Estimation of the Sea State Bias Error Budget for Pulse-limited Satellite Altimetry

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Abstract

We provide an error budget for overall sea state bias (SSB) error, as well as the contributing sources of this error budget. The error analysis compares methods used to derive SSB models from observed altimeter measurements, collinear differences of measurements from adjacent repeat cycles, and methods using both collinear and crossover differences of measurements. Our error analysis reveals systematic error caused by ionosphere correction uncertainty in SSB models obtained from direct measurements, and wet troposphere correction uncertainty in SSB models generated using difference measurements. Results also expose a correlation to altimeter measurement error, with the backscatter coefficient accounting for over 20% of the SSB evaluation error and SWH accounting for approximately 50-60%. By comparing SSB error budgets from the Topex/Poseidon and Jason-2 missions, we find that increasing the pulse repetition frequency of the altimeter reduces SSB errors. The future for improving empirical, nonparametric SSB estimation primarily depends on improving measured SWH.

Model error

SSB models are derived empirically using nonparametric methods and measurements of SLA uncorrected for SSB (uSLA) (Vandemark et al. 2002; Gaspar et al. 2002; Sylvie Labroue et al. 2004; Tran et al. 2010) . The models are typically defined as a 2D grid of equally spaced nodes in SWH and wind speed with node spacing of 0.25 m and 0.25 m/s.

$$uSLA_{true} = ALT_{true} - \hat{R}_{true} - G_{true} \tag{1}$$

There is a level of uncertainty (ε) that accompanies computed orbit altitude ($ALT_{true} = ALT_m - \varepsilon_{ALT}$), the measured range and modeled atmospheric delays ($\hat{R}_{true} = \hat{R}_m - \varepsilon_{\hat{R}}$) and modeled geophysical effects ($G_{true} = G_m - \varepsilon_G$) that maps into the final SSB solution. We estimate these contributing errors by first deriving a reference SSB model from our preferred choice of environmental and geophysical corrections (ref in Table 1). For the same time span of data, we then derive multiple alternative SSB models by substituting one of the environmental or geophysical corrections with an alternative (alt in Table 1). We then evaluate SSB at every 1 Hz measurement for both the reference SSB model and alternative SSB models for an independent time span of data. The weighted mean square of the differences between reference SSB-derived values and alternative SSB-derived values for each node, n, is our estimate of the error in the SSB model due to uncertainty in the substituted variables in the alternative model (Figure 1).

Table 1. Preferred and substituted variables for Jason-2

Substituted variable	ref	alt
SWH	Measured SWH	Measured SWH + ΔSWH[(1)]
sig0	Measured sig0	Measured sig0 + $\Delta\sigma^o$ [(1)]
Range (R)	R	Measured R + ΔR [(1)]
Ionosphere correction (I)	GIM	Altimetry (unsmoothed, Tran)
Mean Sea Surface (MSS)	CNES/CLS 2011	CNES/CLS 2015
Geocentric ocean tide correction (GOT)	GOT 4.8	FES 2004
Wet troposphere correction (WTC)	Radiometer	ECMWF
Altitude (ALT)	CNES	JPL
The pole tide and solid earth tide errors, as well as the dry troposphere and the inverted barometer correction error do not give cause for significant error.		

Measured altimeter range adopts a similar approach (Figure 1e), except in this case the alternative is the reported range plus randomly distributed noise (ϵ) computed by multiplying the reported RMS assigned to each 1 Hz measurement of range by a random sample, k, from the standard normal distribution.

$$\epsilon = \frac{e^{\frac{-k^2}{2}}}{\sqrt{2\pi}} * RMS \tag{2}$$

A similar approach is also used to account for SSB binning errors that arise from the independent variables (Figure 2), which are effectively significant wave height (SWH) and the backscatter coefficient (sig0), since wind speed is a function of sig0 and SWH. The reference uses reported values of SWH and sig0, while the alternative adds randomly distributed noise to the reported values using Equation (2).

The total SSB model error is then the root-sum-square of each of the contributing errors. Figure 3 provides the total Jason-2 SSB model error alongside the corresponding SSB model.

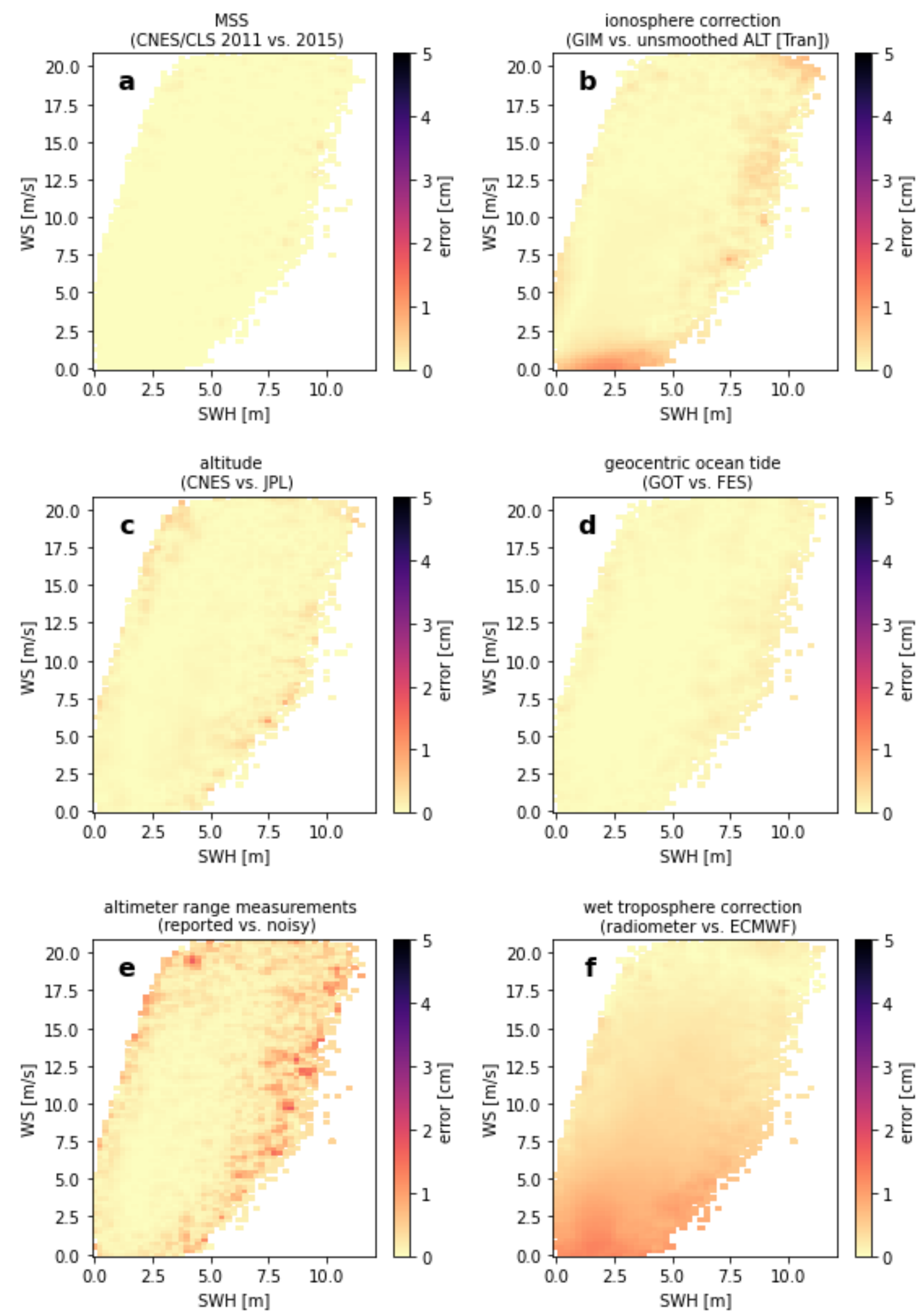

Figure 1. Jason-2 SSB model error corresponding to uncertainty in (a) MSS, (b) ionosphere correction, (c) altitude, (d) geocentric ocean tide, (e) altimeter Ku-band range measurements and (f) wet troposphere correction. The SSB model errors for each individual error source at 2.5 m SWH and 7.5 m/s wind speed are (a) 0.001 cm, (b) 0.073 cm, (c) 0.023 cm, (d) 0.014 cm, (e) 0.028 cm and (f) 0.458 cm.

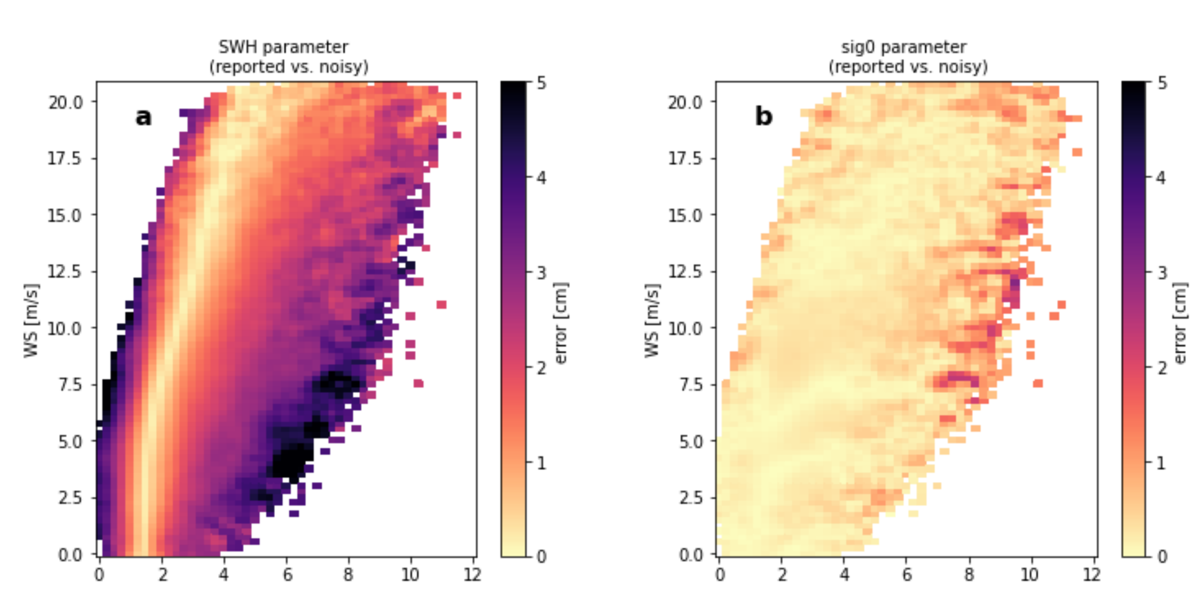

Figure 2. Jason-2, Ku-band SSB model error caused by (a) SWH uncertainty and (b) sig0 uncertainty. The SSB model errors for each independent variable error source at 2.5 m SWH and 7.5 m/s wind speed are (a) 0.945 cm and (b) 0.231 cm

SSB nodes corresponding to low SWH values battle a rise in noise due to the ~0.5 m retracker resolution (Desjonqueres, J.D. 2021), which causes a high degree of uncertainty for SWH measurements less than 1 m. There is no way to provide a true estimate of SWH measurement uncertainty, nor have confidence in the RMS provided by the product. Therefore, the final error budget will not provide SSB model error for nodes less than 1 m SWH. This cut removes approximately 1.5% of the total measurements used to generate the SSB model.

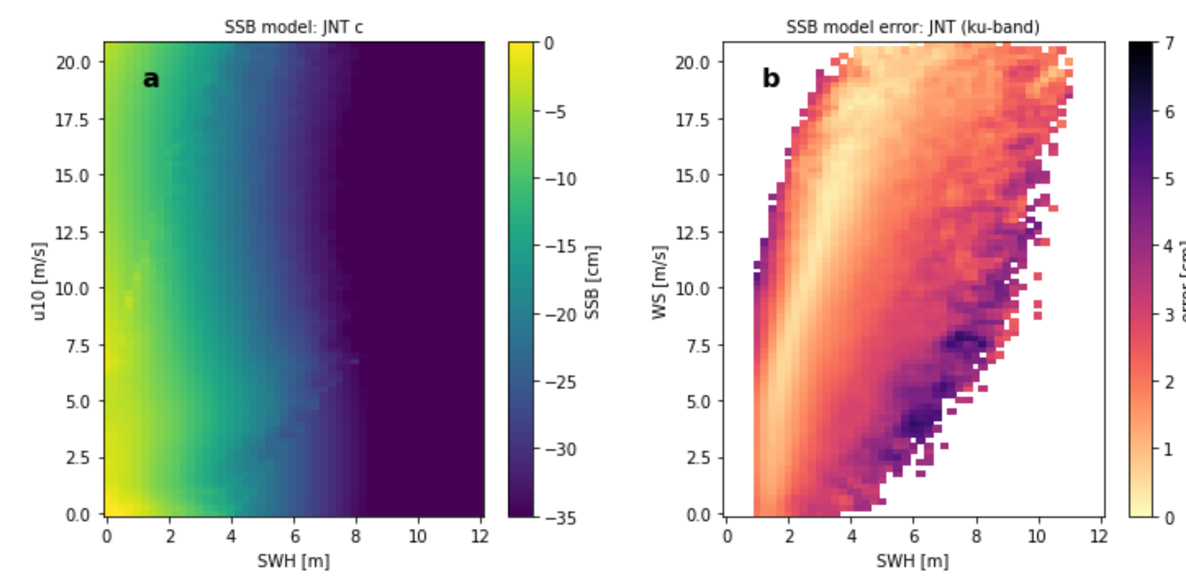

Figure 3. Jason-2, 2009, Ku-band (a) SSB model compared to the (b) estimated SSB model error, which is the combination of all errors displayed in Figures 1 and 2. The SSB model uncertainty at 2.5 m SWH and 7.5 m/s wind speed is -11.223 ± 1.079 cm

Input error

To account for error introduced through the input parameters (i.e. SWH and wind speed) when evaluating an SSB model, we once again use a time span of data independent of the data used to derive the SSB model itself. The parameter error of a particular node, n, is then estimated as the weighted mean square difference between the evaluation of the reference model using reported parameters as inputs and the evaluation of the reference model using as input reported parameters with added noise (ϵ) from Equation (2) (Figure 4). Equations (3) and (4) provide the input parameter errors of SWH and sig0, respectively.

$$\sigma^2_{swh,n} = \frac{\sum w_n \left(ssb[swh, ws(swh, sig0)]_{ref,n} - ssb[swh+\epsilon_{swh}, ws(swh+\epsilon_{swh}, sig0)]_{ref,n}\right)^2}{\sum w_n} \tag{3}$$

$$\sigma^2_{sig0,n} = \frac{\sum w_n \left(ssb[swh, ws(swh, sig0)]_{ref,n} - ssb[swh, ws(swh, sig0+\epsilon_{sig0})]_{ref,n}\right)^2}{\sum w_n} \tag{4}$$

The total input error is the square root of $\sigma^2_{swh} + \sigma^2_{sig0}$.

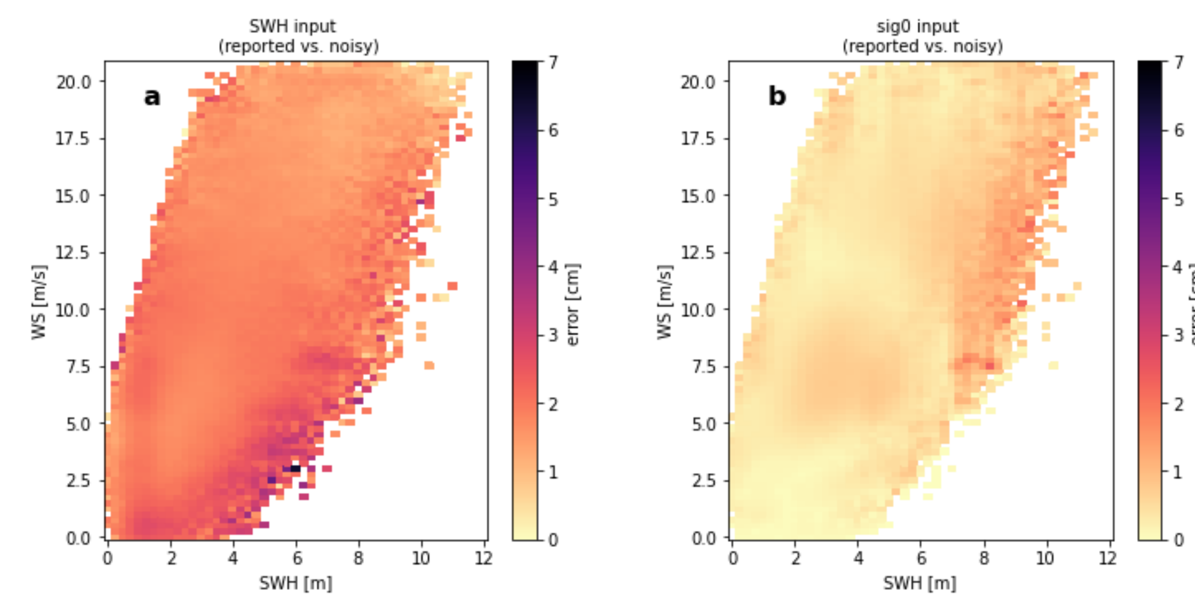

Figure 4. Jason-2, Ku-band SSB input error due to (a) SWH uncertainty and (b) sig0 uncertainty. The SSB input errors at 2.5 m SWH and 7.5 m/s wind speed are (a) 1.766 cm and (b) 0.67 cm

Evaluation error

The evaluation error, or total error that the user experiences is the root-sum-square of the model and input error. Figure 5 compares the estimated Jason-2 SSB evaluation error to the evaluation error provided by (“OSTM/Jason-2 Products Handbook” 2011), which is equal to 1%SWH.

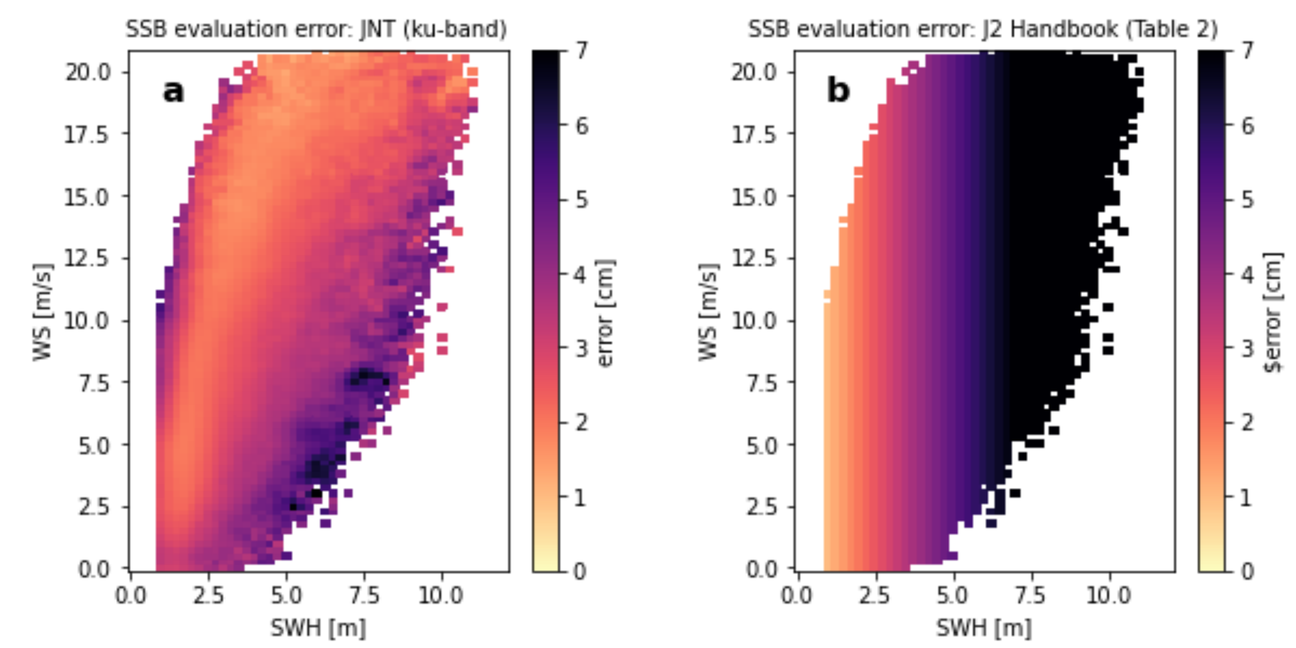

Figure 5. Jason-2, Ku-band (a) JNT SSB evaluation error compared to (b) the SSB evaluation error provided by (“OSTM/Jason-2 Products Handbook” 2011), error = 0.001 ∗ *SWH*. The SSB evaluation errors at 2.5 m SWH and 7.5 m/s wind speed are (a) 2.175 cm and (b) 2.50 cm

Table 2. Error at 2.5 m SWH and 7.5 m/s wind speed

SSB model	SSB model error Ku-band [cm]	Evaluation error Ku-band [cm]	SSB model error C-band [cm]	Evaluation error C-band [cm]
	— Jason-2 —			
JNT	1.079	2.175	1.234	2.440
COL	1.061	2.160	1.228	2.427
DIR	0.642	2.000	2.191	3.392
	— Topex/Poseidon —			
JNT	0.526	0.818	0.546	0.893
DIR	0.269	0.759	1.592	1.899

Conclusions

- Ionosphere correction uncertainty causes significant error in C-band SSB models obtained from direct measurements.
- SSB models generated using difference measurements are more affected by altimeter measurement error and wet troposphere correction uncertainty than direct SSB models.
- Significant wave height uncertainty accounts for over 60% of sea state bias estimation error in Jason-2, and about 50% in Topex/Poseidon.
- Raising pulse repetition frequency of an altimeter reduces measurement uncertainty and improves sea state bias estimation accuracy.

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