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A Geosat Altimeter Wind Speed Algorithm and a Method for Altimeter Wind Speed Algorithm Development

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A Geosat altimeter wind speed algorithm is derived by cross-calibrating Geosat and Seasat altimeter estimates of the normalized radar cross section σ_0 and modifying an existing Seasat altimeter wind speed model function to obtain a model function appropriate for Geosat observations. It is argued that the σ_0 distribution measured by an altimeter is relatively stable over a sufficiently large geographical region and a long enough time period. Systematic differences between σ_0 estimates from two altimeters can therefore be identified based on comparisons of their σ_0 histograms. Any such systematic differences can then be corrected using independent σ_0 estimates. When this method is applied to the Geosat and Seasat altimeters, a systematic difference between the two σ_0 histograms is shown to be consistent with differences between Seasat altimeter and nadir Seasat scatterometer estimates of σ_0 deduced independently by a previous study. This supports the conclusions that (1) the σ_0 distribution is stable, and (2) the Seasat altimeter estimates of σ_0 were miscalibrated. After modifying the existing Seasat altimeter wind speed algorithm to account for this apparent σ_0 error, the resulting Geosat estimates of wind speed agree with high-quality buoy observations to within an rms difference of less than 2 m/s.

1. INTRODUCTION

Previous studies have demonstrated that estimates of near-surface wind speed can be inferred to within an rms accuracy of 2 m/s from altimeter measurements of the normalized radar cross section σ_0 of the sea surface [*Brown*, 1979; *Brown et al.*, 1981; *Chelton and McCabe*, 1985; *Chelton and Wentz*, 1986; *Dobson et al.*, 1987]. Aquiring an adequate in situ wind speed data set for such algorithm development is a long-standing problem. In part, this is due to the sparseness of high-quality wind speed observations over the open ocean. In addition, since the likelihood of acquiring coincident satellite and in situ observations of high wind speeds is small, high wind speeds are generally not well represented in calibration data sets. The advantage of using a reliable wind speed algorithm derived for a previous altimeter, thus alleviating the need to acquire a new in situ calibration data set, is obvious. Because of the nature of the relation between σ_0 and wind speed, however, small errors in σ_0 lead to large errors in wind speed. This is especially true at high wind speeds where the approximate logarithmic dependence of σ_0 on wind speed [see *Chelton and McCabe*, 1985] is very flat. It is therefore essential that σ_0 be accurately calibrated. In this paper a technique for cross-calibrating σ_0 measurements from two altimeters is developed, thus allowing the use of the same wind speed algorithm for both altimeters.

Direct cross-calibration of σ_0 measurements from two altimeters obviously is possible only if the two satellite missions overlap. Even then, an accurate cross-calibration is difficult because nearly coincident σ_0 observations from two satellites are infrequent. For example, only 19 coincident σ_0 measurements occurred over a 100-day overlap period for the Geos-3 and Seasat altimeters [*Fedor and Brown*, 1982]. In this study, a calibration adjustment of the Seasat altimeter σ_0 estimates is derived from independent coincident estimates of σ_0 from the Seasat-A satellite scatterometer (SASS). The adjusted Seasat altimeter σ_0 estimates are found to be much more consistent with the Geosat altimeter estimates of σ_0. A very similar calibration adjustment is also derived by an independent comparison of histograms of σ_0 from the Seasat and Geosat altimeters. The adjusted Seasat altimeter estimates of σ_0 are used to derive a new wind speed algorithm for the Geosat altimeter based on a previous wind speed algorithm developed for the Seasat altimeter. The accuracy of the new Geosat wind speed algorithm is independently assessed by comparing the resulting Geosat wind speeds with coincident observations from buoys.

2. CROSS-CALIBRATION OF GEOSAT AND SEASAT

For nadir incidence and a given radar frequency, σ_0 is a fundamental property of the sea surface and is thus independent of the instrument used to make the measurement. In principal, a wind speed algorithm derived for one altimeter should therefore be directly applicable to another altimeter. In practice, however, this approach is valid only if σ_0 estimates from the two altimeters are accurately cross-calibrated. A direct cross-calibration of σ_0 measurements from two different altimeters is obviously a problem if there is no overlap of the two satellite missions. However, if it can be argued that the histogram of wind speed (and presumably of σ_0 as well, since σ_0 depends mostly on wind speed) is stable from year to year over sufficiently large geographic regions and long enough time periods, then systematic differences between σ_0 measurements from two altimeters can be identified from a comparison of the σ_0 histograms from the two instruments. In this case, any systematic differences between the two histograms would be due to systematic errors in one or both estimates of σ_0. Clearly, the spatial and temporal domain over which this comparison is performed must be chosen carefully to avoid confusing geographical or seasonal differences with systematic errors in the σ_0 estimates.

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This method of σ_0 comparison can be investigated with data from the Seasat and Geosat altimeter missions, separated in time by nearly a decade. The most logical choice of time interval for the comparison is July 7 to October 10, the period of the Seasat mission. The choice of spatial domain is somewhat less obvious. In general, the stability of the σ_0 histogram can be maximized by choosing as large an area as possible. This area should also be chosen such that the geographical sampling (e.g., the percentage of total observations within each latitude band) is approximately the same for the two instruments. Data dropouts due to off-nadir pointing of the Geosat spacecraft occurred over large areas of the northern hemisphere from July to October of 1987 and 1988 [see *Cheney et al.*, 1988]. For this reason and because the dynamic ranges of wind speed and σ_0 are larger in the southern hemisphere than in the northern hemisphere, the region between 15°S and 65°S (accounting for about 35% of the world ocean) was chosen for the comparison of Geosat and Seasat σ_0 observations. The latitudinal distributions of Seasat and Geosat observations are nearly identical over this geographical region (see Figure 1).

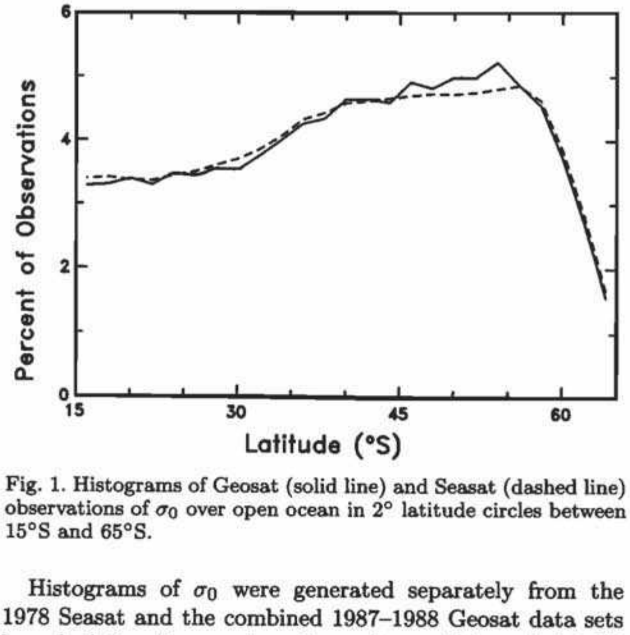

Fig. 1. Histograms of Geosat (solid line) and Seasat (dashed line) observations of σ_0 over open ocean in 2° latitude circles between 15°S and 65°S.

Histograms of σ_0 were generated separately from the 1978 Seasat and the combined 1987–1988 Geosat data sets by calculating the number of σ_0 values within each 0.2 dB interval for the time period between July 7 and October 10 and the latitude band between 15°S and 65°S. Geosat σ_0 values were taken directly from the Exact Repeat Mission Geophysical Data Records. The Hancock algorithm [see *Chelton and McCabe*, 1985] was used to calculate σ_0 from Seasat altimeter AGC (automatic gain control) values. For both instruments, observations with off-nadir pointing angles larger than the antenna half-beamwidths (0.5° for Seasat and 1.0° for Geosat) were eliminated and only observations over open ocean were retained.

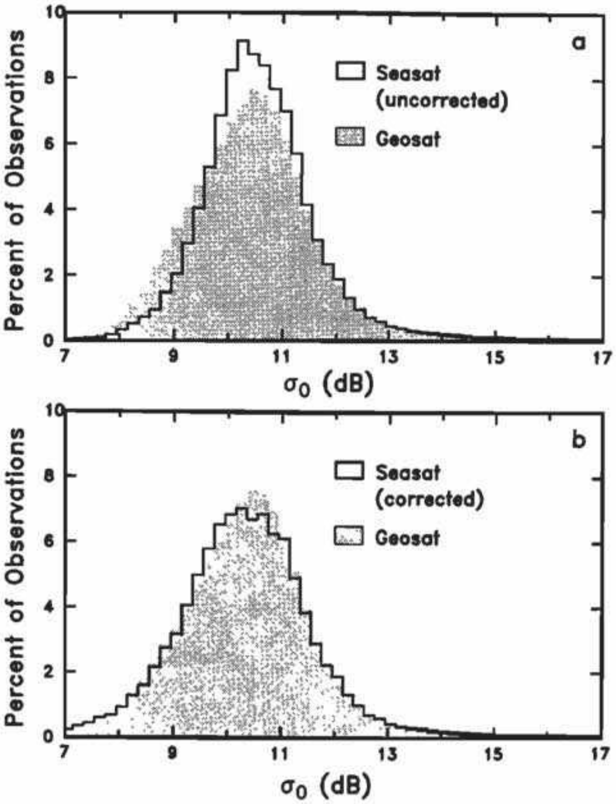

Fig. 2. Histograms of 2,974,973 Geosat σ_0 observations from 1987-1988 (shading) and 1,360,808 Seasat σ_0 observations from 1978 (solid line) for the period between July 7 and October 10 in the region between 15°S and 65°S. The Seasat histogram is shown (*a*) prior to correcting and (*b*) after correcting for the apparent systematic error in the Seasat altimeter σ_0 estimates suggested from Figure 4.

As shown in Figure 2*a*, the resulting histograms are visibly different for $\sigma_0 \lesssim 11$ dB. For σ_0 values up to about 11 dB, there are fewer small σ_0 estimates from the Seasat altimeter than from the Geosat altimeter. Quantitatively, this difference is apparent from inspection of simple statistics of the two distributions. The average Geosat and Seasat σ_0 values are 10.54 dB and 10.69 dB, respectively, and the rms difference between the two histograms (in units on the y axis in Figure 2*a*) is 0.63%. Candidate explanations for these differences include normal year-to-year fluctuations in the strength of the southern hemisphere wind field (and hence σ_0) and the possibility of systematic instrument-related errors in either the Geosat or Seasat σ_0 values.

While it is difficult to assess interannual variability in the σ_0 histograms from the short record of altimeter data presently available, the temporal stability of the southern hemisphere σ_0 distribution can be investigated to a limited degree using the two separate years of Geosat observations. For the spatial and temporal domains described above, Geosat σ_0 histograms were computed separately for 1987 and 1988. As shown in Figure 3, the resulting histograms are similar for the entire range of σ_0 values observed over open ocean. The average of the distributions are 10.54 dB for 1987 and 10.55 dB for 1988 and the rms difference between the two histograms is 0.11%, approximately 6 times smaller than the rms difference between the Seasat and combined 1987–1988 Geosat histograms. Obviously, a comparison of 2 years of altimeter observations does not represent the full range of interannual variability in the wind field. A more complete measure of interannual variability cannot be obtained from altimeter data alone due to the lack of other accurate, long-term altimeter data sets. To assess longer term variability, an alternative data type must be used.

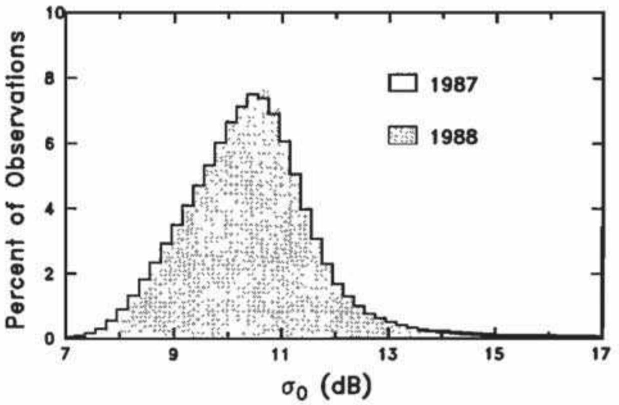

Fig. 3. Histograms of Geosat σ_0 observations for the periods July 7 to October 10 of 1987 (shading) and 1988 (solid line) for the region between 15°S and 65°S. A total of 1,626,069 observations were used to generate the 1987 histogram, and 1,348,904 observations were used to generate the 1988 histogram.

A second, but less direct, measure of the temporal stability of the σ_0 histograms was derived based on the southern hemisphere gridded wind analyses produced by the Australian Bureau of Meteorology (ABM). For each year between 1977 and 1989, twice-daily fields of 1000-mbar winds were converted to σ_0 by inverting the altimeter wind speed model function derived in section 4 below. Thirteen σ_0 histograms (one for each year) were then constructed using only observations between latitudes 15°S and 65°S and the time period between July 7 and October 10. The spread between the highest and lowest percent of observations in each σ_0 bin was chosen as an indicator of the range of interannual variability in the southern hemisphere σ_0 distribution. For σ_0 values between 7 dB and 17 dB, the rms variability in the σ_0 histograms was 0.27%, less than half of the rms difference between the Geosat and Seasat histograms in Figure 2*a*.

Based on comparisons of the two different years of Geosat σ_0 observations and the 13 years of ABM wind fields, the difference between the Geosat and Seasat σ_0 histograms seems to be much greater than can be explained by interannual variability in the wind field. A more likely explanation is that there is a large systematic error in either the Geosat or Seasat σ_0 estimates.

An independent previous comparison of Seasat altimeter and nadir SASS σ_0 estimates found that the altimeter values differed systematically from the SASS values [*Chelton and Wentz*, 1986]. There was a general bias of 0.5 dB which was subsequently shown by *Chelton et al.* [1989] to be due to the use of a flat-earth approximation to determine the altimeter footprint area. After correcting for this bias, the Seasat altimeter and SASS σ_0 values still differ for values of $\sigma_0 \lesssim 11$ dB (Figure 4), the same regime for which Geosat and Seasat σ_0 estimates differ significantly. This strongly suggests that the difference between Seasat and Geosat σ_0 histograms in Figure 2*a* is due to a systematic error in the Seasat altimeter data. *Chelton and Wentz* [1986] noted that altimeter estimates of σ_0 are computed from only a gate-limited portion of the returned signal, rather than the total returned power, which is sampled by SASS. If the power in the gate-limited return is not properly scaled to account for the unsampled portion of the return, altimeter σ_0 estimates will be systematically in error.

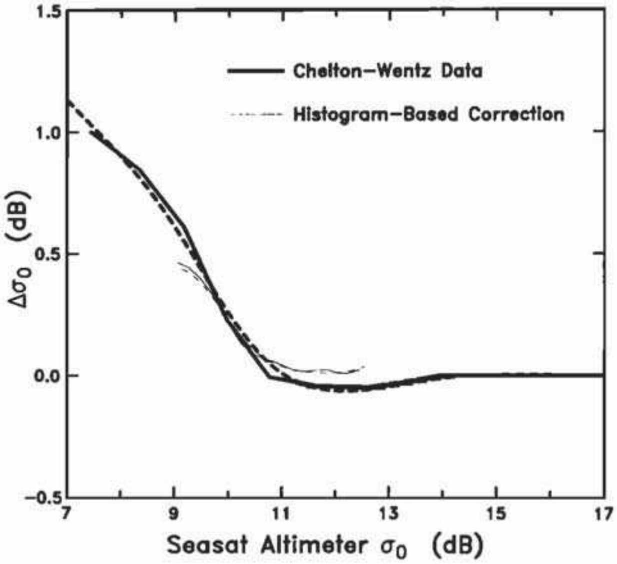

Fig. 4. The calibration error for Seasat altimeter estimates of σ_0 determined by two different methods. The heavy solid line shows the Seasat altimeter minus nadir Seasat scatterometer estimates of σ_0 (from *Chelton and Wentz* [1986], with the altimeter data adjusted by 0.5 dB to account for the spherical Earth geometry). The thin solid line shows the Seasat altimeter minus the Geosat altimeter estimates of σ_0 obtained by the Histogram Alignment technique described in the appendix. Dashed lines correspond to smoothing spline fits through the respective calibration curves.

From Figure 4, the difference between the Seasat altimeter and SASS estimates of σ_0 is negligible for $\sigma_0 \gtrsim 11$ dB and increases approximately linearly with decreasing σ_0 to a value of about 1 dB at $\sigma_0 = 7$ dB. Hypothesizing that this systematic trend is symptomatic of an error in the Seasat altimeter estimate of σ_0, a smoothing spline was fit to the *Chelton and Wentz* [1986] data in Figure 4 and the value of the spline fit was subtracted from each original Seasat altimeter estimate of σ_0. A histogram of the adjusted Seasat altimeter σ_0 values is shown in Figure 2*b*. In addition to bringing the Seasat altimeter σ_0 histogram into close agreement with that from the SASS, it can be seen that the adjusted Seasat altimeter histogram also agrees remarkably well with that from the Geosat altimeter. The average Seasat altimeter σ_0 value decreased from 10.69 dB to 10.53 dB by applying the correction. This value agrees well with the average of 10.54 dB computed based on the 1987–1988 Geosat histogram. The rms difference between the Geosat and Seasat histograms was similarly reduced from 0.63% to 0.25% by correcting the Seasat σ_0 values. This is within the range of expected interannual variability inferred from the ABM data. The possibility that part of the residual error may be due to more subtle systematic errors in the Seasat altimeter, SASS, or Geosat altimeter estimates of σ_0 also cannot be ruled out.

While the technique presented here required the independent SASS data set of coincident σ_0 observations to correct the Seasat altimeter σ_0 estimates, it is demonstrated in the appendix that essentially the same correction can be obtained based solely on the histograms of σ_0 measured by the Seasat and Geosat altimeters. This alternative cross-calibration procedure eliminates the need for an independent simultaneous σ_0 data set.

We conclude that the evidence is strong that the Seasat altimeter σ_0 estimates were in error by approximately the amount suggested in Figure 4. The cause of this apparent systematic error is still unknown. When this error was first suggested by *Chelton and Wentz* [1986], it was shown that the large tracker bias known to exist in the Seasat altimeter data could account for only part of the observed systematic difference. We have thus far been unable to explain the remaining error. For present purposes, however, we feel that the evidence for an error in Seasat altimeter estimates of σ_0 is sufficiently strong to warrant the correction procedure deduced from the cross-calibration of Seasat altimeter and SASS estimates of σ_0.

3. SEASAT ALTIMETER WIND SPEED ALGORITHM

An accurate wind speed algorithm for the Seasat altimeter has been developed by *Chelton and Wentz* [1986] from a comparison of 50 km along-track averages of altimeter estimates of σ_0 with nearby 100 km averages of wind speed at 24° incidence angle measured by SASS. Although the altimeter and SASS measurements were separated spatially by about 200 km, *Chelton and Wentz* [1986] showed that differences in wind speed at the two locations due to short spatial scale variability in the wind field average to zero over a large number of comparisons. A total of 241,000 SASS observations were used to derive the relation between Seasat altimeter estimates of σ_0 and wind speed at a height of 19.5 m above the sea surface. This calibration data set is much larger than could ever practically be obtained from in situ data over the lifetime of a single satellite altimeter mission.

The resulting Seasat altimeter wind speed model function (referred to hereafter as the CW model function) was derived in tabular form for σ_0 ranging from 8.0 dB to 19.6 dB in steps of 0.2 dB. This tabular model function is valid for wind speeds ranging from 0 to 21.1 m/s. Seasat measurements of σ_0 are converted to wind speed by linear interpolation of the table values. Values of σ_0 exceeding 19.6 dB are assigned zero wind speed and the wind speeds for values of σ_0 less than 8.0 dB are determined by linear extrapolation of the first two entries in the table.

A previous comparison of 1623 buoy and SASS wind speed estimates showed agreement between the two measurements to within 1.6 m/s rms [*Wentz et al.*, 1986]. To the extent that SASS wind speeds at 24° incidence angle are accurate, application of the CW algorithm yields accurate estimates of wind speed from raw Seasat altimeter measurements of σ_0, despite the likelihood of errors in the Seasat altimeter σ_0 described in section 2; any errors in Seasat altimeter estimates of σ_0 are implicitly accounted for by the method used to derive the CW model function. The rms difference between the Seasat altimeter and starboard 24° incidence angle SASS estimates of wind speed was less than 3 m/s. SASS port measurements of wind speed were deliberately excluded from the CW model function development to retain an independent data set for assessment of the quality of the altimeter wind speed algorithm. The rms difference between altimeter and port 24° incidence angle SASS estimates of wind speed was the same as for the starboard comparison. Assuming that the wind speed measurement errors are equally partitioned and uncorrelated between SASS and the altimeter, the rms error in the altimeter estimates of wind speed obtained using the CW algorithm is less than 2 m/s.

4. NEW GEOSAT WIND SPEED ALGORITHM

Because of the apparent systematic error in Seasat altimeter σ_0 measurements demonstrated in section 2, the CW algorithm of section 3 cannot be applied directly to Geosat σ_0 observations. The resulting wind speeds would contain systematic errors due to the systematic differences between Geosat and Seasat σ_0 estimates. The CW model function must therefore be modified before application to Geosat data to account for the apparent error in Seasat altimeter estimates of σ_0.

A smooth approximation to the correction derived previously in section 2 (see Figure 4) was applied to the CW tabular wind speed model function to obtain a 19.5 m wind speed model function appropriate for Geosat observations. Since most high-quality buoy wind speed observations are calibrated to a height of 10 m above the sea surface, an algorithm for altimeter estimates of 10 m wind speed may be more useful than the 19.5 m wind speed algorithm. For neutral atmospheric stability, wind speeds at 19.5 m can be adjusted to the 10 m level by a reduction of 5.7%. The resulting Geosat model function for both 19.5 m and 10 m wind speeds (referred to hereafter as the Modified Chelton and Wentz, or MCW, model function) is given in Table 1. The 10 m MCW wind speed model function is also shown graphically by the heavy solid line in Figure 5. For comparison, the CW model function (adjusted to 10 m) is shown by the dotted line in Figure 5.

The MCW model function provides wind speed estimates for σ_0 values ranging from 19.6 dB to 7.0 dB (corresponding to 10 m wind speeds between 0 and 20.2 m/s). Wind speeds for $\sigma_0 > 19.6$ dB are assumed to be zero. Wind speeds for $\sigma_0 < 7.0$ dB could be estimated by linearly extrapolating the first two table entries, although the accuracy of these high wind speeds has not yet been verified. As shown in Figure 5, the CW and MCW model functions are virtually identical for $\sigma_0 \geq 11$ dB. For this range of σ_0, the correction derived in section 2 is nearly zero. For $\sigma_0 \lesssim 11$ dB, the correction is much larger (see Figure 4), and the MCW algorithm yields lower wind speed estimates than the CW algorithm developed specifically for the Seasat altimeter.

5. COMPARISON WITH BUOY OBSERVATIONS

The quality of the Geosat MCW wind speed algorithm of section 4 can be independently assessed by comparison with high-quality wind speed observations from buoys. A total of 119 coincident Geosat and buoy observations were obtained from 43 National Data Buoy Center buoys located in the North Pacific, North Atlantic, Great Lakes, and Gulf of Mexico by digitizing Figure 11 of *Dobson et al.* [1987]. To ensure spatial and temporal coincidence between the two data types, the buoy wind speeds had been screened by *Dobson et al.* [1987] to eliminate observations separated by more than 50 km spatially and 30 min temporally. The Geosat observations had also been screened to eliminate altimeter measurements with off-nadir pointing angles greater than 0.75°.

A scatter plot comparison of buoy and Geosat MCW wind speeds is shown in Figure 6. The close agreement is encouraging. The rms and average (MCW minus buoy) differences between the two estimates are 1.9 and 0.45 m/s, respectively. The same comparison performed using the CW model function applied to Geosat estimates of σ_0 yields

TABLE 1. The Modified Chelton and Wentz Wind Speed Model Function Relating Geosat Measurements of σ_0 to Wind Speed at 19.5 m ($U_{19.5}$) and 10 m (U_{10}) Above the Sea Surface

σ_0, dB	$U_{19.5}$, m s^{-1}	U_{10}, m s^{-1}
7.0	21.373	20.154
7.2	20.781	19.597
7.4	20.189	19.038
7.6	19.579	18.463
7.8	18.958	17.877
8.0	18.321	17.277
8.2	17.662	16.655
8.4	16.979	16.011
8.6	16.276	15.348
8.8	15.555	14.669
9.0	14.821	13.976
9.2	14.075	13.273
9.4	13.316	12.557
9.6	12.545	11.830
9.8	11.763	11.092
10.0	10.970	10.345
10.2	10.169	9.590
10.4	9.361	8.827
10.6	8.546	8.059
10.8	7.739	7.298
11.0	6.975	6.577
11.2	6.279	5.921
11.4	5.642	5.321
11.6	5.051	4.763
11.8	4.509	4.252
12.0	4.021	3.792
12.2	3.582	3.378
12.4	3.196	3.014
12.6	2.871	2.708
12.8	2.595	2.447
13.0	2.342	2.208
13.2	2.113	1.992
13.4	1.927	1.817
13.6	1.777	1.676
13.8	1.641	1.547
14.0	1.505	1.419
14.2	1.370	1.292
14.4	1.238	1.167
14.6	1.120	1.056
14.8	1.031	0.972
15.0	0.970	0.915
15.2	0.925	0.873
15.4	0.883	0.833
15.6	0.842	0.794
15.8	0.800	0.755
16.0	0.759	0.716
16.2	0.718	0.677
16.4	0.676	0.637
16.6	0.635	0.599
16.8	0.593	0.559
17.0	0.552	0.520
17.2	0.510	0.481
17.4	0.469	0.442
17.6	0.427	0.403
17.8	0.385	0.363
18.0	0.344	0.324
18.2	0.302	0.285
18.4	0.261	0.246
18.6	0.219	0.207
18.8	0.177	0.167
19.0	0.136	0.128
19.2	0.094	0.089
19.4	0.053	0.050
19.6	0.012	0.011

rms and average differences of 2.2 and 0.8 m/s, respectively. The MCW algorithm thus represents an improvement over the CW algorithm when applied to Geosat observations. The large errors in wind speed obtained from the CW algorithm are evidently due to the systematic differences between σ_0 measurements from the Seasat and Geosat altimeters. The rms difference of 1.9 m/s obtained from the MCW algorithm is especially encouraging in view of the fact that *Dobson et al.* [1987] calculated an expected rms difference of 1.8 m/s based on the estimated errors in altimeter and buoy measurements and on differences between the spatial and temporal sampling characteristics of the two instruments.

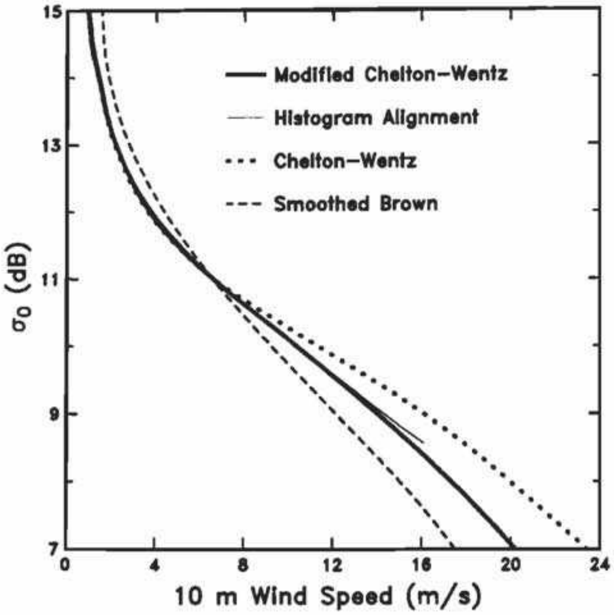

Fig. 5. Wind speed model functions relating σ_0 to wind speed for the Modified Chelton and Wentz algorithm (heavy solid line), the Histogram Alignment algorithm (see appendix), which applies to 10 m wind speeds between 2.77 and 16.35 m/s (thin solid line), the Chelton and Wentz algorithm (dotted line), and the Smoothed Brown algorithm (dashed line).

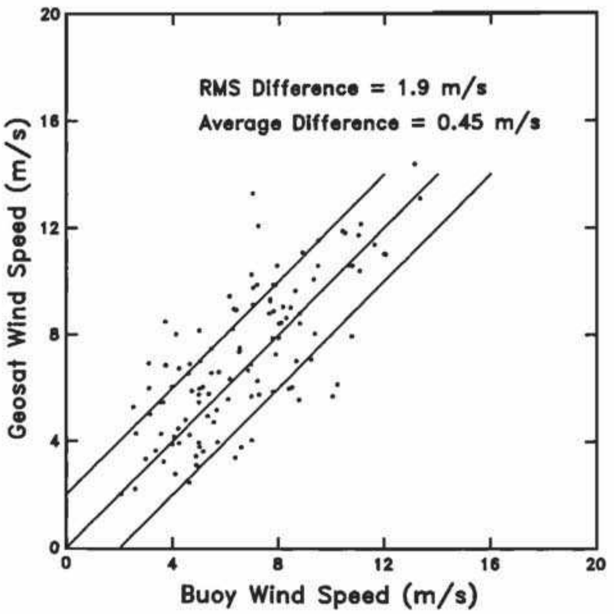

Fig. 6. A comparison of 119 NDBC buoy and Geosat altimeter wind speed observations computed by the MCW algorithm.

The performance of the MCW algorithm can be compared with that of the Smoothed Brown (SB) algorithm developed for the Geosat altimeter by *Dobson et al.* [1987]. The SB model function (shown by the dashed line in Figure 5) was obtained by a least-squares fit of a fifth-order polynomial to the *Brown et al.* [1981] three-branch wind speed model function. The *Brown et al.* [1981] model function was originally derived for the previous-generation Geos-3 altimeter by comparison of σ_0 with 184 pairs of coincident buoy observations of wind speed. As shown in Figure 5, the MCW, CW and SB model functions all intersect at $\sigma_0 \approx 11$ dB. For smaller σ_0, the MCW model function lies approximately halfway between the SB and CW model functions. The SB algorithm yields higher wind speed estimates than both the MCW and CW algorithms for $\sigma_0 > 11$ dB (6.6 m/s wind speed) and lower wind speeds than the MCW and CW algorithms for $\sigma_0 < 11$ dB. This is consistent with results obtained by *Dobson et al.* [1987] from their comparison of SB and buoy wind speeds. A least squares fit straight line through the data in Figure 8 of *Dobson et al.* [1987] would show that the SB algorithm overestimates wind speeds below about 6 m/s and underestimates wind speeds above about 6 m/s.

The rms and average difference between buoy and SB wind speeds was reported by *Dobson et al.* [1987] to be 1.7 and 0.3 m/s, respectively. Although the statistical accuracies of the MCW and SB algorithms are therefore essentially the same over the small set of buoy observations considered here, we feel that the MCW algorithm is preferable for several important reasons. Probably the most important is that the SB model function is based on a relatively small calibration data set; there were only 184 buoy wind speed observations, as compared with 241,000 SASS estimates of wind speed for the MCW algorithm. Moreover, approximately 1/4 of the SASS observations (i.e., >50,000 observations) correspond to wind speeds larger than 10 m/s, while only about 36 observations in the SB calibration data set correspond to wind speeds above 10 m/s [*Brown et al.*, 1981]. It is not surprising, then, that the SB and MCW wind speed model functions differ most at high wind speeds. A second concern is that the SB algorithm was derived based on comparisons between buoy observations of wind speed and Geos-3 altimeter observations of σ_0. The Geos-3 altimeter mission preceded Geosat by more than a decade and differed technologically from Seasat and Geosat in several fundamental respects [e.g., *Chelton et al.*, 1989], resulting in inherently greater σ_0 measurement noise. Moreover, no attempt to cross-calibrate the Geos-3 and Geosat estimates of σ_0 has yet been conducted. However, *Fedor and Brown* [1982] compared 19 coincident σ_0 observations from Seasat and Geos-3 and concluded that the two differed only by a simple bias. If true, this would imply an error in Geos-3 similar to that suggested here for Seasat. This may be particularly problematic at high wind speeds where the accuracies of wind speed estimates are most sensitive to small errors in σ_0. Finally, the spatial and temporal sampling domains of SASS and the altimeter are roughly comparable; both instruments provide spatially averaged estimates of wind speed [see *Chelton and Wentz*, 1986]. Buoys, on the other hand, estimate time-averaged wind speed at point locations. Spatial and temporal disparities in the sampling patterns of the altimeter and buoys, errors in buoy wind speed estimates, and differences between the time of the buoy report and the altimeter overflight are collectively responsible for approximately an rms difference of about 1 m/s between the two wind speed estimates [*Monaldo*, 1988].

6. SUMMARY AND CONCLUSIONS

Estimation of near-surface wind speed to an rms accuracy of 2 m/s from altimeter measurements of σ_0 has been convincingly demonstrated by numerous past studies. However, developing a new model function relating σ_0 to wind speed for each altimeter can be difficult. The most common approach is to compare the altimeter measurements of σ_0 with a large number of coincident high-quality buoy observations of wind speed. The problem with this method is that compilation of an adequate calibration data set spanning a wide range of wind speeds requires a considerable amount of time since the altimeter measures σ_0 along a very narrow "swath" of less than 10 km width. An alternative approach is to use a wind speed model function derived previously for another altimeter. This requires cross-calibration of σ_0 measurements from the two altimeters since wind speed estimates are very sensitive to the accuracy of σ_0. Such a cross-calibration can be a problem if the two altimeter missions do not overlap.

A method of cross-calibrating σ_0 measurements from different altimeters was proposed here and applied to data from the Seasat and Geosat altimeter missions, separated in time by nearly a decade. Histograms of Geosat measurements of σ_0 over the southern hemisphere for the period July 7 to October 10 were compared for two separate years (1987 and 1988) and found to be much more similar than histograms constructed separately from the 1978 Seasat and the combined 1987–1988 Geosat σ_0 observations. A second comparison of 13 years of Australian Bureau of Meteorology wind analyses yielded a similar result. Based on these comparisons, we have speculated that the σ_0 histogram is a relatively stable statistic over a sufficiently large geographical region and a long enough time period. The large differences between the 1978 Seasat and 1987–1988 Geosat histograms are then most likely indicative of a systematic error in either the Seasat or Geosat σ_0 estimates.

Seasat altimeter estimates of σ_0 were adjusted to remove a suspected systematic error suggested by an independent previous comparison with Seasat nadir scatterometer measurements of σ_0. The histogram of the adjusted Seasat estimates of σ_0 over the southern hemisphere for the period July 7 to October 10, 1978, was compared with the Geosat σ_0 histogram for the same time periods during 1987 and 1988 and found to be very similar. This result supports the speculations that (1) Seasat altimeter estimates of σ_0 are indeed in error for $\sigma_0 \lesssim 11$ dB and (2) the histogram of σ_0 is a relatively stable quantity and can therefore be used to test for systematic differences between σ_0 estimates from different altimeters.

An advantage of the proposed method of cross calibration of σ_0 from the Geosat and Seasat altimeters is that the *Chelton and Wentz* [1986] (CW) wind speed algorithm derived specifically for the Seasat altimeter can then be used to estimate wind speeds from the Geosat altimeter. Note that in view of the apparent error in Seasat altimeter estimates of σ_0, the CW algorithm is only applicable to Seasat altimeter data. For application to other altimeters, the CW model function must be modified to account for the apparent error in the raw Seasat estimates of σ_0. The resulting model function (the Modified Chelton and Wentz, or MCW, model function) is given in Table 1. Geosat wind speeds computed based on the performance of the MCW model function agree with independent measurements from 119 buoy observations to within an rms difference of 1.9 m/s. While the MCW model function in this limited comparison data set is not statistically significantly different from other recently developed wind speed model functions, we feel that the MCW algorithm is preferable because it was developed based on a very large calibration data set (241,000 SASS observations) which included many ($> 50,000$) observations at high wind speeds.

The comparison of Geosat and Seasat σ_0 presented here demonstrates the importance of cross-calibrating σ_0 before applying any existing wind speed algorithm to a new altimeter. This cross-calibration procedure is essential for all altimeter wind speed algorithms, irrespective of the source of their calibration data sets (i.e., in situ or satellite observations). If σ_0 observations from future satellite altimeters prove to be calibrated with Geosat estimates of σ_0, the MCW algorithm can be used directly to estimate wind speeds from these other altimeters. Otherwise, a wind speed algorithm for the new altimeter can be derived using either a direct cross-calibration technique such as that presented in section 2 or the histogram alignment cross-calibration technique described in the appendix.

APPENDIX: EMPIRICAL CROSS-CALIBRATION BASED ON HISTOGRAM ALIGNMENT

The technique presented in section 2 requires independent, coincident σ_0 observations to correct any systematic differences between σ_0 estimates from the two altimeters. In most cases, however, a large and accurate calibration data set (such as that obtained by the Seasat scatterometer) is not available, and an alternative method must be used. Here, we present an empirical technique for cross-calibrating σ_0 using only the σ_0 histograms from the two instruments.

Assuming that the wind speed distribution (and hence the σ_0 distribution) is stable from year to year over large geographic regions, empirical σ_0 distributions from two altimeters should be very similar if there are no systematic errors unique to either instrument. It is therefore possible, in principal, to correct for any such systematic differences by an empirical alignment of the two σ_0 histograms. Since the empirical cumulative probability distribution function (cpdf) is, by definition, a monotonically increasing function, a correction which aligns the cpdfs of two altimeters can be derived. The procedure to adjust one cpdf so that it agrees with a second (fixed) cpdf is as follows.

1. Compute cpdfs for the two distributions.
2. Fit a smoothing spline to the fixed cpdf.
3. Determine the cumulative percentage point for each binned value σ_0^a of the cpdf to be adjusted.
4. From the spline fit to the fixed cpdf, determine the value σ_0^f which corresponds to this cumulative percentage value.
5. Adjust each value σ_0^a by an amount $\sigma_0^a - \sigma_0^f$.

This adjustment brings the two histograms into exact agreement.

Corrections derived using this method are most susceptible to errors at σ_0 values near the tails of the histograms where there are few observations and random errors in individual measurements do not, in general, average to zero. Thus the resulting uncertainties in the histograms will be reproduced in the cpdfs, which will ultimately yield errors in the correction $\sigma_0^a - \sigma_0^f$. For bins containing large numbers of observations, this is not a concern since random errors tend to cancel within a given bin. A second, and perhaps more important, source of error arises from the lack of temporal and geographic stability in the empirical σ_0 distribution at extreme σ_0 values. Observations of these values of σ_0 are generally due to sampling statistically rare sea surface conditions. Since random errors in individual measurements and the stability of the histograms are most problematic at extreme σ_0 values, these difficulties can be avoided by computing the correction only for the σ_0 bins containing large numbers of observations.

As an example of this technique, Geosat and Seasat σ_0 estimates were cross-calibrated by adjusting the Seasat cpdf to agree with the Geosat cpdf. The decision to hold the Geosat distribution fixed was made based on the evidence for Seasat calibration errors presented in section 2 above. To avoid sampling problems at extreme values of σ_0, corrections were computed only for σ_0 values within the middle 90% of the Seasat cpdf (i.e., raw Seasat σ_0 values between 8.95 dB and 12.55 dB).

The correction function obtained by the five step adjustment procedure (shown by the thin solid line in Figure 4) agrees remarkably well with the correction derived in section 2 from the cross-calibration of Seasat altimeter and Seasat scatterometer σ_0 estimates. The rms difference between the two corrections is 0.02 dB for σ_0 values between 9.95 and 11.15 dB (comprising 50% of all raw Seasat altimeter σ_0 observations) and 0.07 dB for σ_0 values between 8.95 dB and 12.55 dB (comprising 90% of all raw Seasat altimeter σ_0 observations).

The wind speed model function obtained by fitting a smoothed representation of this correction function to the CW wind speed algorithm is shown by the thin solid line in Figure 5. Because this algorithm (referred to here as the Histogram Alignment, or HA, model function) was derived based on the center 90% of σ_0 values, it applies only to Geosat σ_0 values between 8.5 dB and 12.5 dB, corresponding to 10 m wind speeds between 2.77 and 16.35 m/s. As expected from the good agreement between the corrections shown in Figure 4, the HA and MCW algorithms provide similar estimates of wind speed. For most σ_0 values, the difference between wind speeds estimated from the HA and MCW algorithms is smaller than the thickness of the lines plotted in Figure 5. The example presented here thus demonstrates that the HA technique can be used to obtain a wind speed model function which agrees well with model functions derived from direct calibration with SASS estimates of σ_0.

As noted above, the foremost advantage of this alternative cross-calibration technique is that corrections for systematic differences between two σ_0 distributions can be derived without a direct cross-calibration of coincident data. This has particular relevance for developing wind speed algorithms for future altimeter missions. This cross-calibration procedure should be applied cautiously, however. Any instrument-related temporal drifts in σ_0

must be eliminated and the stability of the wind speed distribution over the spatial and temporal calibration domain must be established prior to calibrating the σ_0 distributions. As with any new algorithm, wind speeds derived based on σ_0 estimates computed using this technique should be independently verified by comparison with buoy data as in section 5.

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