SATELLITE OCEANOGRAPHY, HISTORY AND INTRODUCTORY CONCEPTS

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> Oceanography from a satellite – the words themselves sound incongruous and, to a generation of scientists accustomed to Nansen bottles and reversing thermometers, the idea may seem absurd.
>
> Gifford C. Ewing, 1965

A Story of Two Communities

The history of oceanography from space is a story of the coming together of two communities – satellite remote sensing and traditional oceanography.

For over a century oceanographers have gone to sea in ships, learning how to sample beneath the surface, making detailed observations of the vertical distribution of properties. Giff Ewing noted that oceanographers had been forced to consider ‘the class of problems that derive from the vertical distribution of properties at stations widely separated in space and time.’

With the introduction of satellite remote sensing in the 1970s, traditional oceanographers were provided with a new tool to collect synoptic observations of conditions at or near the surface of the global ocean. Since that time, there has been dramatic progress; satellites are revolutionizing oceanography. (The Appendix to this article provides a brief overview of the principles of satellite remote sensing.)

Yet much remains to be done. Traditional subsurface observations and satellite-derived observations of the sea surface – collected as an integrated set of observations and combined with state-of-the-art models – have the potential to yield estimates of the three-dimensional, time-varying distribution of properties for the global ocean. Neither a satellite nor an *in situ* observing system can do this on its own. Furthermore, if such observations can be collected over the long term, they can provide oceanographers with an observational capability conceptually similar to that which meteorologists use on a daily basis to forecast atmospheric weather.

Our ability to understand and forecast oceanic variability, how the oceans and atmosphere interact, critically depends on an ability to observe the three-dimensional global oceans on a long-term basis. Indeed, the increasing recognition of the role of the ocean in weather and climate variability compels us to implement an integrated, operational satellite and in situ observing system for the ocean now – so that it may complement the system which already exists for the atmosphere.

The Early Era

The origins of satellite oceanography can be traced back to World War II – radar, photogrammetry, and the V-2 rocket. By the early 1960s a few scientists had recognized the possibility of deriving useful oceanic information from the existing aerial sensors. These included (1) the polar-orbiting meteorological satellites, especially in the 10–12-μm thermal infrared band, and (2) color photography taken by astronauts in the Mercury, Gemini, and Apollo manned spaceflight programs. Examples of the kinds of data obtained from NASA flights collected in the 1960s are shown in **Figures 1** and **2**.

Such early imagery held the promise of deriving interesting and useful oceanic information from space, and led to three important conferences on space oceanography during the same time period. In 1964, NASA sponsored a conference at the Woods Hole Oceanographic Institution (WHOI) to examine the possibilities of conducting scientific research from space. The report from the conference, entitled *Oceanography from Space* (Ewing, 1965), summarized findings to that time; it clearly helped to stimulate a number of NASA projects in ocean observations and in sensor development. Moreover, with the exception of the synthetic aperture radar, all instruments flown through the 1980s used techniques described in this report. Dr Ewing has since become justifiably regarded as the father of oceanography from space.

A second important step occurred in 1969 when the ‘Williamstown Conference’ was held at Williams College in Massachusetts. The ensuing report (Kaula, 1969) set forth the possibilities for a space-based geodesy mission to determine the equipotential figure of the Earth using a combination of (a) accurate tracking of satellites and (b) the precision measurement of satellite elevation above the sea surface using radar altimeters. Dr William Von Arx of WHOI realized the possibilities for determining

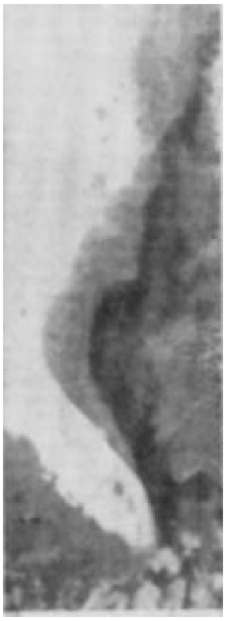

Figure 1 Thermal infrared image of the US south-east coast showing warmer waters of the Gulf Stream and cooler slope waters closer to shore taken in the early 1960s. While the resolution and accuracy of the TV on Tiros were not ideal, they were sufficient to convince oceanographers of the potential usefulness of infrared imagery. The AVHRR scanner (see text) has improved images considerably. (Figure courtesy of NASA.)

large-scale oceanic currents with precision altimeters in space. The requirements for measurement precision of 10 cm height error in the elevation of the sea surface with respect to the geoid was articulated. NASA scientists and engineers felt that such accuracy could be achieved in the long run, and the agency initiated the 'Earth and Ocean Physics Applications Program,' the first formal oceans-oriented program to be established within the organization. The required accuracy was not to be realized until 1992 with TOPEX/Poseidon, which was reached only over a 25-year period of incremental progress that saw the flights of five US altimetric satellites of steadily increasing capabilities: Skylab, Geos-3, Seasat, Geosat, and TOPEX/Poseidon. (See **Figure 3** for representative satellites.)

A third conference, focused on sea surface topography from space, was convened by the National Oceanic and Atmospheric Administration (NOAA), NASA, and the US Navy in Miami in 1972, with 'sea surface topography' being defined as undulations of the ocean surface with scales ranging from approximately 5000 km down to 1 cm. The conference identified several data requirements in oceanography that could be addressed with space-based radar and radiometers. These included determination of surface currents, Earth and ocean tides, the shape of the marine geoid, wind velocity, wave refraction patterns and spectra, and wave height. The conference established a broad scientific justification for space-based radar and microwave radiometers, and it helped to shape subsequent national programs in space oceanography.

The First Generation

Two first-generation ocean-viewing satellites, Skylab in 1973 and Geos-3 in 1975, had partially responded to concepts resulting from the first two of these conferences. Skylab carried not only several astronauts, but a series of sensors that included the S-193, a radar-altimeter/wind-scatterometer, a long-wavelength microwave radiometer, a visible/infrared scanner, and cameras. S-193, the so-called Rad/Scatt, was advanced by Drs Richard Moore and Willard Pierson. These scientists held that the scatterometer could return wind velocity measurements whose accuracy, density, and frequency would revolutionize marine meteorology. Later aircraft data gathered by NASA showed that there was merit to their assertions. Skylab's scatterometer was damaged during the opening of the solar cell panels and as a consequence, returned indeterminate results (except for passage over a hurricane), but the altimeter made observations of the geoid anomaly due to the Puerto Rico Trench.

Geos-3 was a small satellite carrying a dual-pulse radar altimeter whose mission was to improve the knowledge of the Earth's marine geoid, and coincidentally to determine the height of ocean waves via the broadening of the short transmitted radar pulse upon reflection from the rough sea surface. Before the end of its 4 year lifetime, Geos-3 was returning routine wave height measurements to the National Weather Service for inclusion in its Marine Waves Forecast. Altimetry from space had become a clear possibility, with practical uses of the sensor immediately forthcoming. The successes of Skylab and Geos-3 reinforced the case for a second generation of radar-bearing satellites to follow.

The meteorological satellite program also provided measurements of sea surface temperature using far-infrared sensors, such as the Visible and Infrared Scanning Radiometer (VISR), which operated at wavelengths near 10 μm, the portion of the terrestrial spectrum wherein thermal radiation at terrestrial temperatures is at its peak, and where coincidentally the atmosphere has a broad passband. The coarse, 5 km resolution of the VISR gave blurred temperature images of the sea, but the promise was clearly there. **Figure 1** is an early 1960s TV image of the south-eastern USA taken by the

Figure 2 Color photograph of the North Carolina barrier islands taken during the Apollo-Soyuz Mission (AS9-20-3128). Capes Hatteras and Lookout, shoals, sediment- and chlorophyll-bearing flows emanating from the coastal inlets are visible, and to the right, the blue waters of the Gulf Stream. Cloud streets developing offshore of the warm current suggest that a recent passage of a cold polar front has occurred, with elevated air–sea evaporative fluxes. Later instruments, such as the Coastal Zone Color Scanner (CZCS) on Nimbus-7 and the SeaWiFS imager have advanced the state of the art considerably. (Figure courtesy of NASA.)

NASA TIROS program, showing the Gulf Stream as a dark signal. While doubts were initially held by some oceanographers as to whether such data actually represented the Gulf Stream, nevertheless the repeatability of the phenomenon, the verisimilitude of the positions and temperatures with respect to conventional wisdom, and their own objective judgment finally convinced most workers of the validity of the data. Today, higher resolution, temperature-calibrated infrared imagery constitutes a valuable data source used frequently by ocean scientists around the world.

During the same period, spacecraft and aircraft programs taking ocean color imagery were delineating the possibilities and difficulties of determining sediment and chlorophyll concentrations remotely. **Figure 2** is a color photograph of the North Carolina barrier islands taken with a hand-held camera, with Cape Hatteras in the center. Shoals, sediment- and chlorophyll-bearing flows emanating from the coastal inlets are visible, and to the right, the blue waters of the Gulf Stream. Cloud streets developing offshore of the warm Stream suggest a recent passage of a cold polar front and attendant increases in air–sea evaporative fluxes.

The Second Generation

The combination of the early data and advances in scientific understanding that permitted the exploitation of those data resulted in spacecraft sensors explicitly designed to look at the sea surface. Information returned from altimeters and microwave radiometers gave credence and impetus to dedicated microwave spacecraft. Color measurements of the sea made from aircraft had indicated the efficacy of optical sensors for measurement of near-surface chlorophyll concentrations. Infrared radiometers returned useful sea surface temperature measurements. These diverse capabilities came together when, during a 4 month interval in 1978, the USA launched a triad of spacecraft that would profoundly change the way ocean scientists would observe the sea in the future. On June 26, the first dedicated

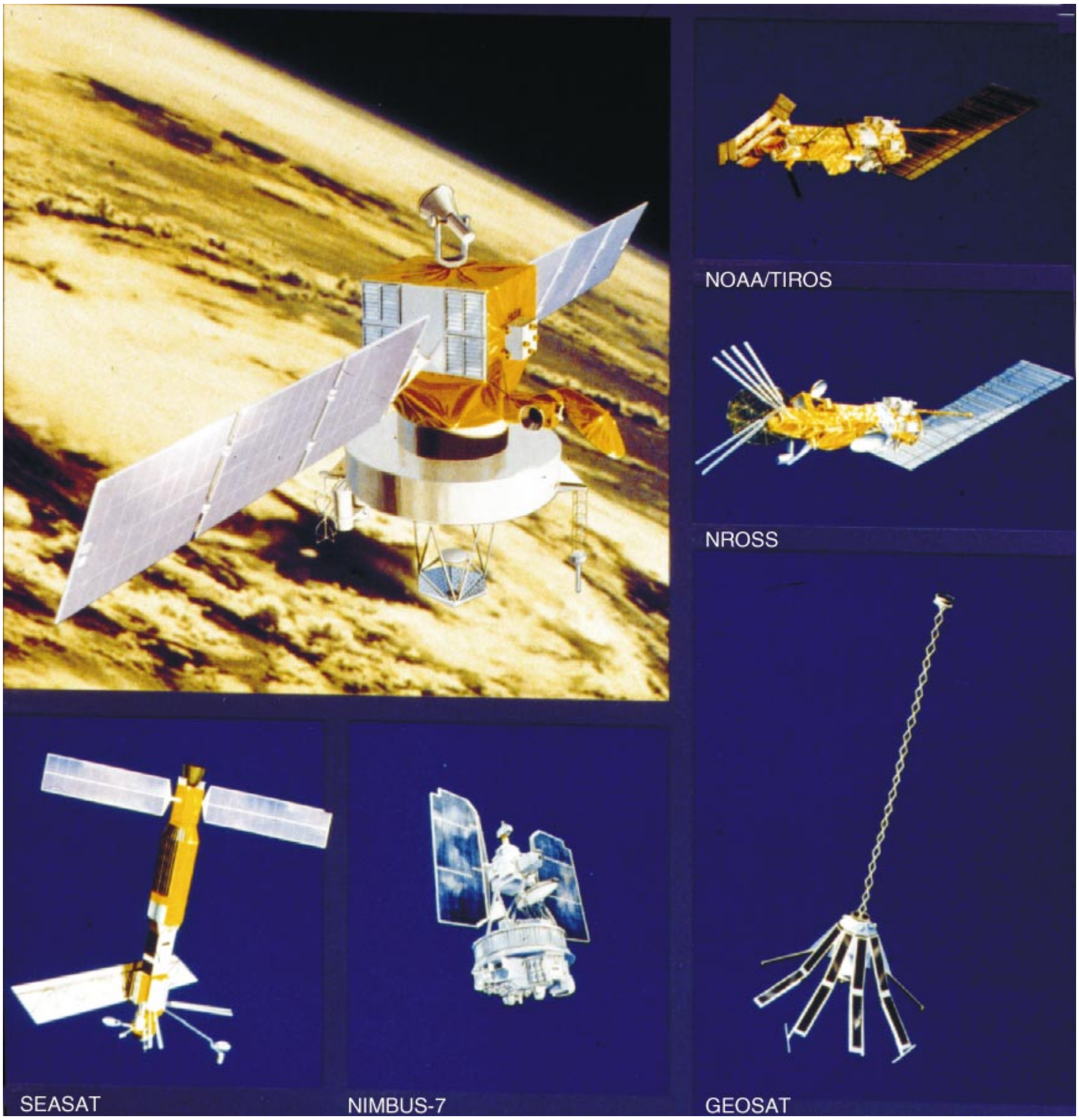

Figure 3 Some representative satellites: (1) Seasat, the first dedicated oceanographic satellite, was the first of three major launches in 1978; (2) the Tiros series of operational meteorological satellites carried the AVHRR surface temperature sensor; Tiros-N, the first of this series, was the second major launch in 1978; (3) Nimbus-7, carrying the CZCS color scanner, was the third major launch in 1978; (4) NROSS, an oceanographic satellite approved as an operational demonstration in 1985, was later cancelled; (5) Geosat, an operational altimetric satellite, was launched in 1985; and (6) this early version of TOPEX was reconfigured to include the French Poseidon; the joint mission, TOPEX/Poseidon, was launched in 1992. (Figure courtesy of NASA.)

oceanographic satellite, Seasat, was launched; on October 13, Tiros-N was launched immediately after the catastrophic failure of Seasat on October 10; and on October 24, Nimbus-7 was lofted. Collectively they carried sensor suites whose capabilities covered virtually all known ways of observing the oceans remotely from space.

This second generation of satellites would prove to be extraordinarily successful. They returned data that vindicated their proponents' positions on the measurement capabilities and utility, and they set the direction for almost all subsequent efforts in satellite oceanography.

In spite of its very short life of 99 days, Seasat demonstrated the great utility of altimetry by measuring the marine geoid to within a very few meters, by inferring the variability of large-scale ocean surface currents, and by determining wave heights. The wind scatterometer could yield oceanic surface wind velocities equivalent to 20 000 ship observations per day. The scanning multifrequency radiometer also provided wind speed and atmospheric water content data; and the synthetic aperture radar penetrated clouds to show features on the surface of the sea, including surface and internal waves, current boundaries, upwellings, and rainfall patterns. All of these measurements could be extended to basin-wide scales, allowing oceanographers a view of the sea never dreamed of before. Seasat stimulated several subsequent generations of ocean-viewing satellites, which outline the chronologies and heritage for the world's ocean-viewing spacecraft. Similarly, the early temperature and color observations have led to successor programs that provide large quantities of quantitative data to oceanographers around the world.

The Third Generation

The second generation of spacecraft would demonstrate that variables of importance to oceanography could be observed from space with scientifically useful accuracy. As such, they would be characterized as successful concept demonstrations. And while both first and second generation spacecraft had been exclusively US, international participation in demonstrating the utility of their data would lead to the entry of Canada, the European Space Agency (ESA), France, and Japan into the satellite program during this period. This, paper, however, will focus on the US effort.[1]

Partnership with Oceanography

Up to 1978, the remote sensing community had been the prime driver of oceanography from space and there were overly optimistic expectations. Indeed, the case had not yet been made that these observational techniques were ready to be exploited for ocean science. Consequently, in early 1979 the central task was establishing a partnership with the traditional oceanographic community. This meant involving them in the process of evaluating the performance of Seasat and Nimbus-7, as well as building an ocean science program at NASA Headquarters to complement the on-going remote sensing effort.

National Oceanographic Satellite System

This partnership with the oceanographic community was lacking in a notable and early false start on the part of NASA, Navy, and NOAA – the National Oceanographic Satellite System (NOSS). This was to be an operational system, with a primary and a back-up satellite, along with a fully redundant ground data system. NOSS was proposed shortly after the failure of Seasat, with a first launch expected in 1986. NASA formed a Science Working Group in 1980 under Francis Bretherton to define the potential that NOSS offered the oceanographic community, as well as to recommend sensors to constitute the 25% of its payload allocated for research. However, with oceanographers essentially brought in as junior partners, the job of securing a new start for NOSS fell to the operational community – which it proved unable to do. NOSS was canceled in early 1981. The prevailing and realistic view was that the greater community was not ready to implement such an operational system.

Science Working Groups

During this period, Science Working Groups (SWGs) were formed to look at each promising satellite sensing technique, assess its potential contribution to oceanographic research, and define the requirements for its future flight. The notable early groups were the TOPEX SWG formed in 1980 under Carl Wunsch for altimetry, Satellite Surface Stress SWG in 1981 under James O'Brien for scatterometry, and Satellite Ocean Color SWG in 1981 under John Walsh for color scanners. These SWGs were true partnerships between the remote sensing and oceanographic communities, developing consensus for what would become the third generation of satellites.

Partnership with Field Centers

Up to this time, NASA's Oceans Program had been a collection of relatively autonomous, in-house activities run by NASA Field Centers. In 1981 an overrun in the Space Shuttle program forced a significant budget cut at NASA Headquarters, including the Oceans Program. This in turn forced a re-prioritization and refocusing of NASA programs. This was a blessing in disguise, as it provided an opportunity to initiate a comprehensive, centrally led program – which would ultimately result in significant funding for the oceanographic, as well as remote sensing communities. Outstanding relation-

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[1] Additional background on US third generation missions covering the period from 1980 through 1987 can be found in the series of Annual Reports for the Oceans Program: NASA Technical Memoranda 80233, 84467, 85632, 86248, 87565, 88987, and 4025. For information on missions in other countries, see Further Reading: Kawamura (2000) for Japan; Minster and Lefebvre (1997) for France; Guymer *et al.* (2001) for the UK; and Victorov (1996) and Cherny and Raizer (1998) for Russia, Ukraine, and the former Soviet Union.

ships with individuals like Mous Chahine in senior management at the Jet Propulsion Laboratory (JPL) enabled the partnership between NASA Headquarters and the two prime ocean-related Field Centers (JPL and the Goddard Space Flight Center) to flourish.

Partnerships in Implementation

A milestone policy-level meeting occurred on July 13, 1982 when James Beggs, then Administrator of NASA, hosted a meeting of the Ocean Principals Group – an informal group of leaders of the ocean-related agencies. A NASA presentation on opportunities and prospects for oceanography from space was received with much enthusiasm. However, when asked how NASA intended to proceed, Beggs told the group that – while NASA was the sole funding agency for space science and its missions – numerous agencies were involved in and support oceanography. Beggs said that NASA was willing to work with other agencies to implement an ocean satellite program, but that it would not do so on its own. Beggs' statement defined the approach to be pursued in implementing oceanography from space, namely, a joint approach based on partnerships.

Research Strategy for the Decade

As a further step in strengthening its partnership with the oceanographic community, NASA collaborated with the Joint Oceanographic Institutions Incorporated (JOI), a consortium of the oceanographic institutions with a deep-sea-going capability. At the time, JOI was the only organization in a position to represent and speak for the major academic oceanographic institutions. A JOI Satellite Planning Committee (1984) under Jim Baker examined SWG reports, as well as the potential synergy between the variety of oceanic variables which could be measured from space; this led to the idea of understanding the ocean as a system. (From this, it was a small leap to understanding the Earth as a system, the goal of NASA's Earth Observing System.)

The report of this Committee, *Oceanography from Space: A Research Strategy for the Decade, 1985–1995*, linked altimetry, scatterometry, and ocean color with the major global ocean research programs being planned at that time – the World Ocean Circulation Experiment (WOCE), Tropical Ocean Global Atmosphere program (TOGA), and Joint Global Ocean Flux Study (JGOFS). This strategy, still being followed today, served as a catalyst to engage the greater community, to identify the most important missions, and to develop an approach for their prioritization. Altimetry, scatterometry, and ocean color emerged from this process as national priorities.

Promotion and Advocacy

The *Research Strategy* also provided a basis for promoting and building an advocacy for the NASA program. If requisite funding was to be secured to pay for proposed missions, it was critical that government policy makers, the Congress, the greater oceanographic community, and the public had a good understanding of oceanography from space and its potential benefits. In response to this need, a set of posters, brochures, folders, and slide sets was designed by Payson Stevens of Internetwork Incorporated and distributed to a mailing list which grew to exceed 3000. These award-winning materials – sharing a common recognizable identity – were both scientifically accurate and esthetically pleasing.

At the same time, dedicated issues of magazines and journals were prepared by the community of involved researchers. The first example was the issue of *Oceanus* (Wilson, 1981) which presented results from the second generation missions and represented a first step toward educating the greater oceanographic community in a scientifically useful and balanced way about realistic prospects for satellite oceanography.

Implementation Studies

Given the SWG reports taken in the context of the *Research Strategy*, the NASA effort focused on the following sensor systems. Listed with each are the various flight opportunities which were studied.

- Altimetry – the flight of a dedicated altimeter mission, first TOPEX as a NASA mission, and then TOPEX/Poseidon jointly with the French Centre Nationale d'Etudes Spatiales (CNES).
- Scatterometry – the flight of a NASA scatterometer (NSCAT), first on NOSS, then on the Navy Remote Ocean Observing Satellite (NROSS), and finally on the Advanced Earth Observing Satellite (ADEOS) of the Japanese National Space Development Agency (NASDA).
- Visible radiometry – the flight of a NASA color scanner on a succession of missions (NOSS, NOAA-H/-I, SPOT-3 (Systeme Pour l'Observation de la Terre), and Landsat-6) and finally the purchase of ocean color data from the SeaWiFS sensor to be flown by the Orbital Sciences Corporation.
- Microwave radiometry – a system to utilize data from the series of SSMI microwave radiometers

to fly on the Defense Meteorological Satellite Program satellites.

- Synthetic aperture radar (SAR) – a NASA ground station, the Alaska SAR Facility, to enable direct reception of SAR data from the ERS-1/-2, JERS-1, and Radarsat satellites of the European Space Agency, NASDA, and the Canadian Space Agency, respectively.

New Starts

Using the results of the studies listed above, the Oceans Program entered the new start process at NASA Headquarters numerous times attempting to secure funds for implementation of elements of the third generation. TOPEX was first proposed as a NASA mission in 1980. However, considering limited prospects for success, partnerships were sought and the most promising was with the French. CNES initially proposed a mission using a SPOT bus with a US launch. However, NASA rejected this because SPOT, constrained to be sun synchronous, would alias solar tidal components. NASA proposed instead a mission using a US bus capable of flying in a non-sun-synchronous orbit with CNES providing an Ariane launch. The NASA proposal was accepted for study in Fiscal Year (FY) 1983, and a new start was finally secured for the combined TOPEX/Poseidon in FY 1987.

In 1982 when the Navy first proposed NROSS, NASA offered to be a partner and provide a scatterometer. The Navy and NASA obtained new starts for both NROSS and NSCAT in FY 1985. However, NROSS suffered from a lack of strong support within the Navy, experienced a number of delays, and was finally terminated in 1987. Even with this termination, NASA was able to keep NSCAT alive until establishing the partnership with NASDA for its flight on their ADEOS mission.

Securing a means to obtain ocean color observations as a follow-on to the Coastal Zone Color Scanner (CZCS) was a long and arduous process, finally coming to fruition in 1991 when a contract was signed with the Orbital Sciences Corporation (OSC) to purchase data from the flight of their SeaWiFS sensor. By that time, a new start had already been secured for NASA's Earth Observing System (EOS), and ample funds were available in that program for the SeaWiFS data purchase.

Finally, securing support for the Alaska SAR Facility was straightforward; being small in comparison with the cost of flying space hardware, its funding had simply been included in the new start that NSCAT obtained in FY 1985. Also funding for utilization of SSMI data was small enough to be covered by the Oceans Program itself.

Implementing the Third Generation

With the exception of the Navy's Geosat, these third generation missions would take a very long time to come into being. As seen in **Figure 5**, TOPEX/Poseidon was launched in 1992 – 14 years after Seasat; NSCAT was launched on ADEOS in 1996 – 18 years after Seasat; and SeaWiFS was launched in 1997 – 19 years after Nimbus-7. In fact, these missions came so late that they had limited overlap with the field phases of the major ocean research programs (WOCE, TOGA, and JGOFS) they were to complement. Why did it take so long?

Understanding and Consensus

First, it took time to develop a physically unambiguous understanding of how well the satellite sensors actually performed, and this involved learning to cope with the data – satellite data rates being orders of magnitude larger than those encountered in traditional oceanography. For example, it was not until 3 years after the launch of Nimbus-7 that CZCS data could be processed as fast as collected by the satellite. And even with only a 3 month data set from Seasat, it took 4 years to produce the first global maps of variables such as those shown in **Figure 4**.

In evaluating the performance of both Seasat and Nimbus-7, it was necessary to have access to the data. Seasat had a free and open data policy; and after a very slow start, the experiment team concept (where team members had a lengthy period of exclusive access to the data) for the Nimbus-7 CZCS was replaced with that same policy. Given access to the data, delays were due to a combination of sorting out the algorithms for converting the satellite observations into variables of interest, as well as being constrained by having limited access to raw computing power.

In addition, the rationale for the third-generation missions represented a major paradigm shift. While earlier missions had been justified largely as demonstrations of remote sensing concepts, the third-generation missions would be justified on the basis of their potential contribution to oceanography. Hence, the long time it took to understand sensor performance translated into a delay in being able to convince traditional oceanographers that satellites were an important observational tool ready to be exploited for ocean science. As this case was made, it was possible to build consensus across the remote sensing and oceanographic communities.

Space Policy

Having such consensus reflected at the highest levels of government was another matter. The White

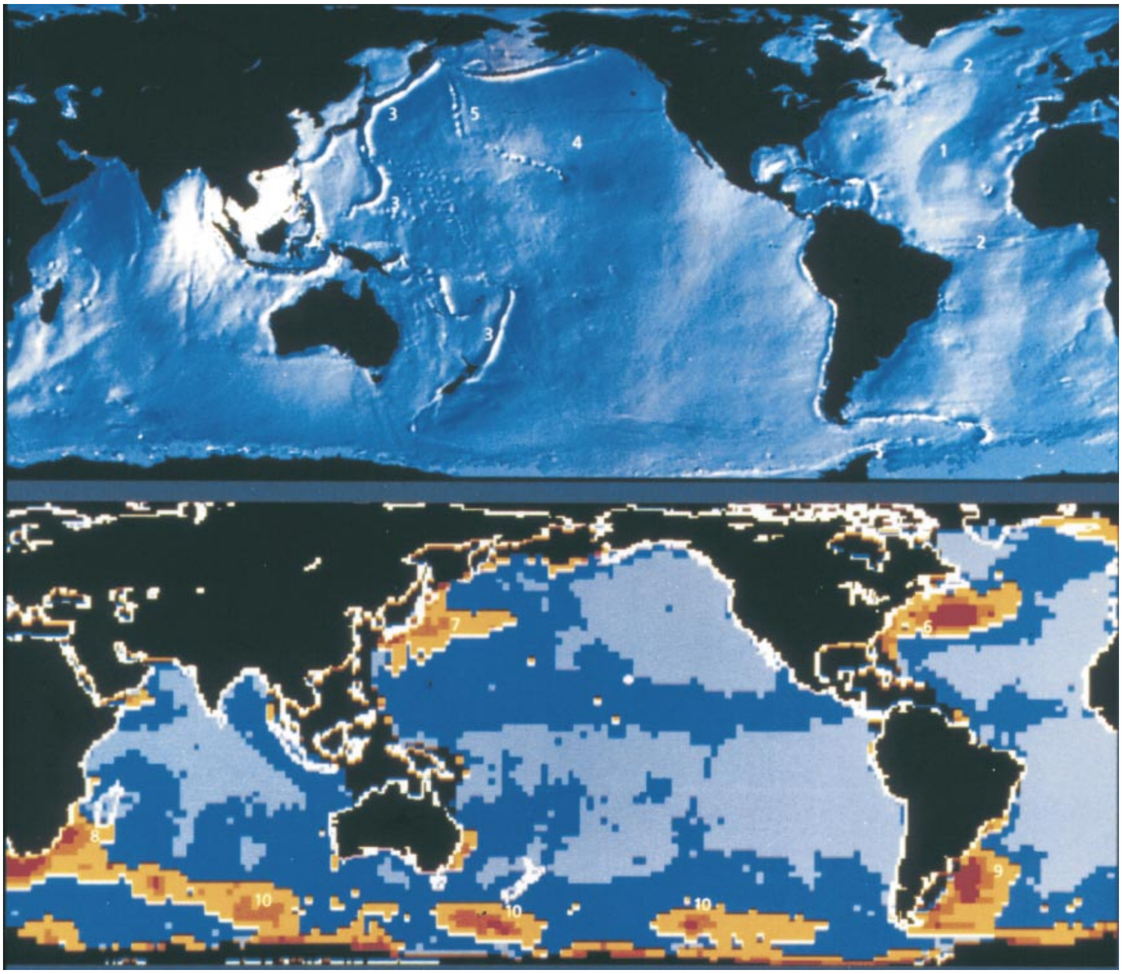

Figure 4 Global sea surface topography *c.* 1983. This figure shows results computed from the 70 days of Seasat altimeter data in 1978. Clearly visible in the mean sea surface topography, the marine geoid (upper panel), are the Mid-Atlantic Ridge (1) and associated fracture zones (2), trenches in the western Pacific (3), the Hawaiian Island chain (4), and the Emperor seamount chain (5). Superimposed on the mean surface is the time-varying sea surface topography, the mesoscale variability (lower panel), associated with the variability of the ocean currents. The largest deviations (10–25 cm), yellow and orange, are associated with the western boundary currents: Gulf Stream (6), Kuroshio (7), Agulhas (8), and Brazil/Falkland Confluence (9); large variations also occur in the West Wind Drift (10). (Figure courtesy of NASA.)

House Fact Sheet on US Civilian Space Policy of October 11, 1978 states, '… emphasizing space applications … will bring important benefits to our understanding of earth resources, climate, weather, pollution … and provide for the private sector to take an increasing responsibility in remote sensing and other applications.' Landsat was commercialized in 1979 as part of this space policy. As Robert Stewart explains, 'Clearly the mood at the presidential level was that earth remote sensing, including the oceans, was a practical space application more at home outside the scientific community. It took almost a decade to get an understanding at the policy level that scientific needs were also important, and that we did not have the scientific understanding necessary to launch an operational system for climate.' The failures of NOSS, and later NROSS, were examples of an effort to link remote sensing directly with operational applications without the scientific underpinning.

The view in Europe was not dissimilar; governments felt that cost recovery was a viable financial scheme for ocean satellite missions, i.e. that the data have commercial value and the user would be willing to pay to help defray the cost of the missions.

Joint Satellite Missions

It is relatively straightforward to plan and implement missions within a single agency, as with NASA's space science program. However, implementing a satellite mission across different organizations, countries, and cultures is both challenging and time-consuming. An enormous amount of time and energy was invested in studies of various flight options, many of which fizzled out, but some were implemented. With the exception of the former Soviet Union, NASA's third-generation missions would be joint with each nation having a space program at that time, as well as with a private company.

The Geosat Exception

Geosat was the notable US exception, having been implemented so quickly after the second generation. It was approved in 1981 and launched in 1985 in order to address priority operational needs on the part of the US Navy. During the second half of its mission, data would become available within 1–2 days. As will be discussed below, Geosat shared a number of attributes with the meteorological satellites: it had a specific focus; it met priority operational needs for its user; experience was available for understanding and using the observations; and its implementation was done in the context of a single organization.

The Next Generation

In contrast to previous long delays, one only has to look at **Figure 5** to see that within the past few years ocean-related satellites are becoming more numerous, and the distinction between generations is getting blurred. In addition to TOPEX/Poseidon, there are altimeters on ERS-2, ENVISAT, and Jason-1; and CHAMP and GRACE are complementary gravity missions. In addition to Quikscat and ERS-2, there are scatterometers on ADEOS-2 and METOP-1; and in addition to SeaWiFS, there are color scanners on Terra, Aqua, ENVISAT, and ADEOS-2. With these observations, satellites will continue to revolutionize oceanography – not only further advancing our understanding of the ocean and how it interacts with the atmosphere, but also laying the basis for a long-term, routine ocean observing system.

The maturing science of oceanography sees the development of a suite of global oceanographic services being carried out in a manner similar to the development of weather services. The delivery of these services and their associated informational products will emerge as the result of the successes in ocean science (research push), as well as an increasing demand for ocean analyses and forecasts from a variety of sectors (user pull).

Integrated and Operational Observing Systems

The next generation of ocean remote sensing systems faces another major paradigm shift. From the research perspective, it is necessary to transition successfully demonstrated – experimental – observing techniques of the third generation into regular, long-term, systematic – operational – observing systems to meet a broad range of user requirements – while maintaining the capability to collect long-term, research-quality observations. From the operational perspective, it is necessary to implement proven, cost-effective observing systems capable of meeting specific societal needs, such as those associated with economic benefits or the protection of life and property. Meeting these sometimes competing, but quite complementary demands will be the challenge and legacy of the next generation of ocean remote sensing satellites.

An essential element of meeting the demands of both the research and a broader user community is stepping back from oceanography from space as a separate endeavor, and moving toward integrated observing systems. Such systems involve combinations of satellites and *in situ* instruments feeding observations into data processing systems capable of delivering a comprehensive view of one or more geophysical variables (sea level, surface temperature, winds, etc.).

Three examples help to illustrate the nature of integrated observing systems. First, the combination of the Jason-1 altimeter, its precision orbit determination system, and the suite of precision tide gauges around the globe is an integrated system which allows scientists to make an estimate of annual global sea level changes. Such information is critical for developing plans for our coastal zones. Second, global estimates of vector winds at the sea surface are produced from the Seawinds scatterometer on Quikscat, a global array of *in situ* surface buoys, and the Seawinds data processing system. Delivery of this product in real-time has significant potential to improve marine weather prediction. The third example concerns the Jason-1 altimeter together with the Argo global profiling float array. When combined in a sophisticated data assimilation system – using a state-of-the-art ocean model – these data enable the estimation of the physical state of the ocean as it changes through time. This information (the rudimentary weather map depicting the circulation of the oceans) is a critical component of climate models and provides the fundamental context for addressing a broad range of issues in chemical and biological oceanography.

Integrated observing systems serve the dual purpose of collecting the data needed as the foundation for the next generation of research in oceanography, while at the same time providing the product and customer focus needed for successfully establishing

Figure 5 Approved US meteorological and international ocean-related satellite missions, arranged by the year of launch for the period 1972–2003. Column headings denote national sponsorship, except for the following joint missions: (1) US/France TOPEX/Poseidon, (2) France/US Jason-1, (3) Japan/US TRMM, and (4) US/German Grace. In addition, the Japanese ADEOS-1 included the US NSCAT in its sensor complement, and the US Aqua included the Japanese AMSR; the USA provided a launch for the Canadian Radarsat-1. The first column shows 38 polar-orbiting operational meteorological satellites launched from 1972 through 2000; each asterisk (*) in this column denotes an additional DMSP satellite launched during the year in question. For a chronology with mission lifetimes – including recent satellites of Brazil, China, India, Republic of Korea, and Taiwan – see Patzert and Van Woert (2000). Additionally, Masson (1991) presents a summary of missions, their payloads, how to access their data, and references.

operational oceanography. Thus, the next generation might most appropriately be characterized as oceanography from integrated observing systems.

Placing the next generation of ocean remote sensing satellites within the context of integrated observing systems necessitates new demands on space systems – long-term continuity of research-quality observations. These are needed to serve both operational oceanography – where the uninterrupted supply of real-time data is critical; and the research community – where long-term observations of subtle and slowly varying ocean phenomena are highly valued. This is a big challenge to be met by the space systems because it demands higher reliability and redundancy, while calling for stringent calibration and accuracy requirements. For example, the next generation of ocean altimetric satellites must incorporate the observations of ocean tides which vary on the order of a meter per day, along with accurate estimates of global sea level which varies on the order of a millimeter per year. The integrated system for winds requires the resolution of light, variable winds in climatically important regions like the western tropical Pacific, as well as high winds in hurricanes. Meeting these demands and delivering the required products requires close cooperation between the research and operational, observational, and modeling communities.

The Meteorological Experience

Meteorologists have had a dramatically different experience than oceanographers with satellites, and it is useful to look at that history when considering ocean observing systems. With the launch in 1960 of the world's first meteorological satellite, the polar-orbiting Tiros-1 carrying two TV cameras, the value of the resulting imagery to the operational weather services was recognized immediately. The very next year a National Operational Meteorological System was implemented, with NASA to build and launch the satellites and the Weather Bureau to be the operator. The feasibility of using satellite imagery to locate and track tropical storms was soon demonstrated, and by 1969 this capability had become a regular part of operational weather forecasting. In 1985 Richard Hallgren, former Director of the US National Weather Service, stated that 'the use of satellite information simply permeates every aspect of the [forecast and warning] process and all this in a mere 25 years.'

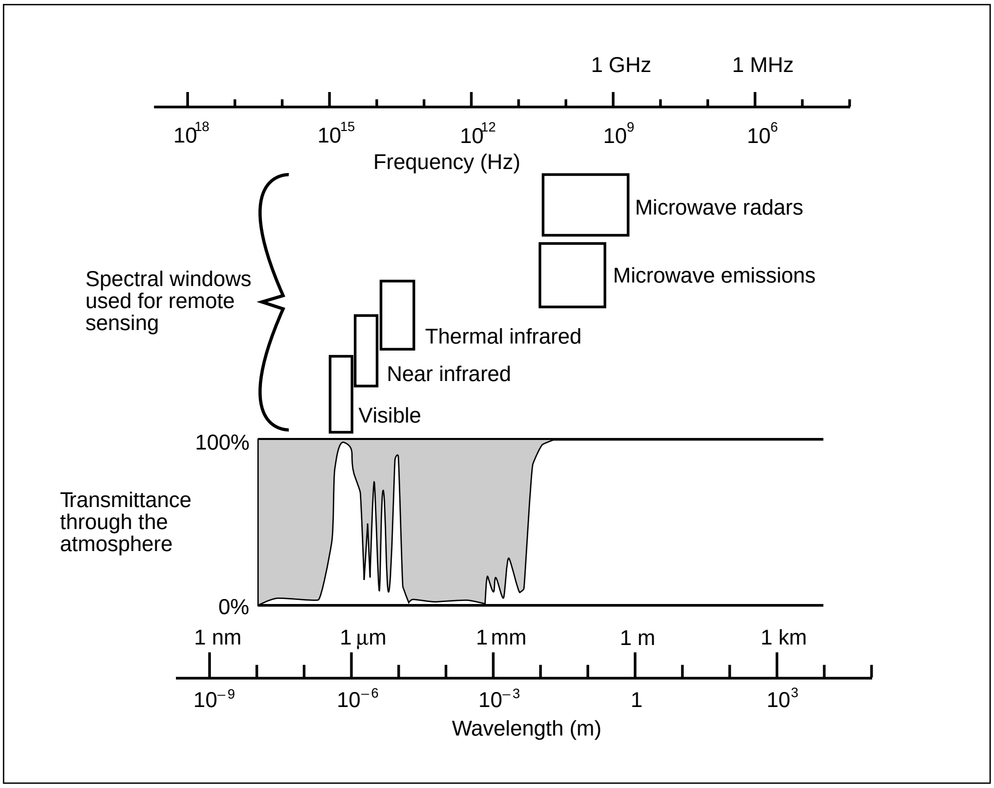

Figure 6 The electromagnetic spectrum showing atmospheric transmitance as a function of frequency and wavelength, along with the spectral windows used for remote sensing. Microwave bands are typically defined by frequency and the visible/infrared by wavelength. (After Robinson and Guymer, 1996.)

Since 1960, there has been a continuing series of 50 US operational, polar-orbiting satellites – 35 civilian and 15 military. If **Figure 5** were to show these satellites, it would have to begin in 1960 and would show slightly more than one satellite every year! Contrast that with the 16 US ocean-related satellites which have flown within the past three decades.

Why the dramatically different experience?

The first meteorological satellites had a specific focus – synoptic meteorology and weather forecasting. Initial image interpretation was straightforward (i.e. physically unambiguous), and there was a demonstrated value of observations to meet a societal need. Indeed, since 1960 satellites have ensured that no hurricane has gone undetected. In addition, the coupling between meteorology and remote sensing started very early. An institutional mechanism for transition from research to operations was established almost immediately. Finally, recognition of this endeavor extended to the highest levels of government, resulting in the financial commitment needed to enable success.

The challenge for oceanography Similar attributes are needed with regard to the ocean. What is the specific focus of the proposed long-term observing system? Koblinsky and Smith (2001) outline a growing international consensus for one such focus and the associated observational requirements. What is the demonstrated value of the resulting observations in terms of meeting a specific societal need? Addressing this question will help ensure an equivalent user pull to complement the research push. And unlike meteorology where there is a National Weather Service in each country to provide an institutional focus, ocean-observing systems have multiple user institutions whose interests must be reconciled. In the US, the dozen agencies with ocean-related responsibilities are using the National Oceanographic Partnership Program to provide a focus for reconciling such interests.

In 1994 – 34 years after the launch of TIROS-1 – a decision was made by President Clinton to merge separate civilian and military systems into the National Polar-orbiting Operational Environmental Satellite System (NPOESS) with its first satellite to

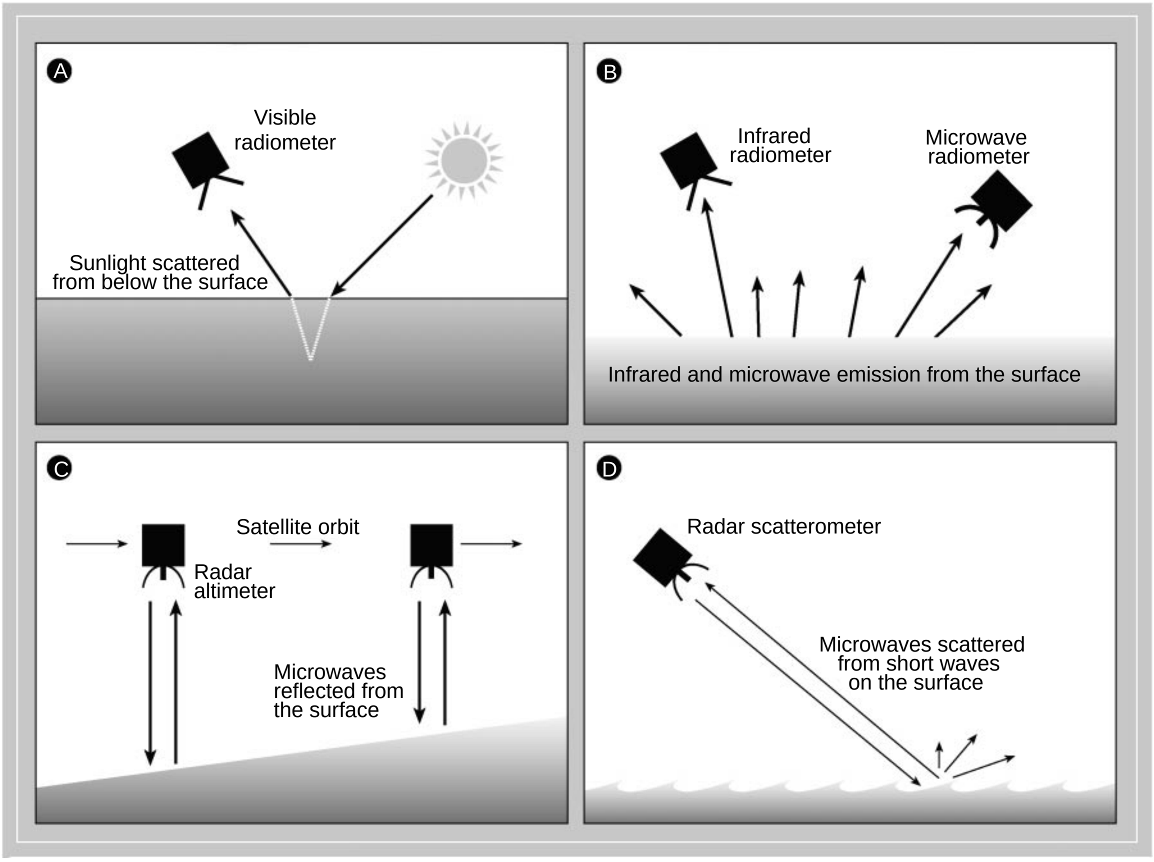

Figure 7 Four techniques for making oceanic observations from satellites: (A) visible radiometry, (B) infrared and microwave radiometry, (C) altimetry, and (D) scatterometry. (After Robinson and Guymer, 1996.)

be launched in ~2008. NPOESS will be an operational and an environmental satellite system, offering significant potential not just for the atmosphere, but also for the ocean and land, and not just for weather, but also for climate. As such, NPOESS is a target for transitioning a broad range of remote sensing capabilities to an operational footing. At the time of writing, the extent to which NPOESS will incorporate specific observational capabilities (including ocean surface topography, surface vector winds, and ocean color) is yet to be determined. Factors to be considered in addressing this issue of its mission configuration include: the demands individual sensors place on the satellite platform, the cost of those sensors, and the demonstrated value of resulting observations to meet specific societal needs.

In a major policy speech delivered to the American Geophysical Union on December 6, 1998, NASA Administrator Dan Goldin said NASA's

> 'role is to push the leading edge of remote sensing science and technology. We have an important but limited role in getting the benefits of new Earth science understanding into the hands of those who can make practical use of it … The next link in the chain is the operational satellite systems, those that can be counted on over the long term … it has become clear that the nation and the world needs an operational ocean observing system to pair with the atmospheric one now extant … NASA has proven the value and achievability of ocean topography, ocean color, ocean surface wind … measurements. The nation must have a plan to supply these and the corresponding in situ measurements on an operational basis.'

The paper by the Ocean Theme Team (2001) prepared under the auspices of the Integrated Global Observing Strategy Partnership www.igospartners.org represents how the space-faring nations are proceeding in this direction. IGOS partners include the major global research program sponsors, global observing systems, space agencies, and international organizations. Ongoing discussions in this forum are allowing for improved strategic planning and optimal use of resources in building a Global Ocean Observing System that will truly integrate space capabilities, *in situ* systems, and deliver the needed products to the greater user community.

Appendix: A Brief Overview of Satellite Remote Sensing

Unlike the severe attenuation in the sea, the atmosphere has 'windows' in which certain electro-magnetic (EM) signals are able to propagate. These windows, depicted in **Figure 6**, are defined in terms of atmospheric transmittance – the percentage of an EM signal which is able to propagate through the atmosphere – expressed as a function of wavelength or frequency.

Given a sensor onboard a satellite observing the ocean, it is necessary to understand and remove the effects of the atmosphere (such as scattering and attenuation) as the EM signal propagates through it. For passive sensors (**Figure 7**(**A**) and (**B**)), it is then possible to relate the EM signals collected by the

	PASSIVE SENSORS (RADIOMETERS)			ACTIVE SENSORS (MICROWAVE RADARS)		
SENSOR TYPE	VISIBLE	INFRARED	MICROWAVE	ALTIMETRY	SCATTEROMETRY	SYNTHETIC APERTURE RADAR
MEASURED PHYSICAL VARIABLE	Solar radiation backscattered from beneath the sea surface	Infrared emission from the sea surface	Microwave emission from the sea surface	Travel time, shape, and strength of reflected pulse	Strength of return pulse when illuminated from different directions	Strength and phase of return pulse
APPLICATIONS	Ocean color; chlorophyll; primary production; water clarity; shallow-water bathymetry	Surface temperature; ice cover	Ice cover, age and motion; sea surface temperature; wind speed	Surface topography for geostrophic currents and tides; bathymetry; oceanic geoid; wind and wave conditions	Surface vector winds; ice cover	Surface roughness at fine spatial scales; surface and internal wave patterns; bathymetric patterns; ice cover and motion

Figure 8 Measured physical variables and applications for both passive and active sensors, expressed as a function of sensor type.

sensor to the associated signals at the bottom of the atmosphere, i.e. the natural radiation emitted or reflected from the sea surface. Note that passive sensors in the visible band are dependent on the sun for natural illumination.

Active sensors, microwave radar (**Figure 7(C)** and **(D)**), provide their own source of illumination and have the capability to penetrate clouds, and to a certain extent, rain. Atmospheric correction must be done to remove effects for a round trip from the satellite to the sea surface.

With atmospheric corrections made, measurements of physical variables are available: emitted radiation for passive sensors, and the strength, phase, and/or travel time for active sensors. **Figure 8** shows typical measured physical variables for both types of sensors in their respective spectral bands, as well as applications or derived variables of interest – ocean color, surface temperature, ice cover, sea level, and surface winds. The companion articles on this topic address various aspects of **Figure 8** in more detail, so only this general overview is given here. (See also Further Reading: Robinson and Guymer (1996), Fu *et al.* (1990). Committee on Earth Sciences (1995) provides an overview of ocean-related satellites in the context of the Earth sciences.)

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See also

Aircraft Remote Sensing. History of Ocean Sciences. IR Radiometers. Ocean Color from Satellites. Satellite Altimetry. Satellite Measurements of Salinity. Satellite Passive Microwave Measurements of Sea Ice. Satellite Remote Sensing Microwave Scatterometers. Satellite Remote Sensing SAR. Satellite Remote Sensing of Sea Surface Temperatures. Upper Ocean Time and Space Variability.

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