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Experimental and Theoretical Determination of Sea-State Bias in Radar Altimetry

Robert H. Stewart

Texas A&M University
Department of Oceanography
College Station, Texas 77843-3146

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Introduction. This is the final report for work funded by NASA grant NAGW-1836 to the Texas A & M Research Foundation entitled "Experimental and Theoretical Determination of Sea-State Bias in Radar Altimetry".

The starting date for NAGW-1836 was nominally 1 June 1989. The fully executed award, however, was not completed until 20 September 1989, and little work was done between May and September 1989. Four semi-annual reports describing work at the Texas A&M University in support of NAGW-1836 were submitted for the periods between 1 June 1989 to 31 January 1992.

The work described here was done by the Principal Investigator Robert Stewart with the help of a graduate students Carole Current, Ramdas Chandrasekhar, and Badarinath Devalla at Texas A&M University. Our work supported a separate task conducted under Profs. W. Kenneth Melville and Jin Kong and their graduate students at the Massachusetts Institute of Technology (MIT). Although my work at Texas A&M University has been independently funded by NASA, I will not make a distinction in the following report between the tasks at the two institutions. I will, however, describe primarily my contributions to the project.

Goals of the Program. The major unknown error in radar altimetry is due to waves on the sea surface which cause the mean radar-reflecting surface to be displaced from mean sea level. This is the electromagnetic bias. The primary motivation for the project was to understand the causes of the bias so that the error it produces in radar altimetry could be calculated and removed from altimeter measurements made from space by the Topex/Poseidon altimetric satellite. The goals of the project were: 1) observe radar scatter at vertical incidence using a simple radar on a platform for a wide variety of environmental conditions at the same time wind and wave conditions were measured; 2) calculate electromagnetic bias from the radar observations; 3) investigate the limitations of the present theory describing radar scatter at vertical incidence; 4) compare measured electromagnetic bias with bias calculated from theory using measurements of wind and waves made at the time of the radar measurements; and 5) if possible, extend the theory so bias can be calculated for a wider range of environmental conditions.

All goals of the program were met when the work at Texas A&M University and the Massachusetts Institute of Technology are considered together.

Summary of Work

Two experiments were conducted to measure electromagnetic bias for a wide variety of oceanic conditions. We helped with the design of the experiments and with the analysis of data from them. The first, the SAXON Experiment, was conducted from the Chesapeake Bay Light Tower in the Atlantic just offshore of the Chesapeake Bay. The second, the Gulf of Mexico Experiment, was conducted from an oil production platform in the Gulf of Mexico offshore of the Texas Gulf coast. Both experiments produced very useful data.

The SAXON Experiment

The SAXON experiment was a large experiment funded and organized by the Office of Naval Research to understand microwave signals scattered from the sea surface. The experiment was conducted at the Chesapeake Bay Light Tower just off-shore of the entrance to the Chesapeake Bay. During the experiment the MIT group deployed and operated equipment to measure radar scatter at vertical and 45° incidence angles for a variety of wind and wave conditions, plus wave height near the point of radar observations, wind speed, and air-sea temperature difference. At the same time, other groups measured other environmental variables, including wind stress. Data were collected for a 24-day period from 19 September to 12 October 1988. During the experiment, hourly averaged values of wind speed ranged from 0.2 to 15.3 m/s, significant wave height ranged from 0.3 to 2.9 m, and air minus sea temperature ranged from –10.2 to 5.4 °C.

The initial results of the SAXON Experiment were published in the *Journal of Geophysical Research* entitled "Measurements of electromagnetic bias in radar altimetry" (Melville, et al., 1991). The abstract from the paper stated:

"The accuracy of satellite altimetric measurements of sea level is limited in part by the influence by ocean waves on the altimeter signal reflected from the sea surface. The difference between the mean reflecting surface and mean sea level is the electromagnetic bias. The bias is poorly known; yet, for such altimetric satellite missions as Topex/Poseidon, it is the largest source of error exclusive of those resulting from calculation of the satellite's ephemeris. Previous observations of electromagnetic bias have had a large, apparently random scatter, in the range of 1–5% of significant wave height; and the observations are inconsistent with theoretical calculations of the bias.

"To obtain a better understanding of the bias, we have measured it directly using a 14-GHz scatterometer on the Chesapeake Bay Light Tower. We find the bias is a quadratic function of significant wave height $H_{1/3}$. The normalized bias β, defined as the bias divided by the significant wave height, is strongly correlated with wind speed at 10 meters U_{10} and much less strongly with significant wave height :

$$\beta = -0.0146 - 0.00215\, U_{10} - 0.00389\, H_{1/3} \quad (r^2 = 0.737) \tag{1}$$

based on 318 hourly averaged values, where r is the correlation coefficient, and units are *m/s* for U_{10} and *m* for $H_{1/3}$. The mean value for β is –0.034; and the standard deviation of the variability about the mean is ±0.0097. The standard deviation of the variability after removing the influence of wind and waves is ±0.0051 = 0.51%. The results are based on data collected over a 24-day period during the SAXON experiment from 19 September to 12 October 1988. During the experiment, hourly averaged values of wind speed ranged from 0.2 to 15.3 m/s, significant wave height ranged from 0.3 to 2.9 m, and air minus sea temperature ranged from –10.2 to 5.4 °C.

"Because U_{10} can be calculated from the scattering cross section per unit area σ_0 of the sea measured by spaceborne altimeters, we investigated the usefulness of σ_0 for calculating bias. We find

$$\beta = -0.0163 - 2.15/\sigma_0^2 - 0.00291\, H_{1/3} \quad (r^2 = 0.528) \tag{2}$$

based on 325 hourly averaged values. The standard deviation of the variability after removing the influence of the radio cross section and waves is ±0.0065 = 0.65%. The results indicate electromagnetic bias in radar altimetry may be reduced to the level required by the Topex/Poseidon mission using only altimetric data. We find, furthermore, the relationship between σ_0 and wind speed agrees with previously published power-law relationships within the accuracy of the measurement.

"The mean value of β, its variability, and the sensitivity of β to wind speed all agree well with previous measurements made using a 10-GHz radar carried on a low-flying aircraft. The mean value of β, its variability, and the sensitivity with wind were all significantly larger than previous measurements made using a 39-GHz radar also carried on a low-flying aircraft. All experiments included a similar range of wind speeds and wave heights. The SAXON data were, however, much more extensive, and the statistical relationships correspondingly more significant. The mean value of β is very close to the mean value determined from global measurements of sea level made by Geosat.

Because only one-half of the variability of bias measured during the SAXON experiment could be explained by correlations with wave height and wind speed, we began further work to understand the bias. The work followed two paths. The first was the analysis of data from the Gulf of Mexico experiment. How did the results compare with the results from SAXON, how did they differ, and why? The second was a deeper analysis of the SAXON data to follow up ideas developed during discussions at the Topex/Poseidon Science Working Team meeting in October 1990. Roman Glazman proposes that the bias should be related to non-dimensional fetch, wave age, and significant wave slope. The problem with his hypothesis, however, is that the wave field usually is a combination of old and new waves. Hence, how to determine the relative importance of each? Because the bias is calculated from the product of wave displacement and scattering cross section, the co-spectrum of the two variables gives the contribution to bias by frequency. Thus, the influence of swell can be separated from the influence of newly developed waves through a co-spectral analysis of the signals recorded during SAXON.

Co-spectral analysis

To determine which waves on the sea surface contribute to electromagnetic bias, we calculated the co-spectrum of sea-surface displacement and scattering cross-section using observations collected during SAXON, paying particular attention to those times when the difference between bias predicted from (1) differed substantially from the measured bias. Calculation of the spectrum required obtaining copies of the raw data collected during SAXON, unpacking the data, and forming time series of wave height and radar scatter. We then calculated the co-spectrum for four-hour sections of data on days between 7 and 13 October 1988, days 18 to 24 in figure 1, when the residual bias varied from a large positive value to a large negative value and back to a positive value. We later analyzed data from 1 October 1988 (day 12) to further understand the influence of swell on bias.

The co-spectra from 10–12 October (figure 2) showed that only the locally generated wind waves made substantial contributions to the bias. This implied that Glazman's ideas have some validity, and we could predict bias from knowledge of the local wind velocity and wave age. Because the locally generated waves responded quickly to the wind, the local waves quickly reached equilibrium with the wind, perhaps wave age could be ignored. Using this hypothesis, we correlated normalized bias (bias divided by wave height) with wave height predicted by Pierson-Moskowitz spectra based on only the local wind to obtain:

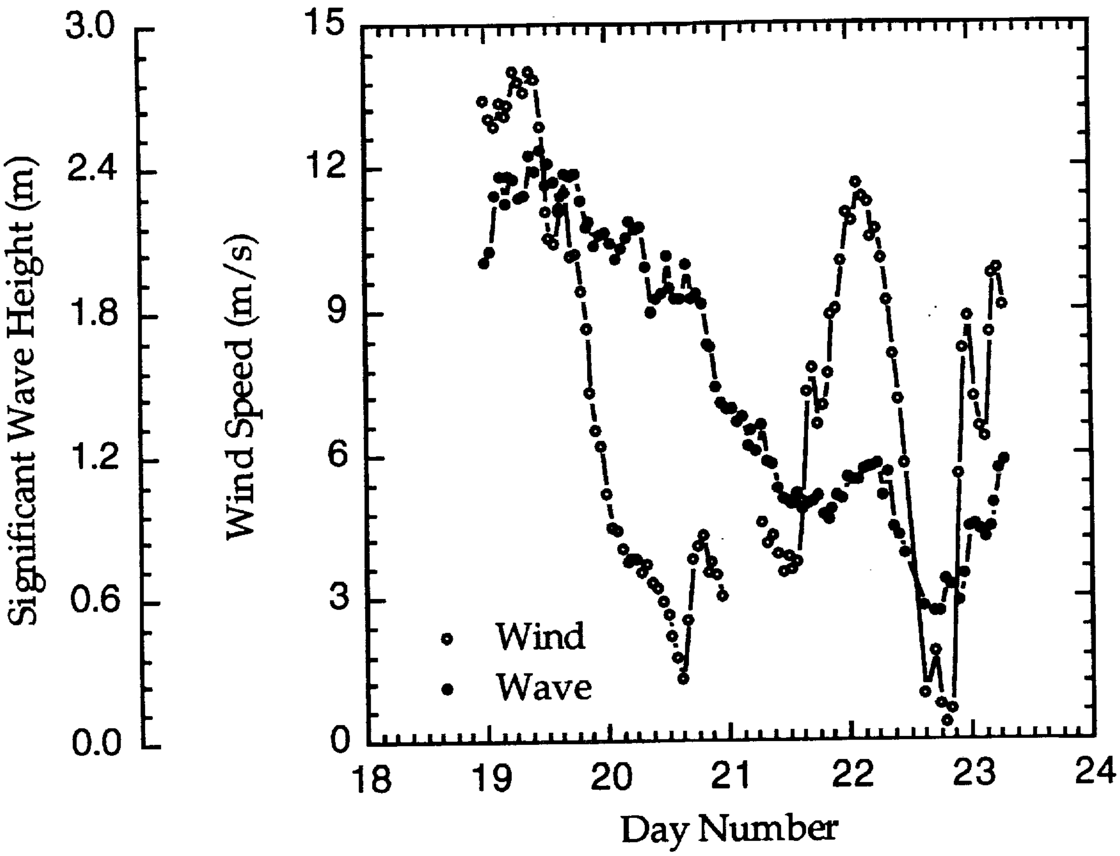

Figure 1. Significant wave height ($H_{1/3}$) and wind speed (U) as a function of time for days between day number 18 (7 October) and 24 (13 October) during SAXON.

$$\beta = -0.0128 - 0.0095\, H_{1/3} - 0.0102\, H_{pm}/H_{1/3} \quad (r^2 = 0.762) \tag{3}$$

where $\beta = bias/H_{1/3}$ = normalized bias, $H_{1/3}$ is significant wave height, and $H_{pm} = 0.0214\, U^2$ = wave height predicted from Pierson-Moskowitz using the local wind velocity U at 10 m above the sea surface. All terms in (3) are statistically significant at the 95% level. Other correlations, based only on H_{pm} were much less successful. Both $H_{1/3}$ and H_{pm} are important for describing the bias.

The mean value for β is –0.034; and the standard deviation of the variability about the mean is ±0.0097. The standard deviation of the variability after removing the influence of wind and wave development ($H_{pm}/H_{1/3}$) is ±0.0048 = 0.48%.

The correlation (3) was slightly better than the published correlation (1); and the residual of (3) is independent of wind speed. Thus the wind speed dependence in (1) is due only to the waves being partly developed. The residual between the bias predicted by (3) and the observed bias was not random. A scatter plot of residual as a

Figure 2. Power spectral density of wave displacement (upper) and coherence between wave displacement and radar cross-section (lower) as a function of frequency on day 21 of SAXON (10 October 1988). Note that coherence is the normalized co-spectrum, and that it gives the contribution to bias as a function of wave frequency. It shows that only locally generated waves contribute to the bias.

function of predicted bias had a slight quadratic dependence on the predicted value. We found that the best functional fit to the observed bias was:

$$\beta = -0.0078 - 0.0124\, H_{1/3} - 0.0138\, H_{pm}/H_{1/3} - 0.0008\, H_{pm}^2 \quad (r^2 = 0.795) \qquad (4)$$

All terms in (4) are statistically significant at the 95% level. The scatter plot of the residual as a function of the bias predicted by (4) appears to be random with no obvious structure. The standard deviation of the variability after removing the influence of wind and wave development is ±0.0048 = 0.45%.

The functions (3) and (4) indicate that both $H_{1/3}$ and H_{pm} influence electromagnetic bias. This is due to the time delay between the onset of winds and the development of long waves in equilibrium with the wind. Using only H_{pm} as a predictor, leads to incorrect estimates of the bias until the local waves reach equilibrium with the wind, usually within a few hours of onset of the wind. Furthermore, normalizing bias with H_{pm} leads to very large errors because as wind speed drops to small values U decreases, H_{pm} becomes small, and $Bias/H_{pm}$ becomes large. Normalizing with $H_{1/3}$ eliminates this problem.

To understand how local waves influence electromagnetic bias, we plotted radar cross-section as a function of wave displacement (figure 3). Previous such plots (Melville, *et al.* 1991) showed that cross-section is a linear function of wave displacement. The figure shows that, when local waves are small compared with significant wave height, the linear relationship breaks down in the wave trough. That is, the

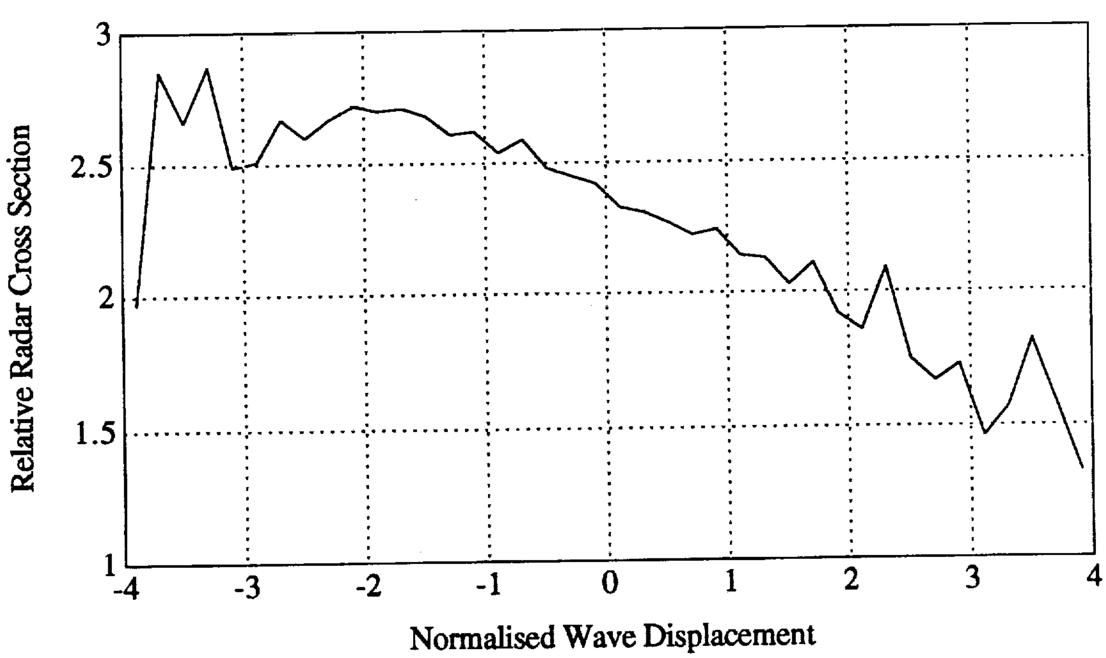

Figure 3. Relative radar cross-section on day 23 (12 October 1988) as a function of normalized wave displacement, where normalized displacement is displacement divided by the standard deviation of displacement.

wave trough is not as good a reflector as expected when locally generated waves are small. Hence, electromagnetic bias, which is due to wave troughs being better reflectors than crests, is reduced; and the mean radar reflecting surface is closer to mean sea level.

These results from the further analysis of SAXON data are being prepared for publication using funds from a continuation of this effort. We expect the results will be submitted for publication early in 1993.

To obtain further information about electromagnetic bias, especially for other radar frequencies and wind conditions, we conducted a second experiment, the Gulf of Mexico Experiment.

The Gulf of Mexico Experiment

The Gulf of Mexico Experiment was designed to measure bias in deeper water for a wider range of winds and waves than at SAXON and at the two radar frequencies that would be used by the NASA altimeter on Topex/Poseidon. The site for the second experiment was chosen in part on the results of the SAXON experiment and in part on the results of theoretical studies. Several sites were evaluated, including: 1) the Floating Instrument Platform, FLIP; 2) an offshore platform in the Gulf of Mexico; 3) the Buzzard's Bay site originally proposed for our experimental studies; and 4) the Chesapeake Bay Light Tower used for SAXON. To be suitable for our experiment: 1) the site had to be in deep, clean water typical of the open ocean; 2) it had to have a variety of wind and wave conditions; and 3) it had to be readily accessible and suitable for the experiments we wished to do.

We found the most useful site was a platform in the Gulf of Mexico. It consists of three structures linked by bridges, the Brazos A-19 Complex operated by Shell Offshore. The bridges allowed a clear view of the water surface undisturbed by airflow around the platform in contrast to the more disturbed conditions seen in the first experiment. The platform was 30 km offshore of the Texas coast in 30 m water depth. The water was deeper than at SAXON, and the platform was further offshore. The platform was stable; and it was available for extended periods of time, so instruments could be deployed for several months. This increased the chance of observing a wider variety of weather conditions than were observed during the first experiment.

Equipment was deployed on the platform by the MIT group beginning in late November 1989. Except as noted below, the equipment was operated continuously until April 1990, when it was removed from the platform. The equipment included: 1) C-band and K-band Doppler scatterometers, 2) an EMI infrared wave gage, 4) a Holometric infrared wave gage modified for measuring infrared reflectance from the sea surface, which was installed in late March 1990, 5) a capacitance-wire wave gage for measuring short wavelength waves, and 6) a meteorological package for measuring wind velocity and air and sea temperatures. Data were recorded digitally and stored on optical disks. Some data were transmitted back each day to MIT for monitoring the operation of the experiment.

During the experiment wind speed ranged from 0 to 15 m/s, significant wave height ranged from 0.2 to 3.0 m, and air minus sea temperature ranged up to –10 °C. Strong northerly winds occasionally blew offshore against the incoming waves allowing observations during very unstable conditions. At other times strong onshore winds blew with the waves, and the air was the same temperature as the sea.

The processed data from the Gulf of Mexico consisted of over 2,500 hourly averaged values from 38 channels of data. The data set included time, wind velocity, air and sea temperature, scattered power at C and Ku band, wave height from seven instruments, electromagnetic bias at C and Ku band calculated from the seven measurements of wave height. Waves were measured by Thorne and Holometrics gages, by a wire gage, and by two Doppler channels of radio data from each of the C and Ku band scatterometers.

Before the data could be used they were edited to remove data recorded when instruments were not operating correctly and to remove observations influenced by wind distortions produced by the platform when it was upwind of the instruments. For example, the sea-temperature gage leaked and was removed from the water, although the output from the gage continued to be recorded. The editing also identified outliers, some of which were correct, some of which were erroneous.

After editing, the data were used for investigating the relationship between electromagnetic bias at C and Ku band. A preliminary analysis of the data (Melville, *et al.* 1990a, 1990b) indicated the electromagnetic bias for 14 *GHz* radio signals was the same as that calculated from SAXON data. The bias at 5 GHz was found to be 20–25% greater than at 14 GHz for larger waves and stronger winds. We found there was a consistent trend for the bias at 5 GHz to exceed the bias at 14 GHz.

Most of the analysis of data from the experiment was included in a Ph.D. thesis by David Arnold, a graduate student at MIT working under Prof. Kong. The information in the thesis is now being summarized for publication in a scientific journal.

Calculation of the Skewness of Ocean Waves

Skewness is an important but little-measured statistic. It is a measure of the nonlinearity of the wave field, and it influences, in part, the performance of very accurate radar altimeters such as the radars carried on Topex/Poseidon.

To understand the significance of skewness for open-ocean waves, we analyzed existing wave observations made during a variety of experiments funded earlier by the Office of Naval Research to calculate the skewness of sea-surface displacement. Sea surface displacement was measured by a specially designed buoy deployed during a series of experiments conducted from 1972 to 1978.

We found that skewness tends to be small, less than 0.02, and that it results from the asymmetrical distribution of extreme values for surface displacement in wave crests and troughs (figure 4). Rare, very large waves dominate the skewness.

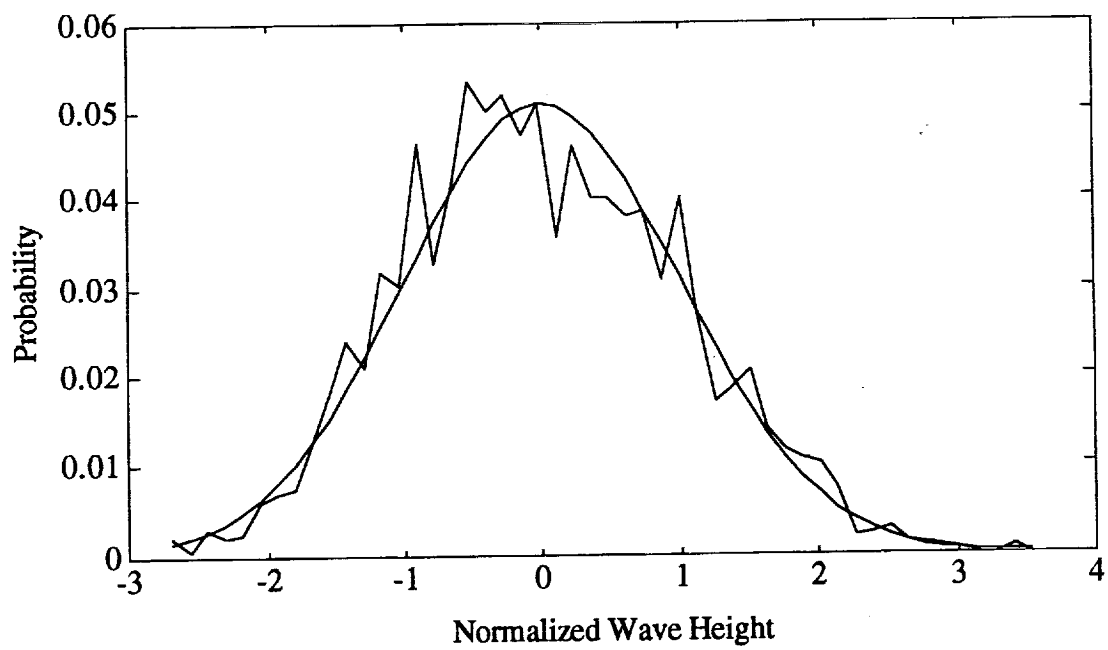

Figure 4. Histogram of surface displacement recorded for an 11-minute period in a trade-wind sea (solid line) superimposed on a normal distribution with the same standard deviation as the data (dotted line). Wave height is normalized by the standard deviation of surface displacement. The skewness of this record is 0.189, while the average skewness of all 16 records recorded in the same experiment is 0.028. The large skewness in this record is due mostly to the observations of a few waves with heights exceeding 3 standard deviations. Note the asymmetrical tails of the histogram.

We also found that skewness is well correlated with significant wave slope (figure 5).

We next calculated the correlation coefficient between skewness and wind speed, significant wave height, significant wave slope, wave age, spectral width, and the slopes of the spectrum near the peak. All of these variables have been stated by various authors to be related to wave skewness. We found that the most significant correlation was with significant wave slope (Figure 5). The linear regression is:

$$\lambda = 5.35\,\pi\ \S - 0.015 \quad (r^2 = 73.1\%) \tag{5}$$

with 26 degrees of freedom, where λ is wave skewness, § is significant wave slope, and r is the regression coefficient. The coefficient of proportionality is significant at the 99% confidence level; but the constant is not statistically different from zero.

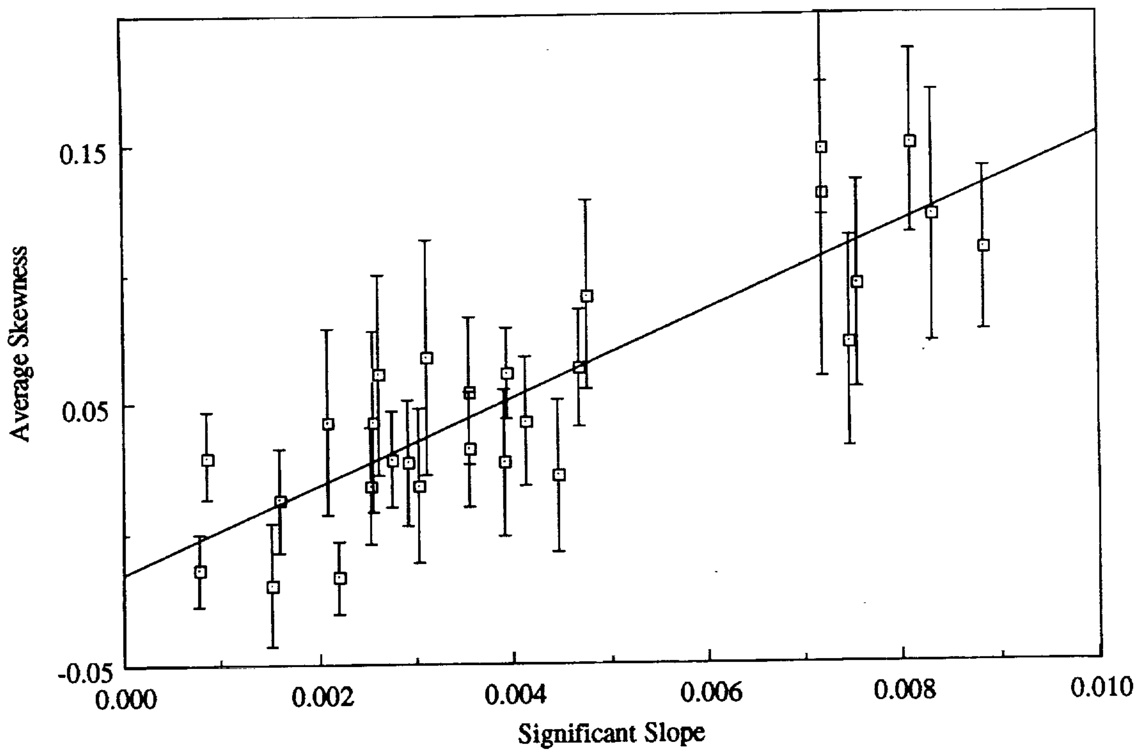

Figure 5. Mean skewness calculated from approximately 3 hours of data collected in each experiment as a function of significant wave slope calculated from the average spectrum of wave displacement. The error bars were calculated from standard deviation of skewness from all 10–20 minutes samples of data recorded during the experiment, divided by the square root of the number of samples. This is an indication of the statistical uncertainty of the mean skewness.

The coefficient is slightly smaller than that obtained by Huang and Long (1980) and by McClain, Chen and Hart (1982), who found:

$$\lambda = 8 \pi \S \qquad (6)$$

from an analysis of wave-tank data and a few satellite and aircraft observations of ocean waves. The coefficients in (5) and (6) are different at the 99% confidence level.

To determine which wave frequencies contribute to the skewness, the series of surface displacement were low-pass filtered, and the skewness calculated as a function of the cut-off frequency. A plot of skewness versus cut-off frequency (Figure 6) clearly shows that only waves near twice the frequency of the spectral peak contribute to the skewness. Short waves which contribute substantially to the variance of wave slope had no influence. The results agree well with work by Srokosz and Longuet-Higgins who showed that wave-wave interactions at second order are the primary contributors to wave skewness. The interaction steepens the wave crest and flattens the wave trough.

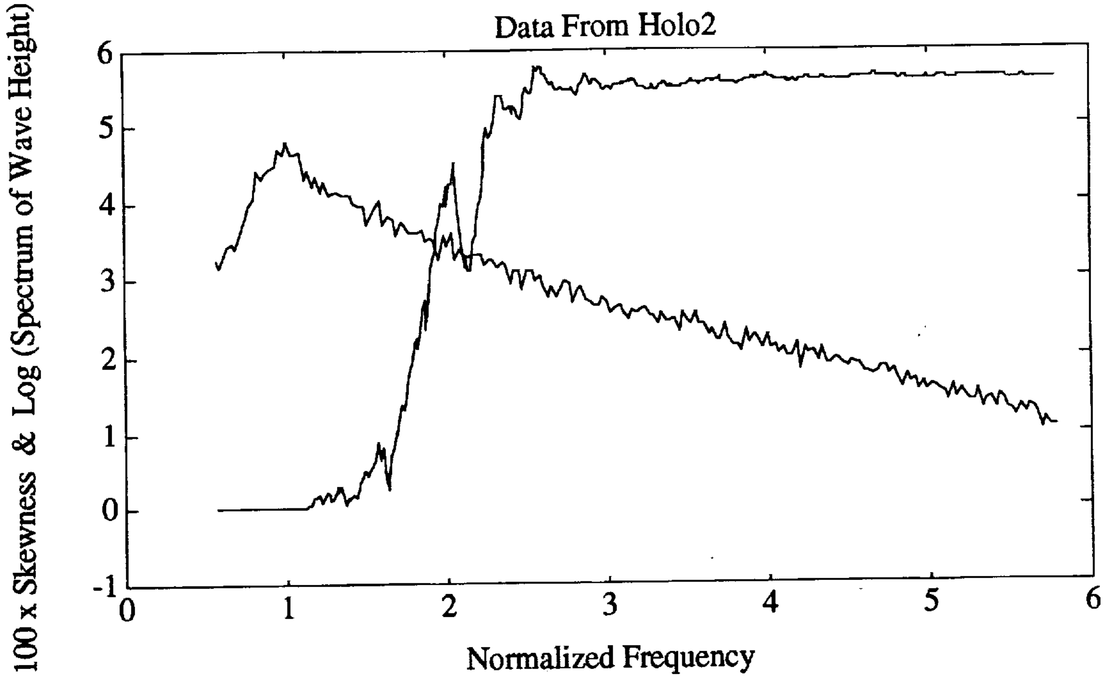

Figure 6. Skewness as a function of frequency using data from a trade-wind sea measured north of Hawaii together with the spectrum of surface displacement. The skewness plot shows that only waves having frequencies between 1 and 3 time the frequency at the spectral peak contribute to the skewness. Normalized frequency is frequency divided by the frequency of the waves at the peak of the ocean wave height spectrum. The curves were calculated from approximately 3 hours of wave data.

Part of this work was supported by NASA Grant NAG-1038 on "Assessment of altimeter satellite accuracy", and the results benefited both projects. The results will be augmented with further data from SAXON and the Gulf of Mexico experiments and submitted for publication. The results were submitted to the *Journal of Fluid Mechanics,* but the referees wanted a more theoretical development.

Theoretical Studies

The investigations of the theory of radio scatter at vertical incidence angles proved to be very useful. David Arnold used numerical calculations of radar scatter from reflecting rough surfaces to show that the short waves on the sea surface strongly influence the scatter of radar signals. The radar cross section of the sea as a function of surface displacement can be well predicted knowing the distribution of meter-wavelength waves on the surface. The work formed the basis for pert of his thesis. He is now writing up his results for publication in a scientific journal.

Management Issues

An important part of the proposed work was to have been done by graduate students. The first student, Carole Current, made useful progress, but she quit unexpectedly after the first year, in January 1991. She was replaced, after some delay by another student, Ramdas Chandrasekhar. Ramdas, however, was very unfamiliar with the work, and Current was unavailable to explain what she had done. As a result, Ramdas was not very productive. He quit in July 1991 to work full time on course work because his studies were more difficult than he had expected and because he was not pleased with his progress. He was replaced in September by Badarinath Devalla. Devalla started slowly because of previous commitments, but he soon made good progress. He had worked on radar data in India, and he is a good programmer. He understood what we were trying to do, and he was enthusiastic about his work. By the end of the grant he had produced very useful results.

Because we made little progress for nearly one year, our spending was slower than planned. We received several extensions to the grant at no cost to NASA.

Publications

Melville, W.K., Kong, J.A., Stewart, R.H., Keller, W.C., Jessup, A.T., Arnold, D. & Slinn, A. (1989). The measurement and Modelling of sea-state bias in Saxon. IGARS 89.

Melville, W.K., Kong, J.A., Stewart, R.H., Keller, W.C., Arnold, D., Jessup, A.T., & Lamarre, E. (1990a). Measurements of sea-state bias at Ku and C bands. International Union of Radio Science Signature Problems in Microwave Remote Sensing of the Surface of the Earth, May 1990a, Hyannis (Abstract only).

Melville, W.K., Stewart, R.H., Kong, J.A., Keller, W.C., Arnold, D., Jessup, A.T., and Lamarre, E. (1990b) Measurements of EM bias at Ku and C bands. Oceans 90 Conference, Washington, D.C.

Melville, W.K., Stewart, R.H., Keller, W.C., Kong, J.A., Arnold, D.V., Jessup, A.T., Loewen, M.R., and Slinn, A.M. (1991) Measurements of electromagnetic bias in radar altimetry. *J. Geophysical Research.* **96** (C3): 4915–4924.

Appendices

The appendices contain reprints of publications.

A. Melville, *et al.* 1989.

B. Melville, *et al.* 1990b.

C. Melville, *et al.* 1991.

THE MEASUREMENT AND MODELLING OF SEA-STATE BIAS IN SAXON

W.K. Melville, J.A. Kong, R.H. Stewart*, W.C. Keller‡, A.T. Jessup, D. Arnold & A. Slinn

Massachusetts Institute of Technology, Cambridge, MA USA.
*Scripps Institution of Oceanography, La Jolla, CA USA.
‡Naval Research Laboratory, Washington, DC USA.

Abstract

Tower-based measurements of sea-state bias were made using a 14GHz scatterometer and a colocated IR wave gauge. The measured bias was found to be an increasing fraction of the significant wave height (SWH) with increasing wind speed. Theoretical modelling of the scattering from a two-dimensional two-scale model of the sea surface leads to a prediction of sea-state bias based on the wave height-dependent scattering cross section in the physical optics approximation. The implications of the measurements and modelling for sea-state bias algorithms are discussed.

Keywords: Altimetry, EM Bias, Sea-state Bias.

1. Introduction

Under reasonable assumptions the larger ocean current systems can be related to the slope of the mean sea surface. Thus measurements of sea level on a global scale can be used to infer ocean currents. Spaceborne radar altimetric systems measure sea level through the use of a radar altimeter to determine the height of the satellite above the sea surface, and tracking systems to measure the height of the satellite above the center of the Earth, the difference between the two measurements being the sea level. While simple in principle, the measurement of sea level is difficult in practice because it must have a precision and accuracy of a few centimeters for many studies in ocean dynamics.

Many sources of error must be accounted for in altimetric satellite measurements, but sea-state induced error is perhaps the largest remaining error for which a correction algorithm is not established. Sea-state induced error is important because it can have a magnitude of many centimeters and because it may have wavelengths of kilometers to megameters that correspomnd to the dominant scales of ocean variability. Sea state induced errors result from two sources: (a) ocean waves distort the altimeter pulse; and (b) ocean waves cause the mean reflecting surface to differ in elevation from the mean sea level. The former error varies with the design of the radar. The latter, which we call "sea-state bias" is common to all altimeters, and is an intrinsic hydrodynamic-electromagnetic property of the sea surface. It results from a weak correlation between the reflectivity of the sea surface and the deviation of the sea surface from its mean value. The fact that the sea state is dynamically coupled to the spatial and temporal gradients in ocean currents and that sea-state increases with latitude makes its determination particularly important if ocean currents are to be accurately resolved by radar altimeters.

The first study of sea-state bias was by Yaplee et al. (1971) using a 10 Ghz pulsed radar on the Chesapeake Light Tower (CLT) off the coast of Virginia. A geometrical optics model of the problem which explicitly neglected the effects of high frequency gravity and gravity-capillary waves was reported by Jackson (1979). He found good agreement with the limited data of Yaplee et al.(1971) and predicted that the sea-state bias was approximately 5% of the significant wave height(SWH= 4* standard deviation). Later studies used airborne radars and laser profilometers (Walsh et al., 1984; Choy et al., 1984; Hoge et al., 1984) and found that:

(a) the sea-state bias expressed as a fraction of SWH was dependent on frequency:

-3.3+/-1.0% at 10GHz
-1.1+/-0.4% at 36GHz
1.4+/-0.8% at UV.

(b) the variability in the bias was apparently unpredictable, being only weakly correlated with other parameters such as wave length, wave slope, skewness, kurtosis and wind speed.

The research described here is part of a larger experimental and theoretical effort designed to (a), collect sufficient data to determine those parameters which affect the sea-state bias over a wide range of environmental conditions; and (b), develop a theoretical model of the microwave scattering which describes the measurements.

2. Experimental Measurement

Measurements of the sea-state bias at Ku-band were made from the Chesapeake Light Tower in the SAXON experiment during September and October 1988. A nadir-look, 14GHz, coherent scatterometer with a two-way 3dB illuminated area of 1.7m diameter was mounted 22m above mean sea level(MSL) at the end of a boom which extended 6.6m out from the southern end of the eastern side of the tower. Colocated with the scatterometer was a Thorn/EMI IR wave gauge having a beamwidth of 1°. A three-element capacitance-wire wave gauge array was mounted on another 6.6m boom attached to the lowest catwalk on the platform. This boom was covered with microwave absorbing material and positioned just out of the footprint of the scatterometer. Direct u^* measurements were provided by Risoe National Laboratory, Denmark, using a sonic anemometer mounted at the end of this lower boom, and 5m above MSL. Other environmental measurements included a weather station recording wind speed, direction, air and sea temperature, and relative humidity.

Approximately 250 hours of useful data were recorded and the sea-state bias was computed from the radar cross section measurements of the scatterometer and the wave measurements from the IR wave gauge. Due to the size of its footprint the IR wave gauge responded to waves out to approximately 1Hz, while the wire wave gauges had a maximum frequency response in the range 5-10Hz for smaller sea states.

3. Measured Sea-State Bias

The measured sea-state bias, ϵ_m was calculated as hourly averages of the difference in elevation between the centroid of the radar cross section and that of the sea surface. The raw data, uncorrected for range effects, are plotted in figure 1 against the hourly averaged standard deviation of the sea-surface elevation $\sigma_w(\sigma_w = SWH/4)$. The data clearly show an increase with wave height with a slope of approximately -0.14, or $d\epsilon_m/dSWH = -0.034$. To leading order, the range correction is given by $\epsilon_r/SWH = -SWH/8z_o$, where z_o is the mean range to the sea surface (22m). This would have the effect of increasing the bias by approximately 3cm for the largest waves in figure 1. In figure 2, the data of figure 1 is plotted as a normalized sea-state bias versus wind speed. These data show that there is a clear correlation of the normalized bias with the wind speed. Further analysis of the data is proceeding based on these preliminary results.

4. Modelling of Sea-State Bias

Previous researchers have attempted to predict the sea-state bias using the geometrical optics solution based on a knowledge of the joint height-slope probability density function of the ocean surface. This approach has two problems. First, this distribution depends on the small scale features of the ocean surface and is difficult to measure; second, it does not predict any dependence on radar frequency.

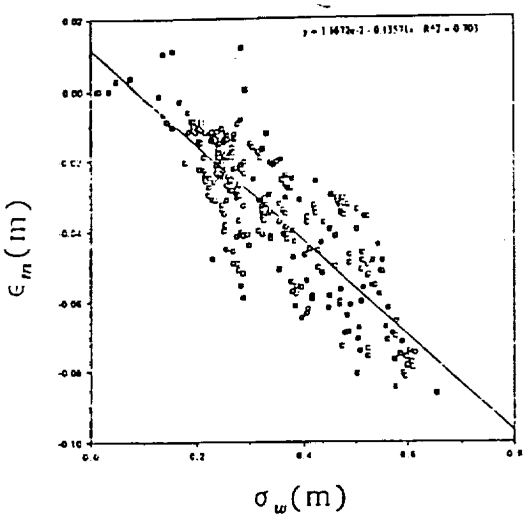

Figure 1. Hourly averages of measured sea-state bias ϵ_m(=SWH/4) versus σ_w the standard deviation of the sea surface displacement; both in meters. The linear regression is $\epsilon_m = 0.0117 - 0.136\sigma_w$.

Here we are investigating the bias in terms of quantities that can be measured, and are attempting to explain the frequency dependence of the bias. Physical optics is used to estimate the backscattered power from the surface based on an ocean surface model whose main parameters are measureable. The physical optics solution provides the first order correction to the bias due to radar frequency.

The scattering problem is formulated in two dimensions to give an integral equation for the electric field in terms of the current. The physical optics approximation is made for the current and an integral equation is derived for the back scattering coefficient. This equation may be solved asymptotically for large radar wavenumber k to give

$$\sigma^{\circ} = \frac{1}{\sigma'}\sqrt{\frac{\pi}{2}}\left[1 + \frac{(\sigma'')^2}{32k^2(\sigma')^4}\right]$$

where σ'^2 and σ''^2 are the slope variance and curvature variance, respectively. The first term is the geometrical optics solution and the second term is dependent on the radar frequency and surface curvature.

Explicit prediction of σ° depends on the model of the sea surface. Preliminary theoretical estimates led to the conclusion that modelling of the short waves riding on the longer wind waves was necessary to account for the observed sea state bias. The surface was divided into large and small scales with the separation wavenumber, k_p corresponding to the size of the footprint of the radar (i.e. O(1m)) and a high wavenumber cut-off for the small scale waves, k_c. Assumption of a one-dimensional k^{-3} spectrum for the small scale waves (Phillips, 1977) then leads to an expression for the scattering coefficient as a function of surface displacement

$$\sigma^{\circ} = \frac{1}{\sigma(z)k_p\sqrt{2\ln(k_c/k_p)}}\sqrt{\frac{\pi}{2}}\left[1 + \frac{k_c^2}{128k^2\ln^2(k_c/k_p)\sigma^2(z)}\right].$$

Estimates of the variance of the short waves as a function of vertical position on the longer waves ($\sigma(z)$) were obtained by high-pass filtering of the fine wire wave gauge measurements.

Figure 3 shows an example of the measured standard deviation of the small scale waves as a function of vertical position on the large scale waves. These data were used in the theoretical model to predict the relative radar cross section as a function of vertical displacement. This is shown in figure 4, along with direct measurements of relative radar cross section obtained from the 14GHz scatterometer and the IR wave gauge. With the exception of

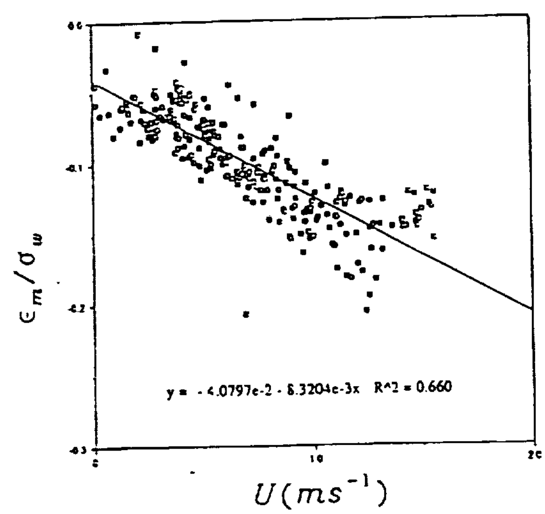

Figure 2. Normalized hourly averaged sea-state bias ϵ_m/σ_w versus wind speed U at 42m. The linear regression is $\epsilon_m/\sigma_w = -0.041 - 0.0083U$.

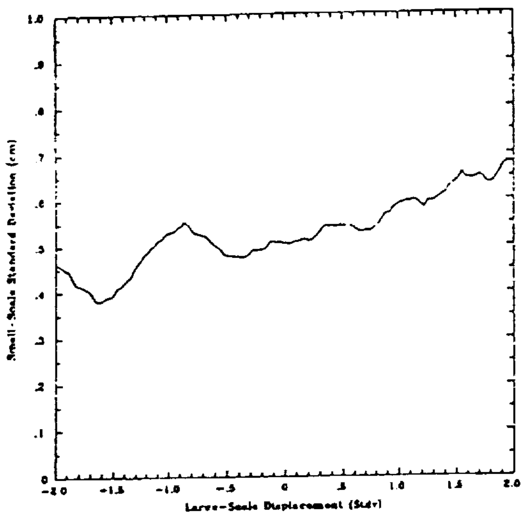

Figure 3. Example of one hour sample of standard deviation of small scale waves (cm) versus the displacement due to the large scale waves (in units of standard deviation). This plot shows an increase in roughness near the crests of the large scale waves.

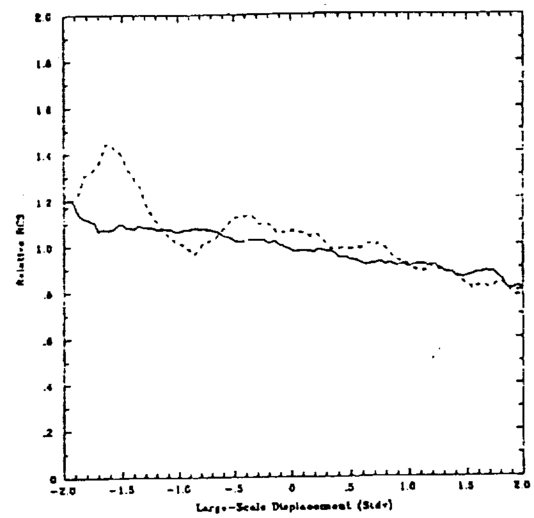

Figure 4. Corresponding plot of measured (solid line) and predicted (dashed line) relative radar cross section versus displacement due to the large scale waves. The predicted RCS is based on the two-scale model and the data of figure 3.

the large oscillations near the trough of the waves (cf figure 3) the agreement is considered to be good.

5. Conclusions

Preliminary analysis of measurements of sea-state bias at 14GHz during SAXON '88 show that the normalized bias increases approximately linearly with wind speed . Theoretical modelling of the bias based on a two-scale model of the ocean surface has led to good agreement with measurements in the limited number of cases for which good high frequency wave measurements are available. Both measurements and modelling point to the possibility that the normalized bias may correlate with the radar cross section through its dependence on the small scale structure of the surface and ultimately the wind.

Acknowledgements

We thank our many colleagues who participated in SAXON '88 for their support.We especially thank Ted Blank for the loan of equipment. This research was supported by contracts from NASA to JAK, WKM and RHS.

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MEASUREMENTS OF EM BIAS AT Ku AND C BANDS

W.K. Melville, David V. Arnold, Robert H. Stewart*, William C. Keller#, Jin A. Kong, Andrew T. Jessup, and Eric Lamarre.

Massachusetts Institute of Technology,Cambridge, Massachusetts
*Texas A&M University, College Station, Texas
#Naval Research Laboratory,Washington, D.C.

Tower-based measurements of EM bias in radar altimetry have been made using a 14GHz scatterometer in SAXON-CLT in 1988, and most recently using both 5GHz and 14GHz scatterometers from a platform in the Gulf of Mexico. In SAXON the EM bias was found to be an increasing fraction of the significant wave height with increasing wind speed, or equivalently, decreasing radar cross section. Preliminary analysis of the simultaneous measurements at both frequencies in the Gulf show that the bias at C band is qualitatively similar to that at Ku band in its dependence on wave height and wind speed. However, the C-band bias is approximately 20-25% greater at the higher values. These results are consistent with a two-scale model of microwave scattering from the ocean surface presented at this meeting [1]. The implications of these results for operational radar altimetry are discussed.

Introduction

Satellite oceanography has revolutionized our ability to observe the oceans over scales ranging from meters up to the global scale. While many of the remote sensing techniques are by their very nature indirect, their primary advantage is that they provide broad coverage with spatial and temporal resolutions which overcome the problems of undersampling associated with many of the classical ship-based and mooring-based oceanographic techniques. The fact that the measurements are often indirect implies that a great deal of effort must be devoted to understanding and quantifying the physical processes underlying the algorithms which relate the direct instrument measurement to the geophysical variables of interest.

A good example of this, and one of the most promising of the satellite-borne instruments, is the radar altimeter, which directly measures the height of the satellite above the sea and indirectly measures ocean currents, waves, and wind. The difference between the height above the sea and the height above the geoid is mainly due to the ocean currents and the tides. From the geostrophic balance between the Coriolis acceleration and the slope of the sea surface(or pressure gradient) ocean surface currents can be inferred from the slope of the sea surface relative to the geoid. Thus radar altimetry can be used to measure ocean currents. While the principle can be simply stated and understood the difficulty of the measurement becomes clear when it is recognized that the sea surface topography may vary by no more than a meter or so over distances of hundreds or thousands of kilometers across the surface of the ocean. This measurement must be made with a precision of several centimeters in the hundred kilometer or so altitude of the satellite.

The radar altimeter works by transmitting a pulse of radio waves and receiving the signal scattered back from the ocean surface. The ocean surface is not flat and the first return comes from the wave crests. The duration of the rising return pulse gives a measure of the distance between the wave crests and troughs, or the wave height, while the maximum scattered power gives a measure of the roughness of the surface, and indirectly the wind. An increase in the wind leads to a rougher surface and a decrease in the radar cross section. If the radar cross section were independent of the surface displacement then radar altimeters would give an unbiased measure of the local mean sea level; however, early measurements[2] showed that the radar cross section was greater at the troughs than at the crests of the waves, leading to a negative bias in the altimeter measurement. That is, the altimeter-measured sea level is generally lower than the true sea level. Previous observations of EM bias have ranged from 1-5% of the significant wave height, and indirect estimates from satellite observations have been in the range 2-4% of significant wave height. These estimates may give small absolute values of bias in benign seas but at high latitudes where the seas are large a SWH of 5m may lead to a 25cm EM bias. Recall that the total variation in the dynamic topography is of the order of a meter. In addition, wave-current interaction, which leads to modulation of the wave field by currents would also lead to a modulation of the EM bias. Thus the EM bias may correlate with the signal of interest. On a larger scale, seasonal variations in the wave field due to winter storms may lead to seasonal variations in the bias which if not accounted for could be interpreted as seasonal variations in sea level.

In 1992 the Topex/Poseidon satellite, a joint altimeter mission of NASA and CNES, the Centre National d'Etudes Spatiales of France, will be launched[3]. One of the primary aims of the mission is to measure ocean circulation and support other global oceanographic experiments including the World Ocean Circulation Experiment (WOCE). In view of the importance of radar altimetry for ocean circulation studies and the need to correctly account for the EM bias, we have for the past several years been conducting a series of experiments to directly measure EM bias, correlate it with the other environmental and altimeter measured variables, and search for the mechanisms underlying the empirical correlations.

The Experiments

SAXON-CLT

For a 24-day periodduring September and October of 1988 we made direct measurements of EM bias during the SAXON experiment at the Chesapeake Light Tower (SAXON-CLT). The platform is located in 15m of water 22km offshore of Cape Henry, Virginia, at the mouth of the Chesapeake Bay. The platform, which was also the site of the measurements of Yaplee et al.(1971)[2], has a relatively open design leading to little distortion of the wind and wave fields while providing stable support for environmental instrumentation. A nadir-looking 14GHz coherent scatterometer, designed and built at the U.S. Naval Research Laboratory, was mounted 22m above the mean sea level at the end of a boom which extended 6.6m out from the southern end of the eastern side of the tower. The scatterometer illuminated an area of sea 1.7m in diameter (defined by the two-way 3dB beam width) and was collocated with a Thorn/EMI IR wave gage illuminating a spot 0.4m in diameter. Capacitance wire wave gages were mounted on an identical boom which was covered with microwave absorbing material, attached to the lowest catwalk on the tower 5m above MSL, and located just outside the main lobe of the scatterometer. Wind speed and direction, air temperature and relative humidity were measured with an R.M. Young meteorological package mounted on a tower extending 16m above the helicopter deck, 42m above MSL. Water temperature was measured at a depth of 1m immediately below the platform. Other redundant environmental data were provided by a standard NOAA package on the tower and by other investigators in the experiment.

The Gulf of Mexico Experiment

For a period of approximately six months from December 1989 through May 1990 we conducted an experiment from a Shell production complex (Brazos-19) in 40m of water off the coast of Texas in the Gulf of Mexico. The aim of this experiment was to directly measure EM bias simultaneously at Ku and C bands (the frequencies of the Topex/Poseidon altimeters) and to directly measure the high frequency wave field in support of modelling of the microwave scattering from the sea surface. Nadir-looking coherent scatterometers at 14 and 5 GHZ were mounted 17m above sea level in the middle of a 60m bridge joining two platforms. Collocated with the scatterometers was a Thorn/EMI IR wave gauge and, for part of the experiment, a single capacitance wire wave gauge was mounted adjacent to the footprints of the scatterometers. These measurements were supplemented by an R.M. Young instrument package which included an anemometer giving wind speed and direction, air and sea temperature, humidity and rainfall. Data were digitally sampled, preprocessed, and the output recorded on optical disks using a PC at the platform. The experiment was run remotely from MIT through a dedicated telephone line to the data acquisition and processing system at the site. This longer-term sampling was supplemented by intensive experiments lasting for a week or so throughout the six month period.

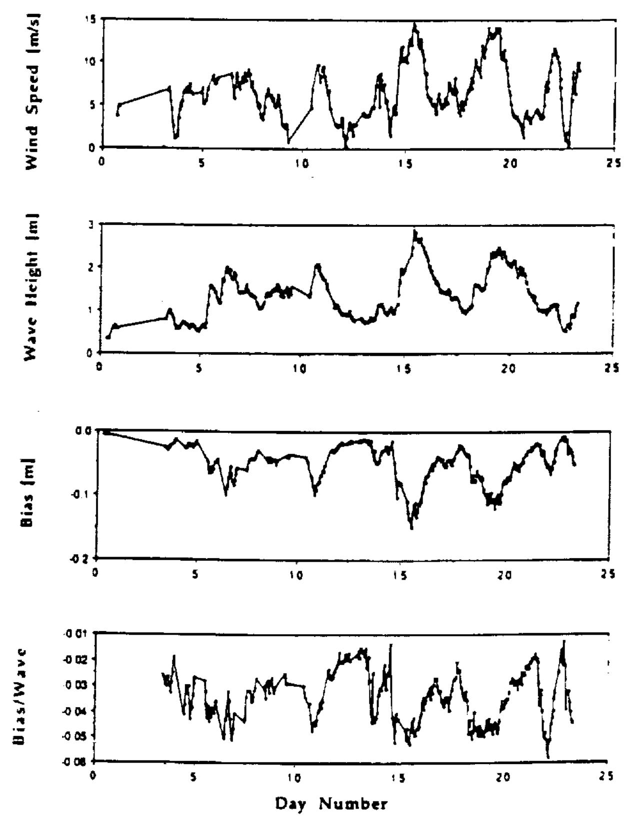

Figure 1. Hourly averages of SAXON data (Melville et al., 1990).

Results

SAXON-CLT

After correcting for wave-induced range changes leading to changes in the backscattered power measured by the scatterometer,the EM bias was calculated from the digitized values of backscattered power per unit area, σ_0, and the displacement of the sea surface measured by the IR wave gauge, ζ using

$$B = \frac{\frac{1}{N}\sum \sigma_0 \zeta}{\frac{1}{N}\sum \sigma_0}$$

where N is the number of samples in the averaging interval. During the experiment hourly averaged values of wind speed ranged from 0.2ms^{-1} to 15.3 ms^{-1}, significant wave height ranged from 0.3m to 2.9m, and EM bias varied from -0.6cm to -15cm, or -1.3% to -5.8% of the SWH (Figure 1). To confirm that the EM bias was due to the correlation between the relative radar cross section and the displacement from the mean sea level several hours of data were processed, and examples of typical results are shown in figure 2. These data are very similar to those shown by Yaplee et al.(1971)[2].

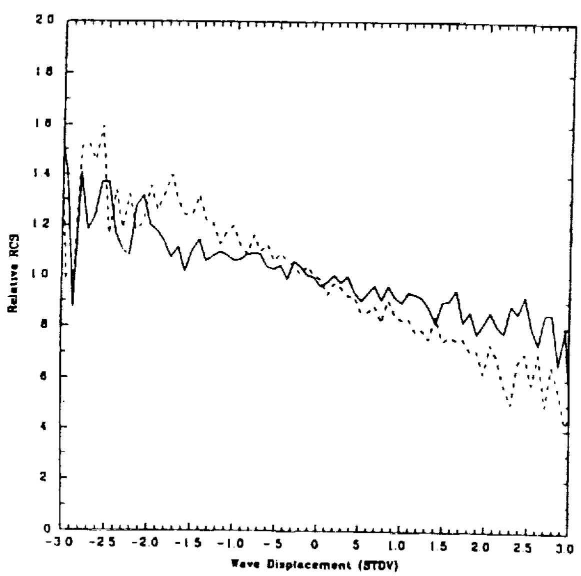

Figure 2. Relative radar cross section as a function of surface displacement (Melville et al., 1990).

The data were used to investigate the relationships between bias B and the wind speed at 10m, U_{10}, the wind stress u_*, the significant wave height $H_{1/3}$, and nonlinearity of the wave field. An analysis showed that the statistically significant correlations could be reduced to those with the significant wave height and the wind speed. Because the strongest correlation was with the significant wave height(Figure 3), we use the dimensionless bias $\beta = B/H_{1/3}$ in the following analysis. The mean value of β averaged over the 347 hours of data was -0.0342 with a standard deviation of 0.01. This standard deviation is too large for β to be considered a constant in practical applications of altimetry.

The quadratic dependence of B on $H_{1/3}$ evident in Figure 3 leads to a dependence of β on $H_{1/3}$.

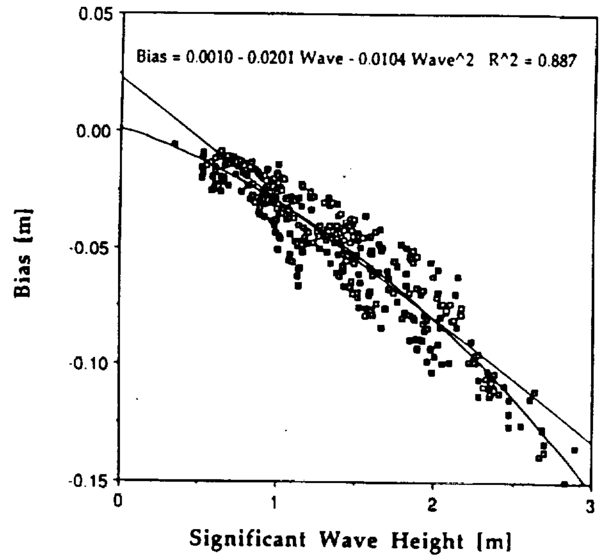

Figure 3. Bias versus significant wave height in SAXON (Melville et al., 1990)

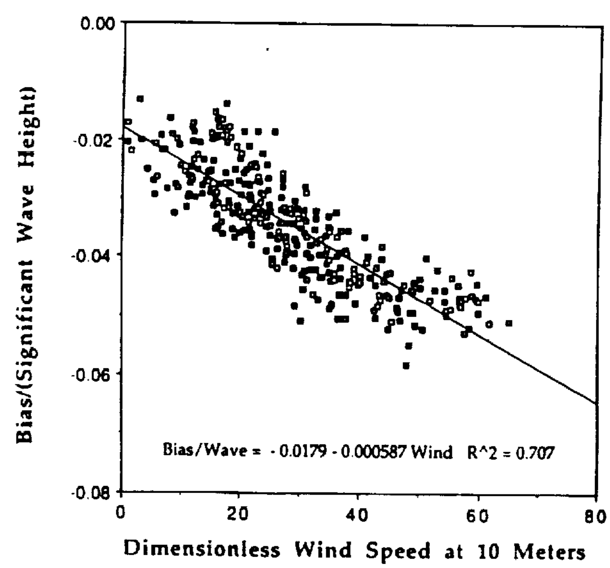

Figure 4. Normalized bias versus wind speed in SAXON (Melville et al., 1990)

In anticipation of bias measurements at other frequencies, and in the interests of using dimensionless regression coefficients, we used the radio wavelength λ_r (2.14cm) and the phase speed of surface waves of length λ_r, c_r (23.7 cm s^{-1}) to nondimensionalize the variables. The dimensionless bias was well correlated with wind speed as shown in Figure 4. The correlation with u_*, which is not shown here, was comparable with that for U_{10}.

By combining the influence of the wind speed and the wave height, the multiple correlation of β with U_{10} and $H_{1/3}$ yielded

$$\beta = -0.0146 - 0.000504 U_{10}/c_r - 0.000083 H_{1/3}/\lambda_r.$$

with a residual having a standard deviation of $\pm$ 0.0051; within the requirements for operational altimeters. Now, there is considerable advantage to having an algorithm for EM bias which is based on variables which can be directly measured by the altimeter. The altimeter measures the wave height but it does not directly measure the wind speed. However, scatterometers and altimeters use their direct measurement of radar cross section σ_0 to infer wind speed. Thus we proceeded to investigate the use of $sigmna_0$ instead of U_{10} by first establishing that our measurements of the radar cross section and its correlation with wind speed were consistent with published correlations based on satellite data.

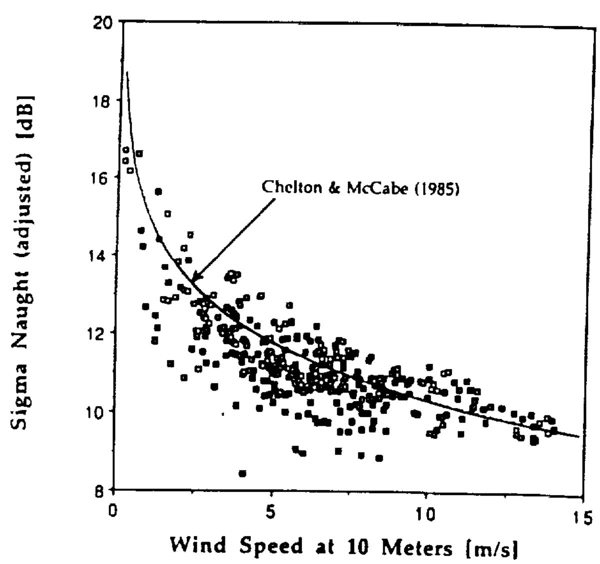

Figure 5. Mean radar cross section versus wind speed in SAXON (Melville et al., 1990) and from Chelton & McCabe (1985)[4].

Figure 5 shows a comparison of our data with a correlation of Chelton & McCabe(1985)[4] based on global altimetric satellite data. We believe the agreement is very good and within the likely calibration errors of the different systems (2-3dB). The correlation of β with σ_0^{-2} as implied by Figure 5 and the earlier correlation with U_{10} is shown in Figure 6 (cf Figure 4). This data then leads to a multiple regression of

$$\beta = -0.0163 - 2.15/\sigma_0^{-2} - 0.000062 H_{1/3}/\lambda_r$$

The correlation is comparable to that based on the wind speed and wave height and has a standard deviation of $\pm$0.0065.

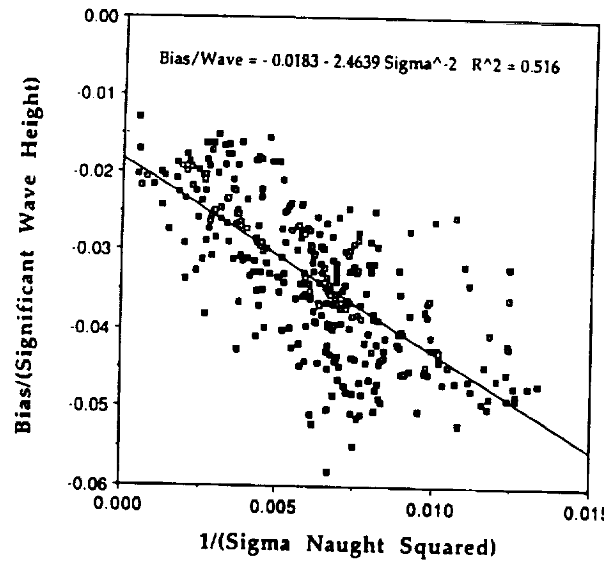

Figure 6. Correlation of normalized bias with the mean radar cross section (Melville et al., 1990).

The Gulf of Mexico Experiment

Data is still being processed from this experiment and only a sample of the results from February, 1990 will be presented here. Difficulties with keeping the optics of the IR wave gage clean for extended periods led to some drop-out in the data and the wave height data presented here was calculated from the doppler shift of the signal received at the scatterometer. Direct comparisons of IR wave gage data and doppler-inferred surface displacements based on the linear kinematic boundary condition have shown good agreement in both experiments. Figure 7 shows hourly-averaged significant wave height, wind speed and EM bias at C and Ku bands.The correlation of the EM bias with the significant wave height is shown in figure 8. The bias at both frequencies displays the same nonlinear dependence on wave height as was found in the SAXON data, with the C-band being a little higher than the Ku-band. This carries through for the correlation of the normalized bias as a function of wind speed as seen in

Figure 9.

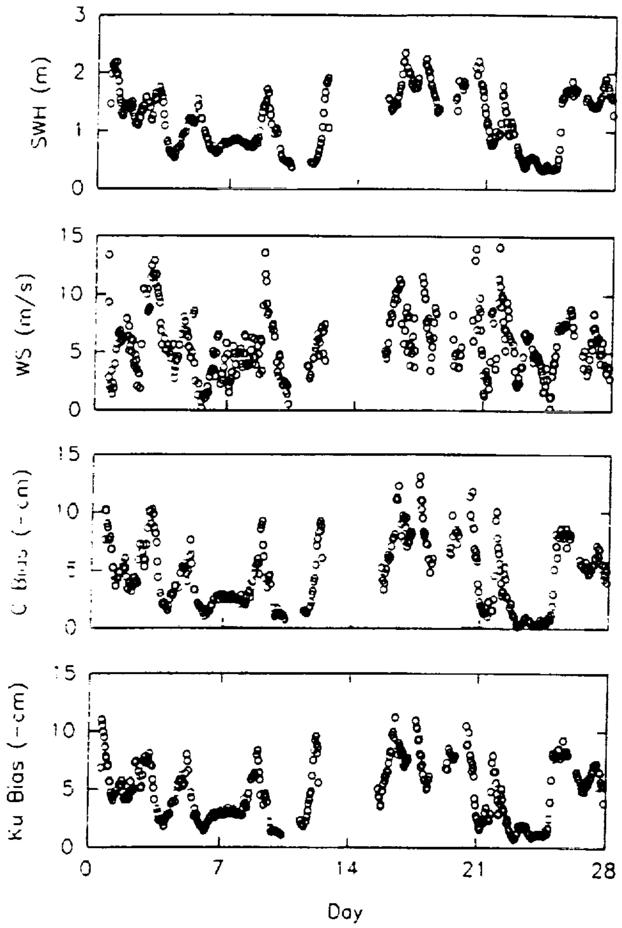

Figure 7. Time series of wave height, wind speed and bias from the Gulf experiment.

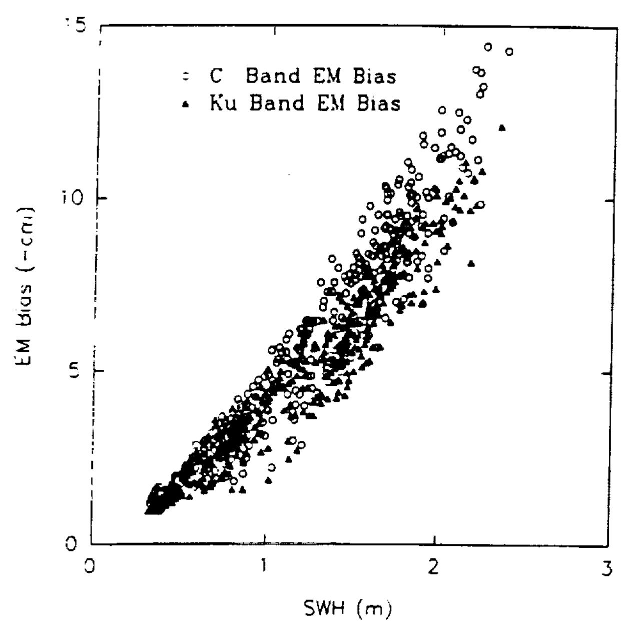

Figure 8. Bias as a function of significant wave height at C and Ku bands.

Finally, in Figure 10, we show the correlation of the simultaneous hourly averages of C and Ku band bias. The two are essentially equal at smaller values(< 5cm say) but begin to diverge at larger values, with the C-band bias exceeding the Ku-band by 20-25% at the larger values.

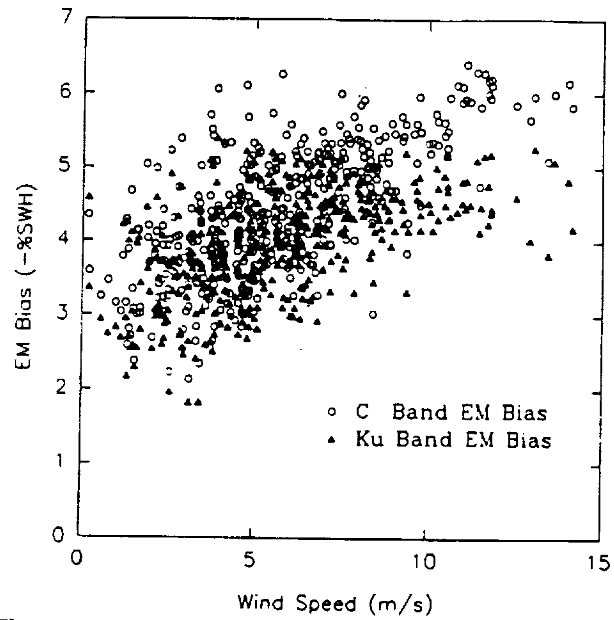

Figure 9. Normalized bias as a function of wind speed at C and Ku bands.

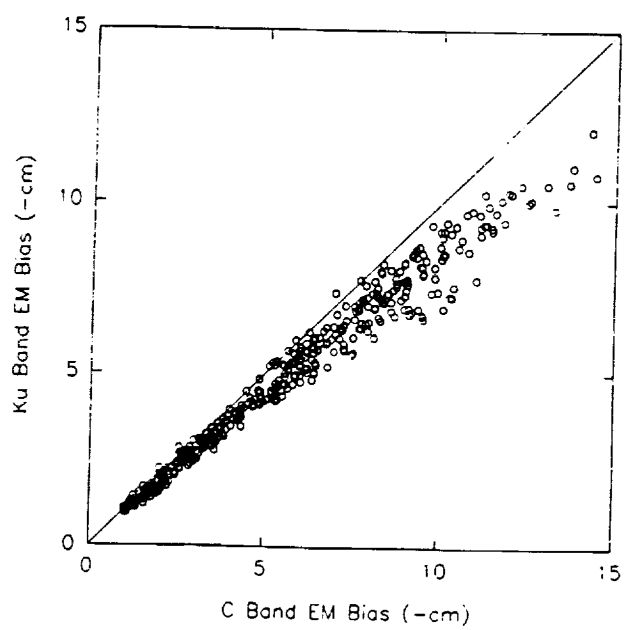

Figure 10. Bias at C and Ku band.

Discussion

Extensive analysis of the Ku-band bias measured during the SAXON-CLT experiment has shown that the bias may be correlated with the wave height and wind speed, or radar cross section, with residuals having standard deviations of approximately 0.5% of the significant wave height. The advantage of correlating the bias with radar cross section rather than wind speed is that the bias may be evaluated from those variables directly measured by the altimeter . The magnitude of the residual is within the design errors allocated to EM bias in the Topex/Poseidon mission[3]. An extensive report on the bias measurements in SAXON is given in Melville et al.,1990)[5].

A preliminary analysis of the Gulf data at both Ku and C bands shows the same qualitative behaviour as found in SAXON at Ku band, but with the C-band bias larger than Ku-band by as much as 20-25% over the range of conditions encountered.

Supporting wire wave gage measurements in both SAXON and the Gulf experiments have led us to conclude that the cause of the EM bias is the modulation of the shorter waves by the longer wind waves and swell. A two-scale model of the scattering process and its predictions of the bias at both frequencies is reported elsewhere at this meeting (Arnold et al., 1990)[1]. This modelling implies that the correlation of the bias with the wind or radar cross section is due to the small-scale roughness of the surface, while the dependence on the wave height is due to the modulation of the small scale roughness by the longer waves.

Acknowledgements

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Measurements of Electromagnetic Bias in Radar Altimetry

W. K. MELVILLE,[1] R. H. STEWART,[2] W. C. KELLER,[3] J. A. KONG,[1] D. V. ARNOLD,[1] A. T. JESSUP,[1] M. R. LOEWEN,[1] AND A. M. SLINN[1]

The accuracy of satellite altimetric measurements of sea level is limited in part by the influence of ocean waves on the altimeter signal reflected from the sea surface. The difference between the mean reflecting surface and mean sea level is the electromagnetic bias. The bias is poorly known, yet for such altimetric satellite missions as the Topography Experiment (TOPEX)/Poseidon it is the largest source of error exclusive of those resulting from calculation of the satellite's ephemeris. Previous observations of electromagnetic bias have had a large, apparently random scatter in the range of 1–5% of significant wave height; these observations are inconsistent with theoretical calculations of the bias. To obtain a better understanding of the bias, we have measured it directly using a 14-GHz scatterometer on the Chesapeake Bay Light Tower. We find that the bias is a quadratic function of significant wave height $H_{1/3}$. The normalized bias β, defined as the bias divided by the significant wave height, is strongly correlated with wind speed at 10 m, U_{10}, and much less strongly with significant wave height. The mean value for β is -0.034, and the standard deviation of the variability about the mean is ± 0.0097. The standard deviation of the variability after removing the influence of wind and waves is $\pm 0.0051 = 0.51\%$. The results are based on data collected over a 24-day period during the Synthetic Aperture Radar and X-Band Ocean Nonlinearities (SAXON) experiment from September 19 to October 12, 1988. During the experiment, hourly averaged values of wind speed ranged from 0.2 to 15.3 m/s, significant wave height ranged from 0.3 to 2.9 m, and air minus sea temperature ranged from $-10.2°$ to 5.4°C. Because U_{10} can be calculated from the scattering cross section per unit area σ_0 of the sea measured by spaceborne altimeters, we investigated the usefulness of σ_0 for calculating bias. We find that β is strongly correlated with σ_0 and much less strongly with $H_{1/3}$. The standard deviation of the variability after removing the influence of the radio cross section and waves is $\pm 0.0065 = 0.65\%$. The results indicate that electromagnetic bias in radar altimetry may be reduced to the level required by the TOPEX/Poseidon mission using only altimetric data. We find, furthermore, that the relationship between σ_0 and wind speed agrees with previously published power law relationships within the accuracy of the measurement. The mean value of β, its variability, and the sensitivity of β to wind speed all agree well with previous measurements made using a 10-GHz radar carried on a low-flying aircraft. The mean value of β, its variability, and the sensitivity to wind were all significantly larger than previous measurements made using a 39-GHz radar also carried on a low-flying aircraft. All experiments included a similar range of wind speeds and wave heights. The SAXON data were, however, much more extensive, and the statistical relationships correspondingly more significant. The mean value of β is very close to the mean value determined from global measurements of sea level made by Geosat.

1. INTRODUCTION

The next generation of oceanographic satellites promises to make accurate measurements of wind velocity and sea level using advanced spaceborne radars. The accuracy of the proposed new measurements will depend critically on the interpretation of the radar signals scattered from the sea surface. We know enough about radar scatter from the sea to proceed with the design of the radars and satellite systems, but important aspects of our understanding of radar scatter seem to be lacking. Consider the important example of radar altimetry for measuring sea level.

A spaceborne, radar-altimetric system measures sea level through a radar altimeter used for determining the height of a satellite above the sea and through tracking systems used for determining the height of the satellite above the center of the Earth, the difference in the two measurements being the sea level. While simple in principle, the measurement of sea level is difficult in practice because the measurements must have a precision and an accuracy of a few centimeters for studies of oceanic dynamics. This requires careful attention to many possible sources of error.

The influence of ocean waves on the altimeter's determination of the height of the satellite above the sea surface is an important source of error. There are two aspects to the sea state induced error: (1) waves distort the altimeter pulse, producing errors in the altimeter's determination of the distance of the satellite above the sea surface, and (2) waves cause the mean reflecting surface sensed by the radar to differ from mean sea level. The former is an instrumental error that varies with the design of the radar. The latter is common to all altimeters and is an intrinsic property of the sea surface. For consistency with *Chelton et al.* [1989] we call the latter the electromagnetic bias and the former the instrumental error. The term sea state bias is used to describe the sum of the instrumental and sea state biases.

Electromagnetic bias arises from a correlation between the reflectivity of the sea surface and the deviation of the sea surface from its mean value. For radio signals with wavelengths of a few centimeters the trough of a wave tends to be a slightly better reflector than the crest, and the mean reflecting surface is biased toward the wave's trough by an amount equal to a few percent of the wave's height.

Our present understanding of the electromagnetic bias is based on (1) direct observation of radar scatter at vertical incidence, (2) studies of the correlation between altimeter errors and sea state, and (3) application of the theory of radar

[1]Massachusetts Institute of Technology, Cambridge.
[2]Texas A&M University, College Station.
[3]U.S. Naval Research Laboratory, Washington, D. C.

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scatter from rough surfaces using a statistical description of the distribution of waves on the sea surface.

1.1. *Direct Observations of Electromagnetic Bias*

Electromagnetic bias can be calculated from direct observations at vertical incidence of the radar reflectivity from a small area on the sea surface as a function of the deviation of the sea surface from mean sea level. The distribution of radar reflectivity as a function of deviation from mean sea level is then compared with the distribution of sea surface elevation [*Jackson*, 1979]. The difference in the mean of the two distributions is the electromagnetic bias.

The first study of electromagnetic bias, by *Yaplee et al.* [1971], used a 10-GHz radar on the Chesapeake Bay Light Tower about 15 miles (24 km) east of Virginia Beach. The radar transmitted 1-ns pulses and recorded the distance to the water surface and the reflectivity of the surface at the same time that the wave height was independently recorded by three wave poles surrounding the area observed by the radar. An analysis of the observations, reported by *Jackson* [1979], showed that radar reflectivity increased nearly linearly from the wave crest to the trough and the electromagnetic bias was 5% of significant wave height.

Later studies used airborne radars for profiling the radar reflectivity at nadir at the same time that the wave height was measured either by the radar or by a laser profilometer [*Walsh et al.*, 1984; *Choy et al.*, 1984; *Hoge et al.*, 1984]. The results of these studies indicated that (1) electromagnetic bias was a function of frequency, being roughly $-3.3 \pm 1.0\%$ of significant wave height at 10 GHz, $-1.1 \pm 0.4\%$ at 36 GHz, and $1.4 \pm 0.8\%$ for ultraviolet light, (2) bias at 10 GHz ranged from 1% to 5% of significant wave height, and (3) the variability in the bias was apparently unpredictable, being only weakly correlated with variations of wavelength, wave slope, skewness and kurtosis of sea surface elevation, and wind speed. It is not clear how much of the variability of electromagnetic bias measured in these experiments was real and how much was due to experimental error such as aircraft motion or distortion of the airflow around towers. The lack of correlation with any variable other than wave height and the difference in measured values for nearly identical conditions cast some doubt on the results.

1.2. *Satellite Observations of Electromagnetic Bias*

Satellite altimeter measurements of the temporal variability of sea level have also been used for determining electromagnetic bias. Because satellite measurements include both electromagnetic bias and instrumental errors induced by waves, the studies are less direct than those based on data from surface experiments. They do, however, place bounds on the magnitude of the error.

Born et al. [1982] used Seasat altimeter measurements of sea level and wave height along repeated subsatellite tracks for determining the correlation between changes of sea level and changes of wave height observed during different repetitions of the track. The changes of sea level measured by the altimeter were due to true changes of sea level, which tend to be small over many oceanic areas, and to errors in the corrections applied to the altimeter measurements, including the error due to sea state bias. Assuming that only the sea state induced errors were correlated with sea state, the correlation between the measurements of sea level and sea state gives the electromagnetic bias plus instrumental errors. The sum of the two errors was found to be 7% of significant wave height on the average for data from Seasat, but it ranged from 2.9% to 13.4%; the correlation accounted for only 50% of the variability of sea level attributable to variability of the surface wave field. This result was later refined by *Douglas and Agreen* [1983], who analyzed a much larger set of Seasat and GEOS 3 altimeter data and determined that the electromagnetic bias plus instrumental errors was $6.4 \pm 0.6\%$ of significant wave height for Seasat and $1.9 \pm 1.1\%$ of significant wave height for GEOS 3.

Further work based on Seasat altimeter data by *Hayne and Hancock* [1982] and *Lipa and Barrick* [1981] led to an independent estimate of the instrumental error due to sea state. This was calculated to be 5–5.5% of significant wave height; hence the electromagnetic bias determined from the Seasat data is 1.5–2.0% of significant wave height.

This result may be questionable, however. The work by Hayne and Hancock, based on a careful analysis of the Seasat altimeter's received waveforms, showed that the instrumental error is a nonlinear function of wave height. Their nonlinear equation for instrumental bias gives values of -0.3% for 1-m waves and 3.7% for 4-m waves. This implies that the electromagnetic bias may range from 7.3% to 3.3% of wave height for low waves. We note, however, that the error in determining the influence of waves on the satellite altimeter measurements is greatest for small wave heights and that the above results may not be statistically significant for smaller waves.

In addition, *Douglas and Agreen* [1983] argue that studies of the variability of ocean currents by *Douglas and Cheney* [1981] do not support a value of electromagnetic bias as large as 5%. Indeed, the maps of global mesoscale variability published by *Cheney et al.* [1983] show great areas of the Pacific and Atlantic oceans having a variability of mean sea level that is less than 5 cm during times when the wave height varied by many meters. This supports the contention that electromagnetic bias was correctly removed from the Seasat data and that it must be close to the values reported by *Born et al.* [1982] and *Douglas and Agreen* [1983].

More recently, several authors have calculated sea state bias from Geosat altimeter observations of sea level. R. D. Ray and C. J. Koblinsky (personal communication, 1990), using data from repeated tracks, found that the bias was $2.6 \pm 0.2\%$ of significant wave height. *Nerem et al.* [1990], using simultaneous solutions for oceanic topography, Earth's geopotential, and errors, calculated a sea state bias of $3.6 \pm 1.5\%$ of significant wave height. Assuming that the instrumental bias is small for Geosat, these values give an upper bound for the electromagnetic bias of 2.5–5% of significant wave height.

In conclusion, the analyses of satellite altimeter data lead to an estimate of electromagnetic bias that is about 2–4% of significant wave height, but the result is not conclusive.

1.3. *Theoretical Basis of Electromagnetic Bias*

The inconclusive and sometimes inconsistent results of the analyses of satellite and aircraft radar observations of the electromagnetic bias are not clarified by an appeal to theory. Using the approximations of physical optics, *Barrick* [1968, 1972] showed that a radar pulse incident on the sea surface at angles close to vertical is reflected by mirrorlike facets that are randomly scattered over the sea surface within the field of view of the radar and are oriented perpendicular to the radar beam. The theory gives the reflectivity of each facet, and if the number of facets is known, the vector sum of the reflection from all facets gives the reflectivity of the surface.

Jackson [1979] and *Barrick and Lipa* [1985] calculated the distributions of facets over the sea surface from the joint probability density of wave slope and elevation evaluated for zero slope in two horizontal dimensions. The distribution was calculated with partial success from the theory for the statistics of nonlinear waves using second- and third-order moments of the sea surface elevation [*Barrick and Lipa*, 1985; *Srokosz*, 1986] together with a model for the spectrum of sea surface elevation such as the JONSWAP (Joint North Sea Wave Project) model. Using this distribution, *Barrick and Lipa* [1985] calculated an electromagnetic bias of 2–3% of significant wave height for heights of 1.0–5.0 m with an uncertainty of at least 20% for the estimate of electromagnetic bias. They implicitly assumed a weak dependence on radio frequency because their theory assumed that waves shorter than some fraction of a radio wavelength do not contribute to the scatter, an assumption consistent with the results of *Tyler* [1976]. The basis for the assumption was that the sea surface appears to be smooth (mirrorlike) even if it has small irregularities, provided that the wavelength of the irregularities is small enough.

Despite the apparent success of the theory, important difficulties remain. First, the theory for nonlinear waves assumed that the wave system conserved energy. Wave breaking and the growth of waves by the wind were both avoided to simplify the analysis. Yet wind blowing over long waves is known to change the distribution of short waves on long waves, producing part of the modulation of radar reflectivity which allows synthetic aperture radars to image long waves [*Weissman and Johnson*, 1986]. Second, the analysis assumed that certain integrals in the analysis could be truncated at an arbitrary upper bound to ensure convergence. The upper bound for wavelengths contributing to the integrals was assumed to be some multiple of the radar wavelength, although the exact relationship between smoothness of the wave facet and the wavelengths of the short waves on the facet is not precise. Third, the theory predicts that the bias should be a function of wave skewness because both skewness and bias are directly related to the nonlinearity of the wave field and vanish for linear waves. Hence this result conflicts with the direct measurements of the bias which showed that it was nearly independent of skewness.

1.4. *Summary of Previous Work*

Direct observations of electromagnetic bias ranged from 1% to 5% of significant wave height, and the variability of the bias was only weakly correlated with other variables describing the sea state. Analyses of satellite data indicate that the bias is less than 5% of significant wave height and that it is around 2–4% of wave height. The theory for electromagnetic bias gives a bias of 2–3% of wave height, but various assumptions used in deriving the results are questionable.

Barrick and Lipa [1985] and others have clearly recognized the limitations of the present theory and experiments useful for understanding the electromagnetic bias. *Barrick and Lipa* [1985, p. 61] state,

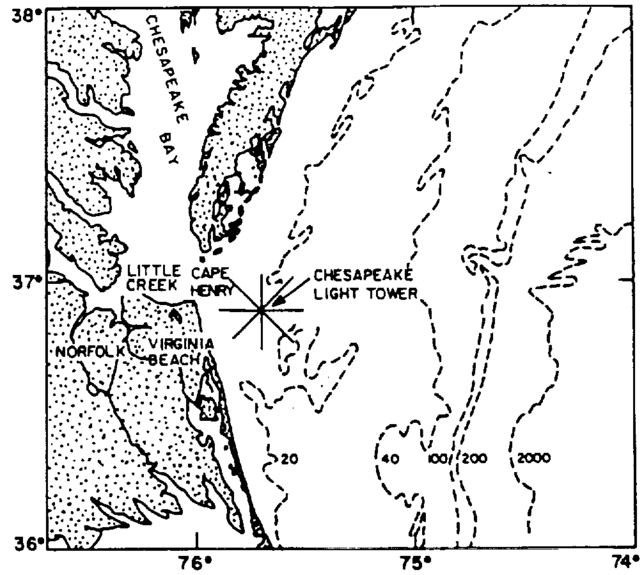

Fig. 1. Map showing the location of the Chesapeake Bay Light Tower off the east coast of North America and the surroundings. Depths are in meters; 1 m =0.55 fathom. (Figure from O. Shemdin, personal communication, 1988.)

> Electromagnetic bias is a height error not easily removed. Although it varies with sea state, it is seen to depend significantly on other factors also. Quantitative estimates of these dependencies from both theoretical and experimental investigations are as yet incomplete. Since altimeter-measured surface heights can be in error by as much as 15–25 cm because of [electromagnetic] bias, further investigations are necessary if accurate sea surface topography is to be realized from future altimeters.

2. DESCRIPTION OF THE EXPERIMENT AND DATA PROCESSING PROCEDURES

To determine the relationship of electromagnetic bias to environmental conditions, we made direct measurements of the bias during the Synthetic Aperture Radar and X-Band Ocean Nonlinearities (SAXON) experiment [*Shemdin and McCormick*, 1988] at the United States Coast Guard's Chesapeake Bay Light Tower for a 24-day period from September 19 to October 12, 1988. The platform is located at 36°55′N and 75°43′W, 24 km offshore of Cape Henry, Virginia, at the mouth of the Chesapeake Bay in water 12 m deep (Figure 1). The site is in the open ocean with long fetches over a wide range of angles. The water depth was sufficient that almost all waves recorded during the experiment were only slightly influenced by the bottom. The platform has an open design leading to relatively little distortion of the air flow at sea level while providing support for environmental instrumentation mounted on the light tower high above the sea (Figure 2).

A nadir-looking, 14-GHz, continuous-wave, coherent scatterometer designed and built at the U.S. Naval Research Laboratory was mounted 22 m above mean sea level at the end of a boom which extended 6.6 m out from the southern end of the eastern side of the tower. The scatterometer is an instrument which transmits a radio signal and then measures the power reflected from a target. It differs from a radar only in being unable to measure range. The scatterometer illuminated an area of sea 1.7 m in diameter defined by the two-way, 3-dB beam width of the transmitting and receiving

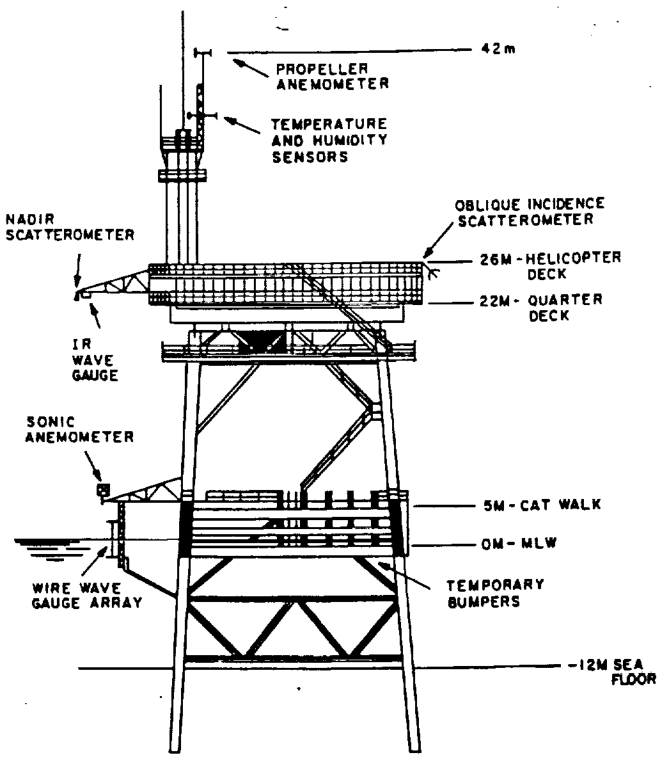

Fig. 2. Side view of the Chesapeake Bay Light Tower as seen from the north showing typical dimensions and the location of instruments.

antennas. A Thorn/EMI infrared (IR) wave gage was colocated with the scatterometer. The gage had a beam width of 1°, illuminating a spot 0.4 m in diameter. A three-element, capacitance wire wave gage was mounted on an identical boom attached to the lowest catwalk on the tower, 5 m above mean sea level. The boom was covered with microwave-absorbing material and was positioned just outside the main lobe of the scatterometer.

The scatterometer was calibrated before and after deployment using corner reflectors of known radio cross section in a calibration range of the U.S. Naval Research Laboratory. The wire wave gages, which do not directly contribute to the measurements reported here, were calibrated at the R. M. Parsons Laboratory of the Massachusetts Institute of Technology to confirm their linear response. They were dynamically calibrated in the field using the IR wave gage as a reference. The field calibrations of the wire gages (based on the IR wave gage) were within 10% of those established in the laboratory. The wire gages were used for providing a check on the spectral response of the IR wave gage, which was found to be flat to a frequency of approximately 1 Hz.

Wind speed and direction, air temperature, and relative humidity were measured with an R. M. Young meteorological package mounted on a tower extending 16 m above the helicopter deck at the top of the platform, 42 m above mean sea level. Manufacturers' calibrations were used for this package. Water temperature was measured at a depth of 1 m immediately below the platform. Additional weather and wave data were obtained from a standard instrument package operated by the U.S. National Oceanographic and Atmospheric Administration. The package included meteorological instruments mounted 40 m above the sea, a Baylor wave gage, and an experimental IR wave gage. A sonic anemometer operated by Risoe National Laboratory, Denmark, was mounted at the end of the lower boom at 5 m above mean sea level. The anemometer was used for measuring wind velocity U_5 and the friction velocity of the wind, u^*, close to the sea surface.

The usefulness and reliability of the measurements reported here were strengthened by intercomparison among measurements of the same variable made by the different equipment described above. The intercomparisons led to the identification of outliers (measurements with large errors), which were removed from the data set. For example, we investigated the influence of the platform on wind speed at the water surface near the area illuminated by the scatterometer by plotting wind speed from the sonic anemometer, U_5, minus wind speed at 42 m, U_{42}, as a function of wind direction. We found unexpected differences only for a narrow range of wind directions near 220°, consistent with being in the wake of the nearest leg of the platform. These data were not used in the following analyses.

The digital data acquisition system sampled one channel of the scatterometer, the IR wave gage, and the environmental instruments at 60 Hz. Data were processed in real time to produce 10-min averages of backscattered power σ_m, significant wave height $H_{1/3}$, electromagnetic bias B, wind speed U_{42}, wind direction, air temperature T_a, sea temperature T_s, and relative humidity H. Raw data were also recorded on an eight track analog tape recorder with a bandwidth of 625 Hz. The analog tapes were later digitized at 1 kHz, and hourly averages of the observations were computed and compared with averages over six continuous 10-min averages of data processed in real time. No significant differences were observed.

The real-time calculation did not correct the measurements of the backscattered power measured by the scatterometer, σ_m, for wave-induced changes in range between the scatterometer and the sea surface. The correction is small but important. The change in backscattered power due to change in range is proportional to r^{-4}, while the change in scattering area is proportional to r^2. Hence the change in backscattered power per unit area σ_0 is proportional to r^{-2} and

$$\sigma_0 = [Kz_0^2/(z_0 - \zeta)^2]\ \sigma_m$$

where z_0 = 22 m is the height of the scatterometer above mean sea level, ζ is the displacement of the sea surface from mean sea level, and K is the absolute calibration constant of the scatterometer. Data were corrected for the change in range before further analyses described below.

Electromagnetic bias B was calculated from the digitized values of σ_0 and the displacement of the sea surface measured by the IR wave gage using

$$B = \left(\frac{1}{N}\Sigma\sigma_0\zeta\right)\left(\frac{1}{N}\Sigma\sigma_0\right)^{-1}$$

where N is the number of samples in the averaging interval.

Preliminary comparisons of the wind measurements from the sonic anemometer at 5 m and from the propeller anemometer at 42 m indicated that the lower measurements were much more variable. We therefore correlated electromagnetic bias with U_{10} and u^* calculated from U_{42} using bulk formulas together with other environmental measurements. The profile of wind above the sea surface is well approximated by the logarithmic profile:

$$U_z = \frac{u^*}{\kappa}\{\ln (z/z_0) - \Psi(z/L)\}$$

where $\kappa = 0.40$ is Karman's constant, z_0 is the roughness height of the surface, and L is the Monin-Obukov stability length. Values of friction velocity u^* and wind speed at 10 m, U_{10}, were iteratively computed using 10-min averages of wind speed, air-sea temperature difference, and relative humidity. For the computation the roughness height was taken to be the sum of a smooth-surface contribution z_s and an aerodynamic roughness contribution z_c as outlined by *Smith* [1988]:

$$z_0 = z_s + z_c$$

$$z_s = 0.11\nu/u^*$$

$$z_c = au^{*2}/g$$

where ν is the kinematic viscosity of air and g is the gravitational acceleration. The value $a = 0.0185$ proposed by *Wu* [1980] was used because of the limited fetch and shallow depth at the light tower. The bulk stability parameter z/L was calculated from the formula proposed by *Large and Pond* [1981] in the last equation, unnumbered, in their section 3c combined with their equation 13. The computed results were then used for computing hourly averaged values for U_{10} and u^*.

3. RESULTS

During the experiment, hourly averaged values of wind speed ranged from 0.2 m/s to 15.3 m/s, significant wave height ranged from 0.3 m to 2.9 m, air minus sea temperature ranged from −10.2°C to 5.4°C, and electromagnetic bias varied from −0.6 cm to −15 cm or from −1.3% to −5.8% of significant wave height (Figure 3). The values for wind, waves, and temperature and the spectra of wave displacement are typical of open-ocean conditions.

To confirm the correlation between electromagnetic bias and cross section measured by the scatterometer, several hours of data from the experiment were processed to obtain cross section as a function of displacement from mean sea level (Figure 4). The cross section was an almost linear function of displacement of the sea surface from mean sea level. The slope of the function is the electromagnetic bias.

The SAXON data were then used for investigating the relationships between bias B and wind speed at 10 m, U_{10}; the wind stress u^*, including the effects of stability; significant wave height $H_{1/3}$; and the nonlinearity of the wave field. An analysis of variance showed that the only statistically significant correlations were with wind speed, significant wave height, and significant wave height squared (Figures 5 and 6). Because the strongest correlation by far was with significant wave height, we used the dimensionless bias, $\beta = B/H_{1/3}$, in the following analysis of the residual correlations of bias with other variables. The quadratic dependence on wave height, which is evident in Figure 5, is accounted for by correlating β with $H_{1/3}$.

Before describing the correlations with other variables, we note that the mean value of β averaged over 347 hours of data was −0.0342 and the standard deviation was 0.0097. Thus electromagnetic bias observed at the SAXON experiment was 3.5% of significant wave height with variability of 1% of significant wave height. Therefore significant wave height alone is not sufficient for accurately predicting electromagnetic bias for radar altimetry.

Dimensionless bias β was well correlated with wind speed at 10 m, U_{10}, the correlation coefficient being $r^2 = 0.706$, and with significant wave height $H_{1/3}$, the correlation coefficient being $r^2 = 0.343$. All correlations had approximately 315 or more degrees of freedom. The latter correlation includes the quadratic dependence of bias on wave height (compare Figure 5) as well as the dependence of wave height on wind speed. The two influences cannot be uniquely determined from the SAXON data, but the large number of independent observations of winds and waves and the weak correlation between them ($r^2 = 0.279$ with 380 degrees of freedom) allows a good separation of the dependence of β on U_{10} and $H_{1/3}$. In addition, the predicted value of β calculated from U_{10} and $H_{1/3}$ has much less error than that of β calculated from $H_{1/3}$ alone. Because of the strong dependence of β on wind, we have chosen to investigate the wind's influence first before considering the multiple correlation of β with wind and waves.

The most significant correlations of bias with the wind were with U_{10} (Figure 6) and with friction velocity calculated from the bulk formulas, u^* (Figure 7). Wind speed at 42 m, U_{42}, and friction velocity measured directly by the sonic anemometer, u^* (sonic), were only slightly less well correlated with β. In searching for power relationships among measured variables we found that dimensionless bias was also well correlated with the square root of the wind speed and with the square root of the friction velocity. Both correlations were about the same as the correlation with wind speed.

After removing the latter sample correlation of β with wind speed we found that β was still weakly but significantly correlated with significant wave height, $r^2 = 0.075$ (Figure 8).

Combining the influence of wind speed and wave height, the multiple correlation of β with U_{10} and $H_{1/3}$ yielded

$$\beta = -0.0146 - 0.00215U_{10} - 0.00389H_{1/3} \qquad r^2 = 0.737$$

for wind speed in meters per second and wave height in meters. The coefficients are significant at the 99% confidence level. The use of wind information significantly improves the estimation of β. The correlation of β with $H_{1/3}$ has a correlation coefficient of only $r^2 = 0.343$ with 345 degrees of freedom, as compared with $r^2 = 0.737$ above.

The residual bias, after removing the observed correlation of β with U_{10} and $H_{1/3}$ (Figure 9), had a standard deviation of ±0.0051, but it was not a random function of time. Rather, its structure suggests that it has a component that may be predictable using variables not considered in the multiple regression. The residual was not correlated with wind direction, which would indicate errors caused by the platform distorting the wind flow, nor was it correlated with the stability of the atmospheric boundary layer. Regardless of the cause of the residual, it is small, and the data indicate that wind speed and wave height alone can be used for predicting normalized bias with an uncertainty of 0.5% for the SAXON data.

Because wind speed can be calculated from measurements

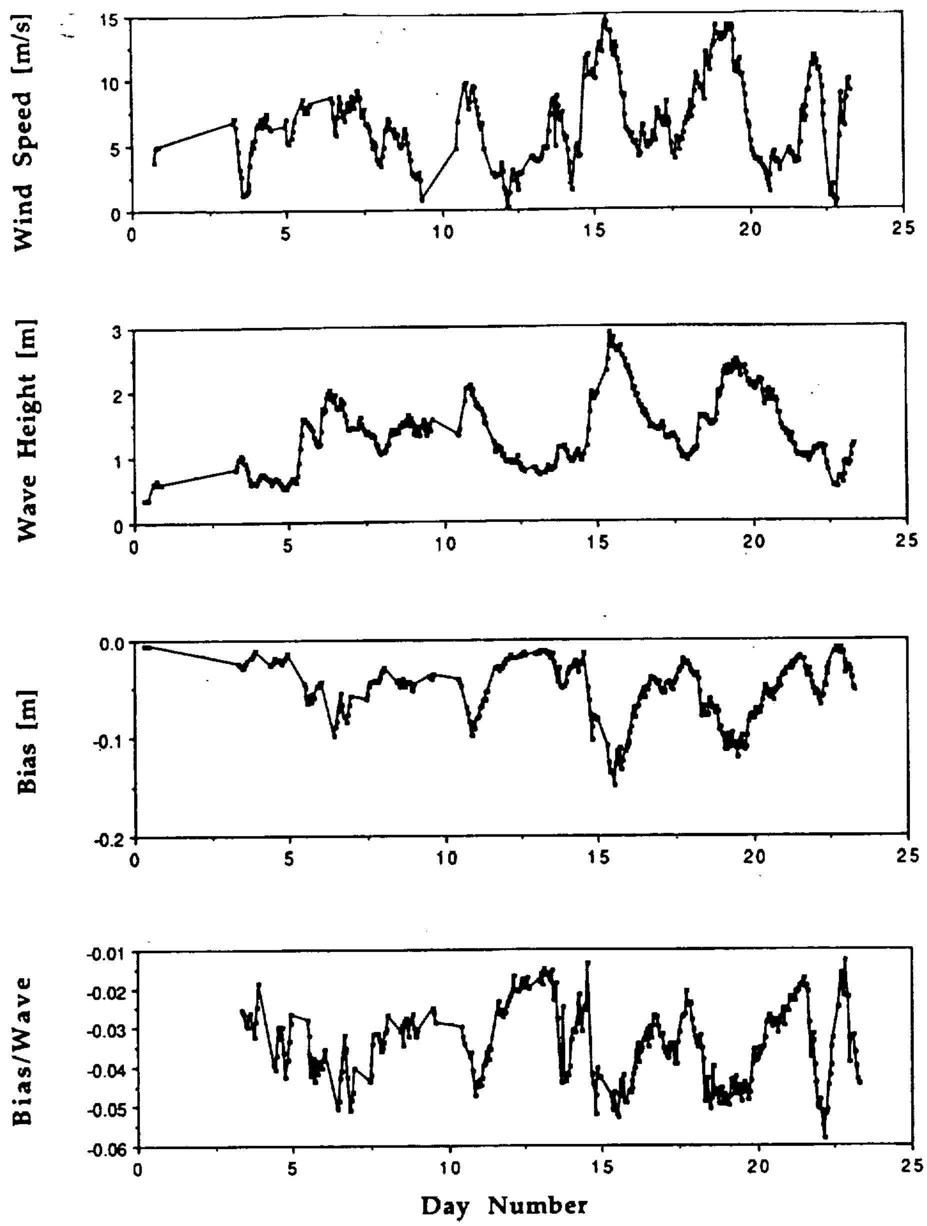

Fig. 3. Time series of wind speed at 10 m, U_{10}; significant wave height $H_{1/3}$; electromagnetic bias B; and bias divided by wave height, β, recorded during the SAXON experiment.

of the scattering cross section per unit area σ_0 made by satellite altimeters, we investigated the relationship between σ_0 and dimensionless bias. But first we compared the relationship between σ_0 measured by the SAXON scatterometer and U_{10} measured by an anemometer with previously published data in order to understand the accuracy of our scatterometer measurements.

A plot of σ_0 in decibels as a function of 10 log U_{10} together with σ_0 in decibels calculated from U_{10} using the algorithm proposed by *Chelton and McCabe* [1985] showed that the two differ by 1.08 dB, a difference well within the uncertainty of the calibration of the Seasat altimeter and our scatterometer. The difference in the two calibrations is estimated to be ±2–3 dB. After reducing our measurements by 1.08 dB, we found (Figure 10)

$$\sigma_0(\text{dB}) = 10[1.389 - 0.364 \log U_{10}] \qquad r^2 = 0.655$$

for wind speed in meters per second, compared with *Chelton and McCabe* [1985], who found

$$\sigma_0(\text{dB}) = 10[1.502 - 0.468 \log U_{10}]$$

based on an analysis of global altimetric satellite data. The two sets of coefficients differ by 4–5 times their small standard error, but Figure 10 shows that the linear regression for the SAXON data is dominated by relatively few observations at low wind speed. A plot of the same data in linear form (Figure 11) shows a close agreement between the SAXON data and the global observations. The agreement suggests that relationships between β and σ_0 based on SAXON data would provide corrections useful for satellite altimetry.

To determine β from σ_0, we used σ_0 directly rather than convert σ_0 to wind speed for use in the correlation of β with

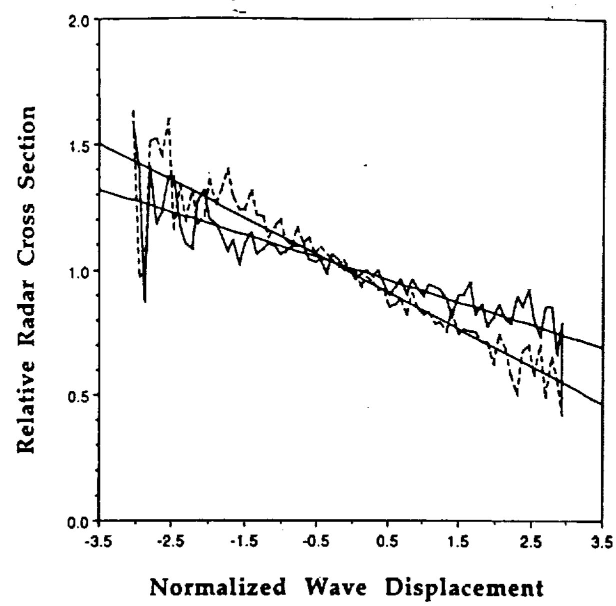

Fig. 4. Two examples of averaged radio cross section of the sea as a function of the displacement of the sea surface from mean sea level. The displacement is normalized by the standard deviation of the displacement. Note that the cross section is a nearly linear function of displacement, whose slope increases with normalized electromagnetic bias. Solid line denotes bias = 1.85 cm, $H_{1/3}$ = 0.92 m, $\beta = -0.020$, and U_{10} = 2.8 m/s. Dashed line denotes bias = −2.9 cm, $H_{1/3}$ = 0.85 m, $\beta = -0.034$, and U_{10} = 9.6 m/s.

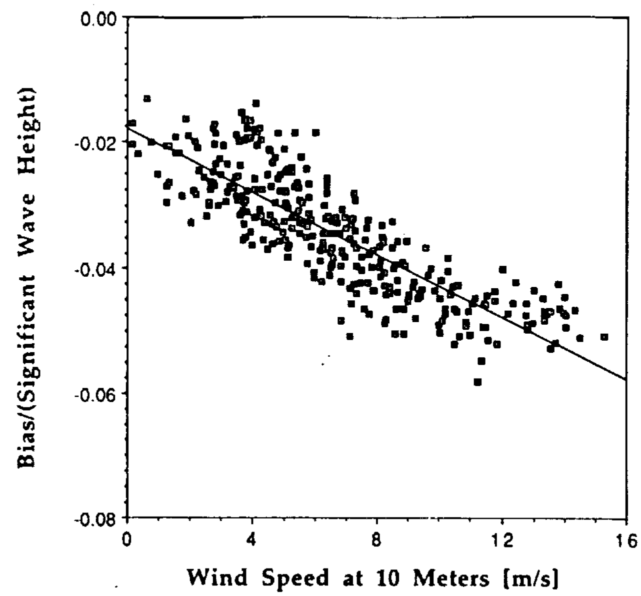

Fig. 6. Normalized electromagnetic bias β, which is bias B divided by significant wave height $H_{1/3}$, as a function of wind speed 10 m above the sea surface, U_{10}. The line through the data is the least squares regression line $\beta = -0.0179 - 0.00250U_{10}$ ($r^2 = 0.707$) for wind speed in meters per second.

U_{10}. This provides a less noisy variable for predicting β. We found previously that $\beta \sim U_{10}$ and $\sigma_0^{-1} \sim (U_{10})^2$; therefore we expected $\beta \sim 1/\sigma_0^2$. This was verified by the correlation of β with σ_0, which yielded (Figure 12)

$$\beta = -0.0183 - 2.46/\sigma_0^2 \qquad r^2 = 0.516$$

Other power laws had poorer fit to the data. The multiple regression of β with $1/\sigma_0^2$ and $H_{1/3}$ yielded

$$\beta = -0.0163 - 2.15/\sigma_0^2 - 0.00291 H_{1/3} \qquad r^2 = 0.528$$

for wave height in meters. The correlation is nearly as good as that between β and U_{10} and $H_{1/3}$. The standard deviation of the variability after removing the influence of the cross section and waves is ±0.0065 = 0.65%. The results are

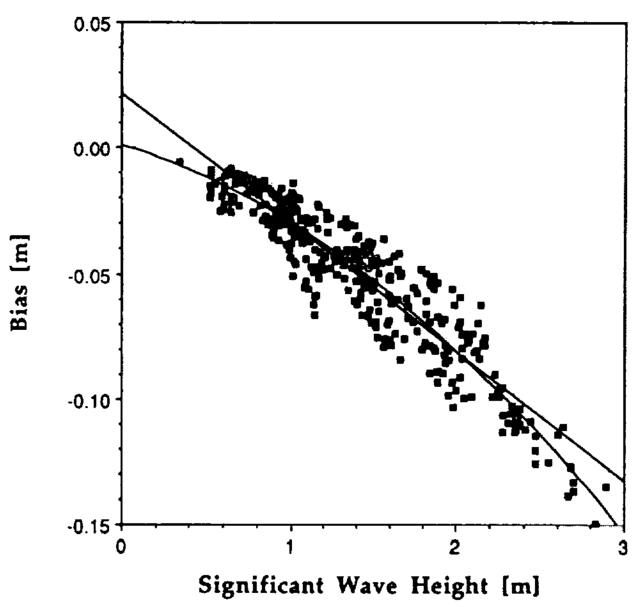

Fig. 5. Electromagnetic bias B as a function of significant wave height $H_{1/3}$ together with the least squares linear and quadratic fit to the data. The best fitting linear equation is $B = 0.00216 - 0.0517H_{1/3}$ ($r^2 = 0.873$), and the best fitting quadratic equation is $B = 0.00100 - 0.210H_{1/3} - 0.0104(H_{1/3})^2$ ($r^2 = 0.887$) for wave height in meters. Both correlations are statistically significant at the 99% level.

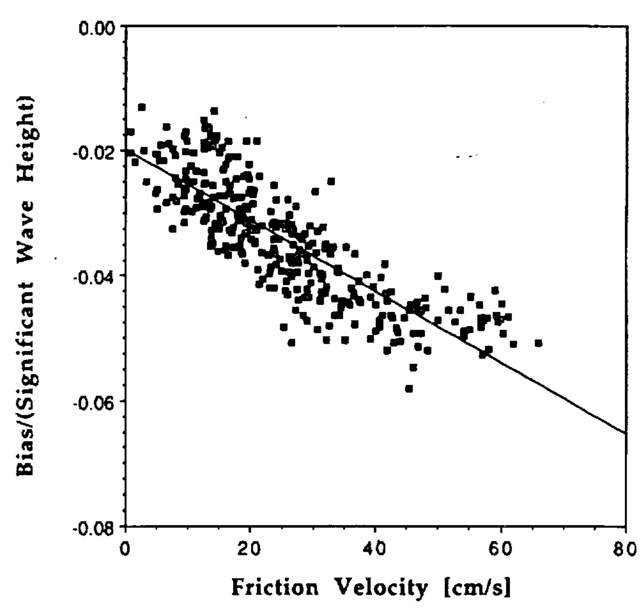

Fig. 7. Normalized electromagnetic bias β, which is electromagnetic bias B divided by significant wave height $H_{1/3}$, as a function of friction velocity u^*. The friction velocity was calculated from U_{10} using a bulk formula. The line through the data is the least squares regression line $\beta = -0.0199 - 0.0565u^*$ ($r^2 = 0.686$) for friction velocity in centimeters per second.

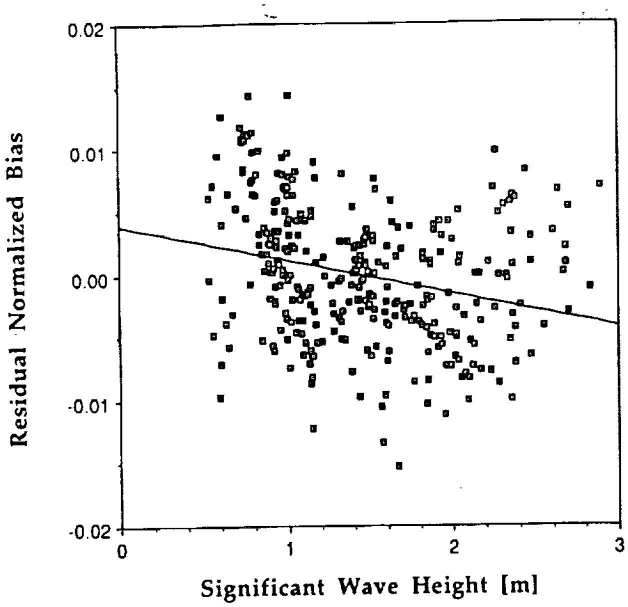

Fig. 8. The residual normalized electromagnetic bias as a function of significant wave height $H_{1/3}$. The residual is the normalized bias β minus the correlation with wind speed calculated from the SAXON data (see Figure 6). The line through the data is the least squares regression line, residual = 0.00387 − 0.00270$H_{1/3}$ (r^2 = 0.075), for wave height in meters. The correlation is statistically significant at the 99% confidence level even though the correlation coefficient is small.

important for the TOPEX/Poseidon mission. The TOPEX/Poseidon satellite will carry an altimeter for measuring sea level with an accuracy of ±14 cm, of which ±2 cm is allocated to errors due to electromagnetic bias for 2-m waves [*Stewart et al.*, 1986]. Our results indicate that the bias could be reduced to the required level using only data from the satellite.

4. Discussion

The mean value of our measurements of electromagnetic bias is the same, within experimental error, as that of the measurements by *Choy et al.* [1984] using a 10.0-GHz radar flown on an aircraft at a height of 150–230 m. Both sets of measurements yielded a bias of −3.3% of significant wave height with a variability of ±1.0%. These values are substantially larger than the mean value of −1.1% and the variability of ±0.4% measured by *Walsh et al.* [1984] using a 36-GHz radar also flown on an aircraft at about the same altitude.

Our measurement of the sensitivity of dimensionless bias to wind speed was nearly the same as that calculated from the data in Table 2 of *Choy et al.* [1984]. We found (Figure 6)

$$\beta = -0.0179 - 0.0025U_{10} \qquad r^2 = 0.707$$

while data in the work by *Choy et al.* [1984] gives

$$\beta = -0.00075 - 0.0028U_{150} \qquad r^2 = 0.258$$

for winds in meters per second. Because there were no winds less than 7.5 m/s in Choy et al.'s data, their value of $\beta(U = 0)$ was not well defined. There were insufficient data for converting wind speed at aircraft altitude, U_{150}, to wind at 10 m, U_{10}, so we used only the correlation with uncorrected wind speed. The dimensionless bias measured at 36 GHz was much less sensitive to wind. All data were observed over approximately the same range of wind and wave conditions. The SAXON data were, however, much more extensive, and the statistical relationships correspondingly more significant. For example, *Choy et al.* [1984] reported only 23 values of wind and bias in their Table 2, as compared with 316 values in Figure 6 of this paper.

The close agreement between measurements made at 10 and 14 GHz and the large difference compared with measurements at 36 GHz indicates that measurements of β should be made close to the frequency used by spaceborne altimeters if the measurements will be used for determining corrections to the satellite data.

Our value for the electromagnetic bias is also nearly identical to the 3.6% value for the bias calculated from Geosat data by *Nerem et al.* [1990], and it is slightly higher than the 2.6% value calculated from Geosat data by R. D. Ray and C. J. Koblinsky (personal communication, 1990). It is also within the range of values calculated from Seasat altimeter data. The satellite data, however, yield only the sea state bias, and the uncertainty in the determination of the instrumental errors in the satellite observations makes the comparison less clear.

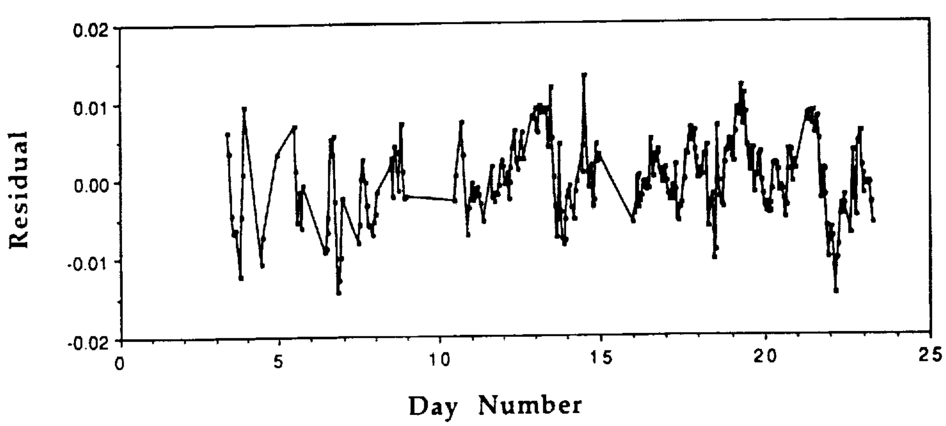

Fig. 9. The residual normalized bias as a function of time in days. The residual is the normalized bias β minus the correlations with U_{10} and $H_{1/3}$. The residual has a weak but systematic structure suggesting that other variables not considered in the multiple regression may be used for further reducing the uncertainty in β. Day 1 is September 19, 1988.

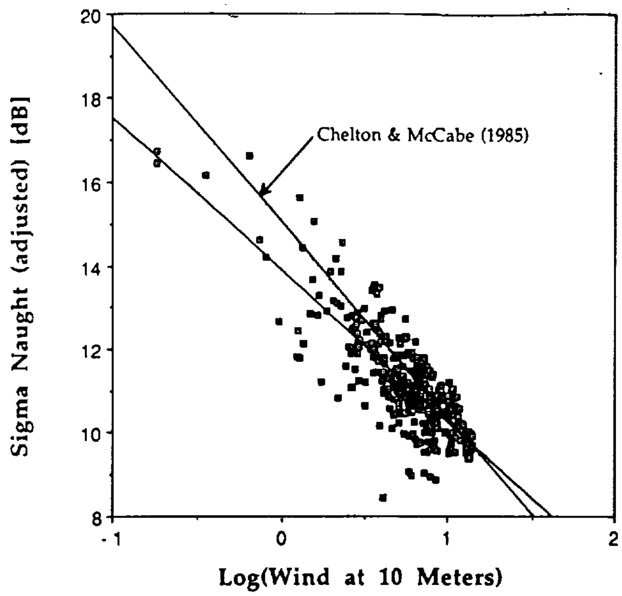

Fig. 10. Adjusted scattering cross section per unit area σ_0 (sigma naught) in decibels as a function of the logarithm of wind speed at 10 m, U_{10}. The data have been adjusted by 1.08 dB for better agreement with the curve proposed by *Chelton and McCabe* [1985] based on an analysis of altimetric satellite data. The adjustment is within the uncertainty of the calibration of the altimeter and the tower scatterometer. The other line through the data is the least squares regression σ_0 (dB) = 13.9 − 3.64 log U_{10} (r^2 = 0.655) for wind speed in meters per second.

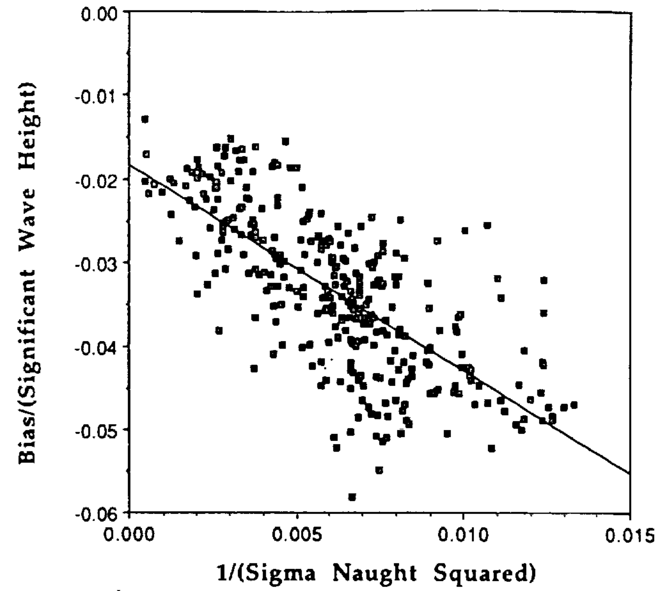

Fig. 12. Normalized electromagnetic bias β as a function of the inverse square of the scattering cross section per unit area σ_0 (sigma naught). The line through the data is a the linear least squares regression $\beta = -0.0183 - 2.46\sigma_0^{-2}$ (r^2 = 0.516).

The analysis of the SAXON data and the agreement with 10-GHz radar measurements suggests that electromagnetic bias in radar altimetry can be corrected with useful accuracy using only data from the altimeter. The instrument measures significant wave height and scattering cross section per unit area, from which U_{10} can be calculated. Either the cross section or the wind speed could be used for calculating the bias. If the correlations observed in the SAXON data hold also for spaceborne radars, then the bias could be calculated with an accuracy of 0.6%. This would be an improvement over existing corrections, and it would be sufficiently accurate for many studies of ocean dynamics.

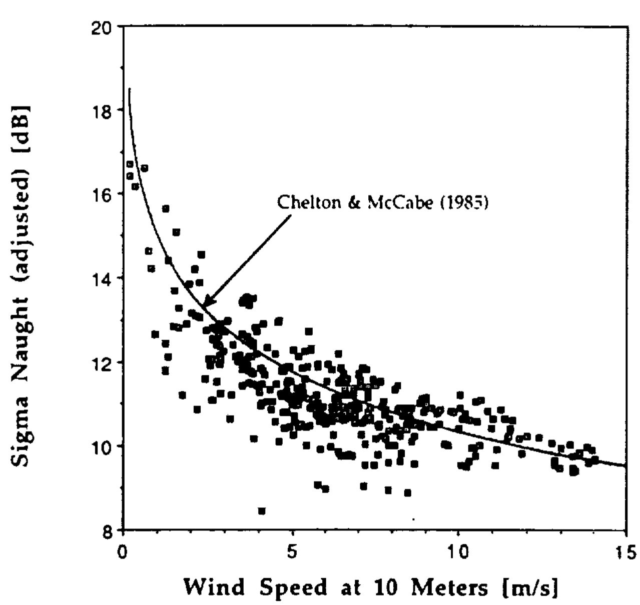

Fig. 11. Adjusted scattering cross section per unit area σ_0 (sigma naught) in decibels as a function of wind speed at 10 m, together with the relationship proposed by *Chelton and McCabe* [1985] based on an analysis of altimetric satellite data.

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D. V. Arnold and J. A. Kong, Department of Electrical Engineering and Computer Science, Building 26-305, Massachusetts Institute of Technology, Cambridge, MA 02139.

A. T. Jessup, M. R. Loewen, W. K. Melville, and A. M. Slinn, Ralph M. Parsons Laboratory, Department of Civil Engineering, Building 48-331, Massachusetts Institute of Technology, Cambridge, MA 02139.

W. C. Keller, U.S. Naval Research Laboratory, Washington, DC 20375.

R. H. Stewart, Department of Oceanography, Texas A&M University, College Station, TX 77843.

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