CHARLES C. KILGUS, JOHN L. MacARTHUR, and PETER V. K. BROWN

REMOTE SENSING BY RADAR ALTIMETRY

A satellite radar altimeter allows remote sensing of the topography of the ocean's surface with the precision of a few centimeters. Appropriate data processing provides measurements of the marine geoid, mesoscale oceanography, significant wave height, and wind speed along the satellite subtrack. APL's role in radar altimetry has included the development of the Geos-C altimeter satellite; the Seasat-1 altimeter; the Geosat-A altimeter, satellite, and ground system; and preprogram development for the NASA Ocean Topography Experiment and the Navy Remote Ocean Sensing System altimeters.

INTRODUCTION

The satellite radar altimeter has proven to be a versatile and powerful tool for remote sensing of the oceans. Data from the Geos-C and Seasat-1 altimeters have supported research in geodesy, bathymetry, mesoscale oceanography, tides, ice topography, winds, and waves.[1,2] The Geosat-A altimeter to be flown in 1985, the Ocean Topography Experiment (TOPEX) and the Navy Remote Ocean Sensing System (NROSS) altimeters under development for launch in 1989, and the multibeam altimeter being developed for future missions will provide data suitable for ocean circulation research and for operational ocean forecasting models now being implemented.

This article traces the evolution of both the measurement capabilities and the engineering implementation of the radar altimeter.

MEASUREMENTS

The radar altimeter is a conceptually simple instrument: a short-pulse radar that measures the distance between the satellite orbit and the subsatellite point on the ocean's surface with the precision of a few centimeters. Because the shape of the orbit can be determined independently, a precise measurement is provided of the shape of the ocean's surface along a line under the satellite.

In the absence of disturbing forces, the ocean would flow under the influence of gravity until its surface conformed to the shape of the geopotential field of the earth, and the altimeter would measure the marine geoid directly. However, this process is disturbed both by time-dependent oceanographic features (e.g., rings and eddies) and time-independent components of ocean circulation (e.g., the Gulf Stream). A long-term average of altimeter data reduces the impact of the "noise" introduced by oceanographic features and produces a "mean surface" that is a good approximation of the marine geoid in many areas (Fig. 1). The direction of the normal to this mean surface, the local vertical, is an important term in navigation models. The Department of Defense interest in precise navigation has made geodesy the most important application of radar altimeter data.

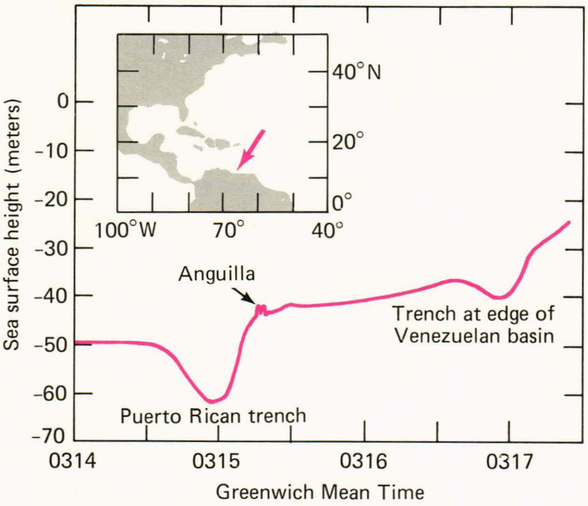

Figure 1 — The depression in the sea surface topography over the Puerto Rican trench as measured by the Seasat-1 altimeter.[3] The flight path is shown by the arrow in the insert.

Time-dependent oceanography, the "noise" on the geodesy, can be recovered from the altimeter data by subtracting out the long-term mean surface (Fig. 2). Recent research has indicated that the time-dependent mesoscale (50 to 300 km) features, like rings and eddies, that can be sensed by the altimeter have a strong impact on underwater acoustic propagation. The generation of tactical acoustic-anomaly data will be an important application of altimeter data from future missions.

Finally, the significant wave height and reflection coefficient of the surface can be determined by measuring the slope of the leading edge and the amplitude of the reflected radar pulse. Ground processing allows the surface wind speed to be derived from the reflec-

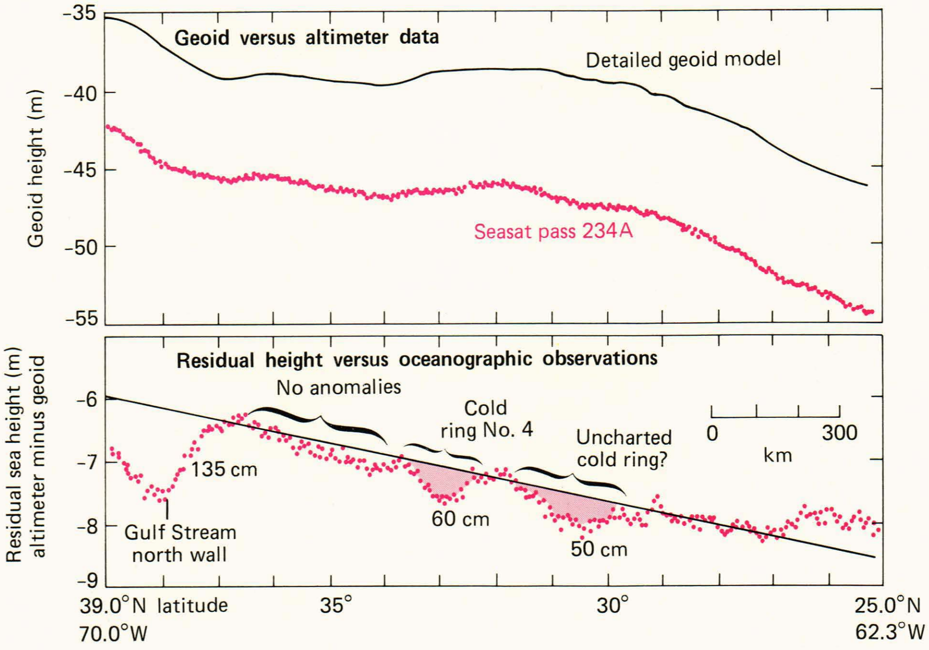

Figure 2 — In some areas of the ocean, the geoid is already known to good precision. Subtracting the known geoid from the radar altimeter data produces an oceanographic "residual" that contains a profile of the mesoscale features on the surface (R. E. Cheney in Ref. 1).

tion coefficient. Because the altimeter measures a narrow swath along the subtrack, this is a sparse data set used primarily for research applications.

MISSIONS

The in-orbit measurement precision of the altimeter improved from 1 meter, accomplished by the Skylab mission, to 10 cm, realized by Seasat-1 (Fig. 3). Unfortunately, the Seasat-1 data were limited by a spacecraft power system failure after 90 days.

The Navy Geosat mission is designed to extend the data set by placing a radar altimeter spacecraft in approximately the Seasat-1 orbit. Ground testing of the Geosat-A altimeter indicates an improvement in precision to approximately 5 cm.

NROSS, the next-generation Navy mission, will use a completely redundant altimeter with approximately the measurement precision of Geosat-A. Advances in the density of electronics will allow that altimeter to be approximately the same weight and size as the nonredundant Geosat-A instrument. NROSS will use a near-polar orbit, and more emphasis will be placed on the altimeter's ability to provide accurate tracking over ice.

TOPEX, a future NASA mission, will measure altitude at both C and Ku bands. The measurements will be combined in order to achieve 3 cm ranging, independent of the long-wavelength ionospheric propagation errors that have contaminated basin-wide ocean circulation measurements in previous altimeters.

IMPLEMENTATION

The altimeter is a high-resolution, nadir-looking, pulse-compression radar that tracks in range only. The basic elements of the system are shown in Fig. 4 and Table 1. A pulse of RF energy is transmitted toward the ocean; the signals reflected from facets on the ocean surface are received and processed to reveal the distance from the spacecraft to mean sea level. In the example shown, which pertains to Geosat-A, a pulse of 102.4 microseconds duration is transmitted at a 1020 hertz repetition frequency. The frequency within the pulse is swept over a 320 megahertz bandwidth (linear-FM) to yield a 3.125 nanosecond resolution capability. There are several unique aspects of this design, which was first used in the Seasat-1 altimeter.

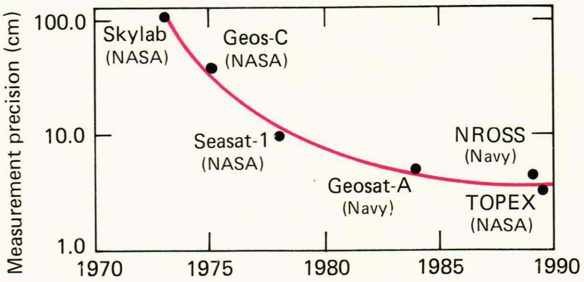

Figure 3 — The evolution of measurement precision for the satellite radar altimeter during the period 1970 to 1990.

Table 1 — Geosat-A characteristics.

Mean altitude (km)	800
Frequency (gigahertz)	13.5
Antenna beamwidth (degrees)	2.1
Peak RF power (watts)	20
Average RF power (watts)	2.1
Pulse width	
Uncompressed (microseconds)	102.4
Compressed (milliseconds)	3.125
Pulse repetition frequency (hertz)	1020

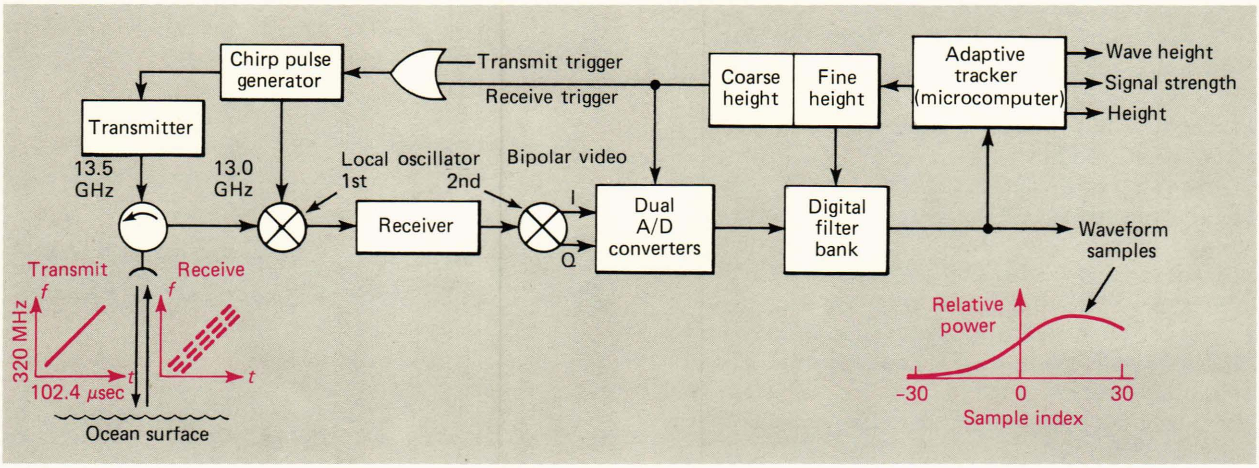

Figure 4 — Block diagram of the Geosat-A radar altimeter.

First, the signals received from reflecting facets on the surface—which are spread in time over a few tenths of a microsecond at most—are mixed with a local oscillator signal that is also a linear-FM pulse rather than the more conventional continuous wave signal. The result of this process, referred to as "full de-ramp stretch," is a transformation of the time (or range) offsets between the various facet reflections into frequency offsets. Advantage is taken of that property of the linear-FM signal that renders small time offsets indistinguishable from frequency offsets. If the signal at the output of the first mixer were applied to a bank of contiguous filters of 9766 hertz bandwidth, the output of each filter would derive from reflecting facets within a particular 3.125-nanosecond resolution element. The real advantage of the technique for this application is that the implementation of 60 range gates, spanning ±14 meters in range to accommodate wave heights up to 20 meters, requires the processing of signals in a ±300 kilohertz band, a substantial reduction from the 320 megahertz bandwidth that would be required by a more conventional approach. The reduced bandwidth makes it possible to implement an all-digital signal processor by first converting to baseband in-phase and quadrature bipolar video, followed by analog/digital conversion and then spectral analysis. The Geosat-A design implements a discrete Fourier transform with sequential filter formation; subsequent designs will use a fast Fourier transform technique to allow for an increased pulse repetition frequency and reduced height noise.

A second unusual aspect of the design is the method by which the height tracking loop is closed. The waveform samples are acted upon by an adaptive tracker to center the fast-rising leading edge of the ocean return within the bank of filters, or range gates. The timing required to adjust to the two-way path delay to and from the ocean surface is set in two parts: (a) a coarse delay that positions the local oscillator pulse in 12.5-nanosecond steps, and (b) a fine frequency offset that positions the center of the overall filter bank in steps that are equivalent to 0.05 nanosecond (0.7 cm) over a ±6.25 nanosecond range. It would be extremely difficult to achieve this level of resolution using only time domain processing.

The adaptive tracker unit also forms estimates of the leading edge slope (related to significant wave height) and signal strength (related to wind speed). The 8080-series microprocessors have been used in the designs to date. The flexibility associated with a microcomputer design has allowed the functions of telemetry formatting, command interpretation, and instrument mode control to be combined with the tracking functions. Future designs (e.g., TOPEX and NROSS) will include an uplink programming ability to allow in-flight optimization of processing algorithms.

Another altimeter subsystem that has undergone evolution is the transmitter. Three previous altimeters (those of Skylab, Geos-3, and Seasat-1) used the same 2-kilowatt, gridded traveling wave tube. Experience with those missions demonstrated that the amplifier tubes did not appear to have a long enough life expectancy to support the planned 1½ to 3 year missions. Accordingly, a long-life, low-power (20 watts) traveling wave tube, space qualified and in production for the Landsat program, was chosen for Geosat-A. The reduction in peak power was compensated for by an increase in uncompressed pulse width and an improved receiver noise figure. For TOPEX, an auxiliary altimeter channel at 5.3 gigahertz (for ionospheric correction) will use a pulsed solid-state transmitter that is currently under development. The design is applicable at 13.5 gigahertz as well, and an 8 watt transmitter at that frequency appears feasible. Enough margin has existed in past designs to allow operation at the 8-watt power level. Even at modest efficiency (10 to 15%), the pulsed solid-state designs require less power than the low-power traveling wave tubes, which are continuous-wave ungated devices. Other advantages include the smaller size and the elimination of the high-voltage power supply that is always a potential problem in the space environment.

FUTURE DEVELOPMENTS

A fundamental limitation in the temporal and spatial coverage of mesoscale oceanography afforded by present nadir-looking altimeters can be illustrated by considering the problem of detecting and tracking oceanographic eddies.

Eddies are mesoscale features that can be generated by the meandering of a frontal region like the Gulf Stream. These rotating masses of water are typically 125 km in diameter with an amplitude of 40 to 50 cm at the center. They persist for months, drifting with an average velocity of 3 km/day; that is, they move a distance equal to their own diameter in approximately 30 to 40 days.

Adequate sampling by remote sensing would require a subtrack that covers the ocean with a spatial grid of about 50 km with a revisit time of 15 to 20 days. Unfortunately, a satellite in a typical remote sensing orbit that provides a spatial grid of 50 km can achieve only a 60-day revisit time. The dilemma could be resolved if an altimeter were available that provides measurements along three swaths, one along the satellite subtrack and one displaced by 50 km on each side of the subtrack. This would improve the coverage by a factor of 3, allowing the 50-km spatial grid and 20-day revisit time that is adequate for mesoscale oceanography.

In principle, increased swath coverage can be accomplished by using offset feed horns in the altimeter dish to generate additional off-nadir antenna beams. Unfortunately, this does not produce returns like those from the nadir-looking beam.

The nadir-looking beam operates in a "pulse limited" mode (Fig. 5a). The leading edge of the transmitted pulse illuminates a large circular patch on the surface, producing a fast rise time on the return pulse. The sharp leading edge can be tracked accurately to obtain a precise measurement of the distance to the surface directly below the satellite.

However, the leading edge of the off-nadir pulse illuminates a strip on the surface (Fig. 5b), producing a smeared return that is limited in time extent only by the antenna beamwidth. The broad return has no sharp leading edge to track. It can be tracked crudely by a centroid tracker in the radar. The centroid tracking accuracy can be improved by increasing the antenna diameter to narrow the return, but a large dish is required to produce the tracking accuracy of the pulse-limited altimeter.

The multibeam altimeter uses a two-antenna interferometer to accomplish the effect of a large antenna with a simpler structure (Fig. 5c). Two small dishes with offset feeds are deployed across track and are fed with the proper phase to produce several lobes of an interferometer pattern at the desired point off nadir. In the time domain, each interferometer lobe produces a return like that from the large antenna, allowing the radar to obtain precision off-nadir altimetry by centroid tracking the central interferometer lobe.

The effect of roll rate on the measurement capability is an important topic in the development of the multibeam altimeter because a 0.4 arc-second roll causes a 10 cm shift in measured attitude. Techniques for directly measuring roll rate and for processing the recovered data to remove the effect appear to be feasible, but a conclusive analysis is not yet available.

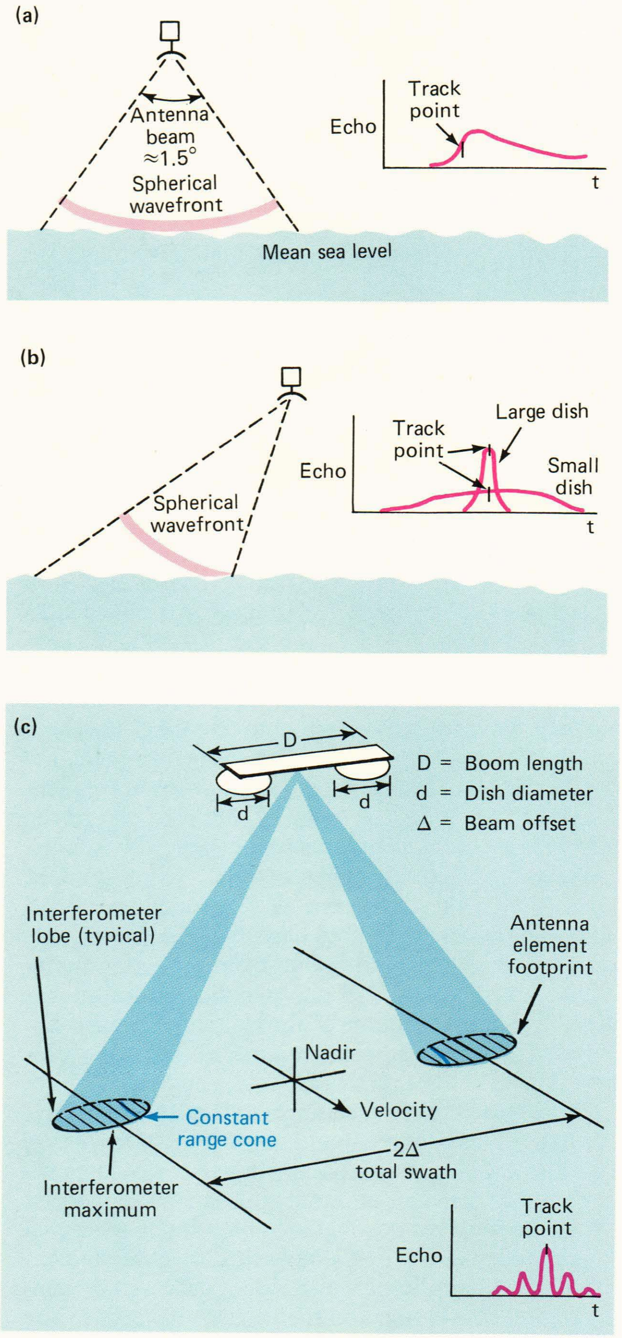

Figure 5—(a) The sharp leading edge of the nadir-looking altimeter return allows precise tracking. Tracking precision degrades if the altimeter is pointed off nadir to widen the measurement swath. (b) A large antenna is required to restore the tracking precision. (c) The multibeam altimeter produces narrow interferometer lobes that allow accurate tracking.

CONCLUSION

In-orbit performance has demonstrated that the radar altimeter is capable of 10-cm measurement precision. The Geosat-A altimeter will produce the dense data set required for geodesy. Future altimeters will incorporate redundancy for long life and dual-frequency operation to remove ionospheric effects. The multibeam altimeter under development will provide the spatial and temporal sampling required for the remote sensing of mesoscale oceanography.

REFERENCES

[1] *Seasat Special Issue I, Geophysical Evaluation,* American Geophysical Union, Washington; reprinted from *J. Geophys. Res.* **87** (C5) (30 Apr 1982).

[2] *Seasat Special Issue II, Scientific Results,* American Geophysical Union, Washington; reprinted from *J. Geophys. Res.* **88** (C3) (28 Feb 1983).

[3] W. F. Townsend, *An Initial Assessment of the Performance Achieved by the SEASAT-1 Radar Altimeter,* NASA Technical Memorandum 73279 (Feb 1980).

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