An Overview of Environmental Satellites and Sensors

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NOAA/Sea Grant
University of Rhode Island
Marine Memorandum 72

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PREFACE

The material presented here was originally written as an introduction to a much more detailed volume, A Guide to Environmental Satellite Data, dealing with United States environmental satellites. It soon became apparent that a number of people were interested in the overview provided by this introduction but not, at least at this time, in the expense or detail of the material that followed. It was also apparent that the introductory material with a few minor changes could be extracted and printed as a stand-alone document. This is what has been done. If, after reading this booklet, one decides to purchase A Guide to Environmental Satellite Data, it is available for $20.00 from:

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University of Rhode Island
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Narragansett, Rhode Island 02882-1197

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CHAPTER 1. INTRODUCTION

OVERVIEW

The first hurdle the potential user must overcome in order to begin working with remote-sensing data products is to determine what is available and how it is acquired. This summary is directed primarily at these questions. The discussions will be limited to satellite-borne sensors and their data products, as opposed to aircraft imagery. The desirability of satellite data products is due to their availability, relatively low cost and comparatively simple interpretation. Although more accurate in almost all respects, aircraft data are often more expensive to obtain. Generally, a tailor-made mission must be flown for the project, and the data are often more difficult to interpret, because of the large number of variables--sun angle, altitude, and speed, for instance--that must be known. These variables will vary during the mission and must be accurately determined. Of course, the professional can use the definition of these variables to advantage when flying a mission and obtain higher-resolution data products than is possible from satellite. Many coastal applications make use of aircraft data for just this reason.

This summary is divided into three chapters addressing those issues important in understanding and ordering environmental satellite data. The first chapter is devoted to a brief overview of satellite data dissemination in the United States as it exists today. Chapter 2 discusses in general terms the types of sensors borne on satellites and the variables they measure. Chapter 3 provides a historical perspective of satellites with potential coastal and oceanographic applications.

ENVIRONMENTAL SATELLITE DATA AVAILABILITY IN THE UNITED STATES, FALL 1981

At present, data and imagery from United States environmental satellites are available from four sources, and these are briefly discussed below. However, the reader is cautioned that the situation is fluid and subject to change.

The source to which one wrote for data used to depend on which agency operated the satellite. In general, the data from meteorological satellites, operated by NOAA, were disseminated by the Environmental Data and Information Service (EDIS) of NOAA in Washington, D.C. Air Force meteorological satellite (DMSP) data were distributed by the University of Wisconsin, Space Science and Engineering Center for NOAA/EDIS. LANDSAT (the Earth Resources Satellite) data were obtained from the United States Geological Survey's EROS Data Center in Sioux Falls, South Dakota. Research data from many of the NASA-launched experimental satellites were available from the National Space Science Data Center (NSSDC) of NASA, located at the Goddard Space Flight Center in Greenbelt, Maryland.

At present, one can still obtain DMSP data from the University of Wisconsin and civilian meteorological satellite data from NOAA in Washington. Although the operation of LANDSAT is now formally under the control of NOAA's National Earth Satellite Service, the EROS Data Center will continue to archive and distribute the actual data under a formal agreement with NOAA. EDIS in Washington has also been made the focal point for research satellite data such as that of SEASAT-1 and the NIMBUS-7 Coastal Zone Color Scanner. Table 1 summarizes current addresses and phone numbers of organizations from which data of each of the associated satellites may be obtained.

Table 1. Organizational Responsibility for the Archival and Dissemination of Satellite Data

	Organization	Acronym	Address	Satellites Covered
1.	Satellite Data Services Div/ National Climate Center/ Environmental Data Information Service/ National Ocean and Atmospheric Administration	SDSD NCC EDIS NOAA	SDSD/NOAA Room 100 World Weather Bldg. Washington, D.C. 20233 Tel: 301-763-8111 FTS: 763-8111	TIROS I-X ESSA 1-9 ITOS-1 NOAA 1-5, 6-7 TIROS-M, -N SMS 1-2 GOES 1-5 GEOS 3 NIMBUS-7 (CZCS) SEASAT-1
2.	National Space Science Data Center/ National Aeronautics and Space Administration	NSSDC NASA	National Space Science Data Center Code 601 NASA/Goddard Space Flight Center Greenbelt, MD. 20771 Tel: 301-344-6695 FTS: 344-6695	HCCM NIMBUS 1-7 except CZCS
3.	EROS Data Center United States Geological Survey	USGS	EROS Data Center User Services Sioux Falls, S.D. 57198 Tel: 605-594-6511 Ext. 151 FTS: 784-7151	LANDSAT 1-3
4.	Space Science and Engineering Center/ University of Wisconsin	SSEC	DMSP Library Space Science & Engineering Center, University of Wisconsin, Madison, WI 53706	DMSP

CHAPTER 2. SENSORS: DESCRIPTION AND CLASSIFICATION

In the following sections, the satellite-borne sensors of interest to oceanography are considered in two separate groups. The first group deals with sensors operating in the visible, near infrared, and thermal infrared bands, the second with those operating in the microwave. The primary reason for this separation is that in general satellite-borne sensors in the visible and infrared are passive--i.e., make use of reflected solar or emitted terrestrial radiation while, except for the SMMR (introduced briefly below), instruments operating in the microwave provide the source of radiation--as well as the detector. Active devices use the strength of the returned signal as well as its frequency and round-trip travel time to describe the target.

The sensors in these two groups can be subdivided into two broad categories: imaging and nonimaging. Imaging devices are those that tend to emphasize spatial information; i.e., they obtain a two-dimensional picture of either the color, temperature, or surface roughness of the area imaged, stressing the variability of these parameters over the area. The spatial dimensions range from several tens of meters (SEASAT, SAR) to about 10 kilometers (GOES, VISSR). Nonimaging devices stress temporal, spectral, or radiometric resolution with little consideration for spatial information; e.g., the altimeter which measures surface elevation and surface roughness only at the satellite suborbital (nadir) point, or the scatterometer which averages surface roughness over squares 50 km on a side or larger to estimate wind stress.

This distinction becomes important when considering data reception and processing. Although data from both systems often require significant processing to obtain the oceanographic variable of interest, those from an imaging device require a sophisticated display device, while standard line printer output is sufficient for those from the nonimaging sensors.

The sensors within both subcategories, imaging and nonimaging, are described in a generic sense. (Details with regard to satellite-borne sensors of environmental interest are presented in <u>A Guide to Environmental Satellite Data</u> available from the Marine Advisory Service, University of Rhode Island, Narragansett, R.I. 02882-1197 at a cost of $20.00.) It should be stressed that although these sensors are presented within the context of satellite remote sensing, the generic descriptions apply equally well to aircraft-borne sensors. In fact, most of the satellite-borne sensors are flight-tested on aircraft prior to their implementation on board a satellite.

Electromagnetic Radiation--The Quantity Measured

Prior to presenting the subclassification of satellite-borne sensors, a discussion of the quantity measured is appropriate. <u>All</u> such sensors measure electromagnetic energy or the intensity of electromagnetic waves. Electromagnetic waves are composed of varying electric and magnetic fields and are defined by three properties: their wavelength, the amplitude or height of the waves, and their direction of propagation. (In the following, we assume the direction of propagation is toward the satellite, so only the wavelength and amplitude will be considered.) Electromagnetic waves may have any wavelength between zero and infinity, but, due to environmental and instrument constraints, only certain portions of the electromagnetic spectrum are useful in satellite remote sensing of Earth resources (Figure 1). Some of the more important constraints are atmospheric absorption, the size of the instrument's antenna, the relationship between the wavelength and the quantity observed, and the power available to operate the equipment (the last primarily for active devices). An additional and extremely important constraint is the data rate; i.e., the volume of data collected. This constraint is determined by the ability to (a) handle the data on the satellite, (b) send these data to Earth, and (c) process such data once they have been received on the ground.

Electromagnetic radiation of interest in remote sensing of Earth falls into three general regions: visible, infrared, and microwave. These are discussed below.

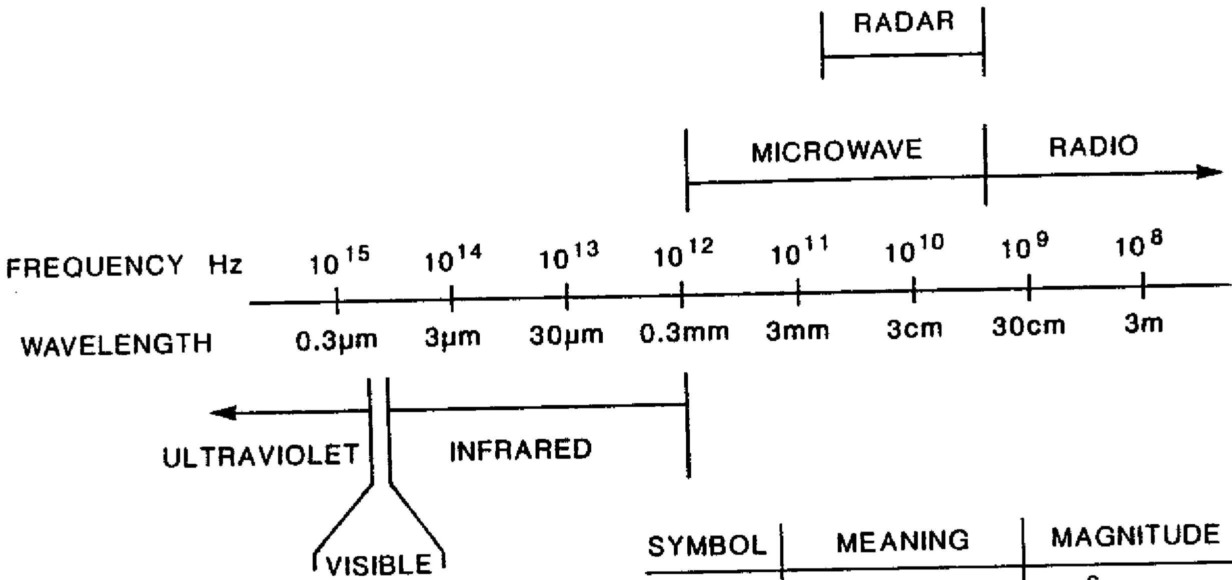
Visible Radiation--Light

Light is one example of electromagnetic radiation (see Figure 1), the color of the light being determined by its wavelength. Red light, the longest wavelength light that we can see unaided, is composed of waves about 0.75×10^{-6} meters long (0.75 micrometers, written 0.75 μm), while blue light, the shortest wavelength we can see, is composed of waves about 0.4 μm long. This portion of the eletromagnetic spectrum from blue to red light is called the visible portion because it is composed of only those wavelengths we can see without instrumentation.

The intensity of light, its brightness, is determined by the amplitude of the waves. Bright light will have relatively larger amplitude waves, while dim light will have relatively smaller ones.

Visible light will propagate through a clean, dry atmosphere with little disturbance and is therefore one of the more important bands of the spectrum for satellite sensing. In a clean, dry atmosphere we have good visibility: a "clear" day. On a hazy day there are a great deal more scatterers and absorbers in the atmosphere and the light can be substantially affected as it passes (propagates) through it.

Most visible radiation reaching a satellite from the Earth is reflected solar radiation; i.e., light from the sun that has been reflected from the Earth or its atmosphere toward the satellite. Note that this means that sensors in the visible can, in general, collect data only during daylight hours.



SYMBOL	MEANING	MAGNITUDE
µm	MICROMETERS	10^{-6} METERS
mm	MILLIMETERS	10^{-3} METERS
cm	CENTIMETERS	10^{-2} METERS
Hz	HERTZ or CYCLES/SEC.	

Figure 1. Electromagnetic Spectrum

A final property of visible radiation that is important in oceanography is its ability to penetrate water. Of the three spectral regions of importance in remote sensing oceanography, light (especially blue light) penetrates water by far the best. Indeed, in the thermal and microwave portions of the spectrum, there is little (on the order of micrometers) to no penetration. Blue light, on the other hand, will propagate through tens of meters of clear ocean water before being significantly attenuated. Red light is sharply attenuated within the first few meters.

Infrared Radiation

The second region of the spectrum important in remote sensing is the infrared, so called because it is "below" red, or beyond the visible red. We cannot see infrared radiation with the unaided eye; however, instruments can record this radiation either electronically or photographically. Once in this form, it is readily converted to an image we can see, or numbers we can interpret. The infrared portion of the spectrum is divided into several regions, of which the near infrared (near IR) and the thermal infrared (thermal IR) are the most important.

The near IR is important because it corresponds to the band of high reflectance for most vegetation; i.e., plants reflect a good deal more energy in the near IR than in the visible. Furthermore, the atmosphere, except for clouds, is transparent to near IR radiation. The wavelengths of interest here range from about 0.8 μm to about 1.5 μm. As in the case of visible radiation, most radiation leaving the Earth in this portion of the spectrum is reflected solar radiation.

Thermal IR radiation (> 4 μm) is important because it is dominated by radiation emitted by the Earth and atmosphere, not reflected solar radiation. The intensity of the emitted radiation depends on the temperature of the source (water, land, etc.) and a physical characteristic of the source, called the emissivity, which is generally sufficiently well known so that the temperature can be determined from an accurate measurement of the thermal IR radiation. The atmosphere is only transparent to thermal IR radiation within several narrow "windows." Two of the most important of these are the 3 μm to 5 μm band and the 9.5 μm to about 13.5 μm band. Outside these windows, almost all thermal IR radiation is absorbed by the atmosphere as it propagates toward the satellite. Within the 9.5 to 13.5 μm window, the radiation is greatly affected by atmospheric humidity, resulting in one of the most significant shortcomings of thermal IR sensors in determining sea surface temperatures (SST). Furthermore, thermal IR radiation does not penetrate clouds to any significant extent. However, because a significant fraction of the radiation is emitted by the Earth, data collection is not restricted to daylight hours.

Microwave Radiation

The third portion of the spectrum important in remote sensing of the Earth is the microwave region. Wavelengths of importance range from about 1 millimeter (1 millimeter = 10^{-3} meters) to several tens of centimeters (1 centimeter = 10^{-2} meters). The cutoff at the lower end is determined by atmospheric absorption while the cutoff at the upper end is more a function of instrument constraints as well as the reflective and emissive properties of the ground, atmosphere, and sea surface. There are several very important differences between sensing in the microwave compared to sensing in the visible and infrared.

First, most microwave radiation will penetrate clouds with little attenuation, or reduction of signal strength. This means that a substantial portion of the microwave spectrum may be used under all weather conditions (except for heavy rain).

Second, the intensities of radiation emitted by the Earth and solar radiation reflected by the Earth are very weak. This means that a passive sensor, depending on the Earth or the sun as its source of radiation, must be very sensitive to obtain useful information. On the other hand, active devices, those which provide the source of radiation and then measure the fraction reflected back toward the sensor, have little background radiation to confound the measurements.

Third, the wavelengths used are comparable to the size of many surface irregularities, sand grain size, capillary waves, etc. Therefore, the intensity of reflected radiation often carries information on the roughness of the surface, which is of particular value when studying oceanographic phenomena.

VISIBLE, NEAR INFRARED, AND THERMAL INFRARED SENSORS

The general classification scheme for sensors in the visible to thermal IR portion of the spectrum is shown in Figure 2. The first division is determined by the detector's operational modes. In the case of the photographic instrument, the recording medium is film. The detection process involves molecular alterations on the film, hence is not reversible; i.e., once a film has been exposed, it cannot be used again. In the case of the electro-optical sensors, the output of the detector is an electronic signal. This signal may then be used to expose a film (as is done by some thermal detectors), may be stored on magnetic storage devices, or displayed on a cathode ray tube (CRT). The detector is not destroyed in the process of detection. Furthermore, the recorded signal is in an appropriate form for transmission or digital processing. A second important difference between photographic and eletro-optical sensors is that the former are restricted to the visible and near infrared (up to about 1.2 μm) portion of the spectrum, while the latter can be made to cover any part of the visible to thermal IR region. Further-

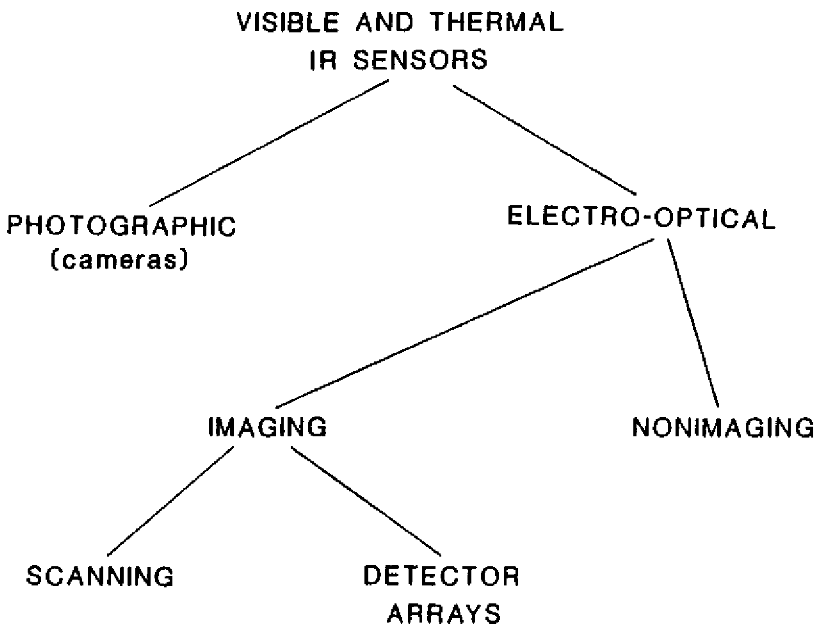


Figure 2. Classification Scheme for Sensors Covering the Visible and Thermal IR Portion of the Spectrum

more, the dynamic range available to electro-optical detectors is in general significantly greater than what is available to photographic ones. For many applications, probably the most important feature is that multispectral data (electromagnetic intensity separated into a number of different wavelength regions) is available simultaneously at each of the ground elements imaged by the sensor. Multispectral information is available from photographic devices--e.g., clusters of cameras or a number of lenses for the same frame--but registration of the resulting images is not easy. For the electro-optical device, on the other hand, registration is often inherent in the treatment of radiation by the instrument. A comparison of electro-optical detection and photographic detection is presented in Table 2. Understanding of photographic equipment by the reader is assumed and will not be dealt with further. The rest of this chapter will be devoted to electro-optical sensors, which are subdivided into imaging and nonimaging. Because the imaging device has as its basis the nonimaging sensor, the nonimaging sensor will be presented first.

Nonimaging Sensors

Radiometer/Photometer. The simplest of the nonimaging devices are radiometers or photometers. These instruments measure the intensity of all the electromagnetic radiation within their field-of-view and wavelength range. The field-of-view depends on the optics of the collector (mirror or lens), the field stop, and/or the geometry of the detector. There may, of course, be additional optical elements within the system which also act to determine the field-of-view. The wavelength range to which the sensor is responsive depends primarily on the optical elements through which the radiation must pass and on the design characteristics of the detector.

The distinction between the radiometer and photometer is based on the wavelength range over which they are sensitive. The radiometer operates at and beyond wavelengths in the infrared; i.e., at wavelengths greater than about one micrometer. The photometer operates at shorter wavelengths, the region of sensitivity corresponding approximately to that of photographic film.

Although the term radiometer is used in this section for detectors operating from 1 μm to radio wavelengths (meters), the primary emphasis is on detection in the thermal infrared. As mentioned previously, electromagnetic energy in the thermal infrared portion of the spectrum is emitted primarily by objects in the 300°K (27°C or 80°F) range. This means that great care must be taken to cool the instrument so that the radiation observed is not that emitted by the sensor itself. In general, this requires that the instrument be equipped with an internal reference to calibrate the observed signal. Internal calibration is not required (although it may be used) for the photometer.

Spectrometer. A spectrometer is a photometer or radiometer with a

TABLE 2. Electro-Optical Detection Versus Photographic Detection

Electro-Optical Advantages	Electro-Optical Disadvantages
- Can image beyond approximately 1.2 μm, the limit for photographic sensors	- In general, substantially more complex than a camera
- Output signal in electronic form may be: transmitted, recorded, digitally analyzed	- Data storage is not as efficient on magnetic tape as on film
	- Coarser spatial resolution
- Has a greater dynamic range	
- Capable of internal calibration	
- Multispectral data is coregistered	

dispersing element. The dispersing element--e.g., a prism or ruled grating--spreads the incoming radiation spatially as a function of wavelength. The dispersed radiation is then detected either by a number of radiometers at different locations or by sweeping the dispersed beam past the same radiometer. The former method provides poorer spectral resolution but greater sensitivity by integrating longer in time. In the laboratory, this results in only a small advantage. In the field, where the incoming energy may be a function of time, this time constraint can be crucial.

Imaging Sensors

Photographic. As mentioned earlier, photographic equipment will not be covered in any detail here. The primary points have already been mentioned in the summary of Table 2.

Return Beam Vidicon Camera. The Return Beam Vidicon Camera, or RBV, is a television system which lies generically between photographic equipment and multispectral scanners, discussed in the next section. The device is similar to photographic equipment in that it images an entire scene at one instant. It is, however, similar to the electro-optical sensors in that the detected radiance is converted to an electronic signal. The RBV, therefore, has some of the disadvantages of photographic equipment (two-dimensional distortion, lack of multispectral registration) and some of the advantages of the electro-optical sensors (electronic output, nondestructive detection, etc.). LANDSAT is currently the only environmental satellite with a television sensor aboard.

Scanners. Electro-optical scanners are devices which generate an image by scanning the scene of interest. This is generally done using a rotating mirror which reflects radiation from different parts of an area into the detection system. Usually the sensor is constructed so that the rotation of the mirror provides radiance data along a straight line. The second dimension of the image is then obtained by advancing the sensor perpendicular to the scanning direction. From the mirror back to the detector, the sensor resembles at least conceptually the simple radiometer or spectrometer discussed above.

All multispectral scanners on the various satellites (MSS on LANDSAT, CZCS on NIMBUS-7, VHRR and AVHRR on the TIROS-NOAA series, for instance) operate basically as described above, using the scanning motion of the mirror to provide the across track information and the motion of the satellite to provide the along track information. The only exception to this method of operation is the Visible Infrared Spin Scan Radiometer (VISSR) on GOES.

The VISSR operates differently because the GOES satellite on which it is flown does not advance relative to the ground. It is in what is referred to as a geostationary orbit, discussed in Chapter 3. For VISSR the scanning motion is achieved by rotating the entire satellite about an axis approximately perpendicular to the plane described by its orbit. The mirror inside the satellite is then stepped about the axis perpendicular to the earth-satellite vector and lying in the orbital plane of the satellite. One step is taken for each rotation of the satellite. The rotation of the satellite then provides the east-west information, while the stepping mirror provides the north-south information.

All of the visible/IR scanners on environmental satellites have at least two spectral channels.

MICROWAVE SENSORS

Because the intensity of emitted terrestrial radiation and reflected solar radiation is down several orders of magnitude in the microwave portion of the spectrum from what it is in the visible to IR portion of the spectrum, passive reception of such energy is quite difficult. Because of this--and because of their expected usefulness--active microwave sensors have received significant attention in the past several years. The ability to control the source of radiation in an active sensor permits the measurement of variables other than just the received radiance. In particular, active microwave sensors make use of the travel time of the emitted pulse to measure distance and the frequency of the returned pulse to measure the speed of the target relative to that of the sensor platform. The change in frequency due to relative motion is referred to as the doppler shift. These two variables, round trip travel time and doppler shift, may also be used to locate a signal geometrically. An active device can use any or all of the three variables outlined above as well as a fourth, polarization. The polarization is a measure of the plane in which the measured electromagnetic vector oscillates. Both active and passive devices measure the polarization. The emitted pulse of active devices may also be polarized.

Nonimaging Microwave Sensors

Radar Altimeter. A radar altimeter is an active device used to measure the distance from the spacecraft to the reflecting surface below with a high degree of accuracy. The primary variable observed, therefore, is the round trip travel time between the spacecraft and the sea surface. The sensor emits a traveling pulse straight down (it looks at nadir) and then looks for the return pulse. Altimeters have orbited on three spacecraft: Skylab, GEOS-3, and SEASAT-1. The vertical resolution of the instruments went from approximately one meter for Skylab to 30 cm for GEOS-3 and 10 cm for SEASAT-1. These resolutions were those obtained by averaging all returned pulses for one second (between 10 and 100 pulses) and correcting for atmospheric effects.

The radar altimeter has also been used quite successfully to determine sea state. This is done by comparing the shape of the returned pulse with that of the emitted pulse.

Scatterometer. Oceanographic applications of the scatterometer have been primarily directed toward the measurement of wind-induced surface stress. This instrument responds to the intensity of reflected radiation at moderately large angles, 10° to 80°. The instrument is active and uses ranging, round trip travel time, to locate the reflected pulse spatially. In order to obtain directional information regarding wind stress, two antennae were used on SEASAT-1 to view the same location from different angles. One beam was emitted 45° from the forward direction and the second 45° from the aft direction. As the satellite advanced, the area covered by the aft-looking beam would cross whatever had been observed by the forward-looking beam. By this method, the direction of the wind stress was determined to point within 20° of one of four directions. In some cases, the directional ambiguity was partially resolved, the stress being determined to lie within 20° of one of two directions.

The electromagnetic pulses emitted by the spacecraft have wavelengths on the order of 3 cm. At this wavelength, capillary waves act as Bragg scatterers, hence the ability to measure wind stress, magnitude and direction. In order to meet the resolution requirements specified for wind stress, the area over which the reflected pulse must be averaged is large since capillary waves are weak scatterers. The scatterometer uses ranging to divide the region viewed into a number of large cells with length scales on the order of 50 km.

Scanning Microwave Radiometer. A number of scanning microwave radiometers have been orbited in recent years on various satellites; primarily, the SMMR on NIMBUS-7 and SEASAT-1, ESMR on NIMBUS-5 and NIMBUS-6, and SCAMS on NIMBUS-6. Two different techniques are used to scan the beam. The beam of electrically scanned radiometers (ESMR) is steered electrically using a phased array. There are no moving parts and the angle of the antenna is stepped across a scan line in discrete intervals. The second technique is to rotate a reflector in front of the antenna in much the same fashion as the visible/IR multispectral scanners described earlier. The primary difference is that the reflector is a metal sheet rather than a mirror. The SMMR reflector is rotated continuously, while the SCAMS reflector is rotated in discrete steps similar to the VISSR on GOES. In all cases, the scan direction provides spatial information normal to the satellite's suborbital track. All of these devices measure two polarizations as well as radiance in a number of channels.

Because the emitted terrestrial radiance or reflected solar radiance is many orders of magnitude lower at microwave frequencies than in the visible or thermal, the sensors must again average over a much larger area. This constraint is also imposed by the size and shape requirements for microwave antennae. For these reasons, the scanning microwave radiometers are included here as nonimaging devices all having resolutions coarser than 25 kilometers.

Imaging Microwave Sensors

Synthetic Aperature Radar. The only microwave imaging sensor orbited to date is the Synthetic Aperature Radar, or SAR, on SEASAT-1. The SAR is an active side-looking device which makes use of both ranging and doppler information to construct an image of the surface with a resolution on the order of 25 meters.

The term "synthetic" refers to the fact that the motion of the spacecraft allows the sensor to "synthesize" the signal normally seen with a much larger antenna system. This is accomplished by making use of all the information available from each target to generate the image. The radar emits many pulses each second, each pulse illuminating a fairly large area. Thus, each element of the sea surface is illuminated by the radar and reflects energy back to the spacecraft a number of times as the spacecraft passes. These multiple views of each target may be used to resolve features not visible to the radar using just ranging and doppler information.

CHAPTER 3. SATELLITE OVERVIEW

HISTORICAL PERSPECTIVE

In April 1960, only three and a half years after the first man-made satellite orbited the Earth, the United States began its environmental satellite program with the launch of TIROS-I (Television and Infrared Observation Satellite), the first in a series of ten satellites launched for the purpose of meteorological research. The TIROS satellites follow a near polar orbit. Such an orbit is generally circular, carrying the satellite to within ten degrees or so of the poles and allowing coverage of almost all the Earth. These orbits are further constrained in that the satellite passes overhead at approximately the same local sun time everywhere on the surface of the Earth. Such orbits are called sun-synchronous. The objective of the TIROS series was to determine through experimentation an acceptable configuration for a United States operational series of meteorological satellites. This task involved experimentation with the spacecraft, its sensors, and the satellite-to-ground communications link (called the "downlink").

TIROS-X, although included in most historical descriptions as the last research satellite in the TIROS series, actually served as the prototype for the first generation of operational, polar-orbiting, meteorological satellites referred to as ESSA.* This series was inaugurated in February 1966 with the launch of ESSA-1. The ESSA series consisted of two satellites which collected data simultaneously. The odd-numbered satellites stored data which was then sent to the Wallops Island, Virginia, and the Fairbanks, Alaska, Command and Data Acquisition stations. The even-numbered satellites relayed the received data directly to ground via the Automatic Picture Transmission capability. The second ESSA satellite was launched in late February of 1966, and the last in the series, ESSA-9, was launched in February 1969. See Figure 3 for a chronological arrangement of United States meteorological satellites. It is of interest to note that ESSA-3, launched in October 1966, was also called TOS-1 (TIROS Operational Satellite or System). This alias is used interchangeably with the remainder of the ESSA series, ESSA-9 being TOS-7.

The NIMBUS ("cloud" in Latin) series, designed to carry on the research and development (R&D) function for the polar-orbiting, meteorological satellites, was initiated with the launch of NIMBUS-1 in August 1964. (Note the overlap with the last R&D TIROS satellite.) In addition to the development and flight testing of advanced meteorological sensors, NIMBUS also played a research role in the exploration of natu-

* From TIROS-X on, the prototype for each generation of operational, polar-orbiting, meteorological satellites has been called TIROS--TIROS-M for the second generation and TIROS-N for the third generation.

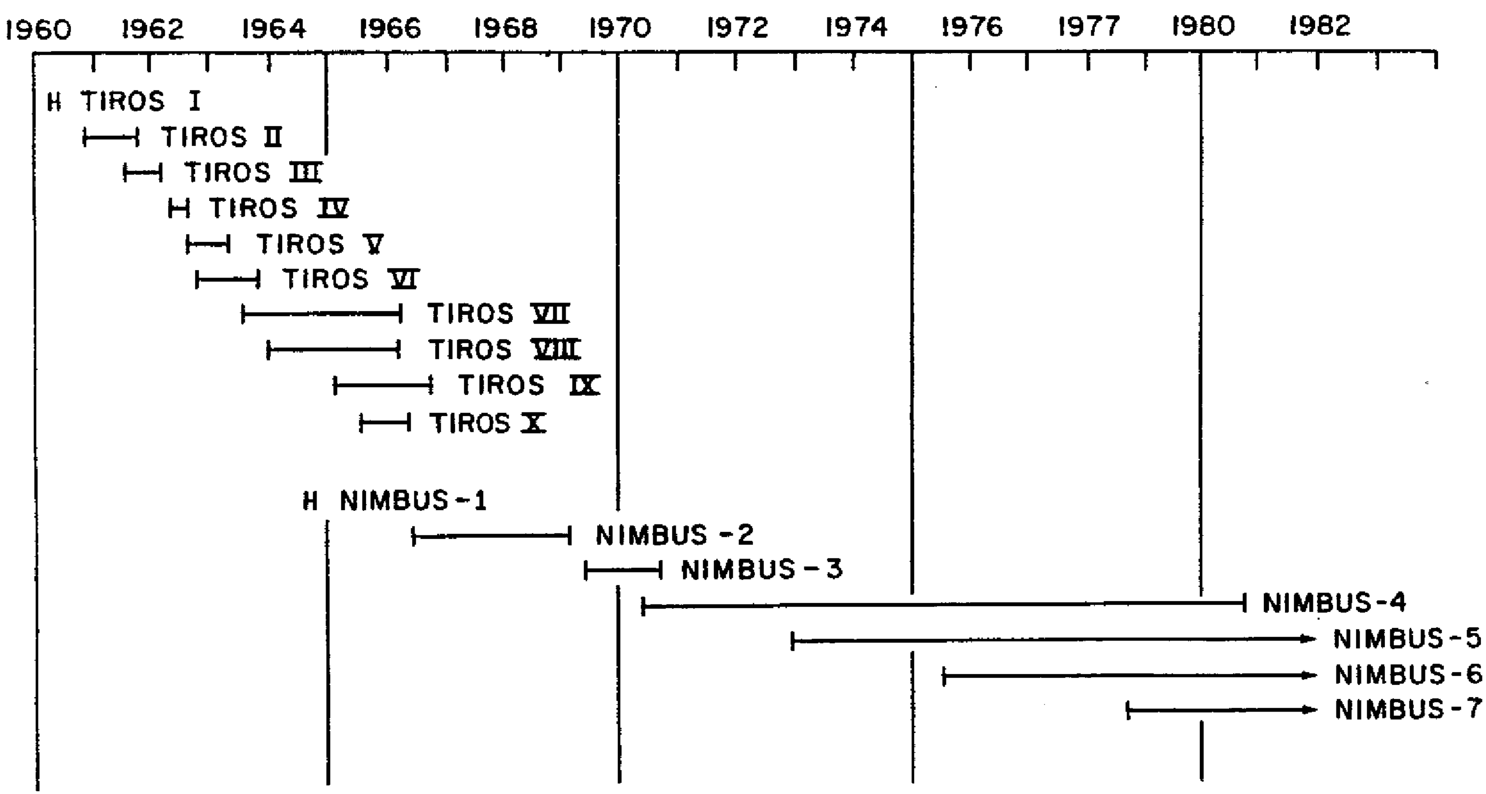
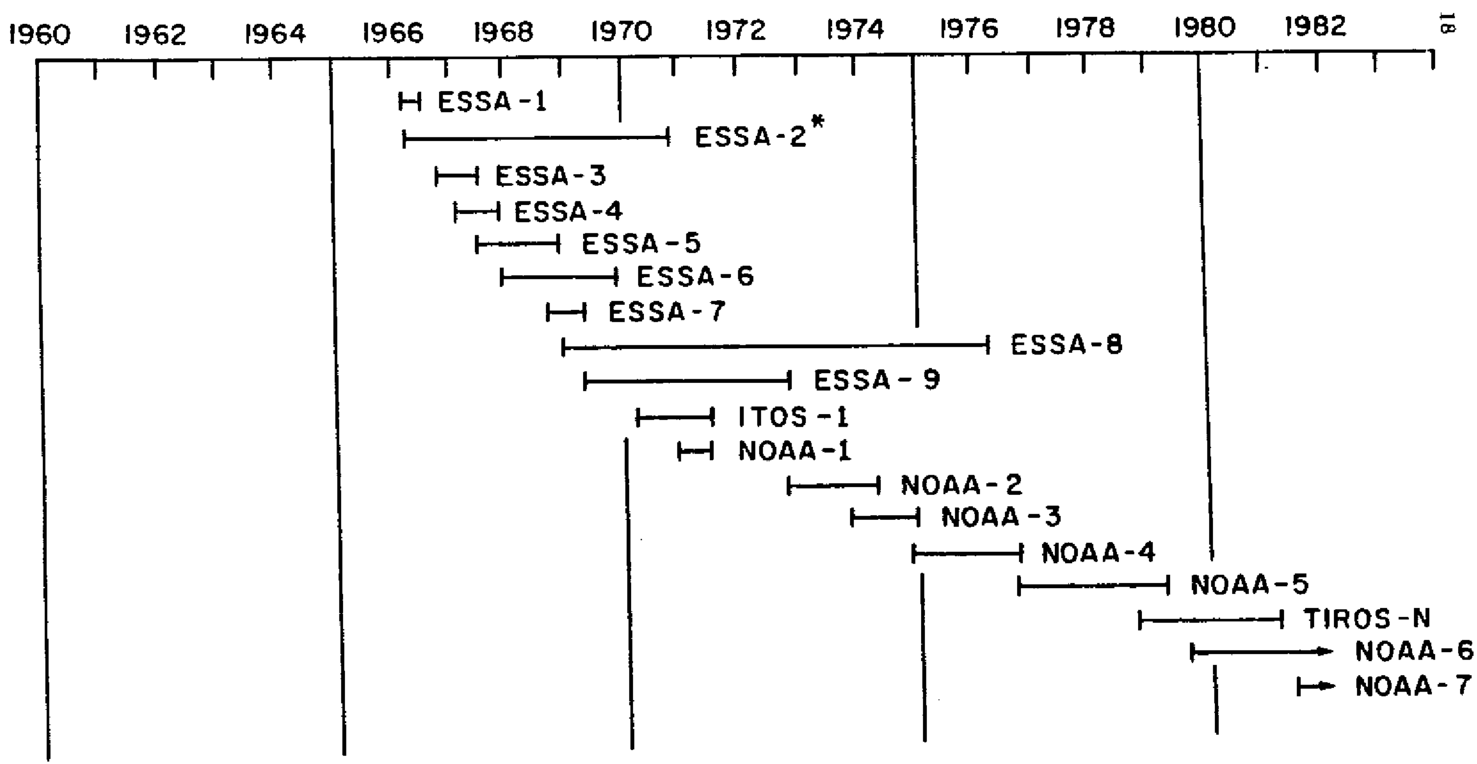


Figure 3a. Research Polar Orbiting Meteorological Satellites



*The ending date for odd numbered ESSA satellites corresponds to the date the satellite ceased operation. The ending date for the other satellites corresponds to the last day for which data exists in the NOAA archive.

Figure 3b. Operational Polar Orbiting Meteorological Satellites

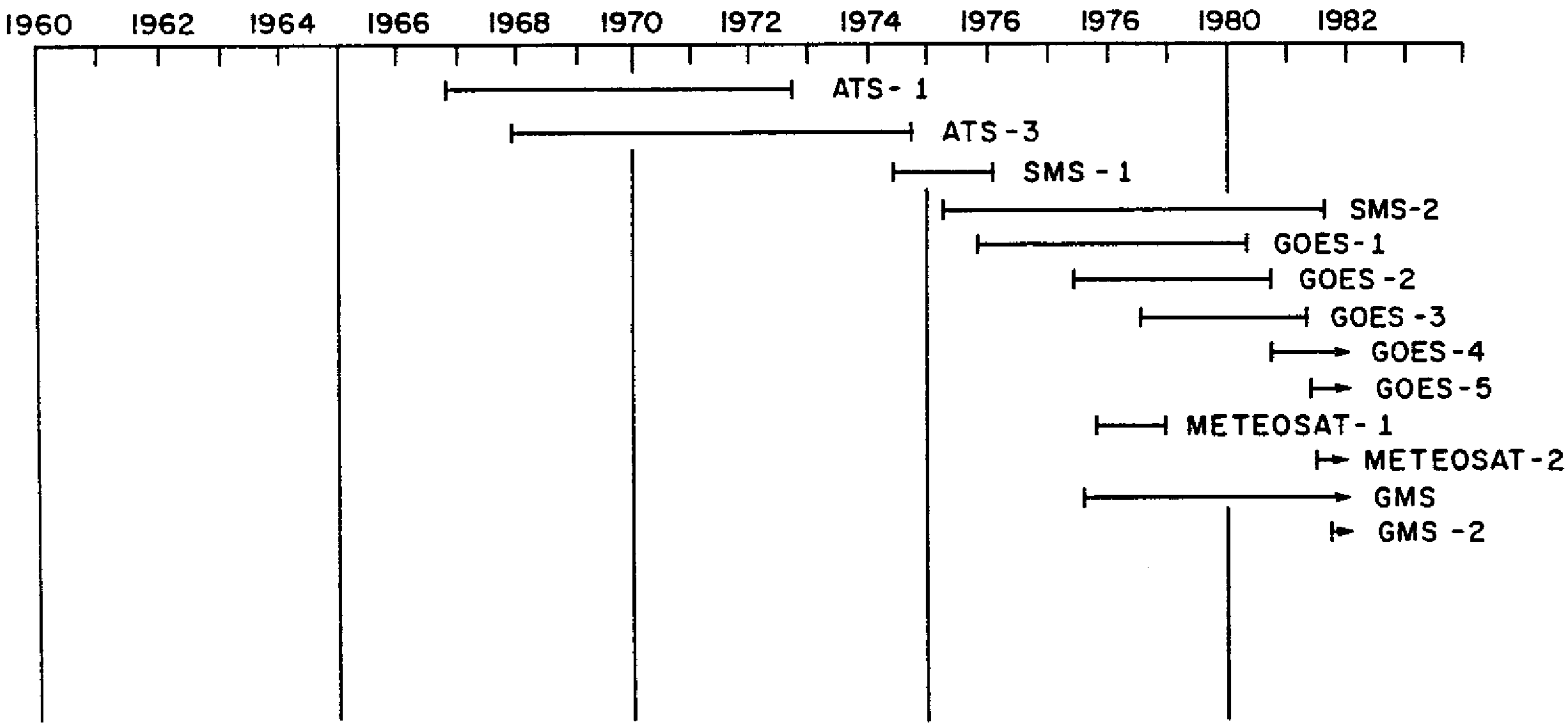


Figure 3c. Research and Operational Geosynchronous Meteorological Satellites

ral resources and geophysical phenomena. This necessitated sensors capable of detecting various forms of air pollution, providing data on various oceanographic variables, etc. In particular, some of the more recent NIMBUS satellites have been equipped with sensors dedicated to oceanographic studies. The last satellite in the series (NIMBUS-7) was launched in October 1978, and was still performing reliably at the time of this writing.

Advances made early in the NIMBUS program were incorporated on TIROS-M (launched in January 1970), the prototype for the second generation of polar-orbiting, meteorological series. TIROS-M was also known as ITOS-1, the Improved Tiros Operational Satellite. The first operational satellite in this series was designated NOAA-1 and launched in December 1970. This series included high resolution thermal IR sensors as well as visible sensors. The last satellite in this series, NOAA-5, was launched in July 1976.

TIROS-N, the prototype of the third generation, was launched in October 1978, and the first operational satellite in the third generation, NOAA-6, was orbited in June 1979. NOAA-6 was operational and providing useful oceanographic data at the writing of this report, TIROS-N having failed in the fall of 1980. NOAA-7 was launched in June 1981.

Parallel to the development of the polar-orbiting series, two other series also evolved. One of these, the Defense Meteorological Satellite Program (DMSP), developed by the military, is polar-orbiting and collects much the same data as the NOAA satellites. The early development of the system was secret, hence little information is available from this period. The Air Force announced the existence of the series in February 1973, at which time DMSP data was made available to the public. Since the public announcement of the series, the early Block 5B/C satellites have been replaced with a newer generation called the Block 5D.

The other meteorological satellite series developed parallel to TIROS/ESSA/NIMBUS/NOAA was ATS/SMS/GOES. These satellites fly in a geosynchronous orbit rather than a polar orbit. A geosynchronous satellite orbits the Earth about the equator, one revolution taking 24 hours. In this fashion, the satellite will remain above the same point on the equator at all times. The advantage of such an orbit is that continuous coverage of an area is provided. However, the resolution is coarse, since a geosynchronous orbit requires the satellite to be much higher than the polar orbiters, 35,000 km as opposed to 1,000 km. Also, the satellites cannot monitor the poles because they are always over the equator; and they see only one section of the Earth. In order to capitalize on the advantages of both systems, the United States decided to deploy an operational geosynchronous series in addition to the polar-orbiting series.

The Applications Technology Satellites (ATS), first launched in December 1966, served as the R&D series for the geosynchronous system, although this was not their primary mission. A number of spacecraft and sensor experiments were carried out on the early ATS satellites. SMS-1 (Synchronous Meteorological Satellites), the prototype of the operational geosynchronous meteorological series, was launched in May 1974. The third satellite in the series, SMS-C, was renamed GOES-1 (Geosynchronous Operational Environmental Satellite), and launched in October 1975. Two geosynchronous satellites are needed to cover the United States; hence GOES-2 was also launched. In addition to the GOES satellites, the Europeans have orbited a similar satellite, called METEOSAT, and the Japanese have one called GMS Geosynchronous Meteorological Satellite. These two satellites cover those sections of the Earth of interest to the associated countries.

Following the early success of the meteorological satellites, as well as the promising results of numerous airborne missions, the United States embarked on its land-oriented satellite research program in July 1972. The first satellite in the series, ERTS-1 (Earth Resources Technology Satellite), carried two sensors spanning the visible and near infrared portion of the spectrum. The primary sensor was the Return Beam Vidicon (RBV) camera, actually a set of three television cameras sensing in the green, red, and near infrared. The secondary sensor was the multispectral scanner (MSS), an electro-optical sensor sensitive to radiation in four spectral bands. Shortly after the launch of ERTS-1, the RBV failed, and although it was included on ERTS-2, the second satellite in the series, it never saw much use. The MSS, however, included on ERTS-1 "at the last minute," has provided exceptional ground-cover data, and although ERTS was conceived as an R&D series, data dissemination as well as sensor continuity has been treated in an operational fashion. In 1975, after the launch of ERTS-2, the satellites were renamed LANDSAT-1 and 2. Since then LANDSAT-3 has been launched, with an improved RBV system and a thermal infrared channel on the MSS. A LANDSAT-D and D2 are planned for launch in the near future.

A second research satellite (manned in this case), from which a number of ground cover, oceanographic and meteorological experiments were carried out, was SKYLAB, launched in May 1973. Many of the experiments carried out on SKYLAB laid the groundwork for sensors launched on later satellites. For example, the results of the radar altimeter experiment were utilized in the design of the GEOS-3 (Geodetic Experimental Oceanographic Satellite) satellite (April 1975), whose primary sensor was a radar altimeter. GEOS-3 is included in most summaries as an oceanographic satellite because the radar altimeter, its primary instrument, collected data only over the oceans, providing data such as ocean topography and significant wave heights. There were two other satellites in the GEOS series, but their sensors provided data of little interest to oceanographic phenomena and will not be discussed here.

The last satellite launched to date with oceanographic data collection as its primary mission was SEASAT-1. Most of its sensors became operational on June 27, 1978, but after 99 days (October 10, 1978) of near flawless operation a major power failure incapacitated the spacecraft, terminating all data collection. There was to be a SEASAT-2, but this project was dropped in favor of the proposed NOSS (National Oceanic Satellite System), which was scheduled for a 1986 launch. In the interim, no other civilian United States oceanographic satellites are planned. NOSS now also appears to have been dropped.

The only other satellite with potential application to remote sensing of the oceans that will be discussed is HCMM (Heat Capacity Mapping Mission), launched in April 1978. The mission of HCMM was to provide comprehensive, accurate, high-spatial-resolution thermal surveys of the Earth's surface. The objective of these measurements was to determine, from the observed thermal differences between day and night, the thermal inertia of the ground and thereby the geological structure. High-resolution thermal imagery is, however, also of interest in oceanographic studies.

SATELLITE CLASSIFICATION SCHEMES

Satellites can be classified in a variety of ways. An outline is therefore presented of some of the attributes of a satellite or satellite system that might be used for classification. Probably the most important is the satellite mission.

Application Areas--Satellite Mission

To date, satellites have been launched by the United States to address meteorological questions, observe the oceans, classify geological structures, determine the shape of the globe, and classify land cover, particularly agricultural cover. Future satellites are planned which will allow surface mapping, topographic feature extraction, ice cover analysis, and magnetic field strength determination. There also exist a variety of satellites with planetary, solar, and other astronomical missions; military satellites with classified missions; communications satellites; and navigational satellites. These, however, will not be discussed here as they do not fall within the group of environmental satellites and have no utility in remote sensing of the oceans.

For simplicity, we reduce the various application areas outlined above to the following three categories: meteorological (weather), oceanographic, and terrestrial (land-oriented). Although our primary area of interest is the ocean, data from satellites in all three application groups have proven useful in oceanographic research.

Operational Mode

The second characteristic of a satellite or satellite system that can be used to classify it is its mode of operation. There exist in general three modes, although the distinction between them is sometimes nebulous. These operational modes are:

a. Research. The satellite is launched to study sensor characteristics, orbit alternatives, etc., and there is no guarantee that in the future the nation will support a similar satellite. Civilian research satellites are launched and operated by the National Atmospheric and Space Administration (NASA).

b. Prototype. This designation is used for the first satellite in a series of operational satellites. The satellite (civilian) is launched and operated at first by NASA. Control is eventually turned over to the National Oceanic and Atmospheric Administration (NOAA).

c. Operational. Such satellites come in series. The civilian ones are launched by NASA and operated by NOAA. In general, the country has made a commitment that the series as well as subsequent series will continue the observation program for a number of years into the future.

The word "civilian" has been used a number of times. These satellites are to be compared with a series of meteorological satellites, launched and operated by the military, the data of which is in the public domain. There is no commitment on the part of the military to supply meteorological data to the public in the future. Indeed, the military reserves the right to restrict their satellites to military use at any time. This military/nonmilitary dichotomy indicates another manner in which satellites may be categorized. This categorization will not be used here.

Satellite Orbit

The last characteristic to be considered is the satellite's orbit. It is convenient to consider three different types of orbits:

a. Sun-synchronous (sometimes called polar-orbiting). The local sun time at the nadir point (the point directly beneath the satellite), on the sunlit side of the Earth, is approximately the same independent of latitude. Such orbits are important when reflected solar radiation dominates the observed radiance and of little consequence if the satellite's sensors are active, providing their own source of radiation. Such orbits are about 1,000 km above the Earth's surface.

b. Geostationary (Geosynchronous). These satellites orbit the equator at the rate at which the Earth rotates; hence, they always remain over the same point on the equator. These orbits are useful where repeat coverage at short time intervals is desired and spatial resolution is not as important. Their orbits are about 36,000 km above the Earth's surface.

c. General. This defines all possible orbits. Cases a and b above are special cases of the general or nonspecific orbit but are separated here because of their importance. The general orbit shall be used to define all orbits that are neither sun-synchronous nor geostationary.

In Table 3, existing satellite systems are categorized using the various categories outlined above. Across the top of the table is the mode of operation--research, prototype, and operational--while the columns are divided into application areas. Each application area is further subdivided by orbit where applicable.

Some peculiarities are evident in Table 3. NIMBUS appears in both the meteorology and oceanography application areas. The NIMBUS series was originally conceived as the research series for sun-synchronous, meteorological applications. Recently, however, the NIMBUS platform has been used to test sensors --e.g., the Coastal Zone Color Scanner (CZCS)--which have oceanographic applications.

A second point of confusion is the designation of TIROS as the prototype for the sun-synchronous meteorological satellites. This is only true for the more recent TIROS satellites. For example, TIROS-N is the prototype for the third generation, meteorological, polar-orbiting satellites. The confusion arises from the fact that the early TIROS satellites (from TIROS-I launched in 1960 to TIROS-X launched in 1965) served as research satellites, while the later ones are prototypes.

The designations of the various series of sun-synchronous, meteorological satellites can also be confusing. For example, the third satellite in the ESSA series was also named TOS-A (TIROS Operational Satellite). TIROS-M, the prototype of the second-generation, sun-synchronous series, is also known as ITOS-1 (Improved TIROS Operational Satellite). The number of aliases associated with a series often leads the casual observer to the conclusion that there are many more satellites than in fact exist. A final point to note here is that a satellite in a series generally has a letter designation prior to launch. If the launch is successful, the letter is converted to a number. For example, prior to launch, SEASAT-1 was referred to as SEASAT-A; after the launch its name was changed to SEASAT-1. This procedure, however, is not followed for the TIROS prototypes. TIROS-N remains TIROS-N. To add to the confusion, the first operational satellite in the third generation was designated NOAA-A prior to launch and NOAA-6 after launch. Because NOAA-B failed at launch, NOAA-C became NOAA-7.

There are several points concerning LANDSAT worth noting. First, the name of the series, originally ERTS, was changed to LANDSAT in 1975; hence, documents written prior to 1975 often use the acronym ERTS. Second, LANDSAT is included in both the research and operational categories. Although it has been quasi-operational for a number of years, it was not until late 1979 that control was transferred from NASA to NOAA, along with a long-term federal commitment to maintain such a satellite system. It is in this sense that it is included as an operational series.

TABLE 3. ENVIRONMENTAL SATELLITES OF THE UNITED STATES

APPLICATION AREA	ORBIT TYPE	RESEARCH	PROTOTYPE	OPERATIONAL
METEOROLOGY	SUN SYNCHRONOUS	TIROS I-X, NIMBUS	TIROS	ESSA, NOAA, DMSP
	GEO SYNCHRONOUS	ATS		SMS/GOES
	NON SPECIFIC			
LANDUSE	SUN SYNCHRONOUS	LANDSAT, HCMM		LANDSAT
	GEO SYNCHRONOUS			
	NON SPECIFIC			
OCEANOGRAPHIC	SUN SYNCHRONOUS	NIMBUS-7		
	GEO SYNCHRONOUS			
	NON SPECIFIC	SEASAT-1, GEOS-3		

TABLE 4. SATELLITES WITH SENSORS APPLICABLE TO COASTAL AND OCEANOGRAPHIC PROBLEMS

Satellite	Application Area	Mode	Thermal IR	No. of Bands Visible Near IR	Altimeter	Data Collection System (DCS)
NIMBUS	Meteorology/ Oceanography	Research	X	5		
ITOS/NOAA	Meteorology	Operational	X	1		
TIROS-N	Meteorology	Prototype	X			X
DMSP	Meteorology	Operational	X	1		
SMS/GOES	Meteorology	Operational	X	1		X
GEOS-3	Oceanographic	Research			X	
SEASAT	Oceanographic	Research	X	1	X	
HCMM	Earth Resources	Research	X	1		X
LANDSAT	Earth Resources	Research/ Operational	X	4		X

TABLE 5. ORBITAL CHARACTERISTICS OF OPERATIONAL AND EXPERIMENTAL SATELLITES

Satellite	Application Area	Mode	Altitude (km)	Inclination	Period (min)	Orbit Type
NIMBUS	Meteorology/ Oceanography	Research	955	99.0°	104.1	Sun Sync
ITOS/NOAA	Meteorology	Operational	1470	101.9°	115.0	Sun Sync
TIROS-N	Meteorology	Prototype	833	98.7°	101.5	Sun Sync
DMSP	Meteorology	Operational	837	98.8°	101.6	Sun Sync
SMS/GOES	Meteorology	Operational	35790	1.0°	1436.0	Geostationary
GEOS-3	Oceanographic	Research	845	115.0°	101.8	General
SEASAT	Oceanographic	Research	755	108.0°	100.2	General
HCMM	Earth Resources	Research	620	97.8°	96.8	Sun Sync
LANDSAT	Earth Resources	Research/ Operational	910	99.1°	103.2	Sun Sync