Measurements of Electromagnetic Bias in Radar Altimetry

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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

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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,
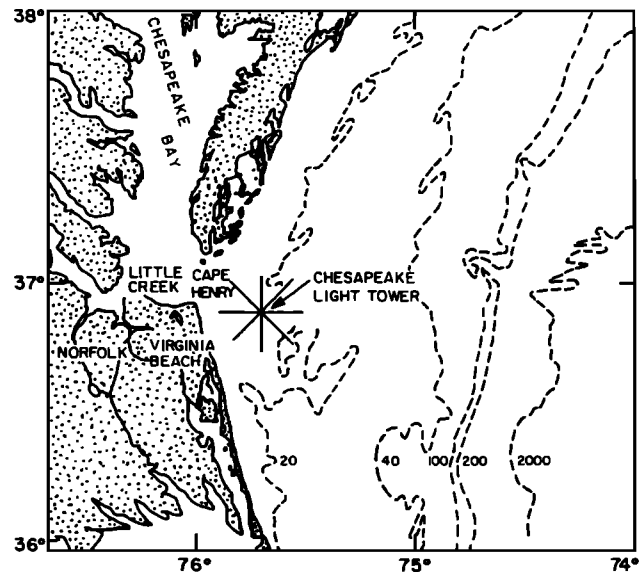

Fig. 1. Map showing the location of the Chesapeake Bay Light Tower off the east coast of North America and the surroundings. Depths are in meters; 1 m =0.55 fathom. (Figure from O. Shemdin, personal communication, 1988.)

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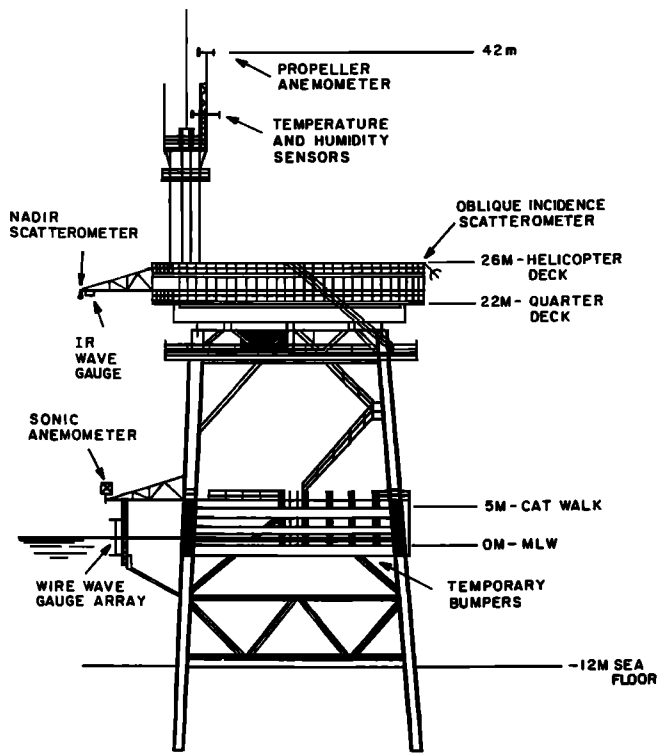
Fig. 2. Side view of the Chesapeake Bay Light Tower as seen from the north showing typical dimensions and the location of instruments.

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 measure-

ments. 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.
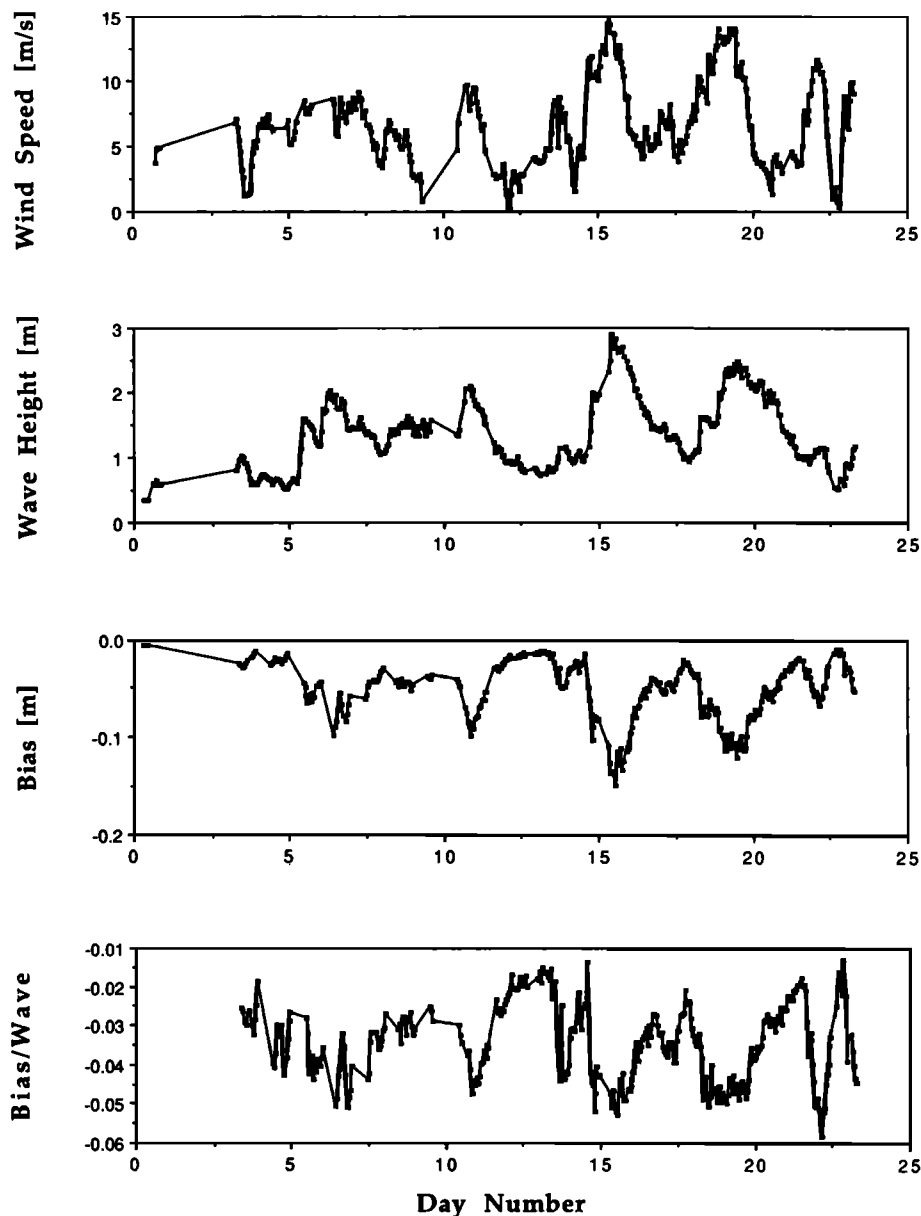
Because wind speed can be calculated from measurements

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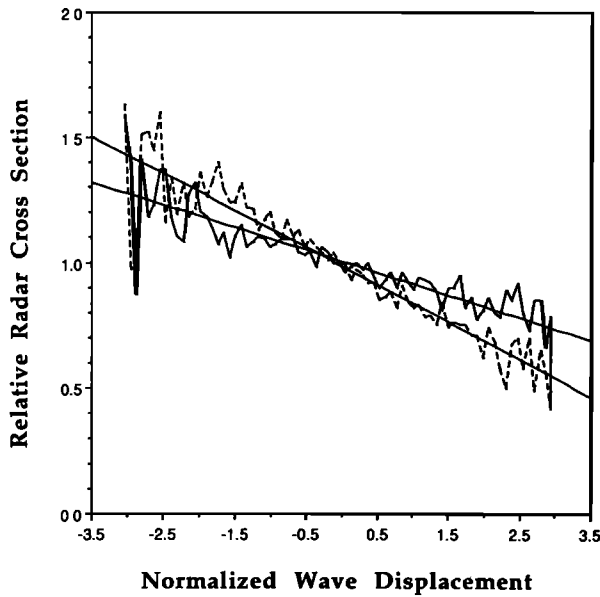
Fig. 4. Two examples of averaged radio cross section of the sea as a function of the displacement of the sea surface from mean sea level. The displacement is normalized by the standard deviation of the displacement. Note that the cross section is a nearly linear function of displacement, whose slope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

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)

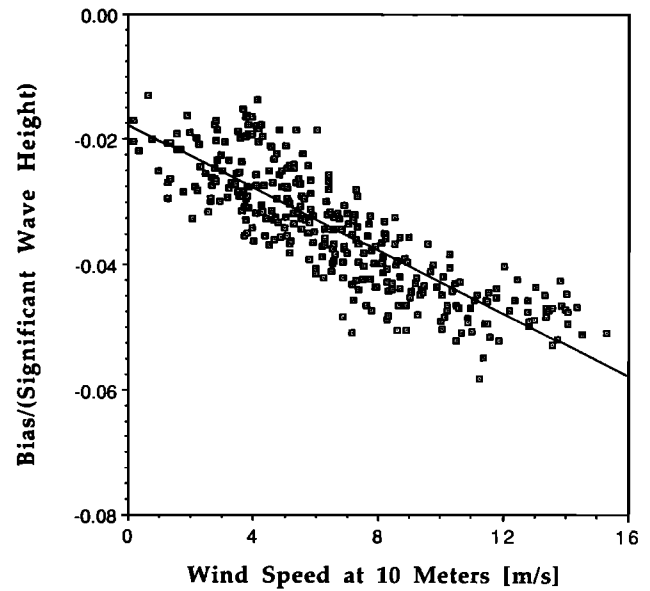$$\beta = -0.0183 - 2.46/\sigma_0^2 \qquad r^2 = 0.516$$

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.

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

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

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.
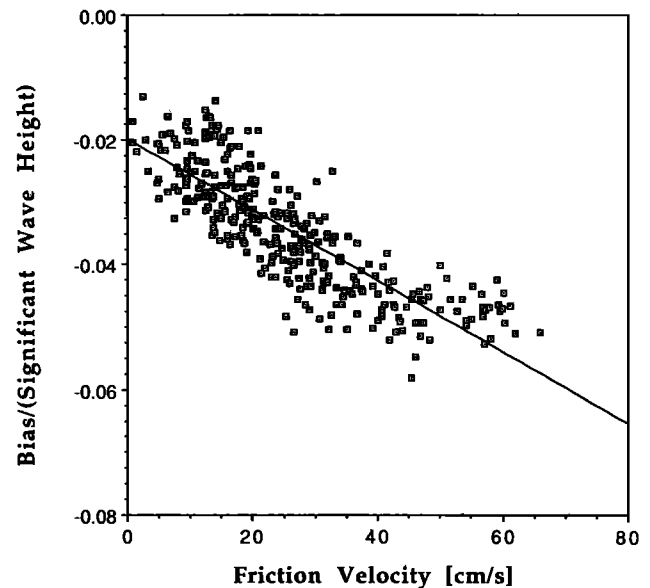

Fig. 7. Normalized electromagnetic bias β, which is electromagnetic bias B divided by significant wave height $H_{1/3}$, as a function of friction velocity u^*. The friction velocity was calculated from U_{10} using a bulk formula. The line through the data is the least squares regression line $\beta = -0.0199 - 0.0565u^*$ (r^2 = 0.686) for friction velocity in centimeters per second.
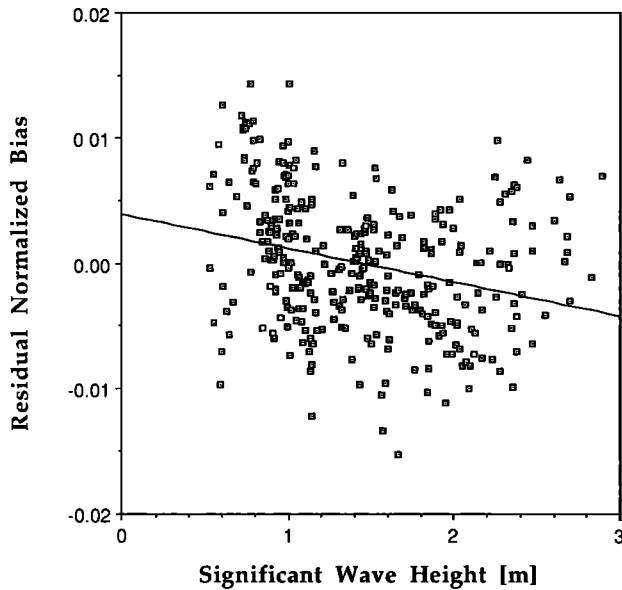
Fig. 8.   The residual normalized electromagnetic bias as a function of significant wave height $H_{1/3}$. The residual is the normalized bias β minus the correlation with wind speed calculated from the SAXON data (see Figure 6). The line through the data is the least squares regression line, residual = $0.00387 - 0.00270H_{1/3}$ (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)

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

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

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

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.
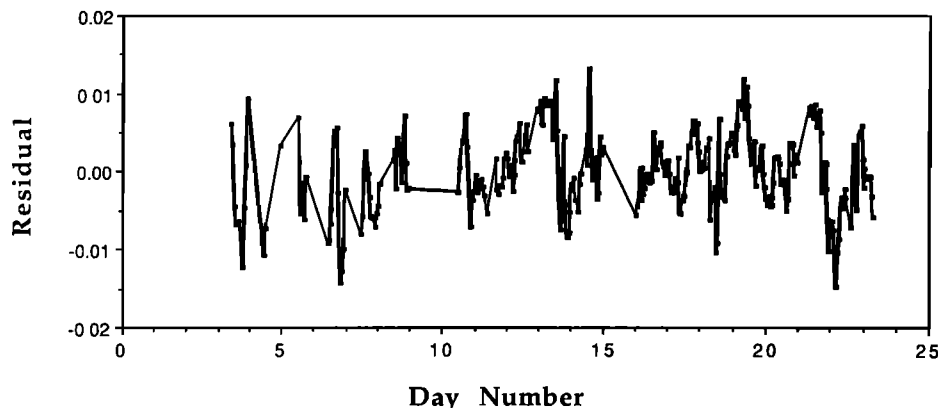

Fig. 9.   The residual normalized bias as a function of time in days. The residual is the normalized bias β minus the correlations with U_{10} and $H_{1/3}$. The residual has a weak but systematic structure suggesting that other variables not considered in the multiple regression may be used for further reducing the uncertainty in β. Day 1 is September 19, 1988.
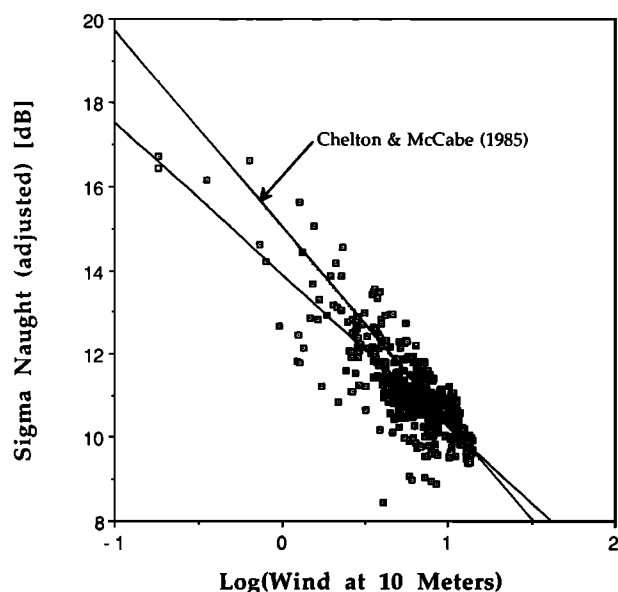
Fig. 10. Adjusted scattering cross section per unit area σ_0 (sigma naught) in decibels as a function of the logarithm of wind speed at 10 m, U_{10}. The data have been adjusted by 1.08 dB for better agreement with the curve proposed by *Chelton and McCabe* [1985] based on an analysis of altimetric satellite 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.

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
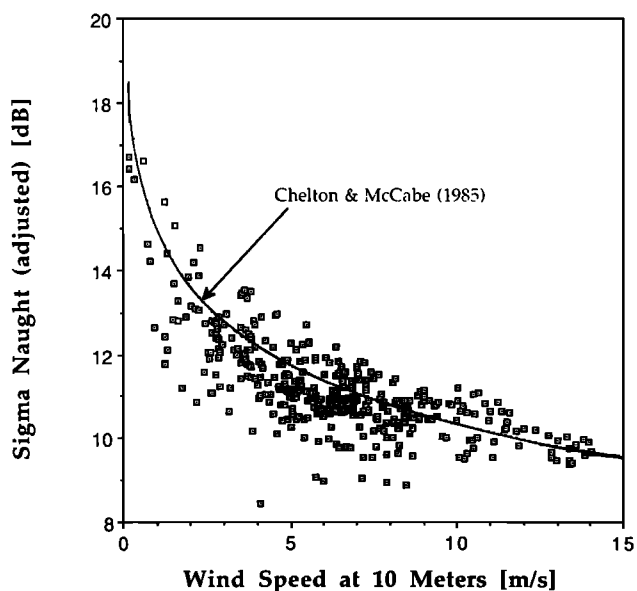

Fig. 11. Adjusted scattering cross section per unit area σ_0 (sigma naught) in decibels as a function of wind speed at 10 m, together with the relationship proposed by *Chelton and McCabe* [1985] based on an analysis of altimetric satellite data.
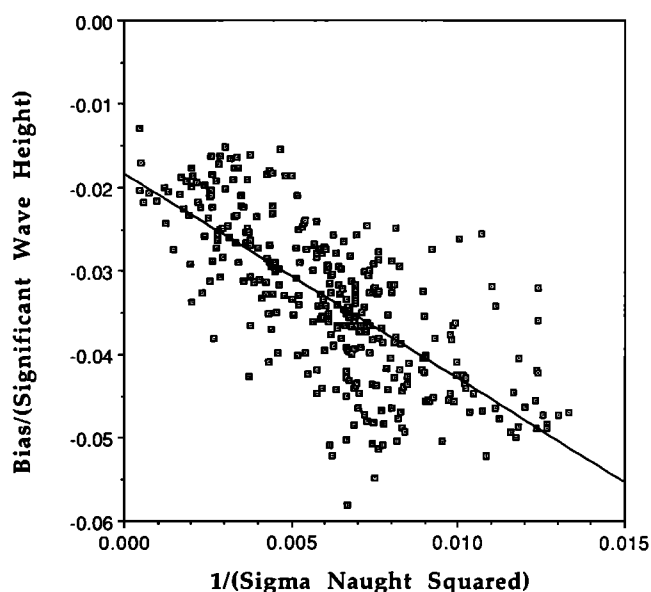

Fig. 12. Normalized electromagnetic bias β as a function of the inverse square of the scattering cross section per unit area σ_0 (sigma naught). The line through the data is a the linear least squares regression $\beta = -0.0183 - 2.46\sigma_0^{-2}$ ($r^2 = 0.516$).

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.

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