Reprinted from

Eleventh International Symposium

Machine Processing of

Remotely Sensed Data

with special emphasis on

Quantifying Global Process: Models, Sensor Systems, and Analytical Methods

June 25 - 27, 1985

Proceedings

Purdue University
The Laboratory for Applications of Remote Sensing
West Lafayette, Indiana 47907 USA

THE EVOLUTION OF REMOTE SENSING SCIENCE AND APPLICATIONS

JOHN H. McELROY

National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
Department of Commerce
Washington, D.C.

ABSTRACT

The first twenty-five years of earth observations from space produced many new discoveries and led to the deployment of operational systems. These systems have contributed to the understanding of meteorology, oceanography, the land sciences and applications, and the Earth's solar-terrestrial environment. The next twenty-five years will see these functions continue and expand, but with an accelerating trend toward the use of common observational platforms. The trend will be most obvious in the merger of meteorological and oceanographic observation systems. Contributing to and assisting that trend will be the Polar Platform of NASA's Space Station program. It will bring enhanced capacity, flexibility, and cost-effectiveness to earth observations.

I. INTRODUCTION

Man has observed the earth from space for more than twenty-five years. Meteorology, oceanography, the land sciences, and the study of the solar-terrestrial environment have all received great benefit from these observations.

Initially, the disciplines proceeded separately, with satellites being flown that specialized in each area. Weather satellites were distinct from those studying the radiation environment in the near-earth region of space, which were in turn distinct from those that directed their attention to the oceans or the land.

The separation of the missions did not last very long. The weather satellites soon became the natural home for space radiation sensors, and an imaging device originally intended for meteorological and hydrological applications was also found to have great utility for oceanography. More recently, the same imaging device has been found to have value in mapping the dynamics of vegetation over large scales and at moderate resolution.

Similarly, land satellites were found to have value in estuarine and other marine applications, and this led to a multispectral sensing capability that permitted analysis of the biological productivity of the oceans and the examination of mesoscale ocean dynamics.

One of the factors that led to the separation of the earlier missions was the limited capacity of the satellites. Having a capability to carry only a few instruments made it natural to focus them on a single or narrow set of disciplines. Also, the principal investigator approach that was so successful in early space research also led to missions that were largely dedicated to a particular group of investigations.

Another factor was the manner in which missions were approved--usually through a budget initiative carried out under the auspices of a single office structured around a few disciplines. Finally, many of the early missions were essentially exploratory, with little thought being given to permanent ongoing observations or synergistic and correlative measurements that might be made in related disciplines.

All of the above considerations are changing. The global synoptic measurements made possible by satellites are giving rise to a new way of studying earth dynamics that has been given impetus by the comparatively recent concern that man is the principal agent of change in the earth environment and that those changes may be detrimental. New programs are now being proposed under such titles as "Global Habitability"

(Malone, 1984) and "Global Change" (Friedman, 1983) that focus on the total system dynamics of the earth and the interactions among its constituent parts and cycles (e.g., the carbon cycle, the hydrologic cycle, etc.).

The multidisciplinary nature of most earth observation systems is now well understood and accepted, notably in the areas of meteorology and oceanography. Even more importantly, the technical constraints that separated disciplines in the past are being removed. Space systems are becoming more capable, and NASA's Space Station Program, notably the Polar Platform of that program, will add even more capability, capacity, and reliability (McElroy and Schneider, 1984).

This paper traces the evolution of spaceborne earth observation systems and attempts to demonstrate what the author believes to be very evident trends. It then connects these trends to the Space Station Program and shows that the program not only supports the trends but will make an extremely substantive contribution to the field of earth observations.

II. SATELLITE METEOROLOGY

On April 1, 1960, the first weather satellite was launched, TIROS-I. This has been followed by a long series of polar-orbiting weather satellites launched by the U.S.S.R. and the United States. They were later joined by geostationary weather satellites from the United States, Europe, Japan, and India. On a daily, routine basis the entire world's weather patterns are monitored.

The ring of geostationary weather satellites provided by the international community will continue into the future, with relatively modest upgrades--aimed principally at improving longevity. The U.S. satellites will continue to advance the techniques of atmospheric sounding from geostationary altitude, and this function will be made independent of the multispectral imaging operations (Epstein, et al., 1984). The other nations' satellites will include only the imaging function through at least the mid-1990's. This near-global data set (global except for the high latitudes) will be a vital element in the study of earth dynamics.

The polar-orbiting meteorological satellites complete the global picture. But, in addition to studying the higher latitudes that are inaccessible to the geostationary satellites, they also perform other measurements that would be infeasible from the higher altitude.

The current Advanced TIROS-N (ATN) satellites carry the multispectral imaging radiometer mentioned above and a three-element atmospheric sounder. These two functions are permanent passengers for any future environmental satellite, even though the technological means to satisfy the requirements will change with time.

The present multispectral imaging radiometer provides nominally 1-km spatial resolution simultaneously in five spectral bands. Later in the 1980's, one of those bands will be day-night time-shared so that six-band coverage is provided without increase in data rate or processing needs (Epstein, et al., 1984). The sensor will continue to be used for meteorological, hydrological, land, and oceanographic applications. It is likely to evolve modestly to using a somewhat increased number of bands and, perhaps, slightly greater spatial resolution, but the basic instrument capability will remain the same. Because of the globally distributed user community, a direct readout capability must be provided from this instrument at both full and reduced spatial resolution. This is analogous to the current Automatic Picture Transmission (APT) and High Resolution Picture Transmission (HRPT) system on the ATN.

The three-element atmospheric sounder on the ATN consists of infrared, microwave, and stratospheric elements. The microwave and stratospheric subsystems will be replaced in the late 1980's by an advanced microwave sounding unit (AMSU) that will be developed jointly by the United Kingdom and the United States. This will provide greatly enhanced all-weather sounding capability and expand the number of soundings that are available for the numerical forecasting models. As with the imaging system, direct readout capability must be provided to the global user community. The present ATN satellites have the Direct Sounder Broadcast (DSB) capability that will be retained indefinitely in future systems.

The afternoon ATN satellite also carries a solar backscatter ultraviolet instrument to provide a global map of ozone and a precision radiometric instrument to examine the earth's radiation budget.

In addition to the imaging, sounding, and other instruments, the ATN satellites carry two subsystems that receive signals from low-cost ground terminals. One of these subsystems, the ARGOS data collection and platform location system, receives low-power transmissions of environmental data and calculates the position of the transmission. The second receives the emergency signals from crashed aircraft and ships in distress. Both the ARGOS and search and rescue systems require direct readout capability.

From the above discussion, it is evident that the meteorological satellites have gradually evolved into multidisciplinary satellite platforms carrying instruments with utility far beyond the bounds of meteorology. In addition to providing a three-dimensional view of the atmospheric temperature and water vapor, the satellites supply two-dimensional views of ocean currents, snow cover, ice floes, and the land. Their view of clouds is also, in many respects, two-dimensional as well, because the vertical distribution of the clouds cannot be extracted with precision from the satellite images. Finally, the data from the satellites are also essential to the understanding of the changes that may be occurring in the earth's climate and in the ozone layer.

It is important to note that the above measurements and capabilities are permanent requirements. Although they will evolve with time, they represent a core set of measurements around which a permanent observational capability can be built and, indeed, justified.

Table 1 summarizes the permanent observational requirements and services derived from the current meteorological satellites. It can be seen that six measurement classes are defined (that may involve more than one instrument per class). Four of the six require direct readout capability from the space system, which in turn suggests some degree of onboard processing or at least formatting of the sensor data.

Table 1. Permanent Observational Requirements and Services Derived from Meteorological Satellites

Moderate-Resolution Multispectral Imaging with Direct Readout Capability at Full and Reduced Spatial Resolution

Global, All-Weather, Atmospheric Soundings with Direct Readout Capability

Global Ozone Mapping

Earth Radiation Budget Monitoring

Table 1. Continued.

Environmental Data Collection and Platform Location System with Direct Readout Capability

Search and Rescue Transponder with Direct Readout Capability

III. SATELLITE OCEANOGRAPHY

Enhanced knowledge of the oceans is required from four perspectives: (1) the increasingly sophisticated operations of the maritime community require commensurate increases in environmental data and forecasts, (2) weather forecasting models require an improved characterization of the boundary between the oceans and the atmosphere, (3) the oceans play an inadequately defined role in climate change, and (4) the oceans represent an essential source of food--man's ability to seek it efficiently and harvest it responsibly is controlled by his knowledge of the sea and its dynamics. In each category defining a requirement for enhanced ocean knowledge, there are both research and applications/operational objectives.

The heritage of GEOS-3, Seasat, and Nimbus-7 has demonstrated incontrovertibly that satellite observations can provide accurate, global measurements of important marine parameters. It is no longer speculative to assert that surface winds and waves, significant wave height, sea surface temperature, and biological productivity can be determined to a useful precision by satellite-borne instruments (McElroy, 1985).

It is understandable that the recognition of the value of oceanic satellite observations has spread worldwide. The European Space Agency, Japan, and Canada have joined the United States in the development of major new ocean missions that will be orbited from 1985 through 1990 (Sherman and McElroy, 1985). Indeed, more than $1.0 billion will be invested in such systems over this period. By the beginning of the next decade, routine measurements of all significant ocean and sea ice parameters will be made on a daily, global basis.

The measurements required by the maritime community are based on currently available techniques and technology. In the next several paragraphs, the measurements and the missions from which they stem will be discussed.

Data fields or contour maps of the significant wave height are of great importance to many areas of marine operations. They play an important role in ship routing and in the alerting of ship or oil drilling platform operators of sea conditions that can endanger personnel and equipment or interrupt activities. The current data bases are sparse and inadequate, but upcoming satellite missions will begin to rectify this shortcoming. The Geosat satellite launched in 1985 carries a radar altimeter that will add many daily measurements of significant wave height. It will be followed by the European Space Agency's ERS-1 satellite and the Navy Remote Ocean Sensing Satellite (N-ROSS). This composite set of missions will produce global data sets that are updated on approximately a six-hour basis. Continuing the collection of such data in the 1990's will require the maintenance of at least two radar altimeters in orbit at all times, with appropriate orbital parameters to ensure adequate daily, global sampling.

In addition to significant wave height, the maritime community requires data on surface wind speed. To some extent, these data will be available from the radar altimeters, but a somewhat more precise sensor will also be available. Beginning in 1986, the Defense Meteorological Satellite Program (DMSP) will fly a sensor called the Special Sensor Microwave Imager (SSM/I). This sensor will measure surface wind speed with an accuracy of plus or minus 2 meters per second over a range from 3 to 25 meters per second.

The SSM/I will also have other capabilities as well, including an all-weather capability to measure sea-ice areal extent, edge location, and age. This sensor will continue to fly in the era of N-ROSS, leading to two being in orbit at any given time. The 1990's will see a requirement for this proven, well-understood sensor to be maintained on at least two space platforms until it is replaced by newer technology.

While wind speed is an important and useful quantity, it is a scalar quantity to which wind direction must be added for a full understanding of the marine environment. A radar scatterometer, such as will be flown on both ERS-1 and N-ROSS, provides the additional information. It provides surface wind direction with an accuracy of plus or minus 20 degrees over the full range of 360 degrees. A sufficiently frequent updating of marine models requires that two scatterometers be maintained in orbit simultaneously, as will be the case during the overlap of the ERS-1 and N-ROSS missions.

Another major ocean parameter that must be monitored is sea surface temperature. It delineates ocean fronts, currents, eddies (both warm and cold core), and upwellings. It provides data for ship routing and for the indirect identification of promising fishing areas. It can observe the large climatic events, such as the El Nino that produced so many disastrous effects in 1982 and 1983.

The present multispectral imaging radiometer mentioned above in the discussion on meteorology produces a multichannel sea surface temperature analysis that has good spatial resolution, but that is limited by cloud cover. Both ERS-1 and N-ROSS will deploy microwave systems to gain all-weather capability. The microwave radiometer that will be flown on N-ROSS is intended to provide 0.5 K temperature resolution and a 10 km spatial resolution. The continued flight of such instruments will complement the other instruments already listed above.

While sea surface temperature provides inferential information regarding likely areas for substantial fish catch, a special sensor that was flown on NASA's Nimbus-7 satellite provides more direct information through the measurement of plankton distribution. The Coastal Zone Color Scanner (CZCS) has demonstrated this capability. Somewhat more unexpectedly, it also demonstrated a powerful capability in following mesoscale ocean dynamics, where the plankton served as a "tracer." This capability, whether as an independent instrument or merged into another, will continue in the 1990's.

The final instrument in the ocean instrument suite is an ocean-related synthetic aperture radar (SEASAR). Based on the results of Seasat, and the expected results of Europe's ERS-1, Japan's JERS-1, and Canada's Radarsat, SEASAR's will find routine use in navigation of the polar ice regions and in providing all-weather high-resolution imaging of the oceans.

As in the instance of the meteorological measurements, the above discussion of satellite oceanography defines a set of permanent observational requirements. Table 2 summarizes the requirements that are derived from the past ocean missions and those that will be orbited in advance of the Space Station. It is also expected that a family of marine services will be defined for direct broadcast that will be analogous to the APT, HRPT, and DSB services mentioned under meteorology. This will produce a further need for some degree of on-board processing.

Table 2. Permanent Observational Requirements and Services Derived Oceanic Satellites

Moderate-Resolution Multichannel Infrared Sea Surface Temperature Imaging
Global, All-Weather, Coarse-Resolution Sea Surface Temperature Measurements
Radar Altimetric Measurements of Significant Wave Height
Coarse-Resolution Microwave Imaging for All-Weather Sea Ice, Wind Speed, and Precipitation Measurements
Radar Scatterometry for Surface Wind and Wave Speed and Direction
Multispectral Ocean Color Imaging for Plankton Mapping and Analysis of Mesoscale Ocean Dynamics
High-Resolution, All-Weather Imaging of the Oceans and Polar Regions
Direct Readout to Ships and Ocean Platforms of a Family of Marine Services

IV. LAND SCIENCES AND APPLICATIONS

The Landsat program has demonstrated the great capability of multispectral sensing systems to detect important geological features, to measure vegetation change, to observe hydrologically important parameters such as water reservoir acreage and the extent of floods, as well as many others.

Unfortunately, the program has been handicapped by the assertion by some that such information should be collected only if it is financially self-supporting--a condition that is difficult, if not impossible, to reach in any mapping function. Many maps are generated for many purposes, but their sales rarely if ever recover the full cost of their preparation. The Landsat products are simply another form of map product, a product whose value is realized through secondary, tertiary, and quaternary degree applications. Society as a whole benefits from increasing mankind's knowledge of the planet. The assessment of the value of that increasing knowledge is not necessarily measured by the number of Landsat scenes that can be sold to the public.

It is the author's belief that the realization will come eventually that a worthy part of the activities of any spacefaring nation will be the examination of the Planet Earth--irrespective of whether a profit-making business can be created from it. The heritage of Landsat and the related satellites will then be a valuable backdrop for the continuation of land observing systems. This is likely to stem from three measurement capabilities, each of which will be discussed briefly below.

The Thematic Mapper flown on Landsats 4 and 5 proved the value of 7-band multispectral sensing at a spatial resolution of 30 meters. Newer technology will gradually replace the mechanically scanned mirror of the Thematic Mapper with advanced detector technology termed the Multi-Linear Array (MLA). This will permit greater reliability, more spectral bands, and higher spatial resolution in the future. It will extend the current capability to a more operational status.

NASA is also advocating even more advanced technology in an instrument called the High-Resolution Imaging Spectrometer (HIRIS). The HIRIS uses simultaneous imaging in many contiguous bands to create a reflectance spectrometer that allows easier identification of observed surface materials. While it may eventually supplant the MLA, it appears likely that the two will coexist for some period of time.

The third sensor is the land-related synthetic aperture radar (GEOSAR) that will follow the Seasat-derived Shuttle Imaging Radars (SIR) of the 1980's. The GEOSAR will complement the multispectral imaging provided in the visible and infrared wavelengths by the MLA and HIRIS.

In addition to these dedicated sensors for land applications, the moderate resolution multispectral imaging sensor used for meteorology and oceanography will continue to play a vital role in rapid time-scale drought and vegetation assessments. The less frequent, but higher spatial resolution, data gained from the MLA and HIRIS will provide the core data base against which change detection will be carried out using the more frequent data from the meteorological sensor.

In the past, cooperative ventures with foreign countries have proven productive in which a local readout capability has been provided. This will be of continuing value in the future. Therefore, direct transmission of various data sets to worldwide ground stations will be an element of future earth observation systems.

Table 3. Permanent Observational Requirements and Services Derived from Land Satellites

High-Resolution (Spectral and Spatial) Multispectral (Infrared and Visible) Imaging with Direct Readout Capability
High-Resolution Synthetic Aperture Radar Imaging for Land Applications (GEOSAR)
Moderate Spatial Resolution, High Temporal Resolution Visible and Infrared Imaging for Vegetation Analysis

V. THE UPPER ATMOSPHERE AND SOLAR-TERRESTRIAL INTERACTIONS

The earlier section of this paper addressing meteorological applications stressed the dynamics of the troposphere. These dynamics are principally of a relatively short-term nature. Over longer time scales, other dynamical processes are also of interest. These include the variations in atmospheric constituents--e.g., carbon dioxide--that might contribute to a global warming. The processes also include man-induced changes in the earth's ozone layer (McElroy, 1985).

The variations in the earth's atmospheric constituents have been the subject of a number of highly successful missions. The experiments carried on the Nimbus series of satellites and the Solar Backscatter Ultraviolet experiment carried on the most recent ATN satellite are illustrative of successful past programs. The latter was mentioned in Section II above under satellite meteorology.

In the late 1980's, NASA's Upper Atmosphere Research Satellite will continue and dramatically extend these investigations. Nine principal instruments will measure the concentrations and temperatures of trace gas species from the stratosphere to the lower mesosphere and make many other measurements as well. These instruments will give rise to successor instruments that will conduct a continuing scientific evaluation of the earth's atmosphere and its variability. Among the successor instruments, there is likely to be a series of laser or lidar devices for active sensing of both constituents and atmospheric winds.

The highest reaches of the atmosphere are also affected by the various fluxes of energy that originate from the sun. These fluxes have both scientific and applied/operational interest. Geomagnetic storms produce disruptions in cable communication systems, electrical power grids, and oil pipelines. Solar events also perturb the ionosphere and affect long-distance communication. Such events can also pose a hazard to astronauts.

The operational weather satellites, both civil and defense, carry a full complement of instruments for operational monitoring of the solar-terrestrial environment. This complement includes sensors for x-rays, protons, electrons, and alpha particles. It also includes, on the geostationary weather satellites, a magnetometer. The package on the polar-orbiting satellites is called the Space Environment Monitor (SEM), and it, or its derivatives, will be a permanent observational requirement for the 1990's.

There are also major scientific questions associated with the solar fluxes and their interaction with the upper atmosphere. They have been investigated by such spacecraft as the Solar Maximum Mission and the Dynamics Explorer. As with all research programs, the past missions will raise further questions to be answered by future investigations (McElroy, 1985). This is an additional justification for a permanent observational capability.

Table 4 summarizes the permanent observational requirements that result from the review in this section. The global ozone measurement was included in Table 1 and is not repeated here.

Table 4. Permanent Observational Requirements and Services Derived from Upper Atmospheric and Solar-Terrestrial Investigations and Aplications

Advanced Space Environment Monitor for Operational Applications
Research Measurements of Atmospheric Trace Constituents and Their Dynamics
Research Measurements of Solar Fluxes and Their Interactions with the Earth
Lidar Instruments for Analysis of Atmospheric Constituents and Winds

VI. THE ROLE OF THE POLAR PLATFORM

The brief review above shows the breadth of the foundation underlying future earth observations missions. The understanding of research and operational needs and the capabilities of spaceborne sensors to meet those needs are rich and comprehensive. There is no technical impediment to continuing future activities in the mold of the past.

There is, however, a financial impediment that will, at least, place a constraint on the pace at which future missions can proceed. The next series of earth observations satellites is very complex and costly. If the pace of future earth observations is to match the intellectual and technological capabilities that are available today, the means must be found to afford the utilization of these capabilities.

As satellites become larger, more complex, and increasingly costly, the past practice of relying exclusively upon subsystem reliability in the absence of servicing and discarding entire spacecraft when key parts fail is less and less defensible. NASA's Space Station program contains as one of its elements a reserviceable platform in sun-synchronous, near-polar orbit. This platform, called simply the Polar Platform below, offers a potential solution to both continuing the technological growth of earth observations and affording it.

A variety of studies are under way to study the utility of the Polar Platform concept (Butler, 1984; McElroy and Schneider, 1985a). These studies show that scientific and operational payloads can be defined that will provide revolutionary new views of the total earth system and its dynamics. Further, one study has addressed the integration of research and applications missions, and shows the great synergism inherent in such an integration (McElroy and Schneider, 1985b).

The period from 1985 to 1988 will determine whether the Polar Platform can evolve in such a manner as to satisfy the economic and technical requirements of the earth observations community. It is the author's opinion that it can, and NOAA is prepared to place its operational meteorological sensors on the platform after the completion of the last of the current series of expendable satellites, NOAA-K through -M.

VII. INTERNATIONAL COOPERATION

Earth observations is inherently one of the most international of disciplines. Its subject matter is international; but, even more importantly, the understanding of remotely-sensed data requires in-situ data gathered from within the observed scene. International cooperation in the conduct of programs is, therefore, a natural element of earth observations activities. This is particularly evident in meteorology and oceanography.

Further, international capability in earth observations from space is growing rapidly, and many countries will be fully competent to participate in the development of space hardware by the early 1990's. It is, therefore, possible to combine the need for in-situ data, the growing international capability, and the broad international recognition of the value of remotely-sensed data to create a favorable climate for cooperative ventures.

The Polar Platform offers many opportunities for international cooperation. They extend from the provision of the Platform itself to the supplying of an instrument to fly on the Platform to the participation in data analysis and application on the ground. The European Space Agency has recognized the great potential value of the Polar Platform in earth observations and is conducting detailed studies as a part of its cooperative program with NASA on the Space Station.

It seems inevitable to the author that the future of earth observations from space is one of international cooperation. Countries will recognize the enhancements in capabilities and economies that can flow from cooperation; this will lend great impetus to a tendency that is already clearly evident in satellite-based meteorology.

VIII. DATA SYSTEMS

The greatest challenge for the future of earth observations lies not with sensor technology, platform construction or operation, or even international negotiations and cooperation. The greatest challenge lies with the accompanying data processing and distribution systems. If the discipline of earth observations is to attain its full potential, full attention must be paid to providing timely data to the user in a form that he or she desires. This applies equally well to both research and operational users. The long history of inadequate data systems must be brought to a close. Data system inflexibility and data backlogs are simply unacceptable for the now mature earth observations community.

Equally important is the issue of data dissemination. In many instances, those most in need of the data from a remote sensing system are those immediately beneath it. Routing the needed information away from the system over a series of transoceanic links and then back to the concerned area is neither cost-effective nor satisfactory from an applications perspective. Planners for earth observations systems must give up the concepts of single data pipelines through which all information must flow, e.g., via the Tracking and Data Relay Satellite, and accept the greater complexity and sophistication of the present world of earth observations.

IX. CONCLUSIONS

The 1990's will bring to life an earth observations capability of unparalleled capability. It will be multidisciplinary in form and international in character. The system will be based upon the Polar Platform of NASA's Space Station program, and it will utilize the economies associated with the Polar Platform to make the increasing capabilities affordable. The greatest challenges in the realization of this concept will be associated with the processing and dissemination of data to the research and operational communities. These are challenges that can and must be met. The appetite of the user community has been whetted with the pioneering missions of the first 25 years of earth observations; it is now time to satisfy that appetite.

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John H. McElroy is NOAA's Assistant Administrator for Environmental Satellite, Data, and Information Services. In that capacity he is responsible for the nation's civil operational earth observations satellites. McElroy came to NOAA in 1982 from NASA, where he had spent 16 years. His last position in NASA was Deputy Director of the Goddard Space Flight Center. He has a B.S.E.E. from the University of Texas at Austin and an M.E.E. and PhD from the Catholic University of America.