OCEANIC REMOTE SENSING

The field of satellite remote sensing is a scientific discipline that has matured significantly since its birth in the 1960s. The mission of the early earth-orbiting satellites was to provide information for weather forecasting. Many of the ocean applications of remote sensing grew out of the use of weather satellite data. This continues to be true today, but there have been a number of satellite missions dedicated to the study of the ocean. Unfortunately, one of these dedicated satellite missions called SEASAT stopped transmitting after only 90 days of operation (reported to be due to a major power failure) instead of providing data for 2 to 3 years as planned. During this brief period, however, SEASAT was able to prove the utility of many of the first-time microwave satellite sensors. Only very recently have we managed to deploy similar sensors on a variety of spacecraft.

We have chosen to organize the material in this article by dividing the information by sensor wavelength and pointing out the specific applications for each of the wavelength bands. Since many of the applications can be separated by wavelength, this division allows us to really address different applications as we address the individual wavelength bands. We will also discuss situations where more than one single band is needed to estimate the remote sensing application. In most cases the additional channel information is used to correct the parameter estimated in the other channel.

THE ELECTROMAGNETIC SPECTRUM

The electromagnetic (EM) spectrum quantifies the electromagnetic energy as a function of wavenumber or wavelength (Fig. 1). On this diagram are given the names of the spectral bands, the physical mechanisms leading to the creation of the EM signal, the transmission of this energy through a standard atmosphere, and finally the principal techniques used for remote sensing in these wavelengths. Looking at the visible, near-infrared, thermal infrared, and microwave wavelengths, it is interesting that the atmospheric transmission is a maximum for parts of these bands. Known as “windows,” these are the frequencies that are used for sensing the emitted thermal energy from the earth’s surface. From this spectrum we can see where certain parameters should be sensed.

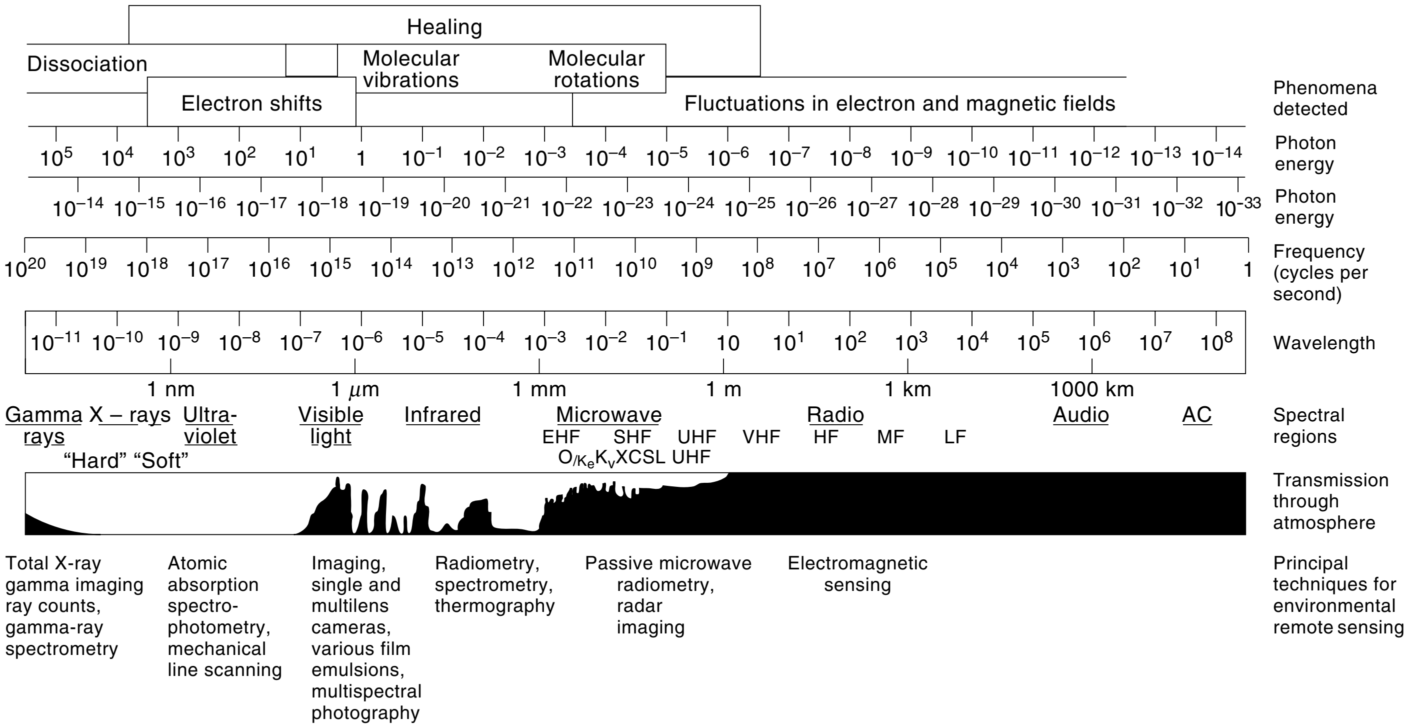

Figure 1. Electromagnetic spectrum and remote sensing measurements.

VISIBLE WAVELENGTHS

The visible bands on operational satellites have been designed to depict the weather through the distribution of and motion of clouds. Most weather satellite visible channels are broadband and average over the visible bands. The first operational narrow band visible color sensor was the multispectral scanner (MSS) that flew on the Landsat series of satellites with visible channels at 0.5 to 0.6 m, 0.6 to 0.7 m, 0.7 to 0.8 m, and 0.8 to 1.1 m. Unfortunately, the lack of a frequent repeat coverage by the MSS made it impossible to monitor changes in the ocean color that would reflect biological activity.

The first dedicated sensor for monitoring and mapping ocean color was the coastal zone color scanner (CZCS) that flew on NIMBUS 7. With a much larger swath width (~1636 km) than the MSS the CZCS overlapped at the equator on consecutive orbits, thus providing global coverage. The CZCS operated from 1978 until 1986. It was hoped that the United States would soon fly a new ocean color instrument called SeaWIFS which has unfortunately been delayed for many years. There is a new Japanese instrument flying called the ocean color and thermal sensor (OCTS) with ocean color channels.

SENSING OCEAN COLOR

There is considerable data processing required to convert ocean color radiances into relevant biological properties. One of the biggest tasks is to correct for the atmosphere. The possible terms are depicted in Fig. 2: (a) light rays which upwell from below the sea surface and refract at the surface to point toward the sensor within the sensor's instantaneous field of view (IFOV) and contribute to L_w, the water leaving radiance, (b) only a portion of the rays at (a) that contribute to L_w actually reach the sensor, (c) the rays of L_w which are scattered by the atmosphere, (d) sun's rays that reflect into the sensor call "sun glitter," (e) rays scattered in the atmosphere before reflecting at the sea surface called "sky glitter," (f) "glitter" rays which are scattered out of the sensor IFOV, (g) "glitter" rays that reach the sensor, (h) sun rays scattered by the atmosphere into the sensor, (i) rays scattered toward the sensor after earlier atmospheric scattering, (j) upwelling radiation that emerges from the water outside the sensor IFOV and scattered into the sensor IFOV, and (k) rays scattered to the sensor having first been reflected at the sea surface. Since only the rays in (a) are desired, corrections must be developed for the rest of the components (1,2).

The next step is to relate the ocean color measurements to water quality measurements. Thus we need to know how these parameters affect the optical properties of the ocean and what the spectral characteristics of the different constituents are. To accomplish the latter, we need a reference for pure seawater. Water containing phytoplankton has much more complex spectral characteristics. The dissolved organic matter associated with decayed vegetation is known as "yellow substance" or "gelbstoff." This title refers to the fact that the spectrum of absorption shows a minimum in the yellow wavelengths. The complexity of computing all of the terms related to biological activity from only visible color channels is further reduced by dividing all waters into two categories: (1) Case 1 waters are seas whose optical properties are domi-

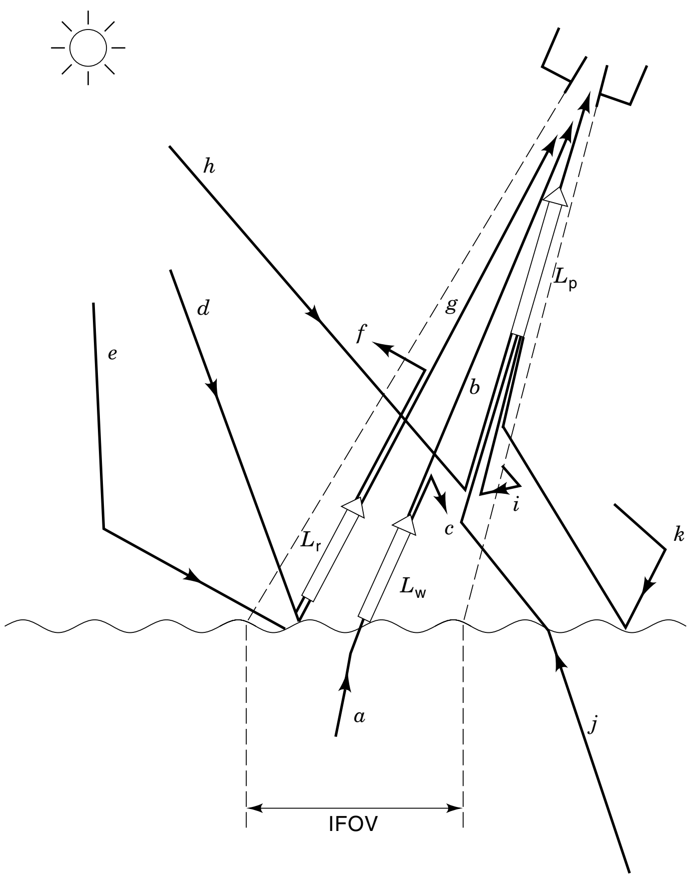

Figure 2. Terms in the calculation of ocean color.

nated by phytoplankton and their degradation products only, and (2) Case 2 waters have non-chlorophyll-related sediments or yellow substance instead of, or in addition to, phytoplankton.

IMAGING SEA ICE AND ICE MOTION

Satellite imagery has provided the polar research community with important information on the space/time changes of the sea ice that dominates the polar world. Prior to the advent of polar-orbiting satellites there was no source of global weather information that could be used by polar climatologists. Most people believe the polar regions to be cloud-covered 90% of the time. If this were truly the case, we would not need to discuss the use of optical satellite data in mapping sea ice near the poles. The true cloud cover is actually about 75% to 78%, but it must be remembered that clouds move and don't persistently cover the same region. Thus we can expect any one polar area to be free of clouds at least 20% of the time. This being the case, it is then possible to produce a clear image using temporal compositing. The composite is over some period of time (10 days, 2 weeks, etc.) and is computed using the maximum of the various channel representation. These values can be converted to sea ice concentrations (3).

An important application is the computation of sea ice motion from successive visible/infrared imagery from the advanced very high resolution radiometer (AVHRR) and special sensor microwave imager (SSM/I) data. The basic idea is that features in the first image will move to another location in the second image which can be located by finding the maximum cross-correlation (MCC) when the second image is shifted relative to the first. The difference in the locations allows one to compute the ice movements (4,5). Using passive microwave imagery from the 85.5 GHz channel on the SSM/I, we have 12.5 km spatial resolution data and can compute comprehensive, all-weather ice motions from these data. An example for the Southern Ocean is shown here in Fig. 3. A full 7 years of these motion fields can be found at http://polarbear.colorado.edu.

THE THERMAL INFRARED

At wavelengths above 10 m we are sensing radiation emitted by the surface depending on temperature as described by Planck's law. Thermal infrared radiation is used to sense meteorological phenomena at nighttime when there is no sunlight. This application is so important that in the AVHRR the infrared channel data are reversed so that cold clouds (which would appear dark due at low temperatures) appear white, similar to their representation in the visible channel.

Since clouds will block the infrared radiation emitted from the surface, it is very important that each image be corrected for cloud cover. This is done in two ways: (a) The clouds are identified and subtracted from the image, and (b) the infrared sea surface temperatures (SSTs) are composited using the maximum temperature (lower temperatures are discarded) over a period of time. Since partial clouds in an image pixel will lower the temperature sensed, we will minimize the effects of the clouds when we composite on the maximum temperature. Thus, satellite SST maps are computed over a period of time, usually 10 days or two weeks. This compositing on the maximum temperature also helps to reduce the effect of atmospheric water vapor which attenuates the infrared signal from the ocean's surface.

ESTIMATING SEA SURFACE TEMPERATURE

The earliest SST maps computed from satellite data used the 8 km spatial resolution scanning radiometer (SR) that flew on early National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. Global data from this instrument were used to compute both global and regional maps of SST using optimum interpolation. These analog temperature measurements were later replaced with a fully digital system with a much higher spatial resolution (1 km) in the present-day AVHRR. Also the SST algorithm was changed to take advantage of the channels available with the AVHRR. In the almost two decades that have passed since the first launch of an AVHRR, it has remained the main source of SST information on a global basis.

The first step in computing SST is to have an algorithm for converting the infrared pixel values to temperature. Unlike the visible channels the infrared channels of the AVHRR are equipped with a system to "calibrate" the measurements during their collection by the sensor. To compensate for sensor drift on each scan the sensor views two separate "blackbodies" with measured temperatures as well as "deep space." These three temperatures are used to "calibrate" the pixel values and turn them into temperature.

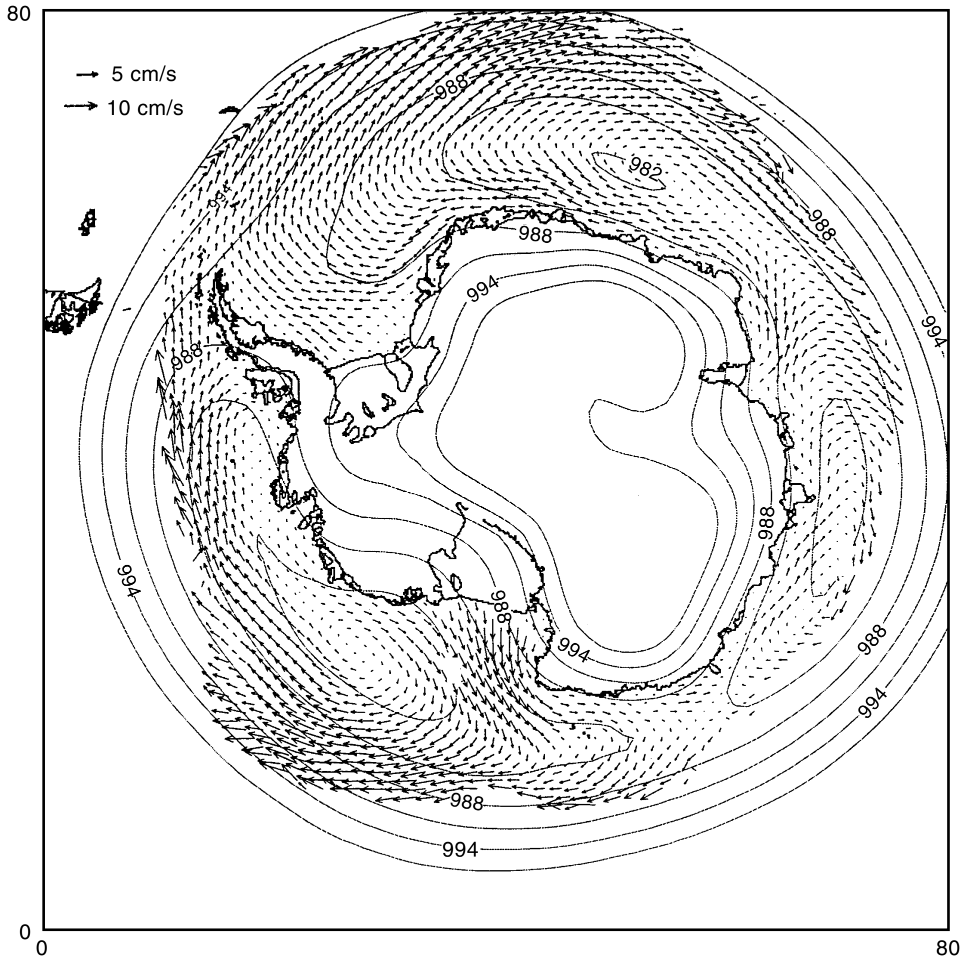

Figure 3. Mean (1988–1994) sea ice motion for the Southern Ocean.

SPLIT WINDOW METHODS

Dual channel methods take advantage of the fact that the atmosphere attenuates infrared energy differently in the two adjacent channels. This approach is generally referred to as the "split-window" since it requires dividing the infrared water vapor window into two parts. The channels most frequently used are the 11 μm and 12 μm bands. Our spectrum (Fig. 1) shows that the 12 μm channel will experience greater atmospheric attenuation when compared to the 11 μm channel. The formulation of the SST using both of these channels is

$$\mathrm{SST} = aT_4 + b(T_4 - T_5) \qquad (1)$$

where T_4 and T_5 are the 11 μm and 12 μm channels. In some cases a third channel will be used as well. For the AVHRR, this is channel 3 (~3.7 μm), which must first be corrected for reflected radiation. The coefficients are usually found by comparisons with SST measured by coincident drifting and moored buoys.

The most widely known split-window algorithm is the multichannel SST (MCSST, 6) which uses Eq. (1) with a = 1.01345 and b = 2.659762 and an additional term to account for solar zenith angle. There have been other algorithms developed as improvements on the MCSST (7) but many comparisons have shown the MCSST to produce values as accurate and reliable as any of these new algorithms.

GLOBAL MAPS AND DATA AVAILABILITY

The MCSST has been processed into global maps of SST. These maps are available at the Data Active Archive Center (DAAC) of the Jet Propulsion Lab. They can be found along with other information on oceanographic data at http://podaac.www.jpl.nasa.gov/.

RELATIONSHIP TO OCEAN CURRENTS. SST MOTION

One important application of satellite SST mapping is the computation of surface currents. The assumption must be made that feature displacements by surface currents dominate all other changes in SST. Under this assumption, two sequential images of the same general area are used to find the displacement (see sea ice motion) that makes all of the features match up over time (8,9). By overlapping these areas, maps of ocean surface currents can be made much in the same way that sea ice motion was tracked.

SKIN SST VERSUS BULK SST AND HEAT EXCHANGE

Infrared satellite sensors can only "see" thermal radiation which, due to the high emissivity of seawater, is emitted from the sub-millimeter-thick "skin" of the ocean. This temperature cannot be measured in situ by ships or buoys since touching the ocean's skin layer will destroy it. The skin SST can be measured using radiometers from ships, and it is hoped that in the future there will be a change to computing skin SST from the infrared satellite data. It is the temperature difference between the skin SST and the subsurface or "bulk" SST that controls the exchange of heat between the ocean and the atmosphere.

PRESENTLY AVAILABLE SENSORS AND FUTURE PLANS

At present the instrument used to compute SST is the AVHRR. This sensor has been flying in one of two forms since 1978. There was a change in 1982 which added another channel to the AVHRR, making it possible to compute split-window SSTs. In 1998 a new sensor called MODIS (moderate field-of-view imaging spectrometer) will be launched with a number of new channels in the thermal infrared which should afford new opportunities for computing an even more accurate skin SST. It is clear, however, that the thermal infrared techniques will remain the primary channels for the computation of SST from space.

FILTERING OUT CLOUDS

One of the most important processing steps in using either infrared or visible data is the detection and removal of cloud cover. This is usually done in two ways: (1) Some method is used to sense clouds and remove them from the image, and (2) a temporal compositing technique is used that suppresses any residual clouds in the image. Even with both of these techniques there are usually some cloud contaminated pixels in the composite images.

VARIOUS METHODS AND THEIR ACCURACIES

There is a wide variety of techniques for the detection and removal of clouds. Most common are the threshold methods where clouds are considered to have high or low values relative to the targets of interest. Fixed thresholds based on the scene histograms are the most common of these methods. Dynamic thresholds are also used where the threshold value is computed dynamically from the histogram during the cloud removal process. Another procedure is to use the "spatial coherence" of the noncloud pixels. Statistical classification methods such as Maximum Likelihood are often used. Frequently, methods are combined with one procedure used to remove most of the clouds and the second method used to remove the remaining clouds.

PASSIVE MICROWAVE

One of the great changes in remote sensing since 1980 has been the increased application of passive microwave imagery to many fields of geoscience. This was motivated by a series of operational passive microwave instruments. The first was the scanning multifrequency microwave radiometer (SMMR), which was followed by the special sensor microwave/imager (SSM/I). The SMMR was first carried by SEASAT, but fortunately after the demise of SEASAT another SMMR was deployed on NIMBUS 7 which operated until 1986. Many of the geophysical algorithms were developed with SMMR data. These algorithms have been further explored with the SSM/I first launched in June 1987, and subsequent instruments continue to operate today.

WIND SPEED

The emitted microwave radiation at the ocean's surface is affected by the roughness of the sea surface, which is correlated with the near-surface wind speed. Atmospheric attenuation of the 37 GHz radiation propagating from the sea surface is very small except when a significant amount of rain in the atmosphere scatters the 37 GHz signal. The Wentz wind speed algorithm relates wind speed at the 19.5 m height to the 37 GHz brightness temperatures, which are computed from the SSM/I 37 GHz horizontal and vertical polarized radiance measurements. Corrections are made in the 37 GHz data for the emission of the sea surface and for atmospheric scattering conditions. The wind speeds computed by Wentz (10) are referenced to a 10 m height as is traditional in meteorology. Comparisons between SSM/I inferred wind speeds and wind speeds measured at moored buoys indicate that the SSM/I wind speeds are accurate to 2 m/s.

ATMOSPHERIC WATER VAPOR

The SSM/I has a number of channels that can be used to sense atmospheric moisture (11). Of these the 22 GHz channel is the most sensitive to water vapor. Retrievals of atmospheric moisture using this channel alone are accurate to 0.145 g/cm^2 to 0.17 g/cm^2. Global water vapor fields computed from SSM/I data demonstrates how this capability can be used to map global patterns of atmospheric moisture, something that has not been possible with radiosonde measurements.

RAINFALL

Precipitation is the primary contributor to atmospheric attenuation at microwave wavelengths. This attenuation results from both absorption and scattering by hydrometeors. The magnitude of these processes depends upon wavelength, drop size distribution, and precipitation layer thickness. For light rain we can neglect the effect of multiple scattering, and the attenuation can be computed from statistical considerations. For heavier rainfall we must include multiple scattering by considering the full drop size distribution.

MERGING THE PASSIVE MICROWAVE WITH THE OPTICAL DATA

One of the most useful applications of the passive microwave data are as corrections for the optical wavelength parameter retrievals. For example, one of the biggest problems in the infrared estimation of SST is the correction for atmospheric moisture. Since the SSM/I senses water vapor it can be used as a correction for SST estimates (3) which improves the estimation of SST to an accuracy of 0.25.

ACTIVE MICROWAVE

One of the greatest benefits of the short-lived SEASAT satellite was the proof that both active and passive microwave sensors could measure quantities of real interest to oceanographers. The brief 90 days of data clearly demonstrated how the all-weather microwave instruments could observe the earth's surface. The three most important instruments were the RADAR Altimeter, the synthetic aperture RADAR (SAR) and the scatterometer (SCAT). The former measures the height of the sea surface above a reference level while the scatterometer measures the wind stress over the ocean. The SAR images the ocean's surface but also has very important applications in polar regions (mapping sea ice) and over land where it is related to the vegetation.

RADAR ALTIMETERS

After SEASAT there were no altimeters in space until 1985 when the US Navy launched GEOSAT designed to map the earth's gravity field for naval operations. After it completed this mission the navy was persuaded to place the satellite in the SEASAT orbit to collect data useful for oceanographic studies. Two years of very useful data were collected and formed the basis for a number of studies. Subsequently a joint altimeter mission between France and the US National Aeronautic and Space Administration (NASA), called TOPEX/Poseidon (TP), was launched in 1992 which became the most successful altimeter ever. Also in operation during this period is the European Resources Satellite (ERS) altimeter, of which there are now two (ERS1, ERS2). It is common to merge the TP data with its 10-day repeat cycle with the ERS data with their longer repeat cycles. The altimeter also accurately measures wind and significant wave-height from the RADAR backscatter.

SCATTEROMETER WINDS

Another instrument demonstrated by SEASAT was the mapping of wind stress over the ocean with the scatterometer. Since it is very difficult to get information on winds over the ocean, this measurement capability is extremely important. Also, scatterometer winds are all-weather retrievals, making it possible to map ocean winds regardless of weather. After SEASAT the first scatterometers were again those on ERS1 and ERS2. More recently a NASA scatterometer (NSCAT) was launched on the Japanese ADEOS platform. There are also plans to launch future scatterometers on non-US spacecraft.

SYNTHETIC APERTURE RADAR (SAR)

The high spatial resolution images produced by the SEASAT SAR were very tantalizing to oceanographers who hoped to use SAR for a variety of applications. The data gap caused by the loss of SEASAT delayed a lot of those expectations. There continues to be no US SAR operating, and these data are now available from the European Earth Resource Satellites ERS1 and ERS2 as well as the RADARSAT satellite launched and operated by Canada. Early in the SEASAT period it was demonstrated that SAR imagery could be used to image directional wave spectra and sense internal waves. SAR images also contain expressions of oceanographic fronts (thermal or saline), but the primary application remained the mapping of sea ice in all weather conditions. Microwaves are not blocked by clouds, making it possible to sense the polar ice surface regardless of weather. The high spatial resolution of SAR made it possible to resolve details not possible with optical systems.

SUMMARY

Oceanography requires sampling over large geographic regions which is time-consuming and expensive for in situ measurements platforms. Satellite remote sensing offers a cost-effective method of sampling these large oceanic regions. The only difficulty is in establishing exactly what the satellites are sensing and how accurately the quantities are being sensed. We continue to develop better instruments with better signal-to-noise ratios that can better resolve the parameters of interest. It is certain that satellite data will continue to be important for future oceanographic studies.

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