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WAVEFORM ANALYSIS FOR GEOSAT DAY 96

A detailed model waveform function has been least-squares-fitted to 10-second averages of waveform sampler data from selected over-ocean portions of day 96 of the GEOSAT mission. Our results confirm that the height corrections already applied in the routine GEOSAT data processing are generally good to well within 10 centimeters. Additional height corrections are provided that can refine height estimates to within the several-centimeter level.

INTRODUCTION

A radar altimeter usually emits a relatively narrow electromagnetic pulse and, some time later (the two-way ranging time), samples the returned surface-scattered energy. GEOSAT has 60 waveform samplers uniformly spaced 3.125 nanoseconds apart in two-way ranging time; three more samplers are located in the middle of the set of 60. The waveform sampler set is positioned by the altitude tracking loop. The tracking loop's microprocessor makes positioning decisions by comparing waveform sampler data to an internal waveform model or template.

Because of the finite computational capability of the microprocessor and the limited time available in which to do the computations, the waveform model implemented in the microprocessor-driven altitude tracking loop is necessarily limited or simplified. A first-order correction for the implemented model's shortcomings is provided by a look-up table in the GEOSAT data processing, the table entries having been supplied by preflight modeling and simulation work by APL.

In ground-based analyses with a larger computer and no real-time computational limitation, a fuller and more complete waveform model can be fitted to waveform sampler data; the results of such refitting or retracking can provide valuable information on the accuracy of the current GEOSAT estimates of altitude and significant wave height (SWH) and on possible small corrections to those estimates.

In informal collaboration with L. Choy of the Naval Research Laboratory, we have been fitting a five-parameter model waveform to 10-second averages of waveform sampler data for GEOSAT day 96. Among the five fitted model parameters are estimates of SWH, attitude angle, and the height tracker's range error. The fitted estimates agree quite well with the GEOSAT hardware estimates. The difference between (a) the height correction on the Intermediate Geophysical Data Record (IGDR) tape and (b) the tracker range error estimated from waveform fitting could be added to the altimeter's range estimate to yield a refined range estimate. The net result would provide a ground-based range retracking. We have not done that because we do not have access to the classified altimeter height estimates, but later we will present the sizes and variations of such range corrections as well as coefficients for simple numerical estimation functions for range and SWH corrections.

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DATA ANALYSIS

Segments of 17 GEOSAT revolutions from day 96 have been analyzed. From 1220 to 2220 seconds in extent, they were taken under relatively well-behaved open-ocean conditions. The cumulative time for all 17 segments was about 19,000 seconds.

The primary input data were the 10-per-second data from the 63 GEOSAT waveform samplers plus the frame count from the Waveform Data Record tape. Also used were SWH and estimates of attitude angle as a function of time, obtained from the (corrected and redistributed) IGDR tapes for day 96. The major software tool was a general iterative, nonlinear, least-squares procedure for fitting a multiparameter model waveform to a set of waveform sampler values. We have used a similar procedure in earlier GEOS-3 and Seasat-1 analyses.[1,2] The five parameters fitted in the present work are a waveform amplitude; track-point position relative to location of the waveform sampler set, hence a track-point correction; SWH; a noise baseline; and the attitude angle. The earlier work[1,2] was based on a scattering description by Brown[3] for a satellite over a flat ocean. That description has been modified in our recent work to account for the finite radius of the earth,[4] but we find that this correction makes only a negligible change in the estimated parameters.

As in our past work with GEOS-3 and Seasat-1 data, the GEOSAT waveform data showed that small, systematic, individual sampler gain adjustments were necessary because of small discrepancies between the calibration and operation modes. A revised set of gain adjustments has been developed from waveform-fit residuals over a portion of our data set.

Five-parameter fits (to 10-second averages of the 63 waveform samplers, corrected by the revised gain adjustments) were produced for the 17 different GEOSAT data segments for day 96 listed in Table 1.

Table 1—Data analyzed.

Data Label	*GEOSAT Revolution*	*Start Frame Count*	*Time Extent (seconds)*
342A	342	25894393	1310
342	342	25911413	1310
343A	343	25952293	1620
343	343	25973193	1590
344	344	26011693	1800
345	345	26069493	1980
345B	345	26095893	700
346A	346	26129093	2200
346	346	26157493	1200
347A	347	26173193	970
347	347	26192093	1320
347B	347	26207893	600
347C	347	26218493	2200
348A	348	26251693	1160
348	348	26269293	600
348B	348	26280293	840
349A	349	26325393	680

The data in Table 1 contain fitted SWH values in the range of 0 to 7 meters and attitude angles in the range of 0 to 1.1 degrees. The waveform-fit results for height error, attitude, and SWH were compared to the IGDR results, and approximate numerical relations were found that allow the use of IGDR quantities to estimate what would have been obtained by waveform fitting. These numerical relations are useful as a final data correction step, and preliminary sets of coefficients are provided in this report for the height and SWH corrections.

HEIGHT BIAS ALGORITHM

Figure 1 shows the entire-data-set comparison of IGDR height error and the height error determined by waveform fit. The IGDR height error is the correction already applied in the GEOSAT data processing and available on the IGDR tape. The agreement is good, but there is a small SWH- and attitude-dependent departure from the 45-degree line in Fig. 1; we now describe a correction procedure using only IGDR quantities to better estimate height error.

The height-bias error is defined as the difference between the height-correction estimate from waveform fitting and the height correction actually applied (the IGDR height error in the above paragraph). The height-bias error is generally positive; that is, the IGDR height correction is usually too small. In earlier digital simulation studies of the GEOSAT altimeter, the height bias was found to be an approximately quadratic function of both the true SWH and the true attitude angle, which suggests that the height-bias error may also be an approximately quadratic function of SWH and attitude. It is found from the data study of GEOSAT day 96 that the height

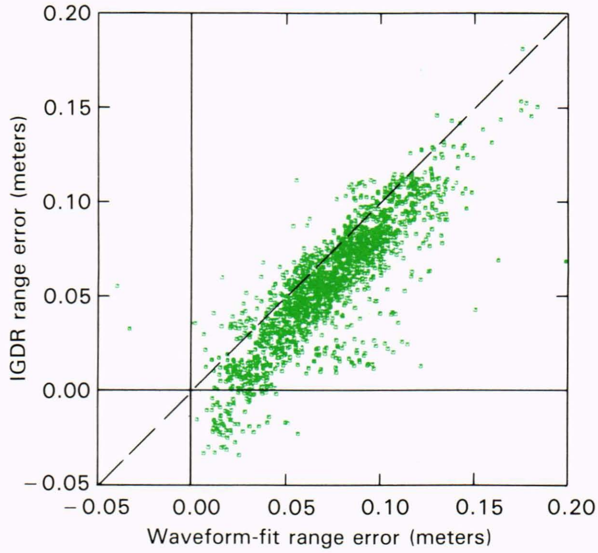

Figure 1—A comparison of the IGDR height correction and the height correction determined by waveform fit for 10-second averages in the study data set.

bias error can be approximated as a quadratic function of the IGDR SWH and the IGDR attitude angle.

Defining S as the value of SWH from the IGDR, and A as the attitude angle from the IGDR, the height-bias error E_h is

$$E_h = a_1 + a_2 \cdot S + a_3 \cdot S \cdot A + a_4 \cdot A + a_5 \cdot S \cdot S + a_6 \cdot S \cdot S \cdot A + a_7 \cdot S \cdot S \cdot A \cdot A + a_8 \cdot S \cdot A \cdot A + a_9 \cdot A \cdot A \,,$$

where the nine coefficients a_i are determined in an entire-data-set least-squares manner. There was negligible dependence on the Gate Index (i.e., the designation of which set of track gates was used in the adaptive tracker) in our work. The interim values for the nine coefficients of height-bias error versus S and A were

$a_1 = +0.10611329\text{E-}02$, $a_2 = +0.30292242\text{E-}02$,

$a_3 = -0.11082159\text{E-}01$, $a_4 = +0.26591876\text{E-}01$,

$a_5 = -0.15802484\text{E-}03$, $a_6 = -0.11133591\text{E-}05$,

$a_7 = +0.24805287\text{E-}02$, $a_8 = +0.81107152\text{E-}05$,

$a_9 = +0.50978306\text{E-}02$,

where the height-bias error and SWH are in meters and the attitude is in degrees. (If dependence on the Gate Index were not negligible, it would have been necessary to find four separate sets of nine coefficients.) For this set of coefficients, Figure 2 shows height-bias error versus A for different S values.

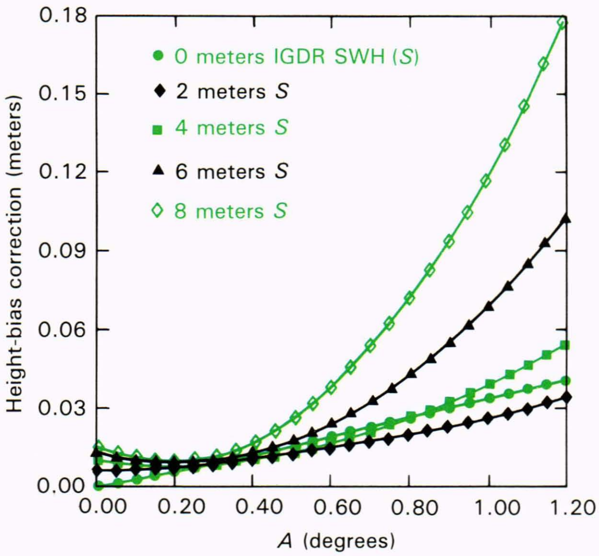

Figure 2—Height-bias correction versus IGDR attitude angle (*A*) for different *S* values, for the numerical coefficients given in the text.

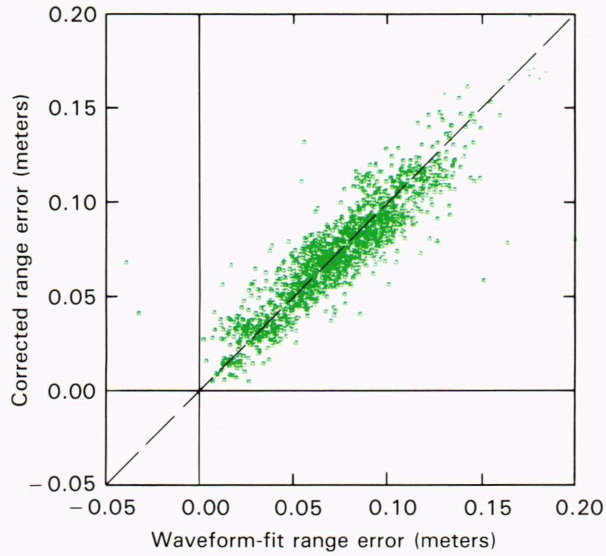

Figure 3—A comparison of "corrected" height bias and waveform-fit-determined height correction for 10-second averages in the study data set.

The above height-bias error can be added to the IGDR height error to produce a "corrected" height bias; Fig. 3 compares the "corrected" height bias with the waveform-fit height bias. This figure can be compared directly with Fig. 1; the improvement is apparent. The height-bias error from the numerical approximation can also be added directly to the IGDR height to produce a final, corrected height.

SWH CORRECTION ALGORITHM

In a manner similar to the height correction, an SWH error is defined as the waveform-fit SWH minus *S*, the SWH from the IGDR tape. Then an entire-data-set fit is made for another biquadratic function expressing the SWH error as a function of *S* and of the *VATT* value, where *VATT* is the "attitude-estimating" voltage[5] used in the GEOSAT attitude estimation and is also available on the IGDR tape. With E_S as the SWH difference and *V* as the *VATT*,

$$E_S = b_1 + b_2 \cdot S + b_3 \cdot S \cdot V + b_4 \cdot V + b_5 \cdot S \cdot S + b_6 \cdot S \cdot S \cdot V + b_7 \cdot S \cdot S \cdot V \cdot V + b_8 \cdot S \cdot V \cdot V + b_9 \cdot V \cdot V ,$$

where interim values for the b_i are

$b_1 = +1.47647679$, $b_2 = +0.49310892\text{E-}01$,
$b_3 = -0.93457617\text{E-}01$, $b_4 = +0.54113668$,
$b_5 = +0.12543133$, $b_6 = +0.986678071\text{E-}07$,
$b_7 = -0.31475897\text{E-}01$ $b_8 = -0.19803398\text{E-}06$,
$b_9 = -0.66511060$,

with E_S and *S* in meters and *V* in voltage units directly from the IGDR tape. Again, only negligible improvement is made by allowing for dependence on the Gate Index, so only a single set of nine coefficients is presented here.

With this set of coefficients, a "corrected" SWH can be produced from IGDR quantities only, by adding the SWH error (from the coefficients above) to the *S* value. Figure 4 shows the original *S* versus waveform-fit-determined SWH, and Fig. 5 shows the "corrected" SWH versus waveform-fit SWH. A comparison of Fig. 5 with Fig. 4 shows the improvement.*

ATTITUDE ESTIMATE COMPARISONS

Some of the estimates of waveform-fit determined attitude angle are less than 0 degree, a noise-induced result of the attitude-estimation procedure. Negative attitude values are meaningless, and a negative estimate should be read simply as zero. Figure 6 shows *A* versus the waveform-fit attitude. Notice that the waveform-fit attitude goes closer to zero while *A* is never less than about 0.3 degree, and that for attitude values greater than 0.8 degree the waveform-fit attitude is slightly larger than that of the IGDR.

The attitude-estimating voltage *VATT* was expected, from simulation studies, to be a quadratic function of both the attitude angle and the SWH. Numerical coefficients were found for *VATT* as a biquadratic function of the waveform-fit attitude and the waveform-fit SWH, and the coefficients were used with the "corrected"

*As the final version of this paper was being prepared, we learned that the SWH correction had been applied with the wrong sign in the Naval Surface Weapons Center data processing that produced the IGDR. This would explain the relatively large SWH differences shown in Fig. 4. The numerical correction in this article is correct for the GEOSAT SWH data *as distributed* on the IGDR tapes from NSWC.

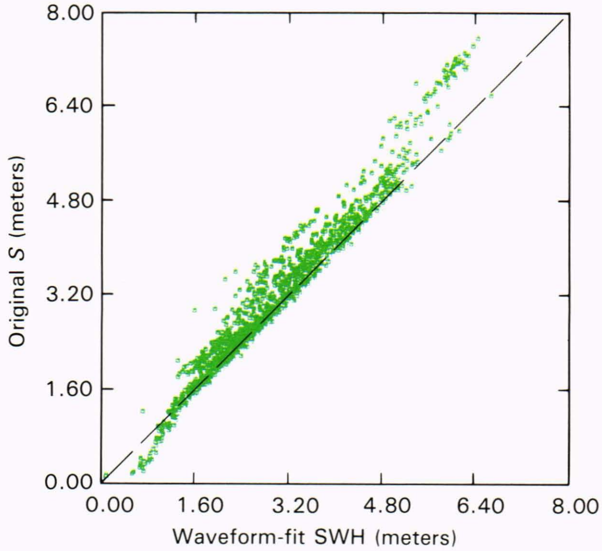

Figure 4—A comparison of SWH derived from IGDR (*S*) and waveform-fit-determined SWH for 10-second averages in the study data set.

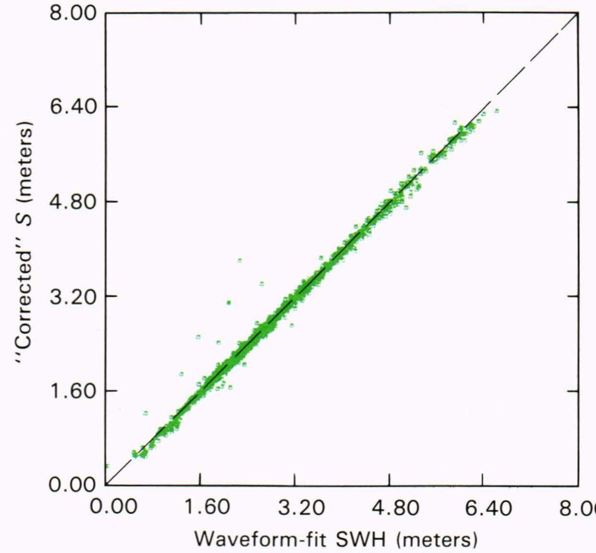

Figure 5—A comparison of "corrected" SWH and waveform-fit-determined SWH for 10-second averages in the study data set.

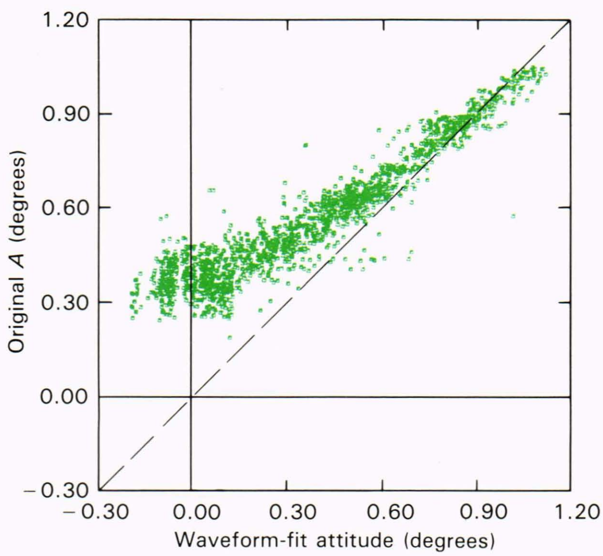

Figure 6—A comparison of IGDR attitude angle (*A*) and waveform-fit-determined attitude angle for 10-second averages in the study data set.

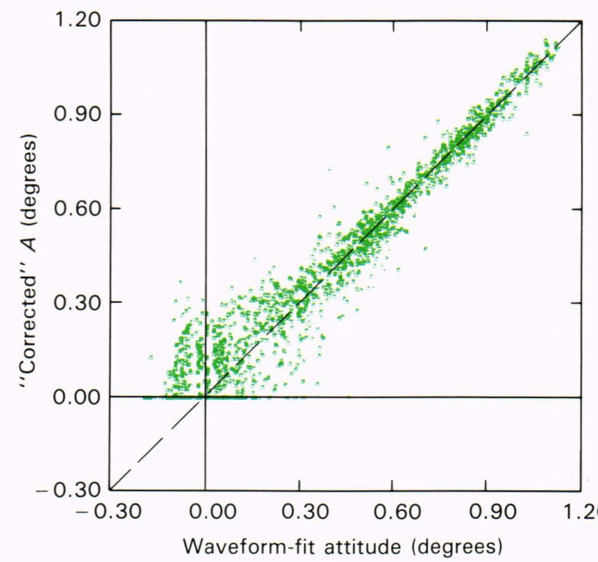

Figure 7—A comparison of "corrected" attitude angle and waveform-fit-determined attitude angle for 10-second averages in the study data set.

SWH (of the preceding section) and the IGDR *VATT* values to produce the "corrected" attitude results shown in Fig. 7. Since attitude is not of primary interest, the coefficients are not given here but they can be supplied upon request.

RESULTS OF INDICATED CORRECTIONS

Figure 8 summarizes the results of the various corrections described as applied to the GEOSAT revolution segment 347c in the study data set. Three different plots are shown in Fig. 8, all plotted versus one-tenth the (reduced) frame count. Since there are 10 data frames per second, the horizontal axis is approximately from 0 to about 2000 seconds of orbit time. The top plot of Fig. 8 shows the (waveform-fitted) attitude and SWH values for reference, the middle plot compares SWH differences, and the bottom plot shows the height-bias-error results.

Referring to the middle plot of Fig. 8, recall that the SWH difference is defined as the waveform-fit result minus the IGDR result, and that, in general, the waveform-fit SWH is lower than the SWH from the IGDR for the study data set. The solid line is the direct difference, and the closed circle shows the "IGDR-estimated" SWH difference. The agreement is very good, showing that the numerical SWH correction scheme described in this ar-

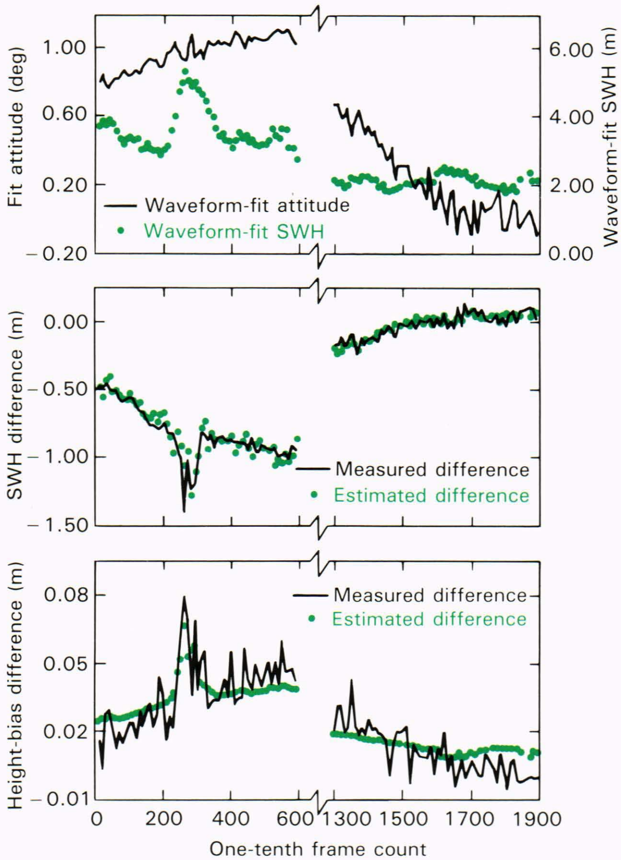

Figure 8—An example of results from revolution segment 347c, where the reduced frame count is the original frame count minus 25894400.

ticle does a good job of producing the SWH estimate from waveform fitting.

Finally, the height-bias error that could be added to the IGDR height is shown in the bottom plot of Fig. 8. The height-bias error of the text discussion is called the height-bias difference on the vertical axis of this plot. Over the entire 347c segment, this height-bias error is in the range of 0 to 6 centimeters, and the IGDR-estimated error is clearly within a centimeter of the directly determined (by differencing waveform-fit and IGDR height biases) error. This example is typical of most of the data in the study data set.

For all the data examined in our limited study, the height-bias error is well within the plot range allowed in Fig. 8: −4 to +8 centimeters. This means that the current GEOSAT data processing already corrects the height for SWH or attitude dependences to within the 10-centimeter level required for the GEOSAT primary mission.

SUMMARY AND CONCLUSION

Results have been described for parameter recovery from model waveform fitting to 10-second averages of waveforms in a data set of 17 different revolution segments for GEOSAT day 96, representing a total time expanse of about 19,000 seconds. The attitude angle, SWH, and height-correction estimates from the waveform fitting were compared to the IGDR quantities. Sets of coefficients were found for biquadratic approximation forms, allowing the use of IGDR quantities to estimate the results that would have been obtained if waveform fitting were employed.

Although data classification prevented our examining the height data, the height corrections for attitude and SWH were available. Our work provides independent confirmation that the height corrections already applied in the routine GEOSAT data processing are good to well within the 10-centimeter level; additional corrections at the several-centimeter level can be made on the basis of our work.

The 17 revolution segments for GEOSAT day 96 constitute, in effect, a training set for the numerical correction algorithms. We intend to continue this work and to make further comparisons with data taken over the ocean, particularly in the vicinity of the Naval Research Laboratory verification area.

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