methods. Table 1 illustrates the sensitivity of the verification statistics to the type of comparison data used for evaluation. The statistics for buoys, weather ships, and transient ships (those with and without anemometers have been combined) were based upon comparisons of several revolutions. The statistics for fields are shown for two revolutions (1140, which contained high winds, and revolution 1298, which was characterized by low winds). The statistics showed that the lowest errors (standard deviations) occurred for the buoys and weather ships where averaging periods ranged from 8.5 to 20 minutes or longer, and the greatest errors occurred with transient ships where a 2-minute averaging period was used. It appeared that the stratification seen in the statistics of these comparisons was attributable largely to the lower accuracy of the 2-minute surface wind measurements from transient ships and their subsequent effect on the fields.

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2. V. J. Cardone, "Specification of wind distribution in the marine boundary layer for wave forecasting" (Publication AD-702490 GSI-TR-69-1, Geophysical Sciences Laboratory, New York University, New York, 1969).
3. A portion of the work described in this report represents results of one phase of work conducted at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS7-100.

20 April 1979

Seasat Altimeter Calibration: Initial Results

Abstract. *Preliminary analysis of radar altimeter data indicates that the instrument has met its specifications for measuring spacecraft height above the ocean surface (± 10 centimeters) and significant wave height (± 0.5 meter). There is ample evidence that the radar altimeter, having undergone development through three earth orbit missions [Skylab, Geodynamics Experimental Ocean Satellite 3 (GEOS-3), and Seasat], has reached a level of precision that now makes possible its use for important quantitative oceanographic investigations and practical applications.*

The objective of the Seasat altimeter calibration is to obtain an accurate value of the precision of the altimeter height measurement (*1*), the bias in the height measurement, the bias in the data time tag, and the accuracy of the altimeter in measuring significant wave heights (SWH) and surface wind speeds (*2*). The data required to calibrate the altimeter were obtained during September 1978 in two different regions, the Gulf of Alaska and the Bermuda Calibration Area. The Gulf of Alaska Seasat Experiment data set was used as the primary data source for calibrating SWH and the radar backscatter coefficient, σ^0. For the height bias determination, the spacecraft was maneuvered so that, beginning 10 September 1978, the orbit passed over the Bermuda laser tracking station from northeast to southwest once every 3 days. During the next month the Bermuda laser was successful in tracking the spacecraft during four overflights whose ground tracks passed within 5 km of the laser site. The precision of the laser tracking data was ± 8 cm during each pass.

The altimetry data used for the calibration are the raw measurements corrected for instrument, atmospheric, and geophysical effects. Consequently, determination of the altimeter height bias and the accuracy of SWH and σ^0 measurements requires an associated validation of the correction algorithms. The basic height calibration geometry is shown in Fig. 1 (*3*). By assuming a high-elevation pass with continuous laser and altimeter ranging, one can use the measurements directly over the tracking station for bias estimation by equating the altimeter measurement, extrapolated to the ellipsoid, to the extrapolated laser measurement (*4*). Equating the two measurements (Fig. 1) leads to the following relation (*5*):

$$h_a - b + h_t + \delta h + h_g(\text{a}) = h_g(\text{s}) + h_m + R$$

If all other terms have been evaluated, Eq. 1 can be used to determine b. The terms after the equal sign yield the calculated spacecraft height above the ellipsoid as determined in most orbit determination programs. The terms $h_a - b$ are based on the altimeter measurement, which must be related to the ellipsoid through a tide model (*6*) and a geoid model (*7*). An ionospheric and tropospheric correction model also is required (*8*). Using Eq. 1, one can calculate b (even though the satellite may not pass directly over the laser) if allowances are made for changes in the geoid between the altimeter footprint and the laser site.

Since the altimeter cannot track over land to the accuracy required for the bias determination and the laser cannot track directly overhead because of mount constraints, two special approaches were

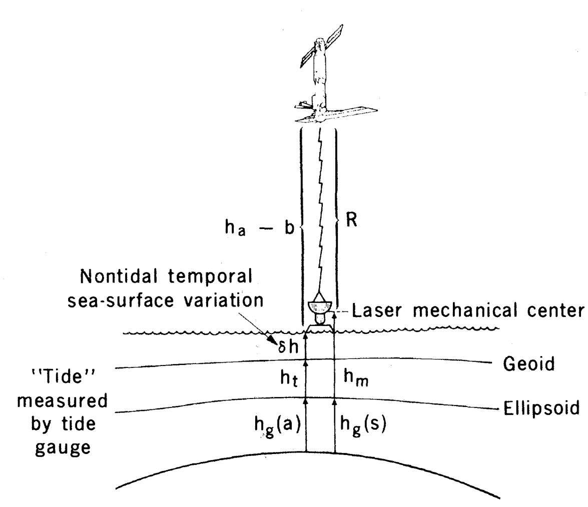

Fig. 1. Calibration geometry based on the use of the overhead pass.

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used to analyze the data (9). In the first the altimeter residuals are interpolated through the data gap which occurs when the altimeter is over the island of Bermuda (10). By interpolating the altimeter residual to the point of closest approach and then evaluating the remainder of the terms in Eq. 1, one can obtain b. This approach was used to obtain the values shown in Table 1 for the four dates listed. The weighted mean bias obtained from these values is $b = -0.50 \pm 0.11$ m. In the second method one uses laser and altimeter measurements as close to the laser site as possible without the inclusion of any land in the altimeter footprint. All quantities in Eq. 1 are extrapolated to the location of the altimeter footprint. The results obtained with this method yield $b = -0.51 \pm 0.30$ m.

In both cases we assume that the altimeter time tags are correct. Since all overflights were in the same direction, a timing error will map linearly into the estimated b. On the basis of the altitude rates for the calibration overflights, the height b can be expressed as (11) $b = -0.50 + 11\Delta t \pm 0.11$ m.

These determinations of b were obtained for SWH values less than 4 m. Further assessment during higher sea states is required to complete the evaluation of the instrument biases and the correction algorithms. In addition, the Bermuda overflights were scheduled after local midnight so that the effects of ionospheric refraction would be minimized. Hence, validation of the ionospheric correction model for daytime hours must be obtained. Finally, to assure absolute accuracy in the height determination, further assessment of the accuracy of the data time tag must be made.

Results obtained during the engineering assessment indicate that the noise (precision) in the altimeter height measurement is on the order of 5 to 8 cm (9) for the 4-m SWH conditions present during the Bermuda calibration activity. Measurements at this precision yield substantial information on the local variations in the sea-surface topography. Figure 2, A and B, shows a comparison of a Seasat pass in the northwest Atlantic and the corresponding profile obtained from the Geodynamics Experimental Ocean Satellite 3 (GEOS-3) mean sea surface (12). The differences shown in Fig. 2B reflect a high level of consistency between the two independent types of data. In the vicinity of the Gulf Stream boundary, these differences provide a measure of the departure of the Gulf Stream as determined by Seasat from its mean signature contained in the GEOS-3 sea surface.

Table 1. Altimeter height bias (in meters) based on the use of smoothed altimeter residuals.

Component	Overflight on 13 September 1978	16 September 1978	22 September 1978	1 October 1978
Residual*	2.38 ± 0.05, ± 0.20	2.08 ± 0.05, ± 0.20	1.73 ± 0.05, ± 0.20	1.84 ± 0.05, ± 0.20
Tide correction†	−0.35 ± 0.04	0.05 ± 0.04	0.31 ± 0.04	0.24 ± 0.04
Dry troposphere	−2.33 ± 0.03	−2.31 ± 0.03	−2.34 ± 0.03	−2.32 ± 0.03
Wet troposphere‡	−0.25 ± 0.02	−0.19 ± 0.02	−0.26 ± 0.02	−0.33 ± 0.02
Geoid slope§	0 ± 0.03	0 ± 0.03	0.06 ± 0.05	0.10 ± 0.07
Ionosphere	−0.02 ± 0.01	−0.02 ± 0.01	−0.02 ± −0.01	−0.02 ± 0.01
$H_{1/3}$ and tilt‖	0 ± −0.01	−0.01 ± 0.01	0 ± 0.01	−0.01 ± 0.01
Total	−0.57 ± 0.22	−0.40 ± 0.22	−0.52 ± 0.22	−0.50 ± 0.22
Weighted average =	−0.50 ± 0.11			

*The smoothed residual is for the time of closest approach of the ground track to the laser site. The first uncertainty is for the orbit height estimate. The second uncertainty is the result of smoothing the altimeter data across the island. †For 13 and 22 September, the values are tide gauge readings. For 16 September and 1 October, differences between the tide gauge readings and the Mofjeld tide model values were used in the data reductions. ‡Based on radiosonde data except for 13 September, which was based on surface meteorological data. §Estimated error in the geoid model, based on GEOS-3 data, between the laser site and the closest approach of the altimeter ground tracks. ‖SWH and spacecraft attitude corrections.

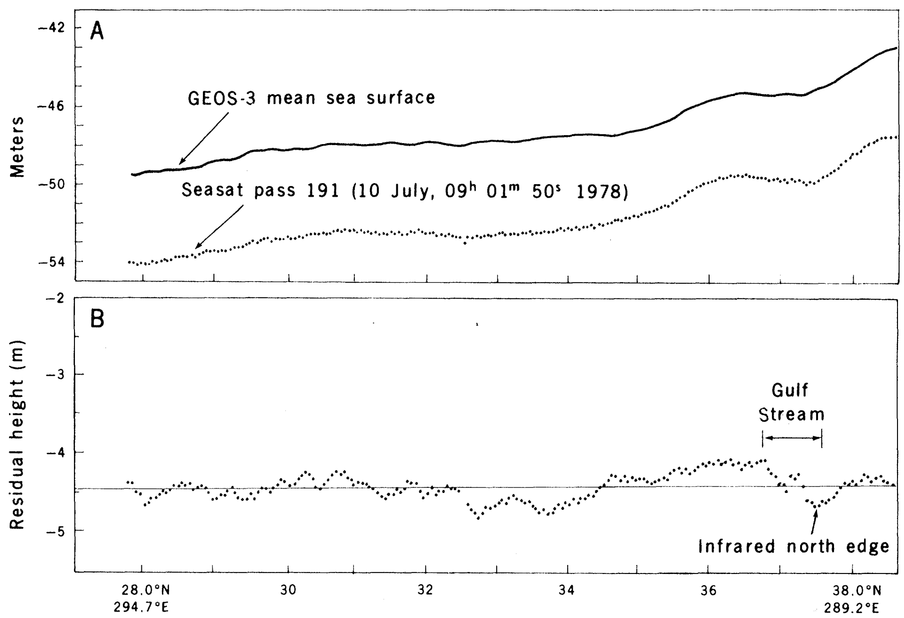

Fig. 2. (A) Seasat altimeter data and GEOS-3 mean sea-surface data; (B) difference between Seasat and GEOS-3.

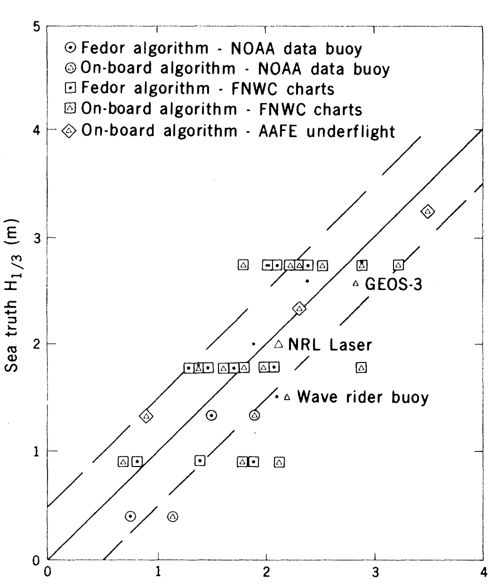

Fig. 3. Scatter diagram of significant wave height data.

To make possible a comparison between the SWH data obtained from the altimeter and that obtained from the surface truth measurements, the SWH as calculated by wave form analysis from both the on-board processor and an algorithm developed by Fedor (*13*) are plotted on the horizontal axis in Fig. 3 with the SWH given by the surface truth measurements on the vertical axis. The surface truth data came from a variety of sources. The Fleet Numerical Weather Central (FNWC) SWH charts are computer hindcasts based on records of surface winds and spot reports of wave height. Also shown is a comparison with the GEOS-3 altimeter and with several underflights of the Advanced Aircraft Flight Experiment (AAFE) altimeter and the Naval Research Laboratory NRL-P3 laser profilometer. The region enclosing the design objective of $\pm$ 0.50 m is indicated on Fig. 3 by the two dashed lines. Although Fig. 3 indicates a good qualitative agreement in the SWH measurements, the comparison suffers to the extent that a limited number of surface truth values over a limited range of wave heights (SWH $\leq$ 4 m) were available for the comparison. In fact, most of the surface observations differed significantly from the satellite ground track in both position (as much as 60 km) and time (as much as 3 hours). However, two-thirds of all comparisons in SWH shown in Fig. 3 differ by less than 0.50 m. This is the result expected from a normal distribution of random events with a standard deviation of 0.50 m.

The ocean radar backscatter coefficient, σ^0, is an indication of the reflectance properties of the ocean surface and can be related to the magnitude of near-surface winds. We compared altimeter measurements of σ^0 with measurements from the Seasat-A scatterometer system (SASS) (*9*) by using the nadir-pointing sidelobes of the main SASS beam. Because of the lower power that results from the use of the sidelobes, the SASS measurements are very sensitive to noise and interference from nearby structures on-board the spacecraft. The comparison indicates that the altimeter-determined σ^0 is in good agreement with that from the SASS horizontal polarization beams for most of the time period considered. However, at times the values disagreed by as much as 0.5 dB, possibly as a result of spacecraft pointing errors.

The algorithm for converting the altimeter σ^0 to wind speed (*14*) estimates the wind speed at a height 10 m above sea level. It has been evaluated by comparing data from GEOS-3 overflights of National Oceanic and Atmospheric Administration data buoys and is in general agreement with the data buoy results to within 2 m/sec. For this investigation, the altimeter σ^0 equation was used to invert the kinematic wind field developed by V. J. Cardone (*9*, vol. 1, pp. 6–15) to obtain comparison values of σ^0. The results indicate that the mean value of the altimeter-derived σ^0 is 1.55 dB higher than that derived from the wind field. Further investigation is required to resolve the differences between the value of σ^0 as determined from these sources.

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References and Notes

1. The altimeter height measurement, h, is determined from the round-trip time required for a radar pulse to travel to the surface of the ocean and return to the altimeter.
2. The effect of ocean waves on the altimeter measurement is to stretch the leading edge of the return radar pulse inversely to the height of the waves: the shallower the slope, the higher the waves. We define SWH to be four times the root-mean-square wave height. The effect of surface winds on the radar pulse is measured by σ^0. The higher wind speeds result in a rougher surface and an attendant lowering of the backscatter cross section.
3. The altimeter height bias can be determined by either short-arc comparisons or direct overflight comparisons. In the short-arc comparisons, the satellite is tracked simultaneously by three or more lasers. An accurate contour map of the mean sea surface must be available or a precise calibration area geoid and tide model must be determined to compute the mean sea surface at the time of altimeter overflight. Because of uncertainties in the calibration area geoid and because the laser network was unable to provide the requisite tracking support, the short-arc calibration results did not provide the required accuracy for the height calibration. Consequently, in this investigation the primary height calibration was obtained from the direct overflight tracking results.
4. C. F. Martin, "Calibration plan for the Seasat altimeter" (Planetary Sciences Department Report No. 002-79, Wolf Research and Development Group, Riverdale, Md., January 1978).
5. In Eq. 1, h_a is the measured altimeter height above the sea surface, corrected for instrument effects and atmospheric refraction; b is the bias in the altimeter measurement; $h_t + \delta h$ is the tide gauge measurement which is composed of the ocean tide, h_t, and the effects of other ocean-surface variations, δh; $h_g(a)$ is the geoid height above the reference ellipsoid at the subsatellite point; $h_g(s)$ is the geoid height at the tracking station; h_m is the height of the tracking station above the geoid; and R is the measured distance from the laser tracking station to the satellite.
6. Since the altimeter calibration requires surface observations in the form of tidal measurements that are accurate to 1 or 2 cm, a new tide gauge was installed by the National Ocean Survey at the location of an Exxon oil dock on the northwestern side of Bermuda. Precise measurements were made of the height difference between the tide gauge and the former bench marks so that the new tide station was surveyed with respect to the axis of the laser tracking station. The contribution of error sources from such factors as topographically trapped waves and currents, local currents, wind setup, tide measurement uncertainty, shelf topography, and tidal wave phase effects was estimated to be 3.5 cm (root-mean-square).
7. J. G. Marsh and E. S. Chang, *Proc. Mar. Geodesy* **1**, 253 (1977).
8. To obtain accurate values for the wet component of tropospheric refraction, radiosonde measurements were taken during the Bermuda overflight periods. The dry tropospheric refraction correction was derived from the meteorological conditions routinely measured at the Bermuda laser site. The ionospheric corrections were based on Faraday rotation data taken at Goldstone, Calif., and Armidale, Australia.
9. G. H. Born, D. B. Lame, J. C. Wilkerson, Eds., "GOASEX Workshop Report" (Report 622-101, Jet Propulsion Laboratory, Pasadena, Calif., 1979) (internal document).
10. The altimeter residual is defined as the difference between the observed and computed values of the altimeter height above the ellipsoid.
11. The quantity Δt is the time tag correction (in seconds) which must be applied. During the Bermuda overflight the altitude rate is on the order of -11 m/sec. At present, it has not been possible to validate the altimeter data time tag. Preliminary quality checks indicate that the maximum possible time tag correction is on the order of 0.1 second.
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