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Altimeter sea state bias: A new look at global range error estimates

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Abstract. A nonparametric SSB model, derived using the TOPEX altimeter, is analyzed to show a new decomposition of the form SSB = bH_s + f(σ_o), where b is 0.03 and the function of radar cross section (σ_o) is an absolute second-order range correction residing outside the conventional nondimensional SSB model. Expected variability in the dominant bH_s term and its ties to the long wave orbital velocity and shorter-scale slope variances are discussed using a physically-motivated restatement of recent EM bias theory. The geometry of steep near-breaking waves, neglected within current theory, is invoked as one plausible explanation for the observed H_s-independent SSB component.

Introduction

The sea state bias (SSB) correction for the TOPEX altimeter is typically 6-8 cm over the global ocean but scales with the rms wave height and thus varies from 2 to more than 40 cm. The observed basis for the effect is a measured decrease in radar backscatter versus increase in elevation relative to the lowest wave troughs [*Yaplee et al.*, 1971]. The variation serves to preferentially weight an altimeter's time-dependent received power signal (proportional to the radar backscatter versus elevation) below mean sea level. The small range shift is often referred to as the electromagnetic (EM) bias, but in the context of the satellite altimeter the effect is carried within the total sea state bias in a fairly complex and indirect manner.

A recent article [*Chelton et al.*, 2001] reviews empirically-derived altimeter SSB correction algorithms. Presently, the TOPEX SSB error is assumed correct to within roughly 1 % of H_s (defined as four times the surface elevation rms). The goal in this arena continues to be the definition of a robust routine that minimizes both geophysical- and tracker-related range shifts related to sea state changes. Studies supporting this goal have been conducted in the areas of theoretical modeling [*Elfouhaily et al.*, 1999, 2000, 2001], altimeter wind speed redefinition [*Gourrion et al.*, 2000], and EM bias field experiments [*Millet and Arnold*, 2000]. These efforts are ultimately in search of new geophysical correlatives that better define the EM bias process and can serve as ancillary SSB model inputs. This paper addresses the import of these efforts within the context of a recent empirically-derived TOPEX SSB model[*Gaspar and Florens*, 1998].

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Nonparametric SSB model analysis

The general form of the SSB model is always given as:

$$SSB = H_s \Sigma(X; q) \quad (1)$$

where H_s is the altimeter significant wave height estimate, Σ the nondimensional, or relative, SSB function, X the vector of the chosen dependent variables and q the vector made of the chosen model coefficients. Numerous studies point out that Eq. 1 then encompasses any range error (not solely the EM bias) correlated with changes in H_s. To date, chosen variables are those actually measured by the altimeter: H_s and σ_o, the radar backscatter coefficient at Ku-band.

The recent nonparametric SSB model of Gaspar and Florens (1998) avoids error inherent within past efforts that solved for Eq. 1 using *a priori* functional assumptions. Results derived from a multi-year global TOPEX crossover difference data set are displayed in Fig. 1a. The model is presented as the relative error $\Sigma = SSB/H_s$ versus σ_o. The model itself is developed as $SSB = \Sigma(H_s, U_{alt})$ where U_{alt} is the wind speed from σ_o using the Modified Chelton-Wentz algorithm [*Witter and Chelton*, 1991]. The results are qualitatively similar to previous parametric developments [*Chelton et al.*, 2001] but there are substantial changes such that this mapping represents the current best estimate over the bivariate input domain. The nondimensional bias, Σ, is at or above 3 % with a slight increase for lower H_s and any value of σ_o. Each curve (for indicated H_s) starts from a 3 % x-axis 'pedestal' value at the highest σ_o, increases in magnitude, and then returns to this bias level (3 % at σ_o = 9 dB). In all cases the maximum occurs within ± 0.2 dB of 10.3 dB. Such variation also holds true for H_s levels not shown.

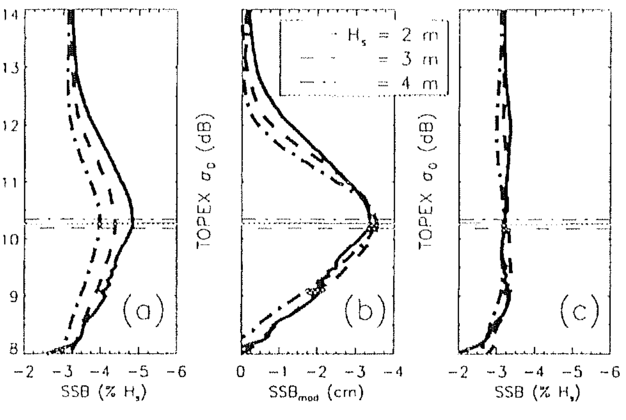

Figure 1. Results taken from nonparametric TOPEX SSB models with curves for varying sea state as indicated. (a) Nominal dual-parameter SSB model with bias given as Σ (relative bias) versus σ_o, (b) SSH_{mod} (see text, Eq. 2) versus σ_o where the bias is now given in absolute range, and (c) same as for (a) but now from a revised SSB model derived after removal of SSH_{mod}.

The local maximum is a recognizable feature of the SSB, both from field experiment [*Walsh et al.*, 1991; *Arnold et al.*, 1995], and on-orbit perspectives. Note however, that the y-axis of Fig. 1 is not the true wind speed, but rather σ_o. Results from EM bias field observations and theoretical studies have always been reported in terms of the true wind speed rather than the measured σ_o. This distinction is raised based on recent work showing that altimeter-derived wind speed errors are systematically correlated with H_s variations. The physical basis for this observation is that an altimeter's σ_o is derived from all roughness (wave) scales including a non-negligible contribution from long waves that are not necessarily coupled to the local wind. A recent study [*Gourrion et al.*, 2000] discusses this point and empirically-derived results are shown in Fig. 2. These curves are derived from a collocation of TOPEX altimeter measurements with surface wind speed estimates from the NSCAT scatterometer. The figure depicts a global average, determined from nonparametric analysis, of the relationship between Ku-band σ_o and the 'true' 10 m wind as inferred from scatterometer data. σ_o varies for a constant wind speed dependent upon H_s. A given σ_o corresponds to higher wind speed values as H_s decreases. This multivaluedness is evidence suggesting caution in direct comparison of field experiment SSB relationships to on-orbit models in terms of 'true' wind speed.

Returning to Fig. 1a, recall that relative SSB modulation versus σ_o is similar at each H_s level. Further, separation between these curves is greatest near the local SSB maximum ($\sigma_o \simeq 10.3dB$). Observed SSB modulations thus appear nearly H_s independent. Fig. 1b presents a model that isolates the observed signal variation as

$$SSB_{mod} \text{ (in cm)} = H_s * (\Sigma - K) \simeq f(\sigma_o) \qquad (2)$$

where K is simply a constant, or SSB pedestal, set to values of 0.031 $\pm$0.005 for each H_s shown. Results collapse to a nearly identical relation versus σ_o. Within the range of 9 to 13 dB there is less than 1 cm deviation. The maximum of this SSB modulation is 4 cm and still resides at σ_o = 10.3 dB $\pm$0.2 dB at all H_s.

While the correction of sea state bias due to the altimeter wind (i.e. σ_o) has always been of second-order, Eq. 2 has not been anticipated nor identified in previous studies. Ramifications are considerable in both the empirical and theoretical arenas. Empirically, the usual nondimensional sea state bias term reduces to a fixed constant value near to 3 %. This relative error decouples from σ_o over most of the TOPEX data domain. Fig. 1c illustrates this point, showing the results of a NP reanalysis performed after removal of the average (computed over H_s= 2-4 m) SSB_{mod} range error. The separation of variables needs consideration in future SSB model solution as well as model residual error analyses and field data examination. Theoretically, EM bias models have yet to address such a form. Rather, their application is to the dominant 3 % sea state term and its variability, as presented in the following section. However, the penultimate section puts forward wave breaking, a process that lies outside existing theory, as a plausible physical source for the observed $f(\sigma_o)$ behavior.

Insight from EM bias theory

The observation of Fig. 1a is not a radical departure from past SSB models where the nominal correction is of order 2-3% of H_s with second order corrections related to σ_o and H_s. Recent EM bias modeling efforts have sought to reproduce this observation from first principles and using an analytic framework designed to elicit the primary physical variables dictacting the phenomena. The models begin by assuming surface statistics of weakly nonlinear waves[*Longuet-Higgins*, 1963]. This assumption is valid for weakly-interacting gravity waves (a small steepness assumption) corresponding solely to the long wave field[*Elfouhaily et al.*, 1999]. For these longer waves, the induced surface motion is irrotational, and the coexistence of wave elevation and horizontal surface velocity dictates the existence of a sea state bias. A further refinement invokes a two-scale surface approximation to permit prediction using a more realistic surface geometry including all roughness scales [*Elfouhaily et al.*, 2000] and to incorporate the expected modulation of short waves by orbital straining associated with the long wave heave [*Elfouhaily et al.*, 2001]. The ensemble is reasonably complete up to the limit of the weakly nonlinear assumption.

Following is a simplified rendering of the cited two-scale EM bias model studies that aims to clearly identify the correlative relationships between the observed bH_s term and

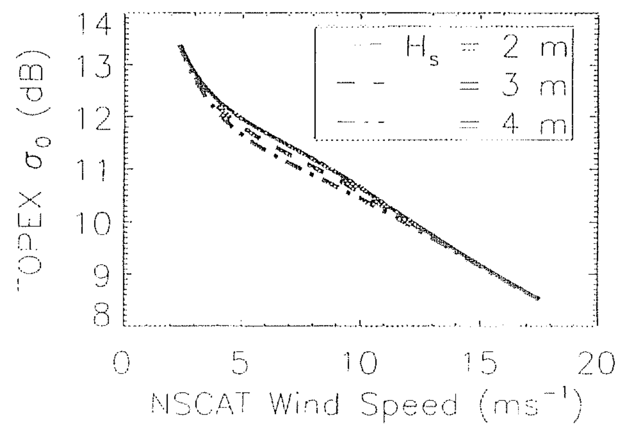

Figure 2. Curves depicting a neural network model that maps between NSCAT scatterometer wind speed, TOPEX altimeter H_s, and TOPEX altimeter σ_o.

recognized wave field measurements. In particular, we wish to highlight the key role that the long wave orbital velocity plays under weakly nonlinear theory. Under a Physical Optics scattering assumption one can write the local contribution to an altimeter's total σ_o measurement as

$$\sigma_o \propto \frac{R}{mss_s}\left(1 - \frac{\nabla_x\zeta^2}{mss_s}\right) \quad (3)$$

where ζ represents the sea surface elevation at a given location, and $\nabla_x\zeta$ the local tilt. In this approximation, mss_s is the slope variance associated with a given tilted patch and nominally much greater than the local tilt squared. R is a surface reflection term carrying the Fresnel coefficient plus possible diffraction effects. The following model assumes negligible diffraction (R held constant) to focus upon two contributions, tilt and hydrodynamic modulation. As an illustration, assume a linear modulation for the short scale roughness mss_s. In this case, σ_o can be formulated as

$$\sigma_o \propto \frac{R(1+\delta)}{mss_{os}}\left(1 - \frac{\nabla_x\zeta^2}{mss_{os}}(1+\delta)\right) \quad (4)$$

where δ corresponds to small fluctuations of the short-scale waves along the long wave profile, and where mss_{os} represents the total short-scale slope variance [*Chapron et al.*, 2000]. Defining Δ to be the variance for these random fluctuations leads to

$$\langle\sigma_o\rangle \propto \frac{R}{mss_{os}}\left(1 - \frac{\langle\nabla_x\zeta^2\rangle}{mss_{os}}(1+\Delta)\right) \quad (5)$$

At this point Eqs. 4 and 5 can be directly applied within the usual EM bias height-σ_o cross correlation. Terms are arranged under the assumed separation $\beta_{EM} = \beta_{EM-tilt} + \beta_{EM-hydro}$ and the expected EM bias tilt contribution becomes

$$\beta_{EM-tilt} = -\frac{\langle\zeta\nabla_x\zeta^2\rangle}{\langle\nabla_x\zeta^2\rangle}\frac{\langle\nabla_x\zeta^2\rangle}{mss_{os} - \langle\nabla_x\zeta^2\rangle(1+\Delta)} \quad (6)$$

where the leading term in the expectation is proportional to the correlation between long wave elevation and squared slope. This term relates to the well-known cross-skewness coefficient defining the EM bias in seminal theoretical studies [*Srokosz*, 1986]. The present form sheds light on this tilt bias term when one permits the long waves to be characterized by a narrow-band elevation spectrum (near to unimodal). Following *Longuet-Higgins* [1963], the nonlinear long wave profiles will exhibit a Stokes-like waveform. To first order, $\langle\zeta\nabla_x\zeta^2\rangle \propto \langle\nabla_x\zeta^2\rangle\langle\nabla_t\zeta^2\rangle g^{-1}$. Thus $\langle\nabla_t\zeta^2\rangle g^{-1}$, readily identified with the orbital velocity variance near to the spectral peak (using the gravity wave dispersion relationship), becomes the leading term in the tilt EM bias component.

The hydrodynamic EM bias contribution can be written as

$$\beta_{EM-hydro} = \langle\zeta\delta\rangle\frac{mss_{os}}{mss_{os} - \langle\nabla_x\zeta^2\rangle(1+\Delta)} \quad (7)$$

These refining developments introduce multiplicative scaling of the expected leading correlation terms: $\langle\zeta\nabla_x\zeta^2\rangle$ in Eq. 6 and $\langle\zeta\delta\rangle$ in Eq. 7. The scaling factors depend in part on the long and short scale slope variances.

Next, assuming small-amplitude and linear fluctuations, the short-wave hydrodynamic modulation term δ can be approximated as $\delta = -\gamma\sin\phi\nabla_x\zeta - \gamma\cos\phi\widetilde{\nabla_x\zeta}$ where γ, and ϕ are the amplitude and phase of the long-wave induced linear modulation, respectively. The term $\widetilde{\nabla_x\zeta}$ is the quadrature tilt. The variance of the modulation δ now becomes $\Delta = \gamma^2\langle\nabla_x\zeta^2\rangle$, and the expected correlation with ζ is obtained as

$$\langle\zeta\delta\rangle = -\gamma\cos\phi\frac{\langle\nabla_t\zeta^2\rangle}{g} \quad (8)$$

Therefore $\langle\nabla_t\zeta^2\rangle g^{-1}$ is also the leading term within the hydrodynamic EM bias. The composite model states that EM bias is thus primarily related to the long wave orbital velocity variance rather than to H_s.

We do not suppose that this model should exactly match the TOPEX SSB observations but it should serve as a tool for field experiment analysis and instructing future on-orbit studies. Of prime interest is the prediction of variability sources resident atop the global average 3 % observation of Figure 1c. First, recognize that statistical parameters associated with a given wavelength scale, e.g. H_s and $\langle\nabla_t\zeta^2\rangle$, will usually be highly correlated. Thus it is not surprising to see the effectiveness of the altimeter SSB algorithm based upon H_s. Still, theory implies that subtle regional or seasonal deviation from the mean (i.e. global average) relation between these two long wave terms will lead to sea level estimate errors. Changes at shorter spatio/temporal scales such as near ocean or atmospheric fronts or coastlines will alter nominal relations between short- and long-wave variance parameters of Eqs. 6 and 7, consistent with a changing wave steepness characterization. In this latter case the relative influence of long wave slope variance becomes more critical.

SSB variation and wave breaking

The EM bias contributions discussed above reside within the assumption of a nearly linear correlation between surface elevation and slope components. The underlying gravity waves have small slopes, propagate and interact weakly with both long and shorter scales. By contrast, waves also break, implying strong interactions on the surface with dramatic modifications of the wave geometry. For this class of interactions, changes occur very rapidly, and the local surface slope and curvature is large. Following the PO model, an EM bias solely associated with the diffraction term can be written as

$$\beta_{EM-diff} \simeq \langle R\zeta\rangle \quad (9)$$

where the correlation only carries contributions corresponding to a discrete set of waves at any scale reaching a critical steepness. A self-similar wave geometry can be invoked [*Phillips*, 1985] for the near-breaking condition where the diffracting area is inversely proportional to the local elevation. The correlation in Eq. 9 would thus be elevation independent. Most importantly, any associated EM bias contribution will only follow if the probability of these events is skewed about mean sea level. This may be approximated as

$$\beta_{EM-diff} \simeq -\epsilon(P_b(\zeta > 0) - P_b(\zeta < 0)) \quad (10)$$

where $P_b(\zeta)$ is related to the conditional probability of a wave to be reaching a critical steepness (as detected by the radar altimeter). ϵ is a range error term related to the wave crest geometry.

The $\beta_{EM-diff}$ component, contrary to the weakly nonlinear contribution, should be nearly independent of long wave statistical parameters. Indeed, the probability of occurrence of breaking diffracting events is most directly related to higher-order moments; i.e. weighted towards the higher wavenumber end of the spectrum. The overall impact of this term should be negligible for wind speeds less than 4-5 m/s and quite small for remaining observations because the occurrence (hence area) of breakers is always infrequent. In addition, the effect is likely radar wavelength dependent. In essence, cm-level range error onset may be associated with the onset of breaking waves as the surface roughness reaches a point where both wind input and wave-wave interactions actively contribute to the generation of short gravity waves having sufficient steepness to break. The critical maximum (σ_o = 10.3 dB, Fig. 1b) is likely associated with the maximum population difference between breakers (as detected by a Ku-band altimeter) residing above and below mean sea level. For σ_o below this critical level, the location of breaking events along the longer wave profiles tends to the limit where waves can break everywhere [*Longuet-Higgins*, 1991]. The relatively small contribution of $\beta_{EM-diff}$ implies this factor's variation may play the largest role in closed basins where H_s is small but the wind speed is high, i.e. fetch-limited cases.

Summary

On-orbit sea state bias observations have been re-analyzed to identify a second-order factor that lies outside the usual non-dimensional formulation. The proposed decomposition of the NP SSB model now leads to a simple form for the TOPEX observations. As found, a small absolute range error term, related only to the altimeter-derived σ_o, augments the dominant H_s-dependent factor. It is also shown that the practice of presenting SSB data in terms of surface wind speed is a source of imprecision, especially when relating field or model studies to on-orbit results. Observed sea state dependence within the actual altimeter wind speed should be acknowledged to differentiate it from a 'true' wind speed in the context of SSB studies.

EM bias theory, under the weakly nonlinear and two-scale assumptions, is shown to explicitly link the dominant sea state-dependent SSB term with the long wave orbital velocity. Strong self-correlation between H_s and the heave is a likely explanation for success of current SSB algorithms. The model also states that long and short wave slope variances and the level of hydrodynamic modulation will each serve to explain unresolved variability. The H_s-independent SSB factor ($f(\sigma_o)$) is physically identified with variation in steep near-breaking waves that cause diffraction and that preferentially reside above mean sea level.

This new look at global altimeter range error estimates suggests several future steps. On-orbit assessments should consider removing the SSB_{mod} component prior to addressing the dominant H_s-related term. Proper characterization of this decoupling between range error terms should be studied using coincident surface information, upcoming dual-freqency altimeter σ_o measurements, (C-Ku for JASON, S-Ku for ENVISAT-RA), and EM bias field experiment data. On-orbit SSB solution residuals should be derived at regional and seasonal scales alongside a wave model analysis to infer subtle changes in long-wave nonlinearity. Finally, breaking wave statistics should be considered in future experimental and theoretical efforts.

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