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SATELLITES SCAN THE SEAS

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ABSTRACT

A brief review of the role played by satellites in the marine sciences up to the present is followed by a more detailed assessment of the significance of adopting micro-wave remote sensors as well as visible and infrared instruments. The sensors carried on Seasat-A — the first satellite entirely devoted to the marine sciences — are described and the potential benefits of the Seasat programme, both to applied and pure research, are considered. These include an improvement in forecasts of wind and wave climate ; monitoring coastal processes ; providing basic data to the study of marine geodesy and ocean tides ; and delineating changing ice patterns in polar regions.

INTRODUCTION

The potential benefits of satellite technology to the scientific study of the sea is being put to the test in 1978 with the recent launching of Seasat-A, the first satellite with a suite of sensors fully dedicated to oceanic requirements. Two other research satellites to be launched in 1978 — Tiros N and Nimbus G — will carry specific instruments that monitor both microwave and infra-red radiation from the sea surface.

We have travelled far in the twenty years since a solitary, bleeping Sputnik was launched on the world. Satellites have contributed greatly to technological advances in a variety of fields ; today we almost take for granted the high quality of intercontinental telephone links produced by the Intelsat network of satellites and ground stations to which over ninety countries now subscribe.

Navigation at sea is a more specialised activity which enjoyed the early benefits of a series of dedicated satellites. The system is run by — and, in the first instance, for — the United States Navy but there are now more civilian users than military. By carrying a small receiver and microcomputer a ship in mid-ocean can routinely obtain positions accurate to

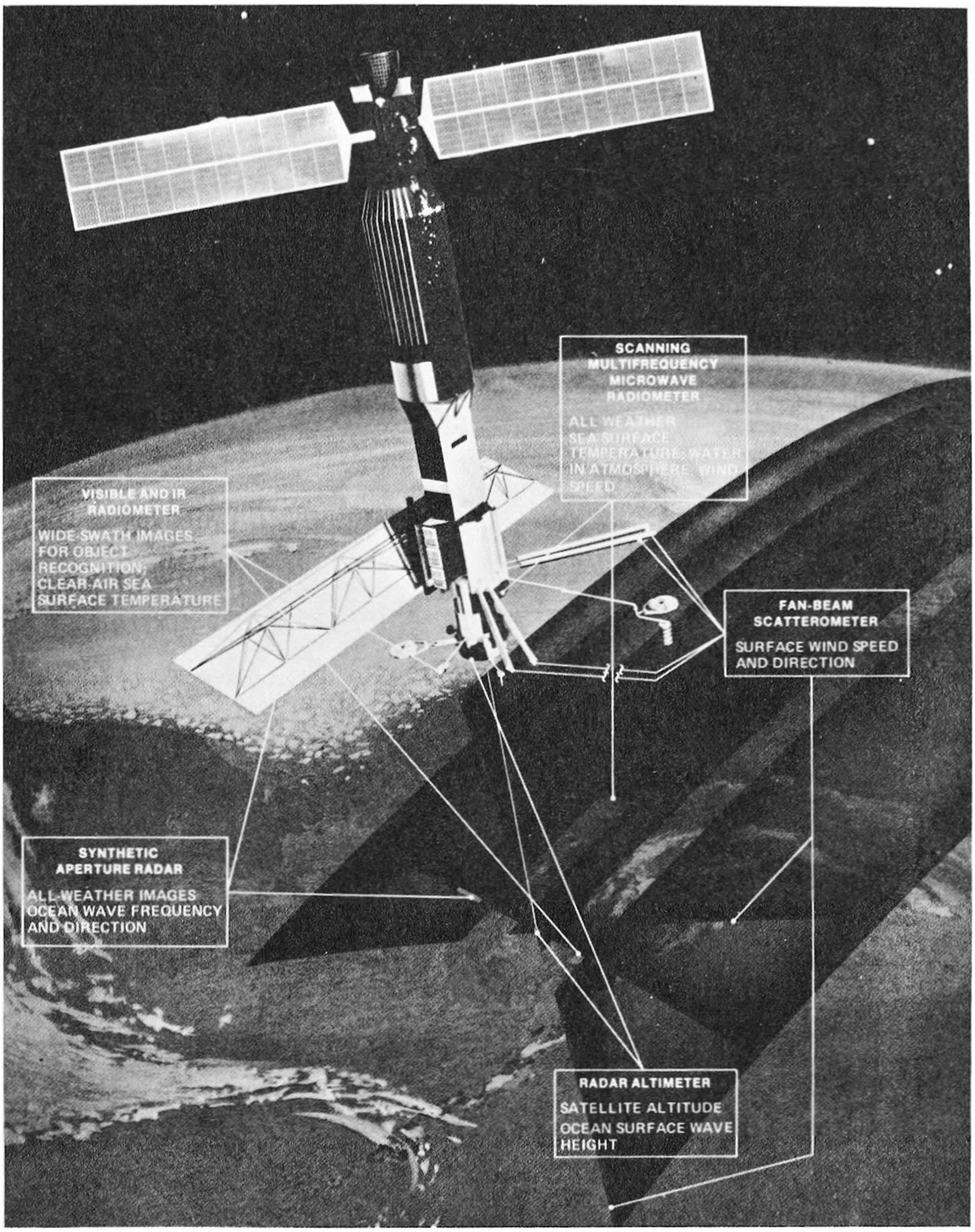

FIG. 1. — Seasat-A, launched in June 1978.

within a few hundred metres from a transmitting satellite — a change from the days of sun and star sights when conditions allowed.

The management of earth resources is another area now beginning to reap substantial benefits from satellite remote sensing. Imaging techniques and sensors have steadily developed to the stage where detailed inventories can now be kept on crops, vegetation, forests and mineral resources. Satellite imagery is proving an indispensable asset in such studies as the impact of expanding urbanisation on surrounding vegetation.

There are now more than 4 000 man-made objects in orbit around the earth (NASA 1977). For many satellites their missions are over but, like riderless horses in a steeple-chase, they continue to circuit with the others. Many satellites are, of course, employed for military surveillance, and much of the progress in satellite technology may be attributed to the impetus of their military applications.

Although satellite remote sensing would appear to be particularly relevant to the environmental sciences of meteorology and oceanography as well as navigation, land resources and defence, it has been only recently — especially in the marine field — that space sensors have been developed with sufficient intrinsic accuracy to provide more than a rather qualitative and fleeting view of large-scale features.

MONITORING THE SEAS

It is hardly surprising that remote sensing from a platform hurtling 800 km above the earth at a speed of 7 ½ km/sec has not yet achieved the accuracy and reliability of spot measurements made at the sea surface. But satellites do possess the great advantage of mobility. A research ship sailing from a Northern European port to embark on a study of the Antarctic could hardly plan to return much within a year. A satellite can be programmed to make over a dozen return journeys in a single *day* and transmit its observations to a conveniently placed ground base. It is the resolve to exploit this remarkable coverage that has spurred scientists and engineers to overcome the daunting limitations of the early sensors.

The majority of remote sensors have operated in the visible and infra-red part of the electromagnetic spectrum. Associated spacecraft data consist largely of high resolution photographs and infra-red imagery reflecting temperature differences over the sea surface (fig. 2). Such information has proved useful. Fishing fleets, for example, can be directed to upwellings of cold, nutritious water detected along continental margins.

Of those which do sense other parts of the spectrum, the GEOS series has perhaps been the most valuable to the marine surveyor by supplying small-scale coastal topographic detail and delineating the limits of large ocean shoals, without specific depth disclosure. Use of the data to date has been promising, though largely experimental.

Why then have marine scientists made only limited use of satellite observations ? There are three main reasons.

First, satellites view only the surface of the sea ; unlike research and survey vessels, their sensors cannot penetrate the ocean depths beyond very shallow limits, and have not furnished quantitative depth data. Secondly, we have seen that the accuracy of satellite sensors has compared unfavourably with that of data obtained directly at sea. Lastly, and most importantly, in all but equatorial latitudes the seas are frequently hidden by a cover of cloud which sensors, operating in the visible part of the spectrum, are unable to penetrate. At a latitude of 50° N in Europe it has been estimated that there is no more than a one-in-twenty chance of obtaining two consecutive satellite images of one area containing less than 30 % cloud (U.K. Department of Industry, 1977). Thus, systematic studies have proved very difficult. The beautiful photographs one sees of land masses, looking as clear as on a map, are the exception rather than the rule.

FIG. 2. — Infra-red image of the western approaches to the English Channel. Cloud covers the top left portion. The change in tone of the sea-surface across a line from Ushant to the Scillies denotes a strong 'oceanic front'.

If sensors could be produced which were not dependent on the weather and which provided substantially higher accuracies than previous instruments, the limitations of viewing only the sea surface might not be too severe since many features in the volume of the sea (such as internal waves) frequently produce a surface expression (NASA 1975, APEL *et al.*, 1975). Besides, the changes in the marine environment which most affect human activity — such as tides, waves, storm surges, ice, pollution and weather patterns — are to be observed at the sea surface.

Satellite technology has now produced a suite of sensors which approach the requirements enumerated by marine scientists. These operate in the microwave part of the spectrum where the centimetric wavelengths are capable of penetrating cloud. The four sensors installed on Seasat-A have been developed from earlier models flown from aircraft and experimental satellites.

SATELLITE ORBITS

The orbit of a satellite is selected according to the tasks to be performed. At the research stage of a programme, a compromise is made between wide coverage over the entire globe and the requirement to follow the changing patterns over one point. Best spatial coverage is achieved from a polar orbit ; in the time required to complete one orbit the earth will have spun a few degrees to the east ensuring that the next orbit traces a different path over the surface. As an example, if exactly 15 circular orbits are completed in 24 hours then each orbit will take 96 minutes (the height of the satellite can be calculated to be 560 km and its speed 7 ½ km/sec), and during one complete orbit the earth will rotate through 24° of longitude which corresponds to a spacing of 2 700 km between successive equatorial crossings. The pattern would be repeated every day, allowing time changes to be monitored. However, if the footprint of the sensor (that is the width of the swath scanned at any instant) is small then large tracts between successive orbits will remain unsurveyed.

To avoid this situation the number of orbits completed in a 24-hour period can be selected not to be an exact integer. In the case of Seasat-A, for instance, 14.3 orbits are made in one day, and the spacecraft will require 152 days to complete its pattern.

Alternatively, if it is required to survey one part of the globe without interruption, then the satellite can be placed in an equatorial orbit circling the earth at the same rate as the earth spins on its axis. To achieve a geostationary orbit the satellite must be placed at a height of 36 000 km above the equator. Programmes such as Meteosat use this concept, whereby a few geostationary satellites achieve a world-wide synoptic view of the weather.

SEASAT-A

The sensors carried on Seasat-A comprise 4 microwave instruments — 3 active and 1 passive — plus a Visible and Infra-Red Radiometer. The primary mission is to determine the performance of this suite of sensors under different environmental conditions and, to this end, contemporaneous ‘ in situ ’ measurements will be made in a variety of locations on both sides of the Atlantic. The microwave sensors are a radar altimeter, multifrequency radiometer, scatterometer and synthetic aperture radar. A brief description of their operation follows.

Altimeter

A short-pulsed radar altimeter will measure the vertical distance from the spacecraft to the sea-surface to an inherent accuracy of ± 10 cm. While the echo from a smooth sea-surface is sharply defined, a rough sea produces numerous reflecting points, which has the effect of 'spreading out' the return pulse. The degree of spread can be measured electronically in the spacecraft and the scale of roughness, or average wave height, estimated to 1 metre. This figure may not be as accurate as devices used on the surface but it is more than adequate over large areas of the oceans where no observations are available.

Likewise, the data on the absolute height of the spacecraft will be valuable in determining variations in 'mean sea level' over areas so remote from land that measurements taken by any other means would be very difficult and time-consuming.

Scatterometer

As its name implies, the scatterometer measures the degree of scatter of microwave energy from the rough surface of the sea, which can then be related to the strength and direction of the wind causing the roughness. It employs two fan beams, each looking forward of the spacecraft at an angle of 45° with respect to the flight path. A duplicate set of beams scans behind, ensuring that each area of the surface is scanned twice. The Doppler shifts in the two viewing directions give a measure of wind direction.

The scatterometer measures out to 1 000 km on either side of the spacecraft with a spatial resolution of 50 km — that is, values of wind velocity are averaged over a square 50 km on the side. Because of its wide sweep, 95 % of the earth's surface its covered each 36 hours.

Synthetic Aperture Radar

The physics of the interaction of microwave energy with the sea are relatively complex, and this is an important feature to be studied in the Seasat programme. The instrument with perhaps the greatest potential value in the programme, but which at the same time generates the most complex interpretive problems, is the Synthetic Aperture Radar (SAR).

Radars with a high resolving power require large antennae. Techniques have been developed for electronically simulating a long antenna by processing each individual scan perpendicular to the track and using the forward motion of the radar to build up a composite image. The SAR is designed to provide images of the waves over a 100 km swath, offset 250 km to the right of the spacecraft as shown schematically in fig. 3. Its spatial resolution is a 25 × 25 metre square — but the price of such detail is an extremely high data rate. If, for example, the spacecraft is tracked by a ground station for a horizon-to-horizon distance of 5 000 km, a total number of 800 million picture elements (pixels) must be treated to resolve features 25 m across. Such an amount of information prohibits storage of the data on the spacecraft and the SAR will only operate if there is a ground station to receive the transmitted data. The official station of the European Space Agency is at Oakhanger in South-East England.

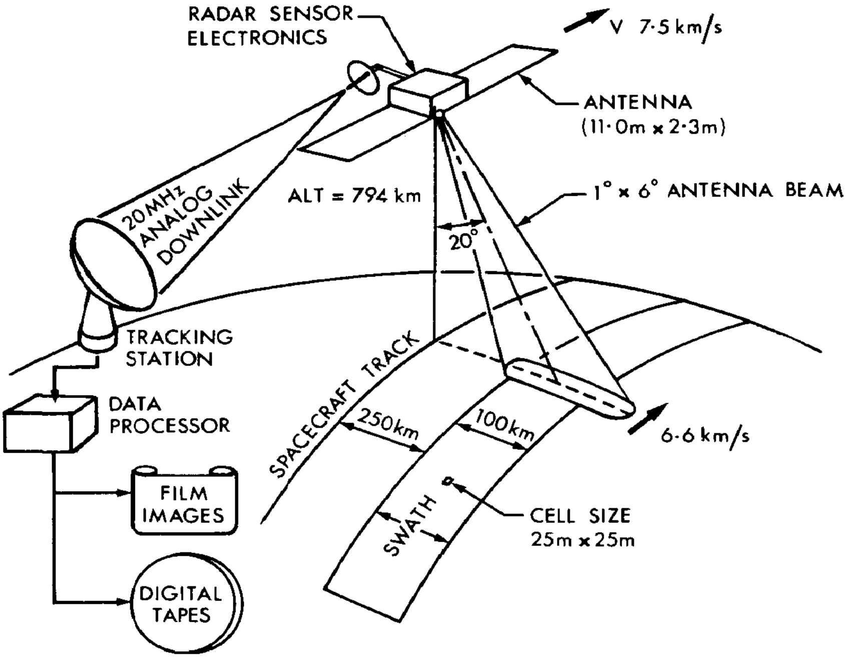

FIG. 3. — Schematic representation of the operation of the Synthetic Aperture Radar.

Scanning Multi-Frequency Microwave Radiometer

The SMMR is a passive instrument receiving energy at five different wavelengths between 8 mm and 45 mm (37 GHz - 6.6. GHz). The apparent ' brightness temperature ' of the radiating sea surface responds to a variety of conditions according to the frequency of the received microwave emission. Thus, at a frequency of 1 GHz the ' temperature ' decreases by 25 °K in passing from fresh water to Atlantic surface water. At 19 GHz the brightness temperature reflects the degree of wind-induced surface roughness, and at higher frequencies water vapour content in the atmosphere and ice coverage can be estimated.

The frequencies used in the SMMR have been selected to provide the maximum of back-up information to the other sensors. An identical unit will be carried on Nimbus-G.

APPLICATIONS

The overall goal of the Seasat programme is to improve the quality and scope of marine environmental monitoring. Satellite surveillance can make significant contributions to such activities as the forecasting of weather, winds and waves ; warnings of natural hazards ; management of marine resources, especially fisheries ; detection of pollution nearshore and in mid-ocean ; monitoring of ice patterns ; and studies of the exact shape of the earth, the movement of tides and the variations in major current systems.

As the precision and resolution of the sensors improve, and the new technology is accepted and understood, satellites will play an increasingly important role in marine discovery. Research ships are constrained to operate in a medium which can change rapidly in space and time so that synoptic data on a large scale are virtually impossible. In the time that it takes a ship to sample a particular feature from one point in the ocean to another the original form may have changed completely. There is therefore a requirement to combine the fine detail of 'in situ' measurements with the synoptic view which only a satellite can acquire.

Improved Estimates of Wind and Wave Climate

Since most of the world's weather is created over the seas a combination of synoptic meteorological and oceanographic observations should lead to more reliable forecasts over longer time scales which, in turn, could permit reductions in ship transit times and damage. Along certain exposed seaboards increased warning of impending hazards such as hurricanes, storm surges and tsunamis could save lives.

The extension into coastal zones of the search for energy has rapidly produced a need for accurate forecasts of the wave climate. Oil platforms must be designed to withstand the force of the highest waves they may encounter during their working lives. An underestimate could prove disastrous while an overestimate can cost over $ 1 million per foot of unnecessary wave height.

The possibility of using waves as an alternative energy source is under consideration in some countries. The many factors to be considered in such a scheme include the average wave heights, their distribution throughout the year and their variation with distance from the shore. Again, the need is for reliable statistics over comparatively wide coastal areas.

But apart from the very practical and immediate aspects of offshore energy, there is a need to improve our knowledge both of the mechanisms for generating waves and of the statistical properties of the entire wave spectrum in the open ocean. The sea surface is considered as a random superposition of plane waves with various wavelengths and directions ; to describe it fully the average energy content of each wavelength in every direction is required and there is presently no way of measuring this. Remote sensing from satellites is unlikely to solve this problem overnight, but refined radar imagery may prove a useful tool of the future.

Another approach to describing the motion of the sea surface is by measuring the strength and direction of the wind. Reaching an adequate empirical relationship between wind and wave fields is one of the longest-standing problems in marine research, and the greater part of the difficulty has been in obtaining good measurements.

In 1805, Admiral Beaufort devised a scale of winds based on the amount of canvas that a fully-rigged frigate could carry in various winds. This scale is still in use today, with qualitative descriptions of the state of the sea surface in various winds — such as, 'force 5, fresh breeze, moderate waves with many whitecaps'.

The invention of the cup anemometer and, much later, of the shipborne wave recorder allowed quantitative records to be taken at sea ; but the anemometer readings are subject to a variety of errors, and the wave recorders are used on no more than six weather ships throughout the world. Visual observations still remain the primary method of obtaining wave data, and no amount of computer power can provide accurate forecasts from low-grade data.

Seasat sensors will produce independent measurements of wind and wave fields which may be used to test current theories of their interaction. There are many problems to be solved ; little is presently known of the relationship between the centimetric waves that produce Bragg scattering of the SAR microwave signals and the larger ocean waves on which they ride. But a combination of theory, laboratory experiments, measurements at sea, and wide Seasat coverage may eventually produce routine procedures for data gathering of fundamental importance to forecasters.

Coastal Processes

It has been estimated that 90 % of man's ocean activities occur in water depths shallower than 30 m, where the effects of tides, currents and waves are particularly important. In many countries a large fraction of the population inhabits the sea shore and it is essential that adequate warning can be given of approaching storm surges.

Forecasting the behaviour of waves in shallow water is particularly difficult because of the varying effects of bottom friction, refraction and breaking. This is an area where a synoptic view is virtually essential for the construction of an adequate physical model. Remote sensing can provide valuable information on the changes in direction of wave trains sweeping across the continental shelf. The formation and migration of sand waves which play an important role in modifying our coastlines can also be monitored by remote sensing techniques, and preventive measures taken if necessary.

Marine Geodesy and Tides

Geodesy is the study of the shape of the earth. One of the earliest scientific results produced by satellites was the observation that the actual orbits varied significantly from those predicted, due to the spatial variation of the earth's gravity field. From later satellite missions we now know that the surface of the sea undulates, with 'holes' and 'peaks' of nearly 100 m amplitude from the average surface (Marsh & Chang, 1976).

A fundamental geodetic problem has been the integration of individual land surveys. It had seemed logical to accept ' mean sea level ' as a common reference level for all land surveys, but it is now known that not only does the sea undulate under the influence of currents, tides and variations in gravity field but the land masses themselves are subject to both vertical and horizontal displacements, due to earth tides, plate tectonics, coastal tilting and other processes.

The best method of trying to resolve those discrepancies is by accurately tracking the satellite orbit and its perturbations while, at the same time, measuring the satellite's height above the sea surface with a high-precision altimeter. During Seasat's operation, laser tracking stations in Europe will operate from Finland, France, Germany, Netherlands and Spain.

The time varying part of the altimeter signal, which is filtered out from the geodetic variations, represents the contribution made by tides, currents and waves, and further filtering will isolate the tidal component. Very little is known about deep ocean tides and there is no accepted global map of the tides. Tidal research has concentrated on the practical problem of computing tables for major shipping ports and, although these are more than adequate, they are founded on local observation rather than a sound knowledge of tidal dynamics of the oceans. The network of harbour tide-gauges has recently been extended to shallow seas, such as the North Sea, and a few gauges now record pressure changes at the bottom of the deep ocean. But the paucity of data does not yet allow the propagation of tidal energy into shallow seas to be computed.

The altimeter of Seasat-A may be able to extend our knowledge of tides world-wide to the point where models could accurately predict tidal oscillations at any point in space without the need for a long record of direct observations.

Polar Ice Caps

More than 10 % of the ocean's surface is covered by ice and, since direct observation is difficult in polar regions, ice surveillance forms an important part of the Seasat programme. The microwave sensors should be particularly useful in this area, since sensors operating in the visual range are severely restricted by darkness in winter and by cloud cover in summer.

The formation of new ice and the changing patterns of leads (cracks) and polynyas (irregular openings) are of obvious importance to shipping as well as to the scientific study of heat exchange over polar regions. The use of side-looking radar imagery for delineating ice features has been practised by Russian scientists for some years. This represents an area for unique scientific collaboration.

CONCLUSIONS

Once the correct interpretative techniques have been evolved, the new generation of microwave sensors deployed on Seasat-A promises to advance considerably our knowledge of the marine environment. There should be early benefits for the forecasters as statistics on waves, winds, ice cover, etc. are built up routinely for areas poorly covered at present. Eventually, good quality data will provide improved input to models of air-sea interaction processes, tides, and marine geodesy.

But this is looking far ahead. As the first satellite in a new programme, Seasat-A has for its primary task to determine the precision with which an orbiting satellite can measure sea surface parameters under different conditions. To this end, extensive checks against ' in situ ' measurements are required, and programmes are being implemented on both sides of the Atlantic. The Seasat Users Research Group of Europe (SURGE) was formed at the end of 1975 to co-ordinate European research in the various marine disciplines to which the Seasat programme will contribute. Working in close cooperation with the European Space Agency, the working groups of SURGE have proposed several fundamental research programmes to be carried out during the operational life of Seasat-A.

Already tentative plans are being laid for the Seasat-B mission, and if the present rate of technological progress is maintained then the scientific study of the sea from space should be well-established by the turn of the century. The 1970's may indeed see the dawn of a new era in marine exploration, and the comparisons that have been drawn with the voyages of Captain James Cook in the 1770's, and with the first scientific exploration of HMS *Challenger* in the 1870's, may prove to be entirely appropriate.

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