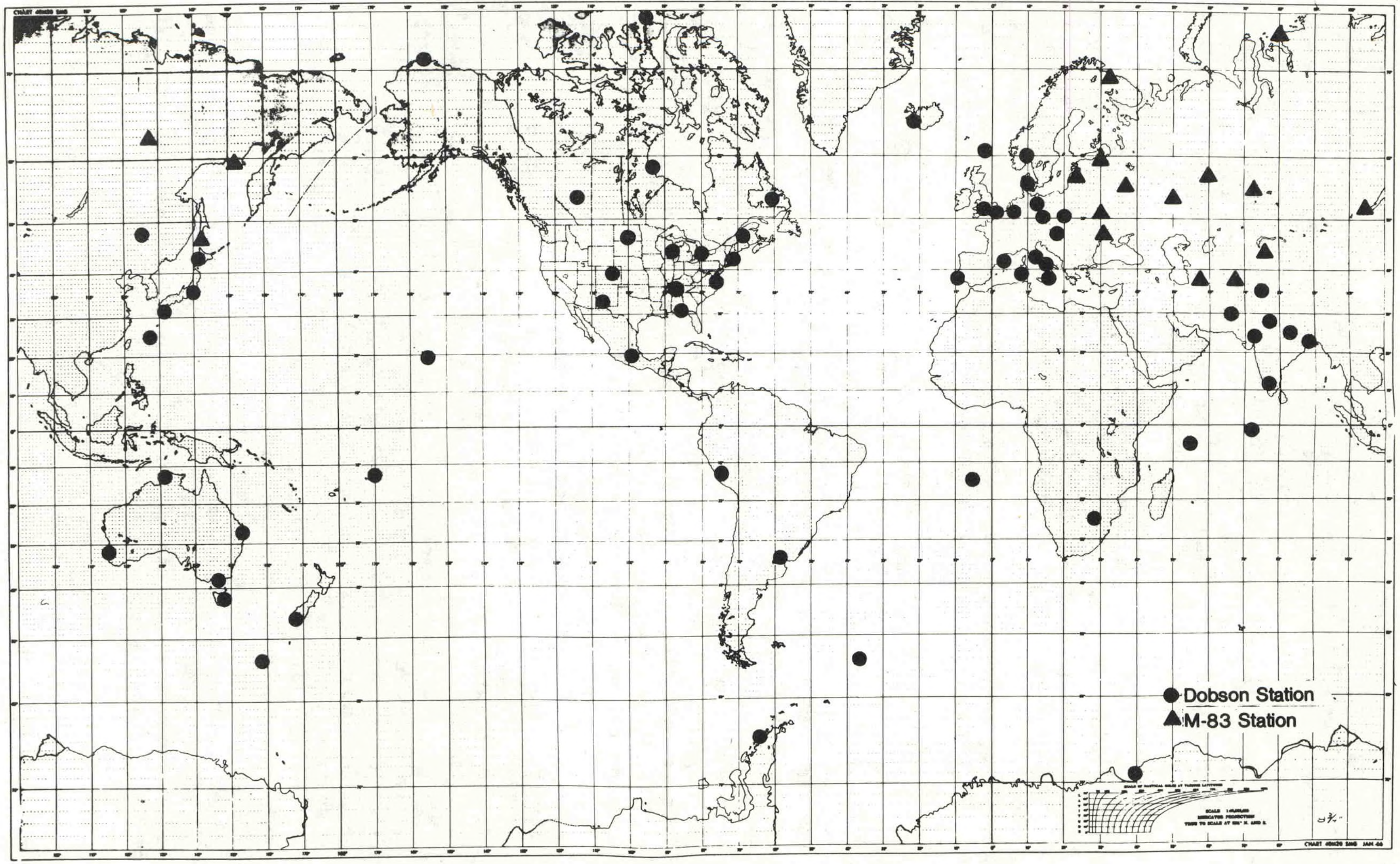

Figure 4. Location of Dobson and M-83 Total Ozone Observing Stations

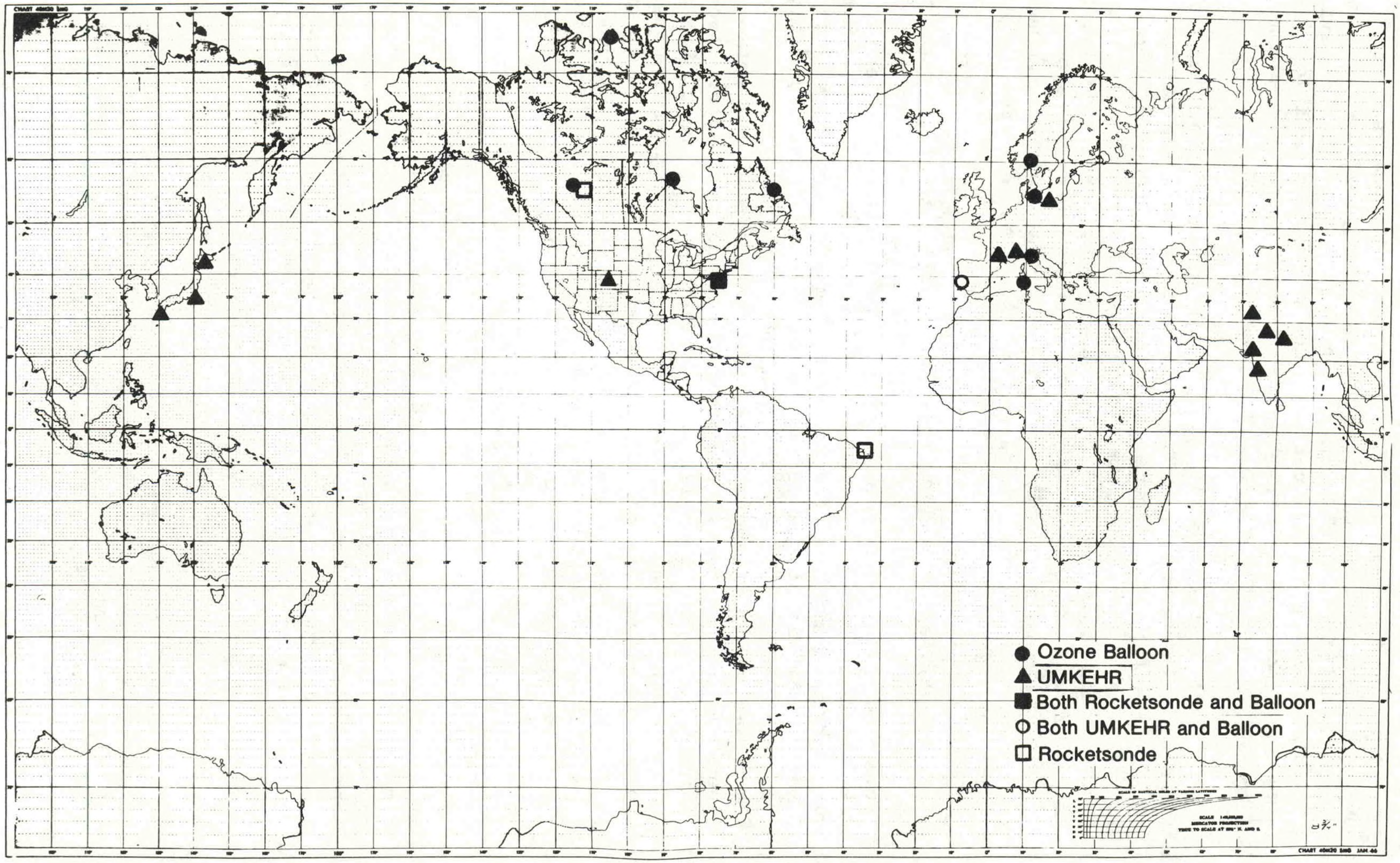

Figure 5. Ground-based Ozone Vertical Profile Measurement Stations

cumstance, a nadir viewing only satellite system (no cross-orbit scan) such as the SBUV is capable of resolving the desired features. The SBUV retrievals are basically limited to the region of 25-55 km, which is precisely the domain which encompasses the major area of ozone photochemistry and heating as well as the area where significant anthropogenic depletion, according to available estimates, is anticipated. This limitation would require an additional satellite or balloon or rocket ozone measurement system for the region from near the surface to about 30 km for complete coverage.

With respect to the question of missing information in the wintertime polar cap, it is shown in Appendix 4 that the uncertainty of the average global 2 mb mixing ratio appears to be very small, on the order of 0.2 percent. This is because the horizontal gradients appear to be much smaller than for the total ozone. If, however, we wish to be conservative and assume as for the total ozone that the 2s (95 percent) uncertainty is about 1 percent, then the precision of the daily estimate of average global mixing ratio is about ±2.0 percent and this decreases to ±1.05 percent for a monthly average.

Verification and calibration of the satellite data in the past has been performed by comparing the satellite data against correlative ground-based observations. In Appendix 2 the precision estimates of such comparisons are presented. It is important to recognize, however, that for the SBUV, contribution functions for several channels extend significantly above the 30-80 km altitude of the rocket ozonesondes, and thus, preclude the possibility of calculating uniquely the radiance that the satellite should have seen. Thus, we cannot uniquely "calibrate" the satellite instrument via the ground-based systems in terms of measured radiances. Several proposals have been presented as to how such radiance calibrations may be achieved, but as of this doucment they are not sufficiently advanced for adequate consideration. Therefore, it is recommended that the major verification/calibration effort be the comparison of satellite and in situ ozonesondes. As the radiance calibration techniques are further evaluated, they will be considered for integration into the monitoring program.

The LIMS retrievals extend from about 15-70 km. As a day-night sensor LIMS can provide information on the diurnal variation. The major limitations of this system are the lack of information on total ozone and the limited lifetime of the instrument. With cryogenic technology, the current design lifetime is 6-7 months, which is too short for operational consideration. One positive feature of LIMS, however, is that it is not limited solely to ozone measurements, but has the capability to determine temperature and minor constituents such as water vapor and oxides of nitrogen. These parameters represent two of the major requirements necessary for understanding the reasons for stratospheric change in ozone. Therefore, any development which would extend the lifetime of the LIMS instrument would increase the value of this system for operational monitoring consideration.

4. Strategy for Ozone Monitoring. The strategy for implementing a stratospheric ozone monitoring program for the period FY 1981-1986 consists of utilization of all measurement capabilities, verification of satellite determinations by in situ or ground-based measurements, quality control of data,

and processing of ozone data from various measurement systems independently with cross-comparisons of data from individual measurement systems.

The individual data acquisition program elements are as follows:

(a) Dobson

(1) Continue the present program of Dobson measurements as part of the WMO Global Ozone Network at the current 11 United States sites.

(2) Accomplish intercalibration of these instruments with the World Standard (Dobson Instrument No. 83) at Boulder at least once every 2 years.

(3) Continue operational analyses of stratospheric ozone (Angell - Korshover method) as measured by the WMO network.

(4) Establish an additional Dobson ozone station on the west coast of the United States.

(5) Implement the short "Umkehr" method for determining vertical ozone distributions at all U.S. Dobson measurement sites, and, if feasible, internationally.

(b) Balloon

(1) Expand the current balloon ozonesonde program of once-per-week launches at one site to include weekly flights at a low and a high latitude site. This schedule will be increased to about three-per-week at the mid- and high-latitude sites during winter.

(2) Evaluate a modified electrochemical balloonsonde capable of ozone measurements up to about 40 km to determine its suitability for validation/calibration of the profiles derived from satellite measurements.

(c) Satellite

(1) Evaluate and incorporate the TIROS N TOVS determinations of global total ozone as a basic element of the satellite operational monitoring programs and extend to subsequent generation environmental satellite operations.

(2) Establish an operational satellite ozone monitoring program beginning with SBUV-2 on the TIROS N series spacecraft in 1984 and extend monitoring to subsequent generation environmental satellites.

(3) Evaluate the utilization of a limb observing system and other ozone measuring systems in combination as a follow-on for the post TIROS N series of operational satellites.

(d) Rocket

(1) Establish a four-station network (low-, mid-, high-latitude in the Northern Hemisphere, plus a mid-latitude station in the Southern Hemisphere) to provide about once-per-week launches of a calibrated ozonesonde to provide verification and calibration data for the satellite program.

(2) After the first year, reduce to a maintenance program schedule of once-per-month rocket ozonesonde comparisons at the high- and low-latitude site, plus once-per-week (total of at least 46) at the Wallops Island, Va., site.

(e) Data analysis

(1) Complete an initial (1 year) verification program of comparisons between vertical profiles derived from satellite measurements (SBUV) and in situ observations at 4 sites, low-, mid-, and high-latitude sites in the Northern Hemisphere plus a mid-latitude site in the Southern Hemisphere. The number of comparisons will be such that ±5 percent (95 percent confidence limit) precision estimates of comparability will be obtained at each site.

(2) Establish a minimum annual verification/calibration program of comparisons between vertical profiles derived from satellite measurements and in site observations at one Northern Hemisphere mid-latitude site such that ±5 percent (95 percent confidence limit) precision estimates of comparability will be obtained. At the same time, it is recognized that it would be highly desirable to maintain a similar comparison at a low- and high-latitude site to provide hemispheric coverage.

(3) Establish an annual verification/calibration program of comparisons between total ozone values derived from satellite measurements and ground based observations such that ±1 percent (95 percent confidence limit) precision estimates of comparability will be obtained.

(4) Establish a quality-controlled, compatible, baseline data set for ozone and related parameters including global synoptic type analyses of total ozone and ozone mixing ratio at 30-, 10-, 5-, 2-, 1-, and 0.4-mb for the period 1970-1984. These data and analyses will be forwarded to the World Ozone Data Center in Toronto, Canada.

(5) Continue and expand the program for ozone trend evaluation using satellite and ground-based data. Anthropogenic effects will be detected by means of statistical analysis.

B. Meteorological Parameters - Pressure-Height, Temperature, and Wind

1. Horizontal Resolution Requirements. Given the WMO monitoring recommendation of ±3-5 percent for the precision of the ozone vertical distribution described in section II.A.1, it is clear that the requirements for other parameters should be consistent with these values. The long-term

precision recommendation for stratospheric temperature, then, becomes about ±2°K (95 percent confidence level) daily with a horizontal resolution on the order of 1000 km (13° longitude at 45°N) and about 2.5° latitude resolution in the lower stratosphere and a horizontal resolution on the order of 2000 km (26° longitude at 45°N) and 5° latitude resolution in the middle and upper stratosphere above 10 mb.

In terms of the meteorological parameters, then, the requirements have been established as follows:

(a) temperature to a precision of ±2°K

(b) height of a pressure surface to a precision of ±100-150 geopotential meters (gpm)

(c) wind speed to a precision of ±5-7 m/s

2. Vertical Resolution Requirements. With respect to vertical resolution, the standard meteorological pressure levels for analysis in the stratosphere are 100-, 70-, 50-, 30-, 10-, 5-, 2-, 1-, and 0.4-mb (16, 18, 20, 24, 30, 35, 42, 48, and 54 km) (staff, UAB, NASA SP-3091, 1976) which represents an approximate 5-km height resolution over the range 16-55 km.

3. Current Instrumentation Qualified for Monitoring.

(a) Ground-Based Systems. When considering the data distribution in the stratosphere, it is necessary to distinquish between the lower stratosphere, 16-30 km, and the upper stratosphere, 30-55 km. The rationale for this breakdown is that the lower region is mainly sampled by rawinsondes while the upper region is sampled by less numerous rocketsonde flights and by satellites.

(1) Radiosonde (Rawinsonde) Instrumentation. Figure 6 depicts the distribution of rawinsonde instruments throughout the Northern Hemisphere. This map indicates that coverage over the land areas is rather extensive but the coverage is achieved with different instrument types. McInturff and Finger (1968) studied the problems posed by not using a common instrument and showed that the data may require adjustments of 5-7°C in order to form a consistent data set. With respect to the Southern Hemisphere, Figure 7, we see that extensive areas exist with little or no coverage and that quite obviously satellite information will be required to fill in the gaps.

The distribution of the heights at which data are available has also been studied (Thomas and Finger, 1974). Above the 100-mb level the percentage decreases very rapidly such that about 45 percent of the observations reach 70 mb and less than 15 percent reach 10 mb. Stratospheric monitoring will require adequate data coverage at all levels.

The main sources of radiosonde error are listed in an Air Weather Service (AWS) Technical Report (1955). Seven sources of error are considered, which contribute to a total standard deviation of ±0.36°C. A value two or three times as large is considered applicable for a radiosonde

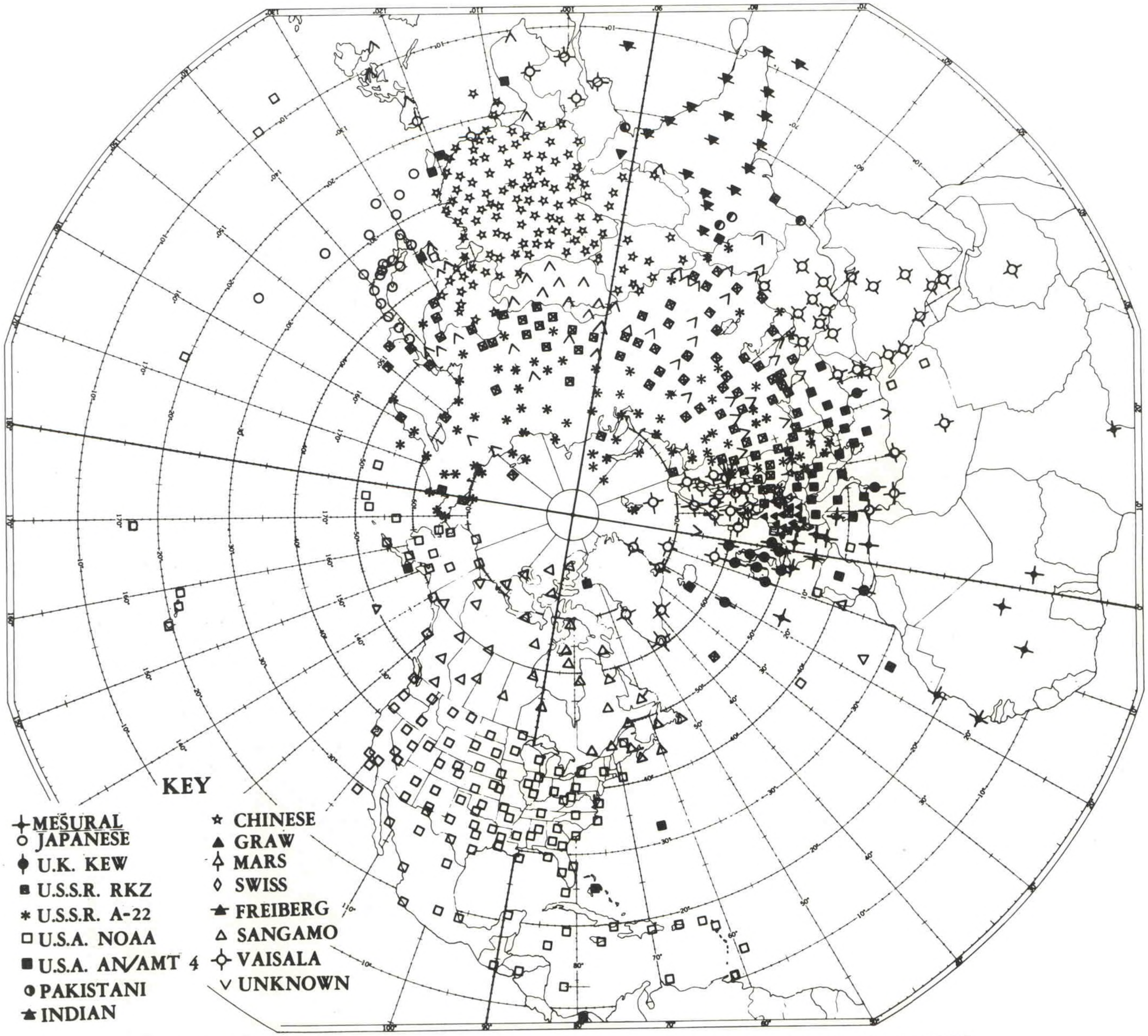

Figure 6. Northern Hemisphere radiosonde stations by Instrument type as of July 1978.

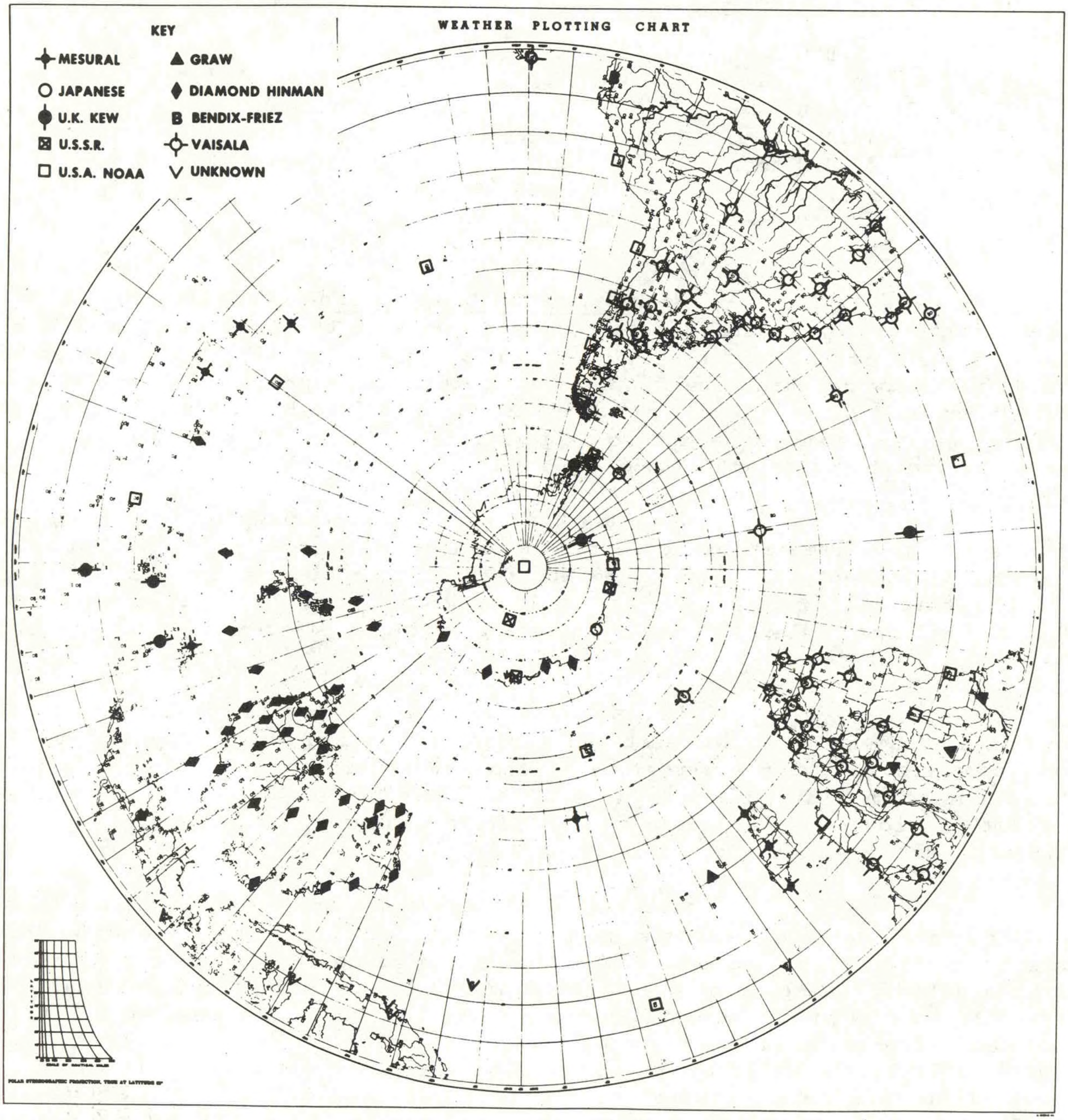

Figure 7. Southern Hemisphere Rawinsonde Stations by Instrument Type as of July 1978

in flight (±1°C is generally accepted as the absolute error). The precisions of the aneroid pressure cell in the rawinsonde are as follows (AWS Pamphlet 105-3, 1971):

Pressure		Computed Height of Pressure Surface	
10,000 feet	±0.7 mb	700 mb	±27 feet
20,000 feet	±1.0 mb	500 mb	±45 feet
30,000 feet	±1.2 mb	300 mb	±80 feet
40,000 feet	±1.0 mb	200 mb	±105 feet
50,000 feet	±0.7 mb	100 mb	±147 feet
60,000 feet	±0.55 mb	50 mb	±180 feet
70,000 feet	±0.40 mb		

(2) Rocketsonde Instrumentation. With respect to the upper stratosphere, Figure 8 depicts the network of current rocketsonde stations of the Northern Hemisphere and Figure 9 those of the Eastern and Western Meridional Network that extend into the Southern Hemisphere. Currently, the United States' sites launch rocketsondes on a 3-5/week schedule while the other countries launch at a rate of approximately 1/week. The height range of these instruments is between 20-65 km.

Recently, however, re-evaluation of agency rocketsonde requirements has occurred resulting in the decision that several stations will be closed in the near future. At this time it appears that the stations that will remain open are Barking Sands, Point Mugu, Primrose Lake, Shemya, Wallops Island, Cape Canaveral, Antigua, Ascension Island and Kwajalein.

As with the rawinsonde information, the use of several instrument types necessitated a comparison among them. The results of such comparisons for the temperatures and winds (Finger et al., 1975) show that temperatures can differ by over 20°K (U.S.S.R.-U.S.), but in most cases are within about 5°K; and rms wind differences show a general increase with altitude, but are basically within about 20 m/s.

Within the United States there have been at least 10 different temperature sensors used in recent years, all of which have different errors. For a summary of what was known up to 1968, Quiroz (1970) and Hoxit and Henry (1972) give an extended discussion of sensors and accuracies. Currently, a common rocketsonde instrument type is being utilized at all U.S. sites and a common adjustment scheme applied (Krumins and Lyons, 1972) that is considered reliable up to about 60 km. Thus, a major source of difficulty in the analysis and interpretation of the data has been alleviated. Staffanson (1976) has shown that the temperature uncertainties below 50 km are about 1.0-1.5°K and increase to 3.6°K at 60 km. The repeatability of this instrument has been discussed by Miller and Schmidlin (1971) from a series of tests whose results indicate an overall repeatability of about ±2°K (2S).

We should note that the measured parameter of the rocketsonde is temperature as a function of height. Pressure is determined by

SCALE 1 40 000 000
POLAR STEREOGRAPHIC PROJECTION TRUE AT LATITUDE 60°
MAP 1608A AUG 71

Figure 8 Northern Hemisphere Meteorological Rocketsonde Stations

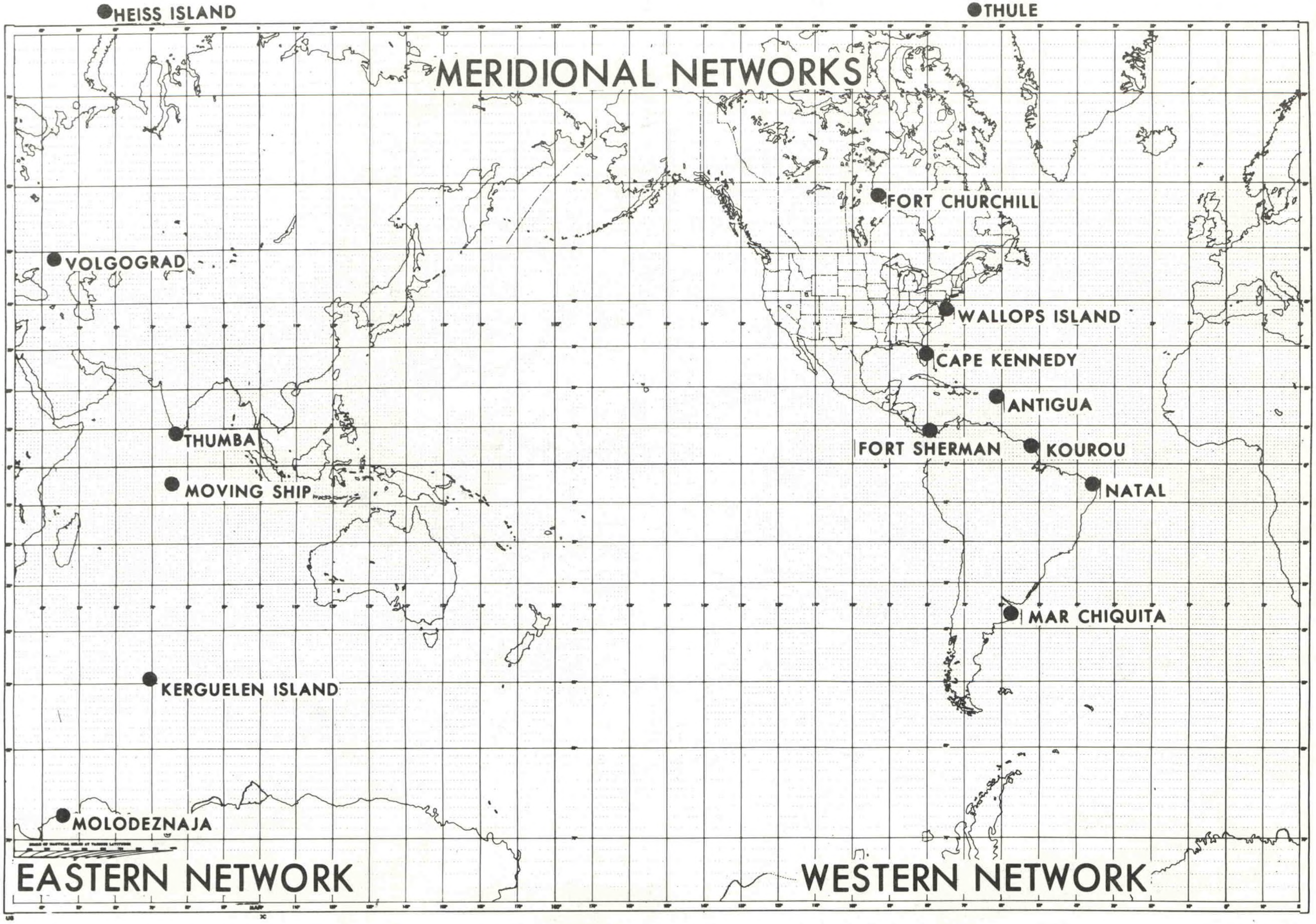

Figure 9. Eastern and Western Meridional Meteorological Rocketsonde Stations

matching the rocketsonde to a supporting rawinsonde in the overlap region at a base pressure and calculating upward using the hydrostatic equation. Densities are then determined from the equation of state. Errors in the pressure, then, are not independent of the errors in temperature.

Wind data from the rocketsondes are obtained by radar tracking of the parachute instrument system as it descends. In discussion of instrumentation errors, it is important to recognize that there are errors in wind direction and velocity attributable to instrumentation as well as errors in hand-calculated data versus machine-processed data. Table 4 indicates the ranges of rocket instrumentation precision for wind data.

TABLE 4. Wind Data Precision of Rocketsondes

Hand calculated:	±5° in direction, ±5 mps in speed,
Machine calculated:	±1° in direction, ±0.5 mps in speed,

b. Satellite Systems. Since April 1969, there has been an operational satellite program whose purpose is to derive temperature-pressure information for input into the analyses and forecast models. While the actual instruments over this period have varied in design, the basic principle has been the same, to measure radiance in selected spectral regions of the atmospheric thermal emission bands and to convert these radiances to temperatures through appropriate algorithms.

Early operational Vertical Temperature Profile Radiometers (VTPR) were designed principally as tropospheric temperature sounding instruments. Additional information in the stratosphere can be gained by utilizing radiance information in other spectral regions. The NOAA TIROS N operational satellite series (first launched in October 1978) includes the TIROS N Operational Vertical Sounder (TOVS). The approximate stratospheric weighting functions for TOVS are depicted in Figure 10, showing the weighting functions for the Microwave Sounding Unit (MSU), the High Resolution Infrared Sounder (HIRS-2), and the Stratospheric Sounding Unit (SSU).

Recent results, shown in Table 5, of studies utilizing a sample of 1200 simulated radiances from the three TIROS N TOVS sounding instruments and the regression techniques of Quiroz and Gelman (1972) indicate the general level of precision that we might expect from this system. The temperature rms differences are on the order of 2°K up to about 10 mb, increase to about 4°K at 1 mb and become about 6°K at 0.4 mb.

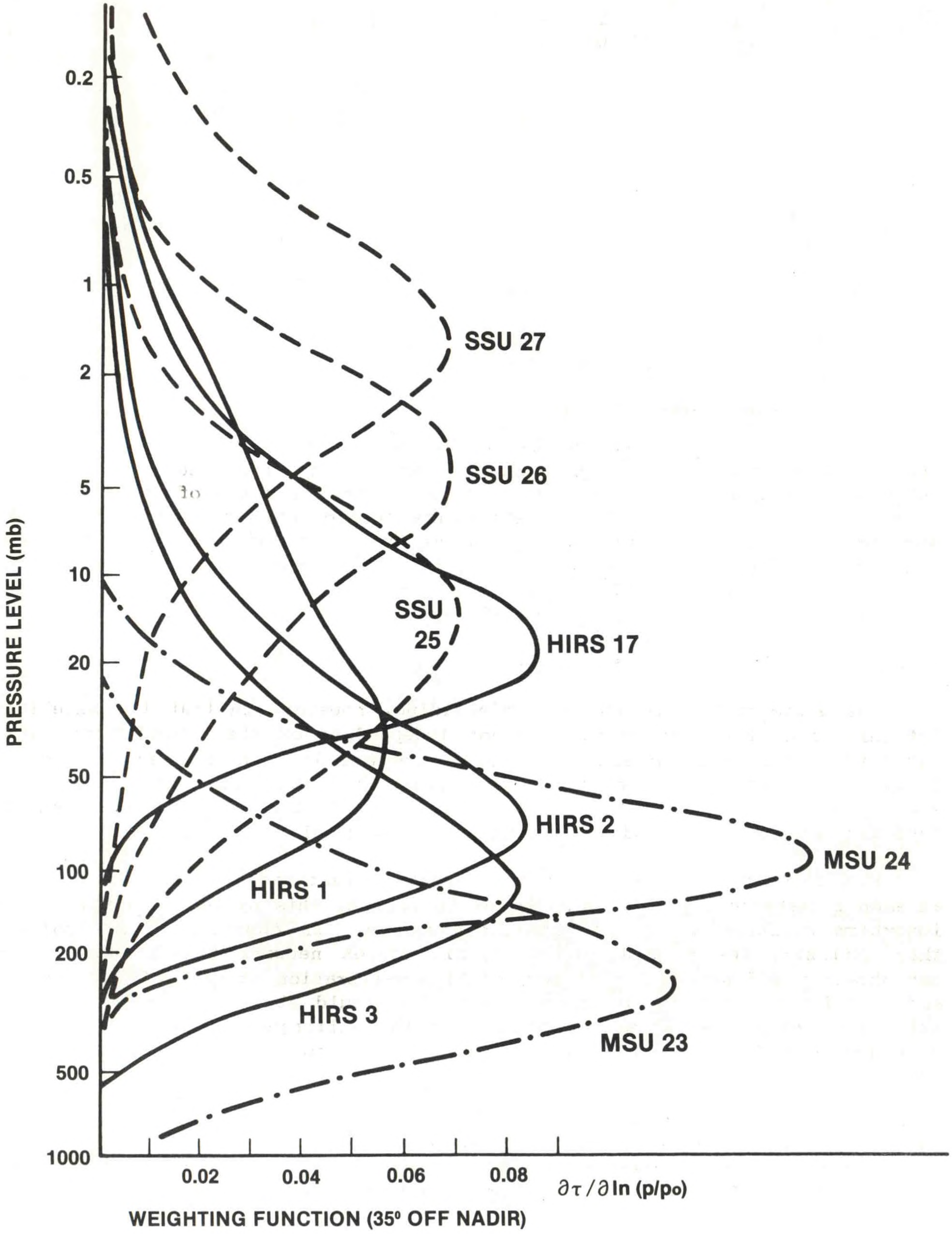

Figure 10.— Stratospheric Weighting Functions for Measurement Systems on the Operational Tiros N. Satellite Series (Pick, 1978)

TABLE 5. RMS Temperature Error as a Function of Pressure Simulated From a Sample of 1200 Observations

Level - MB	RMS Temperature Differences - °K (Retrieval vs. Actual)
100	2.6
70	1.8
50	2.1
30	2.4
10	2.1
5	2.8
2	3.3
1	4.2
0.4	5.7

3. Problem Areas.

a. Ground-Based Systems. We have seen in Figures 8 and 9 that the meteorological rocket network is too restricted geographically to delineate the dynamics of the stratosphere. When the costs of increasing the global coverage of rocketsonde systems are considered, it is clear that we must depend on satellite systems to provide the basic information for the monitoring program. In Appendix 3, the ability of the satellite systems, such as the type to be flown on TIROS N, to satisfy the stated requirements is discussed. It is shown that the satellite system can satisfy the stated requirements of about ±2°K in 5° latitude bands. For the globe, the 95 percent confidence level decreases to about ±1°K.

The above result is somewhat misleading, however, in that the satellite information at the present time is not independent of the ground-based data. Satellite retrievals currently utilize a regression technique and, in practice, it has been found necessary to update the regression coefficients on about a monthly basis. The precision of the satellite retrievals, then, is dependent on the data acquired from the meteorological rocket system.

The rocketsondes have two other important features. The first is that, as each rocketsonde is calibrated prior to launch, this system is suitable for long-term calibration of the satellite sensors. In Appendix 4, we indicate that utilizing the present meteorological rocket network launch schedule we can obtain a (95 percent) ±2°K verification/calibration at each of low-, mid-, and high-latitudes about twice per year. We should stress, however, that the ability to accomplish this is dependent on the willingness of the rocket network personnel to adjust their flight schedule to coincide with satellite overpass.

The second is that the rocketsondes provide wind information in addition to the temperature data. This wind information is desirable both as a check on the temperature analyses by comparing measured versus balance winds, and as the sole source of reliable wind information in the tropics.

b. Satellite Systems. We have indicated above that with the combination of the three instruments on the TIROS N TOVS system (MSU, HIRS-2, and SSU) it should be possible to determine the temperatures with sufficient precision at the standard pressure levels between 15-60 km to satisfy the monitoring requirements. With respect to the horizontal resolution, all three instruments employ a cross-orbital scan feature, and operating both day- and night-time allows them to satisfy the stated requirements. Thus, we have seen that the TIROS N satellite system is capable of satisfying both the precision and spatial requirements for the thermodynamic parameters.

However, one major difficulty, alluded to previously, is that wind information must be computed via some balance technique such as the geostrophic equation. For purposes of monitoring this is probably sufficient except in the region of the tropics. Consequently, it does not appear that the general circulation or the redistribution of the minor species in the tropics will be resolved without continued reliance on the sounding rockets. However, wind sensors for the troposphere and stratosphere are currently being proposed by NASA.

4. Strategy for Stratospheric Monitoring of Meteorological Parameters. Based on the considerations presented above, the following strategy will be employed for monitoring of the meteorological parameters.

a. Utilize the TIROS N TOVS stratospheric meteorological monitoring unit, and extend monitoring to subsequent generation environmental satellites.

b. Continue the U.S. cooperative meteorological rocket network as the calibration/verification standard for the satellite systems.

c. Maintain a quality-controlled, compatible, standardized, accessible data set for the meteorological parameters including daily global synoptic type analyses of height and temperatures at 100, 70, 50, 30, 10, 5, 2, 1, and 0.4 mb.

d. Evaluate the feasibility of utilization of the LIMS satellite instrument as an operational monitoring system for the System 85 post-TIROS N series of operational satellites.

C. Solar Ultraviolet Flux.

1. Rationale for Monitoring. A decrease in total column ozone will result in an increase in biologically damaging solar ultraviolet flux (UV-B: 290-320 nm) to the earth's surface. Such biologically damaging UV-B radiation is associated with increased incidence of skin cancer and, according to laboratory experiments, with decreased productivity and other undesirable effects on important agricultural crops, other plants and aquatic organisms (fish larvae, plankton, etc.).

More accurate measurements and predictive models on total column ozone concentrations and trends and associated UV-B radiation fluxes as functions of latitude and season are needed for use by biologists to make determinations of acceptable levels of ozone change.

The ultraviolet solar flux in the wavelength range 175 to 320 nm provides the major energy source for the earth's stratosphere and mesosphere. The Lyman alpha line at 121.6 nm is also of importance in the mesosphere. The absorption of radiation at wavelengths less than 240 nm by O_2 leads to dissociation and subsequent creation of the ozone layer. Absorption by O_3

over the entire wavelength range mentioned above is the dominant heating mechanism for the stratosphere and mesosphere which in turn determines the thermal structure and global wind systems. Hence, a quantitative knowledge of the incident solar flux and its temporal variation is of prime importance in understanding the composition, energetics, and dynamics of the middle atmosphere.

One of the first measurements to be attempted when large rockets became available for scientific research was to observe the sun's spectrum in the ultraviolet. Numerous measurements have been made since then varying from the x-ray region to the near ultraviolet. Summaries of most of the measurements have been give by Ackerman (1971), Donnelly and Pope (1973), and Heath and Thekakara (1976). Uncertainty estimates in field measurements of solar spectral irradiance range from about 80% (290 nm) to about 20% (320 nm).

Knowledge of the temporal variation in the 175 to 320 nm solar output requires a long term monitoring capability with a high degree of repeatability. The time scales of interest are the 27-day solar rotation period and the 11-year solar cycle. The available data on variations between 175 and 200 nm and in Lyman alpha suggest an observable response in photochemically controlled constituents over a 27-day period. A periodic change in the full disk solar flux reflects changes in the number of active regions. Measurements with high spatial resolution show the emission of an active region to be roughly 2.5 times as intense as that of the quiet solar disk at 200 nm. On this basis, a significant 11-year period in solar output is expected. Knowledge of the natural periodicities in solar output is essential for an understanding of the temporal variability of the wind systems in the stratosphere and mesosphere. Variations in transport properties could be more significant than the more obvious photochemical response to solar flux variations.

2. Calibration Requirements. For aeronomic calculations, it is necessary to have solar fluxes of rather high absolute accuracy so as to assess possible inadequacies in currently accepted photochemical systems. A central calibration facility is needed to develop the radiometric and spectral irradiance standards required to meet the accuracy goals, with the authority to assure that instruments used in the program are established in a uniform manner traceable to fundamental physical units. The National Bureau of Standards has the mission and technology base needed to fulfill this role.

The central laboratory should be designated and supported to improve, unify, and maintain the measurement base for calibrations of total and spectral solar monitoring.

3. Current Instrumentation. Only a small portion of the sun's spectrum is observable from the surface of the Earth. Consequently, measurements of the solar ultraviolet flux must be made using balloons, rockets, and satellites as observing platforms. The balloon-borne measurements can only be considered as indirect measurements since these are limited in altitude to 40 km. At this altitude, there is considerable atmospheric absorption due to O_2 and O_3. In principle the effect of these atmospheric constituents can be taken into account but a direct measurement is to be preferred. Most measurements using rockets have confined themselves to the region below 200 nm and thus cover only a very limited portion of the solar spectrum of stratospheric interest. The most notable exception to this is the work of Broadfoot (1972)

who obtained measurements from 210-320 nm. Recently Guenther of GSFC has made measurements over this same wavelength interval but these results are not yet available. Observations from satellite have been limited to utilizing broad bandpass filters to monitor the solar flux. These measurements depend on a knowledge of the solar spectrum for their interpretation and are subject to loss of calibration over their lifetime in orbit. Satellite observations of the flux for the full solar disk are being obtained from the SBUV instrument on Nimbus-7 and will be available from Spacelab I (1981-2 launch dates).

4. Strategy for Development of a Monitoring Program. Instrumentation and calibration techniques now exist for making measurements of the solar spectrum with an accuracy of about ±5-10 percent. This results from improvements in secondary calibration standards produced by NBS. Measurements produced by a single laboratory using the same instrument and calibration source could result in a repeatability of ±2 percent. Measurements using spectrometers are more useful than filtered photometers. The natural degradation of satellite instruments in orbit raises serious questions as to whether this approach will yield useful information over an 11-year time scale, although such experiments are useful for monitoring short-term flux changes. However, the duration of a rocket flight is short enough that electronic components may not stabilize over the measurement period. Intercomparison of different rocket results would not easily reveal flux changes of less than 10 percent.

Hence, the best approach to observing solar cycle variations in flux appears to be to conduct a series of experiments from the space shuttle, each lasting for a period of days to weeks. The relative calibration of the instrument could then be checked before and after each flight. The problems due to degradation in the space environment would then be eliminated.

The following strategy is adopted for the development of a monitoring program:

a. Investigate the variability of solar flux, 175 to 320 nm, by a series of flights using a single type of instrument over an entire (22-year) sunspot cycle. A frequency of two flights per year are required over the entire (22-year) sunspot cycle, with a precision of ±2 percent corresponding to a total ozone measurement precision of ±1 percent.

b. Plan and execute direct intercomparison of satellite solar flux instruments flown by different experimenters or utilizing different calibration techniques. The National Bureau of Standards is designated as a central laboratory to improve, unify, and maintain the measurement base for calibrations for total and spectral solar monitoring.

c. Develop the radiometric and spectral irradiance standards required to meet the accuracy goals for monitoring. The National Bureau of Standards has the mission and technology base needed to fulfill this essential role of a central calibration facility.

d. Investigate the 27-day variability of the sun from the shuttle spacecraft, utilizing an onboard calibration capability with a precision of ±2 percent. As the SBUV instrument is designed to measure the solar spectral radiance from 160 to 400 nm with a spectral resolution of 1 nm, the possibility of including this instrument on shuttle missions is currently under investigation.

D. Stratospheric Water Vapor.

1. Rationale for Monitoring. Water vapor is important in stratospheric chemistry because of its role in the highly reactive odd-hydrogen chemistry. It is also active radiatively and contributes to the thermal structure of the atmosphere. Changes in temperature will be reflected as changes in (temperature dependent) chemical reaction rate constants; thus, water vapor has a secondary, indirect influence. Further, when the reactive, perturbing chemical substances are converted to relatively nonreactive chemical sink species (e.g., HNO_3), the latter may pass into the troposphere and be removed by heterogeneous processes such as rain-out and wash-out; such processes are yet to be satisfactorily incorporated in the predictive models of the stratosphere. Thus the need is apparent for data on the distribution, and the spatial and temporal variability, of water vapor, not only in the stratosphere but also in the troposphere, for considerations of stratospheric chemistry and the well-recognized need for such data in climate related studies.

Good water vapor data are available for the surface of the earth from the routine observations at the weather stations, and radiosonde data yield good values up to upper tropospheric levels. At higher altitudes, the data become sparse, mostly restricted to the United States and Europe, and exhibit wide variability; the extent to which measurement errors and differences in measuring techniques contribute to this variability has not yet been clearly resolved (Harries, 1976).

2. Measurement Requirements. The WMO Report on Measurements of Rare Species (1977) states that the accuracy in stratospheric water vapor measurements needed for monitoring purposes is ±5 percent (95 percent confidence limit) on a weekly basis.

3. Current Instrumentation Qualified for Monitoring. Other than the instrumentation used in radiosondes, which are good in the troposphere, there is as yet no clearly identified instrument or set of instruments which can be used for routine monitoring of water vapor, especially in the stratosphere. A brief description of the available instrumentation is given below.

a. Nonsatellite Measurement Systems. Water vapor, at stratospheric altitudes tends to sublimate into ice and cling to instrument surfaces, rendering in situ measurements subject to contamination problems. The infrared techniques yield total content within a column above or below the instrument platform and by differencing one can obtain, in principle, local concentrations; but there are inherent difficulties in these techniques in that, frequently assumptions have to be made regarding the water vapor distribution above or below the point of observation. Balloon measurements have also been made with a pressure modulated radiometer. A Lyman alpha sensor has been developed, supported by FAA, NASA and NOAA, and NOAA is flight-testing it in the atmosphere. It uses Lyman alpha radiation from a lamp source to photolyze H_2O and detects the radiation emitted by the excited product OH radicals.

The precision of available measurements is estimated to range from ±15 percent to ±50 percent (WMO, 1977). There has been no systematic intercomparison of the different instruments to date. Efforts are beginning to be made in this regard, with the recent successful completion of an intercomparison experiment conducted under FAA leadership.

Water vapor measurement in the upper atmosphere remains a very active area of research and efforts are being made to constantly improve the existing instrumentation. Specifically, plans are underway to continue the Mastenbrook balloon-borne automatic frost-point hygrometer measurements over Washington, D.C., (Mastenbrook, 1968; ________________, 1971; ___________, 1974) so as to add to the historical data base at this location. These observations will be further expanded to at least one other location using an improved version of this instrument. Other techniques will be evaluated as developed.

b. Satellite Measurement Systems. Nimbus 6 launched in 1975 carried the Limb Radiance Infrared Radiometer (LRIR) and the High Resolution Infrared Sounder (HIRS). The LRIR uses the 22-24 μm rotational band of H_2O while HIRS contained 2 channels at 6.7 and 8.2 μm. Preliminary data from HIRS indicate reasonable agreement with radiosonde data at tropospheric levels. There are, as yet, no reduced data from LRIR.

Nimbus 7 contains 2 instruments, the Stratospheric and Mesospheric Sounder (SAMS) and the Limb Infrared Monitoring of the Stratosphere (LIMS) Experiment. The former has 2 channels, one in the near IR (2.7μm) and another in the far IR (100 μm) with an expected precision of about 15 percent. The LIMS is an improved version of the LRIR; both are cryogenically cooled and thus have limited lifetimes. Observations with LIMS have been made for about the first six months of Nimbus 7 operation. SAMS and LIMS data reduction and evaluation are in progress, with results expected in 1983.

The TIROS N Satellite System will provide water vapor soundings through its TIROS Operational Vertical Sounder (TOVS), primarily in the troposphere.

One of the important aspects of satellite observations is the need for verification against "ground-truth" data. In this regard there are plans to compare the SAMS-derived data on Nimbus 7 with simultaneously obtained data with a balloon-borne Lyman-alpha sensor.

4. Strategy for Development of a Stratospheric Water Vapor Monitoring Program. The following strategy is adopted for developing a stratospheric water vapor monitoring program.

a. Continue the water vapor measurements over Washington, D.C., until transition to a network is completed.

b. Complete the development and further testing of the Lyman alpha water vapor sensor.

c. Plan and execute a systematic intercomparison of instruments so that the data base can be corrected for instrumental differences and measurement errors.

d. Plan and execute "ground-truth" verification of current satellite water vapor instruments, with a view to identifying the optimum measuring system for future monitoring purposes.

E. Other Trace Constituents. The need to monitor the meteorological parameters of the stratosphere in order to interpret changes in the ozone concentrations has been discussed in the previous sections. By the same token a complete analysis of ozone trends requires that we also measure the concentrations of the given families of trace constituents; that is, of NO_x, HO_x, and ClO_x. Although many instruments exist for the measurements of selected species amongst these families, the instruments used must be considered in the experimental stage at this time. Thus we have not considered the monitoring of the trace constituents as part of this planning period. However, that does not take away the necessity for such measurements or for the development of monitoring instruments which can be used to determine the trends in these families of trace constituents with high precision in the future.

Chlorofluromethane amounts in the troposphere will continue to be monitored by the NOAA baseline stations at American Samoa; South Pole; Point Barrow, Alaska; and Mauna Loa, Hawaii.

III. IMPLEMENTATION PLAN

In this section, the activities of each agency that supports the overall monitoring effort are surveyed and compared with the strategies adopted.

A. Agency Programs.

1. NOAA.

a. Ground-based measurement of total ozone, data collection, processing and archiving for 7 U.S. and 4 NOAA baseline stations; maintenance of the world standard instrument (no. 83); calibration of U.S. and international Dobson instruments against the standard; participation in international intercomparisons; conducting aperiodic balloon ozonesonde measurements at various stations under the stratospheric research program.

b. Determination of chlorofluoromethane (CCl_3F, CCl_2F_2), methyl chloroform and water vapor concentrations at 4 NOAA baseline stations by surface air flask sampling.

c. Numerical modeling of the middle atmosphere utilizing 1-, 2-, and 3-dimensional models.

d. Stratospheric grab sampling field measurements at various sites to determine the latitudinal and seasonal variation of certain trace constituents. These include CCl_3F, CCl_2F_2.

e. Developing ground-based remote sensing techniques capable of measuring the vertical profile of winds in the clear atmosphere nearly continuously in time.

f. Conducting monthly water vapor balloon sounding program at Boulder, Colorado. Plans include addition of 2 stations to provide a 3-station network (low-, mid-, and high latitude). Development and testing of the Lyman alpha sensor at the NOAA laboratories in Boulder, Colorado, under partial funding support by the FAA and NASA.

g. Procurement and operation of satellite ozone measurement systems for operational monitoring of total ozone, the vertical distribution of ozone in the stratosphere and the vertical distribution of temperature from the ground through the stratosphere (jointly with NASA).

h. Operational data verification and construction of synoptic type analyses of both ozone (total and vertical distribution) and meteorological parameters from available satellite instruments to develop a quality-controlled 15 year data set (1970-1984) to serve as a baseline for subsequent trend detection.

i. Analysis of trends and delineation of changes in the stratosphere of ozone and other parameters as required to satisfy the requirements of Public Law 95-95 for the early detection of a stratospheric trend change.

j. Operational monitoring products as defined below.

(1) Daily global meteorological charts at standard pressure levels of 100-, 70-, 50-, 30-, 10-, 5-, 2-, 1- and 0.4-mb (corresponding approximately to 16, 18, 20, 24, 30, 35, 42, 48, and 55 km).

(2) Daily global synoptic charts of ozone mixing ratio at standard pressure levels of 30-, 10-, 5-, 2-, 1- and 0.4-mb (based on resolution capabilities of the SBUV). Ozone mixing ratios below 25 km will not be available due to the limitations of the observing systems, but remain an essential requirement.

(3) Daily global synoptic charts of total ozone overburden.

(4) Monthly averages of daily chart products.

(5) Daily, monthly, seasonal and annual spatial averages of hemispheric and global ozone values.

(6) Total ozone and vertical ozone profile data from individual stations in the ground-based network used in calibration of satellite systems.

(7) Ozone trend analyses using satellite and ground-based data analysis techniques for determination of changes exceeding natural variability.

2. <u>NASA</u>.

a. Sensor Development: Development of remote sensors for measuring the concentrations, distributions, and dynamics of minor atmospheric constituents, temperature and solar ultraviolet flux from satellites, aircraft, sounding rockets and balloons.

b. Data Analysis: Analysis of sufficient data for evaluations of the performance of sensor systems and their usefulness in monitoring; this includes a continuing analysis of Nimbus 4 BUV and Nimbus 7 SBUV global ozone data as well as the data from LRIR, LIMS, SAM II and SAGE. The data from SAGE II and HALOE will be analyzed as they become available.

c. Modeling: Participation in the development of numerical atmospheric models simulating the large scale dynamic, chemical and radiative processes of the atmosphere for studying the global or regional environmental effects of pollution and its impact on climate.

d. Other Sampling Support: High-altitude aircraft, sounding rocket, and balloon measurements to provide for initial test of sensors, data upon which to base sensor design, a means for calibration of research and global monitoring sensors, and a compositional benchmark to assist in the analysis of remote sensor data. In-situ sensors will also be developed and flow to help establish the specification criteria for remote sensor development.

3. <u>FAA</u>. The FAA has no direct mission interest for monitoring or long-term measurements of the stratosphere. However, because of its lead-agency designation for the U.S. efforts under the Tripartite Agreement

(U.K., France and U.S.) on Stratospheric Monitoring and its mission interest of avoiding environmental degradation due to stratospheric flight, it does main- tain, through its High Altitude Pollution Program (HAPP), an active role in insuring that aviation-related concerns are adequately addressed. Where it sees a gap, it does seek to fill that gap either by direct support of monitoring-related activities or by bringing it to the attention of the appropriate agency.

The HAPP has been in the past, and is now, supporting the following work related to stratospheric monitoring:

a. Study of total ozone data from radiances measured by the 9.8 micron channel sensor of the temperature sounder aboard the DMPS Block 5D satellite series of the Department of Defense. Intercomparison of total ozone data obtained for the same period from DMSP, Nimbus 7 and Tiros N satellites is planned.

b. Partial support for the Air Resources Laboratory of the international Dobson intercomparisons undertaken at NOAA, Boulder, Colorado.

c. Partial support for the international intercomparison of rocket-borne ozonesondes during FY 1979-81. This effort has been jointly undertaken by WMO, NASA, and FAA. The participating nations are Australia, Canada, India, Japan and the United States.

d. Continuation of support of the Naval Research Laboratory for the in-situ measurements of stratospheric water vapor using the Mastenbrook instrument over Washington, D.C.

e. Partial support of development and testing of the Lyman alpha sensor (photolysis of H_2O by Lyman alpha and the detection of the radiation emitted by the excited product OH radicals) at the Aeronomy Laboratory of NOAA, Boulder, Colorado.

f. Support for the joint U.S.A.-U.S.S.R. balloon-borne in-situ measurements of stratospheric aerosols carried out by the University of Wyoming and Leningrad University.

g. Partial support for an intercomparison of both in-situ and remote sensing water vapor instrumentation.

4. DOD. For a number of reasons, the DOD has an interest in the monitoring of stratospheric ozone. In support of that interest, the DOD supports research for the development of laser probes for ozone profiling of the atmosphere. The interest of the DOD in atmospheric ozone monitoring stems from the DOD need to identify the impact of its operations on the stratosphere, the need to identify the response of the stratosphere to certain solar events that affect the weather forecast, and the need for coping with the health and safety problem involved in controlling the cabin atmospheres of high altitude aircraft.

5. NSF. While the NSF supports no long-term monitoring program, as such, a considerable amount of research supported by contracts or grants

and research carried out at the National Center for Atmospheric Research (NCAR) under NSF sponsorship does provide data on stratospheric composition and radiation balance. The following summary provides an overview of such research.

a. Ground-based radar measurements which remotely sense altitude profiles of three-dimensional wind vectors continuously in time.

b. Ground-based optical "PEPSIOS" instruments capable of measuring daytime columnar contents of, e.g., OH, in Florida, Colorado and Wisconsin, and ground-based (mm wave) instrumentation capable of measuring altitude profiles of ozone and CO, in Massachusetts.

c. A major computing facility at NCAR available for use by scientists from universities, NCAR, and other non-profit institutions.

d. The NCAR Research Aviation Facility aircraft.

e. The National Scientific Balloon Facility (NSBF), a part of NCAR, which provides qualified scientific investigations with operational support for balloon vehicles for stratospheric research. The NSBF capabilities include balloon launch, tracking, recovery and acquisition of data.

f. At NCAR, several computer models are being developed that aid in the determination of the impact of halogens on the ozone layer and also seek to model the stratospheric aerosol distribution.

g. NCAR has several large, on-going measurement programs. One is based on cryogenic sampling of stratospheric air and subsequent gas chromatographic analysis of several important ozone-destruction precursors, e.g., N_2O, CF_2Cl_2, and $CFCl_3$. Another NCAR program concentrates on the end products of the chemical cycles by which stratospheric ozone concentrations are limited. Using both natural and chemically impregnated filters, NCAR has measured HNO_3, HCl, HF, and HBr concentrations in the stratosphere and chemical constituents of aerosols, e.g., SO_4^{-2}, Cl^-, and Na^+.

h. A satellite instrument, yielding global distributions of temperature, ozone and water vapor utilizing infrared measurements in the earth's limb (LRIR, LIMS) is being developed and evaluated at NCAR.

i. A high resolution infrared radiometer has recently been constructed and utilized by NCAR to observe meridional variability in the total overhead burden of stratospheric NO_2 and other gases.

6. DOE. The objectives of the DOE's high altitude sampling program are: to study the concentrations of radioactive debris and selected trace gases in the stratosphere with latitude, altitude, and season; to inventory the stratospheric burdens of critical pollutants; to develop and test stratospheric transport models; and to interface with other scientific programs in studying the ultimate disposition of trace pollutants in the environment. The following projects provide an overview of this high altitude sampling program:

a. Particulate sampling is conducted by both aircraft and balloons. Balloon-borne filtering devices are launched annually by the Air

Force at Fairbanks, Alaska, (65°N) and at the Panama Canal Zone (9°N), and three times a year at Alamogordo, New Mexico (33°N). The float altitudes routinely achieved are 21, 24, and 27 km. The balloon program currently provides about 20 samples per year including quality controls.

b. Project Airstream flights of the WB-57F aircraft are scheduled for April, July and October of each year and are conducted by the National Aeronautics and Space Administration (NASA) along the western regions of North and South America from 75°N to the equator at four altitudes ranging from 12.2 to 19.2 km.

c. The balloon and aircraft composite samples are analyzed at the DOE's Environmental Measurement Laboratory (EML) by Ge (Li) diode spectometry for ^{7}Be, ^{95}Zr, ^{137}Cs, and ^{144}Ce. A contractor (LFE Environmental Analysis Laboratory) performs radiochemical analyses for ^{90}Sr, ^{210}Pb, and $^{239,240}Pu$. Approximately 1500 nuclide analyses are performed per year under the program. These results provide data for estimating the burdens and distributions of nuclear weapon debris, and of cosmogenically and terrestrially produced natural radionuclides in the stratosphere.

d. In a joint cooperative venture with DOE the National Center for Atmospheric Research (NCAR) has studied the distribution of non-radioactive trace pollutants such as Na^{+}, D^{+}, Ca^{+2}, Mg^{+2}, Cl^{-}, $SO_4{}^{-2}$, and $NO_3{}^{-2}$ in the stratosphere. Separate filters were provided to NCAR from the balloon flights, but filters from the aircraft flights were shared between NCAR and EML. Usually EML and NCAR each analyzed 1/3 of a filter, and the remaining 1/3 was reserved in the filter sample library for future use. NCAR terminated their participation in the Airstream program after the July 1977 mission. EML is continuing to prepare filters for chemical analysis of various ions by an outside contractor (the Los Alamos Scientific Laboratory).

e. The stratospheric program has provided inventories of critical radionuclides from 1967 through October 1979.

f. As part of Project Airstream, approximately 40 samples of compressed stratospheric air are collected along the normal flight tracks of each mission. These samples are analyzed by a contractor laboratory (Washington State University) for CCl_3F (F-11), CCl_2F_2 (F-12), N_2O, CCl_4 and SF_6. Analyses of other chlorinated compounds, including methyl chloride, have encountered serious contamination problems and these substances cannot be evaluated using the present gas sampling system.

7. EPA. The Environmental Protection Agency conducts or supports research on:

a. The Robinson-Berger meter national network measurements of the incident integrated solar UV-B flux, corresponding to the biologically damaging portion of the UV spectrum.

b. Modeling calculations based on various chlorofluorocarbon emissions scenarios at the Lawrence Livermore Laboratory of the University of California.

c. Assessments by the National Academy of Sciences of the impact of halocarbons on stratospheric ozone.

d. Modeling calculations of solar UV-B flux to the ground as a function of wavelength, total ozone, total ozone change, latitude and season at the Los Alamos Scientific Laboratory.

B. National Monitoring Strategy Elements Supported by Federal Agency Activities. Presented below is a cross-correlation of the national monitoring strategy elements for each parameter and the agency programs associated with each item.

1. Ozone Monitoring Plan.

a. Continue the present U.S. program of Dobson measurements as part of the WMO Global Ozone Network at the current 11 sites. Accomplish intercalibration of these instruments with the World Standard (Dobson Instrument No. 83) at Boulder at least once every two years. This is being implemented by NOAA (item A.1.a.).

b. Extend geographical coverage and provide for a clean air ozone station in the continental United States by adding a Dobson station on the West Coast. This will be implemented by NOAA (item A.1.a.).

c. Implement the modified, "short" Umkehr method for determining vertical ozone distributions from ground-based Dobson instruments at all Dobson measurement sites. This is being studied by NOAA (item A.1.d.). A report will be available in 1982.

d. Expand the current balloon ozonesonde program of once-per-week launches at one site to include flights at a low and a high latitude site. This will be implemented jointly by NOAA (item A.1.a.) and NASA (A.2.g.).

e. Evaluate a modified electrochemical balloon-sonde capable of ozone measurements up to about 40 km to determine suitability for validation/calibration of the profiles derived from satellite measurements. This is being implemented by NOAA (item A.1.a.).

f. Continue the TIROS-N TOVS determinations of global total ozone as a basic monitoring component and extend to subsequent generation environmental satellite operations. This is being implemented by NOAA (item A.1.h.).

g. Establish an operational satellite ozone monitoring program beginning with SBUV-2 on NOAA F and G spacecraft in 1984 and continue operational ozone monitoring on subsequent generation environmental satellites. This is being implemented jointly by NOAA (item A.1.g.) and NASA (item A.2.a.).

h. Complete an initial (1 year) verification program of comparison between vertical profiles derived from satellite measurements (SBUV) and in-situ observations at 4 sites (low-, mid-, and high-latitude of the Northern Hemisphere plus a mid-latitude site of the Southern Hemisphere). The number of comparisons will be such that ±5 percent (95 percent confidence limit) precision estimates of comparability will be obtained at each site. This is being implemented by NASA (item A.2.d.).

i. Establish minimum yearly verification/calibration program of comparisons between vertical profiles derived from satellite measurements and in-situ observations at one Northern Hemisphere mid-latitude site such that ±5 percent (95 percent confidence limit) precision estimates of comparability will be obtained. At the same time, it is recognized that it would be highly desirable to maintain a similar comparison at a low- and high-latitude site to provide hemispheric coverage. This is being implemented jointly by NOAA (A.1.h.) and NASA (A.2.d.).

j. Establish a yearly verification/calibration program of comparisons between total ozone values derived from satellite measurements and ground based observations such that ±1 percent (95 percent confidence limit) precision estimates of comparability will be obtained. This is to be implemented by NOAA (item A.1.i.) and FAA (A.3.a.).

k. Establish a quality-controlled, compatible, standardized, accessible data set for ozone and its related parameters including global synoptic type analyses of total ozone and ozone mixing ratio at 30-, 10-, 5-, 2-, 1-, and 0.4-mb for the baseline period of 1970-1984. These data and analyses will be archived in the National Climate Center and copies forwarded to the World Ozone Data Center at Toronto, Canada. This is being implemented by NOAA (items A.1.a. and A.1.h.), NASA (item A.2.g.) and the FAA (items A.3.b. and A.3.c.).

l. Establish a program for trend evaluation and early detection of stratospheric change. The trend evaluation program will be implemented by NOAA (item A.1.i.) and NASA (item A.2.c.) to satisfy the requirements of Public Law 95-95, the data to be accessible to the scientific community for evaluation and use.

m. Evaluate the applicability of the limb observing technique and other ozone measuring systems in combination as follow-on for the post TIROS-N series of operational satellites. This is being studied jointly by NSF (item A.5.h.) and NASA (item A.2.a.).

2. <u>Meteorological Parameter Monitoring Plan</u>.

a. Continue the TIROS N TOVS stratospheric meteorological monitoring unit and extend monitoring to subsequent generation environmental satellites.

b. Utilize the U.S. cooperative meteorological rocket network as the calibration/verification standard for the satellite monitoring systems. This is being implemented by NOAA (item A.1.h.).

c. Maintain a quality-controlled, compatible, standardized, accessible data set for the meteorological parameters including daily global synoptic type analysis of height and temperature at 100-, 70-, 50-, 30-, 10-, 5-, 2-, 1-, and 0.4-mb. This is being implemented by NOAA under item A.1.h.

3. Solar Ultraviolet Flux Monitoring Development Plan.

a. Investigate the variability of the solar flux, 175 to 320 nm, by a series of flights using a single type of instrument over an entire sunspot cycle. A frequency of two flights per year are required over the entire (22 years) sunspot cycle, with a precision of ±2 percent corresponding to a total ozone measurement precision of ±1 percent. A research effort is required to develop the technology and program plan elements more definitely and NASA (items A.2.a., A.2.b. and A.2.d.) is currently involved in this effort.

b. Plan and execute direct intercomparison of satellite solar flux instruments flown by different calibration techniques. A research effort is required to develop the technology and program plan element more definitely and NASA (item A.2.a., A.2.b., and A.2.d.) will assume the lead-agency role to accomplish this task. Develop the radiometric and spectral irradiance standards required to meet the accuracy goals, and to improve, unify and maintain the measurement base for calibration of total and spectral solar monitoring. The National Bureau of Standards has the mission and technology base needed to fulfill the essential role of a central calibration laboratory.

c. Investigate the 27-day variability of the sun from the shuttle spacecraft, utilizing an onboard calibration capability, with a precision of ±2 percent. As the SBUV instrument is designed to measure the solar spectral radiance from 160 to 400 nm with a spectral resolution of 1 nm, NASA will explore the possibility of including this instrument on future space shuttle flights.

4. Stratospheric Water Vapor Monitoring Development Plan.

a. Continue the water vapor measurement series over Washington, D.C., until transition to a network is completed. This will be implemented jointly by NOAA (A.1.f.) and FAA (A.3.d., and A.3.e.).

b. Complete development and qualification of the Lyman alpha water vapor sensor. This is being implemented jointly by NOAA (A.1.f.) and the FAA (A.3.e.).

c. Plan and execute a systematic intercomparison of the new sensor(s) with the Mastenbrook instrument for the purpose of establishing a compatible data base. This will be implemented jointly by NOAA (A.1.f.) and the FAA (A.3.e.).

d. Plan and execute "ground-truth" verification of current and planned satellite water vapor measurement instruments, for the purpose of identifying a suitable measuring system for future monitoring purposes.

5. Other Trace Constituent Monitoring

a. Continue monitoring by tropospheric air flask sampling chlorofluoromethanes at the NOAA baseline stations. This is being implemented by NOAA (A.1.b.).

APPENDIX 1

Extracts from Public Law 95-95, Amendments to the Clean Air Act of 1977, Section 126, Part B. Ozone Protection.

PART B--OZONE PROTECTION

"PURPOSES

42 USC 7450. "Sec. 150. The purposes of this part are (1) to provide for a better understanding of the effects of human actions on the stratosphere, especially the ozone in the stratosphere, (2) to provide for a better understanding of the effects of changes in the stratosphere, especially the ozone in the stratosphere on the public health and welfare, (3) to provide information on the progress of regulation of activities which may reasonably be anticipated to affect the ozone in the stratosphere in such a way as to cause or contribute to endangerment of the public health or welfare, and (4) to provide information on the need for additional legislation in this area, if any.

"FINDINGS AND DEFINITIONS

42 USC 7451. "Sec. 151.(a) The Congress finds, on the basis of presently available information, that-

(1) halocarbon compounds introduced into the environment potentially threaten to reduce the concentration of ozone in the stratosphere;

(2) ozone reduction will lead to increased incidence of solar ultraviolet radiation at the surface of the Earth;

(3) increased incidence of solar ultraviolet radiation is likely to cause increased rates of disease in humans (including increased rates of skin cancer), threaten food crops, and otherwise damage the natural environment;

(4) other substances, practices, processes, and activities may affect the ozone in the stratosphere, and should be investigated to give early warning of any potential problem and to develop the basis for possible future regulatory action; and

(5) there is some authority under existing law, to regulate certain substances, practices, processes, and activities which may affect the ozone in the stratosphere.

"DEFINITIONS

45 USC 7452. "Sec. 152. For the purposes of this subtitle-

(1) the term 'halocarbon' means the chemical compounds $CFCl_3$ and CF_2Cl_2 and such other halogenated compounds as the

Administrator determines may reasonably be anticipated to contribute to reductions in the concentration of ozone in the stratosphere;

(2) the term 'stratosphere' means that part of the atmosphere above the tropopause.

42 USC 7453 "Sec. 153.(a) The Administrator [of the Environmental Protection Agency] shall conduct a study of the cumulative effect of all substances, practices, processes, and activities which may affect the stratosphere, especially ozone in the stratosphere. The study shall include an analysis of the independent effects on the stratosphere especially such ozone in the stratosphere of:

(1) the release into the ambient air of halocarbons,

(2) the release into the ambient air of other sources of chlorine,

(3) the uses of bromine compounds, and

(4) emissions of aircraft and aircraft propulsion systems employed by operational and experimental aircraft.

"The study shall also include such physical, chemical, atmospheric, biomedical, or other research and monitoring as may be necessary to ascertain (A) any direct or indirect effects upon the public health and welfare of changes in the stratosphere, especially ozone in the stratosphere, and (B) the probable causes of changes in the stratosphere, especially the ozone in the stratosphere."

"(b) The Administrator shall undertake research on-

"(1) methods to recover and recycle substances which directly or indirectly affect the stratosphere, especially ozone in the stratosphere,

"(2) methods of preventing the escape of such substances,

"(3) safe substitutes for such substances, and

"(4) other methods to regulate substances, practices, processes, and activities which may reasonably be anticipated to affect the stratosphere.

"(c)(1) The studies and research conducted under this section may be undertaken with such cooperation and assistance from universities and private industry as may be available. Each department, agency, and instrumentality of the United States having the capability to do so is authorized and encouraged to provide assistance to the Administrator in carrying out the requirements of this section, including (notwithstanding any other provision of law) any services which such department, agency or instrumentality may have the capability to render or obtain by contract with third parties.

"(2) The Administrator shall encourage the cooperation and assistance of other nations in carrying out the studies and research under this section. The Administrator is authorized to cooperate with and support similar research efforts of other nations.

"(d)(1) The Administrator shall undertake to contract with the National Academy of Sciences to study the state of knowledge and the adequacy of research efforts to understand (A) the effects of all substances, practices, processes, and activities which may affect the stratosphere, especially ozone in the stratosphere; (B) the health and welfare effects of modifications of the stratosphere, especially ozone in the stratosphere; and (C) methods of control of such substances, practices, processes, and activities including alternatives, costs, feasibility, and timing. The Academy shall make a report of its findings by January 1, 1978.

"(2) The Administrator shall make available to the Academy such information in the Administrator's possession as is needed for the purposes of the study provided for in this subsection.

"(e) The Secretary of Labor shall study and transmit a report to the Administrator and the Congress not later than six months after date of enactment, with respect to the losses and gains to industry and employment which could result from the elimination of the use of fluorocarbons in aerosol containers and for other purposes. Such report shall include recommended means of alleviating unemployment or other undesirable economic impact, if any, resulting therefrom.

"(f)(1) The Administrator shall establish and act as Chairman of a Coordinating Committee for the purpose of insuring coordination of the efforts of other Federal agencies carrying out research and studies related to or supportive of the research provided for in subsections (a) and (b) and section 154.

"(2) Members of the Coordinating Committee shall include the appropriate official responsible for the relevant research efforts of each of the following agencies:

"(A) the National Oceanic and Atmospheric Administration,
"(B) the National Aeronautics and Space Administration,
"(C) the Federal Aviation Administration,
"(D) the Department of Agriculture,
"(E) the National Cancer Institute,
"(F) the National Institute of Environmental Health Sciences,

"(G) the National Science Foundation, and the appropriate officials responsible for the relevant research efforts of such other agencies carrying out related efforts as the Chairman shall designate. A representative of the Department of State shall sit on the Coordinating Committee to encourage and facilitate international coordination.

"(3) The Coordinating Committee shall review and comment on plans for, and the execution and results of, pertinent research and studies. For this purpose, the agencies named in or designated under paragraph (2) of this subsection shall make appropriate and timely reports to the Coordinating Committee on plans for and the execution and results of such research and studies.

"(4) The Chairman may request a report from any Federal Agency for the purpose of determining if that Agency should sit on the Coordinating Committee.

"(g) Not later than January 1, 1978, and biennially thereafter, the Administrator shall report to the appropriate committees of the House and the Senate, the results of the studies and research conducted under this section and the results of related research and studies conducted by other Federal agencies.

"RESEARCH AND MONITORING BY OTHER AGENCIES

"Sec. 154. (a) The Administrator of the National Oceanic and Atmospheric Administration shall establish a continuing program of research and monitoring of the stratosphere for the purpose of early detection of changes in the stratosphere and climatic effects of such changes. Such Administrator shall on or before January 1, 1978, and biennially thereafter, transmit such report to the Administrator and the Congress on the findings of such research and monitoring. Such report shall contain any appropriate recommendations for legislation or regulation (or both).

"(b) The National Aeronautics and Space Administration shall, pursuant to its authority under title IV of the National Aeronautics and Space Act of 1958, continue programs of research, technology, and monitoring of the stratosphere for the purpose of understanding the physics and chemistry of the stratosphere and for the early detection of potentially harmful changes in the ozone in the stratosphere. Such Administration shall transmit reports by January 1, 1978, and biennially thereafter to the Administrator and the Congress on the results of the programs authorized in this subsection, together with any appropriate recommendations for legislation or regulation (or both).

"(c) The Director of the National Science Foundation shall encourage and support ongoing stratospheric research programs and continuing research programs that will increase scientific knowledge of the effects of changes in the ozone layer in the stratosphere upon living organisms and ecosystems. Such Director shall transmit reports by January 1, 1978, and biennially thereafter to the Administrator and the Congress on the results of such programs, together with any appropriate recommendations for legislation or regulation (or both).

"(d) The Secretary of Agriculture shall encourage and support continuing research programs that will increase scientific knowledge of the effects of changes in the ozone in the stratosphere upon animals, crops, and other plant life. Such Secretary shall transmit reports by January 1, 1978, and biennially thereafter to the Administrator and the Congress on the results of such programs together with any appropriate recommendations for legislation or regulation (or both).

"(e) The Secretary of Health, Education and Welfare shall encourage and support continuing research programs that will increase scientific knowledge of the effects of changes in the ozone in the stratosphere upon human health. Such Secretary shall transmit reports by January 1, 1978, and biennially thereafter, to the Administrator and the Congress on the results of such programs, together with any appropriate recommendations for legislation or regulation (or both).

"(f) In carrying out subsections (a) through (e) of this section, the agencies involved (1) shall enlist and encourage cooperation and assistance from other Federal agencies, universities, and private industry, and (2) shall solicit the views of the Administrator with regard to plans for the research involved so that any such research will, if regulatory action by the Administrator is indicated, provide the preliminary information base for such action.

APPENDIX 2

Data Verification and Calibration of Ozone Determination

When considering a satellite system, such as the SBUV or TOVS, that retrieves the desired parameters from basic measurements of radiances, it is necessary to consider two aspects of its evaluation: validation and calibration. The former involves determining the reliability of the basic data and the retrieval algorithm assumptions at a given time, while the latter is concerned with the possible long-term drift of the instrument calibration. Clearly, these need not be independent evaluation efforts, but on the other hand it may be cost effective to separate them. Thus, we present below, consideration of the various proposed techniques.

In Section A, we discuss the daily precision of the satellite measurements and their ability to meet the WMO recommendations. In Section B and C, the calibration or accuracy of the satellite measurements against ground truth for total ozone and vertical profiles, respectively, is discussed, and in Section D we discuss the possibility of calibrating one satellite system against another. Section E outlines the recommended verification/calibration program.

A. Precision of Daily Measured Zonal Averages. If we examine the SBUV and TOVS projected data capability within 5° latitude bands, we note that each band is sampled daily by about 28 and 200 data points, respectively.

The expected 1σ (standard deviation) random error component of the SBUV measurements S (random error) is about 2.5 percent for total ozone and 10 percent for the vertical distribution; for the TOVS, about 10 percent for total ozone. We assume the measurements to be unbiased. When we determine the 5° zonal average from the 28 and 200 (n) data points, however, an additional sampling or aliasing error S (sampling error) occurs due to incomplete sampling of the traveling wave patterns. This is about 1 percent for the SBUV (Wilcox, personal communication) and we assume a value of 0.11 percent (i.e., 1% x 28/200) for the TOVS. The total error, $\underline{S_Z^2}$, is, then, the sum of the variance of the two independent components:

$$\underline{S_Z^2} = \frac{S^2 \text{(random error)}}{n} + S^2 \text{(sampling error)}$$

Total Ozone

$$\text{SBUV:} \quad \underline{S}_z,\ t = \left[\left(\frac{2.5\%}{\sqrt{28}} \right)^2 + (1\%)^2 \right]^{1/2} = 1.11\%$$

$$\text{TOVS:} \quad \underline{S}_z,\ t = \left[\left(\frac{10\%}{\sqrt{200}} \right)^2 + (0.11\%)^2 \right]^{1/2} = 0.72\%$$

Vertical Ozone Distribution

$$\text{SBUV:} \quad \underline{S}_z,\ v = \left[\left(\frac{10\%}{\sqrt{28}} \right)^2 + (1\%)^2 \right]^{1/2} = 2.14\%$$

The 95% confidence limits of the daily 5° latitudinal average are:

Total Ozone

SBUV $\pm$ 2.22%
TOVS $\pm$ 1.43%

Vertical Ozone Distribution

SBUV $\pm$ 4.28%

We see, then, that the inclusion of a 1% sampling error for SBUV and the 10% precision for TOVS precludes the possibility of satisfying the WMO recommendation on a 5° latitude basis for total ozone and marginally satisfies it for vertical distribution. If, however, we consider the total area of measured ozone (at least 60N-60S for both SBUV and TOVS) and note that the sampling error should be uncorrelated at about 20° latitude increments, we would have about six independent measurements for SBUV and about 24 for TOVS (this assumes that sampling errors are relatively unimportant for TOVS). The area integral precision then will be reduced by about $1/\sqrt{6}$ for SBUV and by about $1/\sqrt{24}$ for TOVS;

Area Integral Total Ozone

SBUV: $\underline{S}_{a,t} = \dfrac{1.11\%}{\sqrt{6}} = 0.45\%$

TOVS: $\underline{S}_{a,t} = \dfrac{0.72\%}{\sqrt{24}} = 0.15\%$

Area Integral Vertical Ozone Distribution

SBUV: $\underline{S}_{a,v} = \dfrac{2.14\%}{\sqrt{6}} = 0.87\%$

The 95% (2S) confidence limits of the area integrals become

Total Ozone

SBUV: $\pm$ 0.90%
TOVS: $\pm$ 0.30%

Vertical Ozone Distribution

SBUV: $\pm$ 1.75%

We note then, that the daily area integrals can satisfy the WMO recommendations.

B. Ground-based Verification of Total Ozone. The expected 1σ (standard deviation) random error component of the SBUV and the Dobson ground based determination of total ozone is about 2.5%, respectively. For paired comparisons the mean difference is calculated over a period of time and the 95% confidence level of this difference is

$$X = \frac{2\sigma\sqrt{2}}{\sqrt{n}} .$$

Setting X = 1% and solving for n

$$n = \left(\frac{2\sigma\sqrt{2}}{1\%}\right)^2 = \left(\frac{2\ (2.5)\sqrt{2}}{1\%}\right)^2 = 50$$

If we consider that coincident overpass usually allows for a time and space window and if, on this supposition we utilize 3% as the standard deviation to accommodate this window effect, then n becomes equal to 70.

For the TOVS, with a 1σ value of 10%, the formula for paired observations becomes:

$$X = \frac{2S}{\sqrt{n}} \qquad S^2 = [(10\%)^2 + (2.5\%)^2]$$

or

$$n = \left(\frac{2(10.31)}{1\%}\right)^2 = 425.$$

In other words, if the satellite retrieval-ground based observation differences are independent of spatial location we arrive at 1% (95% confidence limit) on the differences by utilizing about 70 and 425 matched observations for the SBUV and TOVS, respectively. Assuming about 3 possible matchups per week for a given site and about 30 sites participating, the above could be accomplished in about 1 week for SBUV and about 5 weeks for TOVS.

One of the major difficulties with this approach is that the Dobson instruments would have to be routinely inter-compared and calibrated amongst themselves. Also, if the differences are not independent of latitude, then a more sophisticated regressional formulation of the differences as a function of latitude must be utilized. Should this be the case, it appears that the current total ozone network will be sufficient to delineate the variation. Finally, we point out that if it is planned to have a second satellite in orbit at the same time, the above verifications should be done for both sets of instruments. It will be highly desirable to be able to merge the data from the two SBUV instruments in one synoptic map.

C. In-situ Ozonesonde Verification. If we assume 1σ values of the satellite and rocket ozonesonde random error component of about 10%, we can solve for the number of paired observations required to allow the 95% confidence level of 5%, viz.,

$$n = \left(\frac{2(10)\sqrt{2}}{5\%}\right)^2 = 32$$

If we increase the 1σ values to 12 percent to allow for the space-time windows, the number becomes equal to 46.

This result means that an initial verification program which involves comparisons at various latitudes should be based on about 46 paired observations at each site. While the cost of such an effort is recognized to be substantial, it would have to be done once only and would be followed by a considerably reduced maintenance program. The suggested schedule for the initial verification program is 46 observations during one year at each of 4 sites;low-, mid-, and high-latitude of the Northern Hemisphere plus a mid-latitude site in the Southern Hemisphere, with this selection of sites based on current operational availability.

For the follow-on maintenance program we must recognize that the problem is basically two-fold:

1. the spectral calibration of the SBUV diffusion grating may be time-dependent.

2. there will be a continued data requirement to ensure that the assumptions of the retrieval algorithm are operative.

Clearly, the optimum solution to the spectral calibration problem is to provide some form of internal calibration within the instrument system. In fact, several suggestions have been put forth as to how this might be accomplished and are currently under examination.

For the long-term data requirement, we have seen above that to achieve the 5% confidence limits we require about 46 satellite-rocketsonde comparisons per year. We propose, then, that such a comparison effort be established at one mid-latitude site (e.g., Wallops Island). At the same time, it would be highly desirable to maintain a comparison program at other sites and we propose that a program of once-per-month comparisons be maintained at a low- and high-latitude site (10% confidence limits) to provide hemispheric coverage.

D. Cross Calibration of Satellite Instruments. In the discussion above, the focus was on the comparison of one satellite system against ground based data. Current plans, however, are for several satellite instruments to be operational at the same time (i.e., two Tiros-N spacecraft in different orbits) and the question is how to cross-calibrate these instruments. One technique is simply to compare the areal average data from the two sensors and presented below are the precisions achievable by this method.

If we take the 60N-60S area average data from each instrument and compute the mean difference, D, between these averages for a 10-day period, we arrive at:

$$\bar{D} = [O_3]_1 - [O_3]_2$$

and a standard deviation of the differences, S(D),

$$S(D) = [(D-\bar{D})^2]^{1/2}$$

At this point we note that, from above, the errors of the zonal average of each 5° latitude band are due to the instrumental precisions plus sampling difficulties and are independent for the two systems.

Since $D = [O_3]_1 - [O_3]_2$

$$\underline{S}^2(D) = \underline{S}^2[O_3]_1 + \underline{S}^2[O_3]_2$$

from Section A.

Total Ozone

SBUV: $\underline{S}_{a,t}\ [O_3] = 0.45\%$

TOVS: $\underline{S}_{a,t}\ [O_3] = 0.15\%$

Vertical Ozone Distribution

SBUV: $\underline{S}_{a,t}\ [O_3] = 0.87\%$

Therefore, for comparison of two SBUV instruments over the 10 days:

Total Ozone

$$\underline{S}\ (D) = \frac{(0.45)\sqrt{2}}{\sqrt{10}} = 0.20\%$$

Vertical Distribution

$$S\ (D) = \frac{(0.87)\ \sqrt{2}}{\sqrt{10}} = 0.39\%$$

The 95 percent confidence limits for the area integral comparisons should be on the order of ± 0.40% for the total ozone and ± 0.78% for the vertical distribution.

For comparison of two HIRS-2 instruments over a 10-day period

Total Ozone

$$\underline{S}\ (D) = \frac{(0.15)\ \sqrt{2}}{\sqrt{10}} = 0.07\%$$

or the 95 percent confidence limits for the area integral comparisons should be on the order of ± 0.14%.

Finally, to compare the SBUV with the TOVS area total ozone values

$$\underline{S}\ (D) = \left(\frac{(0.45)^2 + (0.15)^2}{\sqrt{10}}\right) 1/2 = 0.05\%$$

or the 95 percent confidence limits for the area integral comparisons should be on the order of ± 0.10%.

E. Verification - Calibration Program. On the basis of the above considerations, we recommend a validation and calibration program consisting of:

(1) A yearly verification/calibration comparison program between total ozone measurements from satellites and ground-based Dobson instruments on a routine basis such that ± 1 percent (95 percent confidence limit) precision estimate of comparability will be obtained.

(2) An initial (1 year) verification program of comparisons between vertical ozone profiles derived from satellite measurements and in-situ observationsat 4 sites; low-, mid-, and high-latitude sites in the Northern Hemisphere plus a mid-latitude site in the Southern Hemisphere. The number of comparisons will be such that ± 5 percent (95 percent confidence limit) precision estimates of comparability will be obtained at each site.

(3) A minimum yearly verification/calibration program of comparisons between vertical profiles derived from satellite measurements and in-situ observations at one Northern Hemisphere mid-latitude site such that ± 5 percent (95 percent confidence limit) precision estimates of comparability will be obtained. At the same time, it is recognized that it would be highly desirable to maintain a similar comparison at a low- and high-altitude site to provide hemispheric coverage.

APPENDIX 3

Uncertainties of Average Global Ozone Determinations

When considering the spatial coverage of the SBUV and TOVS ozone measurements, it must be recognized that the data are not completely global. For the SBUV the coverage is limited to the sun-lit portion of the globe (the winter-time terminator is at about 60°) while for the HIRS-2 the retrievals become considerably "noisier" (if at all possible) in the winter-time high latitude region where the temperature strucutre in the lower stratosphere is basically isothermal. Consequently, an estimate of the global ozone amount must include an extrapolation into this domain. Presented below are estimated of the precisions of the extrapolation procedures.

A. Average Global Ozone (AGO)

$$AGO = \frac{\int_{\pi/2}^{\pi/2} O_3 \quad \cos\phi d\phi}{(\sin \pi/2 - \sin(-\pi/2)}$$

$$AGO = \frac{\int_{0^\circ}^{60^\circ} O_3 \cos\phi d\phi + \int_{60^\circ}^{90^\circ} O_3 \cos\phi d\phi + \int_{0^\circ}^{-90^\circ} O_3 \cos\phi d\phi}{2}$$

$$AGO = \frac{300(\sin 60 - \sin 0) + \int_{60^\circ}^{90^\circ} 03 \cos\phi d\phi + 300}{2}$$

polar cap with value at 60°N:

$$\int_{60^\circ}^{90^\circ} O_3 \cos\phi d\phi = 420(\sin 90 - \sin 60) = 056$$

polar cap with extrapolation of linear trend = 065

average polar cap value $\frac{56+65}{2} = 62$ with possible error ± 5

$$AGO = \frac{300 + 260 + 61 + 5}{2}$$

$$AGO = 310 \pm 3$$

The percent error (%) $= \frac{\pm 3}{310} = \pm 0.97\%$

or taking average between A and B in polar cap results in uncertainty of about ±1% in average global total ozone.

B. Average Global 2mb Ozone Mixing Ratio

2 mb Ozone mixing ratio = 11.5/μg/g

$\mu g/g_{60^\circ} = 11.50$
$\mu g/g_{55^\circ} = 11.29$

Average Global 2mb Ozone Mixing Ratio (AG2)

$$AG2 = \frac{\int_{0^\circ}^{60^\circ} O_3 \cos\phi d\phi + \int_{60^\circ}^{90^\circ} O_3 \cos\phi d\phi + \int_{0^\circ}^{-90^\circ} O_3 \cos\phi d\phi}{2}$$

$$AG2 = 11.5(\sin 60 - \sin 0) + 11.5 + \int_{60^\circ}^{90^\circ} \mu g/g \cos\phi d\phi$$

Polar cap with value at 60N

$$\int_{60^\circ}^{90^\circ} /\mu g/g \cos\phi d\phi = 11.5(.134) = 1.54$$

Polar cap with extrapolation of linear trend

$$\int_{60^\circ}^{90^\circ} /\mu g/g \cos\phi d\phi = 1.59$$

$$AG2 = \frac{9.959\ \mu g/g + 11.56 + 1.56 + .03}{2} = 11.51 \pm .02$$

$$\text{Uncertainty} = \frac{.02}{11.5} = .17\%$$

C. Polar Cap Total Ozone. We have seen from above that in winter, taking the average (A) between the extremes results in an uncertainty of about ±1 percent in Average Global Ozone (AGO) with the true answer somewhere between the extremes.

We will assume that A is an unbiased estimate of the true population average and therefore the ±1 percent, above, represents the 2 level of the uncertainty. Under these assumptions we are maximizing the uncertainty with respect to trend determination and are being conservative. For example, the true population may be biased with respect to A, but this implies a smaller uncertainty and the bias in the trend should be approximately removed. The uncertainty in A may not, however, be statistically independent on a daily basis and for a monthly average our best estimate is the same value obtained on the daily basis.

$$\text{Daily:}\quad \sigma^2(AGO) = \sigma^2(\text{sample}) + \sigma^2(\text{polar})$$

$$= (0.45)^2 + (.5)^2$$

$$= 0.4525$$

$$\sigma = \pm 0.67\%$$

$$2\sigma = \pm 1.34\%$$

Monthly: $\sigma^2(\text{AGO}) = \dfrac{\sigma^2\ (\text{sample})}{30} + \sigma^2\ (\text{polar})$

$= .0675 + .25$

$= 0.25675$

$\sigma = 0.5067\%$

$2\sigma = 1.01\%$

APPENDIX 4

Data Verification and Calibration of Stratospheric Temperature Profiles

In a manner similar to that discussed for the ozone measurements in Appendix I, the verification and calibration of stratospheric temperatures are applied to averages within 5° latitude basis. In section A we discuss the daily precision of the satellite measurements and their ability to meet the stated recommendations, and in section B we discuss the validation/calibration of the satellite data using "ground truth." Presented below are the precision estimates (2σ) for both the rocket/rawinsonde and TIROS N satellite system temperature determinations:

	Height Range (km)	Rocket/Rawinsonde (°K)	TIROS N (°K) (simulated)
a.	15-30	3	4
b.	30-50	3	6
c.	50-60	4.5	12

A. Precision of Daily Measured Zonal Averages. If we examine the TIROS N data system within 5° latitude bands, we note that, as in Appendix I, each band is sampled daily by about 200 data points, and we assume a conservative zonal average sampling or aliasing error of about 1°K

$$(1\%) \times (14/200)$$

The total error, $\underline{S}_z$, is then,

layer a $\underline{S}_{z_a} = ((1)^2 + (2/\ 200)^2)^{1/2} = \pm 1.01$

layer b $\underline{S}_{z_b} = ((1)^2 + (3/\ 200)^2)^{1/2} = \pm 1.02$

layer c $\underline{S}_{z_c} = ((1)^2 + (6/\ 200)^2)^{1/2} = \pm 1.09$

The 95% confidence limits of the daily 5° latitudinal averages are:

15-30 km: ±2.02
30-50 km: ±2.04
50-60 km: ±2.18

We see that if the TIROS N system operates at expected precision levels, it is capable of satisfying the stated requirements for 5° latitude bands. If, further, we consider the total area of measured temperatures, 80N-80S, then we should have about 6 independent measurements. The precision of the area integral then becomes:

15-30 km $\underline{S}_a = (1.01)/\ 6 = \pm 0.41$
30-50 km $\underline{S}_b = (1.02)/\ 6 = \pm 0.42$
50-60 km $\underline{S}_c = (1.09)/\ 6 = \pm 0.44$

The 95% (2S) confidence limits of the area integrals become:

15-30 km: ±0.82
30-50 km: ±0.84
50-60 km: ±0.88

B. Ground-Based Verification and Calibration of Satellite Instruments. As discussed in Appendix I, the ground-based calibration can be conducted along two strategies. The first utilizes rocket/rawinsonde temperature profiles coincident with satellite overpass and the satellite weighting functions to calculate the radiance that the satellite should have observed. This bypasses the satellite temperature retrieval process and, in effect, calibrates the measurements of the satellite. Unfortunately, for several channels of the TIROS N system the weighting functions extend above the peak altitude of the rocket which may introduce a non-random error into such calibrations. The second approach is simply to compare the temperature profiles of the two instruments in the same manner as discussed for the ozone profiles.

The formula for paired observations is:

$$X = \frac{2S}{\sqrt{n}} \qquad S = [\sigma_1)^2 + (\sigma_2)^2]^{1/2}$$

For the TIROS N - rocketsonde system, then, using X = 2°:

$$15\text{-}30\ \text{km:}\quad n = \frac{4S^2}{4} = S^2 = ((1.5)^2 + (2)^2) = 6$$

$$30\text{-}50\ \text{km:}\quad n = ((1.5)^2 + (3)^2) = 11$$

$$50\text{-}60\ \text{km:}\quad n = ((2.25)^2 + (6)^2) = 41$$

Acknowledging that the satellite and in-situ observations can never actually be coincident in space and time (only nearly so), we must increase the S values slightly to account for this effect. We see, then, that to obtain a ±2° verification/calibration of the temperature profiles over the complete altitude region 15-60 km, we require about 50 comparisons.

It is highly desirable to be able to discern any real differences as a function of latitude. Fortunately, the current U.S. rocket network operations of about 3 launches per week at the sites outlined in section II.B. should provide at least one matchup per week per site. With 2 high-latitude (50°N-pole), 3 mid-latitude (20N-50N), and 2 low-latitude sites (20N-20S) this amounts to about 50 comparisons in each region per 6 months. Thus, we can certify and calibrate the satellite retrievals to the recommended precisions twice per year utilizing the current rocket-rawinsonde program.

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TABLE OF ACRONYMS

BUV	Backscattered Ultraviolet
HIRS	High Resolution Infrared Sounder
IRIS	Infrared Interferometer Spectrometer
LIMS	Limb Infrared Monitor of the Stratosphere
LRIR	Limb Radiance Infrared Radiometer
MFR	Multifilter Radiometer
MSU	Microwave Sounding Unit
SAGE	Stratospheric Aerosol and Gas Experiment
SBUV	Solar Backscattered Ultraviolet
SSU	Stratospheric Sounding Unit
TOMS	Total Ozone Mapping System
TOVS	Tiros Operational Vertical Sounder
VTPR	Vertical Temperature Profile Radiometer

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