OVERVIEW OF THE IMPROVEMENTS MADE ON THE EMPIRICAL DETERMINATION OF THE SEA STATE BIAS CORRECTION

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1. ABSTRACT

It has long been known that the sea level measured by radar altimeters is lower than the true sea level because the backscattered power per unit area is greater for the wave troughs than for the wave crests. This effect is known as the electromagnetic bias. Other sea-state-related biases additionally affect the altimeter range measurements. They are generally combined with the electromagnetic bias to form the sea state bias (SSB). This total bias ranges from a few centimetres up to a few decimetres and is still one of the major sources of error in satellite altimetry. Its theoretical modelling and understanding remains an important challenge. Therefore, the SSB correction still largely relies on empirical models, calibrated on the altimeter data themselves. The goal of this paper is to summarize all the improvements realised in this field, over the past ten years. The SSB correction has been estimated for almost all operating altimeters (ERS2, EnviSat, GFO, TOPEX and Jason-1) with one of the most efficient statistical method, the so-called non parametric technique (NP). The results obtained for the three available frequencies (Ku-band, C-band and S-band) are presented and discussed. An overview of the quality assessment of the SSB correction is also provided.

2. SSB EMPIRICAL DETERMINATION

The main difficulty of the empirical determination of the SSB from the altimeter measurements is to extract a signal related to the sea state from sea surface height (SSH) data containing, of course oceanic signals, but also residual orbit errors, geophysical and environmental corrections, added to instrument related noise. The consequence, inherent to the empirical approach, is the possibility to include non-SSB signals in the estimated SSB correction because of artificial correlations between the SSH residual errors and the sea state descriptors. Hence, the estimation requires, on one hand a model or, failing that, an estimation process which does not corrupt the retrieved signal and, on the other hand, the most accurate data as possible, both for the SSH observations and their correlatives. The improvements made in the field of the estimation method are first presented and then, a discussion is carried on several aspects of the data accuracy.

2.1. Improvements in the estimation approach towards a non parametric technique

The first missions dedicated to space oceanography by radar altimetry had to cope with relatively large orbit errors which dominated the altimeter error budget as for the Geosat mission. The results on the SSB derived with an empirical approach were still affected by such errors. The improved accuracy of the TOPEX/POSEIDON mission, launched in 1992, allowed developments in the empirical determination of the SSB correction. Reference [1] experimented in details parametric formulation for the SSB correction, fitted on TOPEX and POSEIDON data. They compared several models expressed as a function of the significant wave height (SWH) and the wind speed (U), these two correlatives being directly retrieved from the altimeter measurements.

Empirical parametric SSB models are generally fitted on altimeter-derived sea surface height (SSH) differences, either at crossover points or along collinear tracks [2]. The use of SSH differences rather than SSH measurements themselves is a simple way to directly eliminate the poorly known geoid signal from the estimation process. However, [3] demonstrated that such parametric models based on SSH differences, instead of the SSH themselves, are not true least square approximations of the SSB. The origin of this problem comes from the fact that one has to fit an inevitably imperfect parametric model on SSH differences rather than on SSH measurements themselves. To avoid that problem, [4] developed and refined a non parametric SSB estimation technique (NP) based on kernel smoothing. The combination of a locally linear estimator, with both appropriate kernel function and adaptative smoothing factor by taking into account the data density, has produced some remarkable results, first seen on TOPEX SSB correction. The complete description of the method can be found in [4].

More recently, reference [5] demonstrated that the mean sea surface (MSS) is now known with sufficient accuracy to stop worrying about residual geoid signals in sea level anomalies (SLA, that is deviations of instantaneous SSH measurements from the MSS), at least for SSB estimation purpose. Indeed, using such measurements, [5] directly obtained an estimate of the SSB for the TOPEX side-A altimeter in close agreement with that obtained by [4] with a nonparametric model fitted on crossover differences. Reference [6] slightly refined these results, replacing the simple bin average approach tested by [5], with the NP kernel smoothing. In the same state of mind, reference [7] proposed a so-called hybrid model, mixing this direct approach with a parametric model associated to a smoothing window, in order to define the SSB correction, even for unlikely correlatives pairing. They also compared, for the first time, the SSB correction derived with this method for all the flying altimeters.

So, in summary, the SSB can be estimated using three rather different altimetric data sets: crossover differences, collinear differences and SLAs. Reference [6] compared the results obtained from each data set with the NP technique and they discussed their advantages and drawbacks for Jason-1 altimeter. The choice of using one approach rather than the others is mainly dictated by the characteristics of the altimeter mission. The main difference between the direct approach using SLA relative to a mean sea surface, and the ones derived with SSH differences resides in the oceanic signal influence. Indeed, forming crossover differences cancels a large part of the ocean component whereas the SLA measurements still contain a large ocean dynamics. The key for the success of such a method resides in a temporal averaging of very different ocean conditions for a given sea state, as performed by [5].

2.2. Improvements in the altimeter data accuracy

Since the beginning of the altimetry, dramatic improvements have been made on orbit determination and on all the geophysical and environmental corrections used to form the corrected SSH measurements.

Recently, efforts have focused on the inverse barometer (IB) correction which was replaced by a new high frequency correction, the so-called MOG2D correction [8]. This latter is now implemented in the operational ground segment for the Jason-1 and EnviSat missions. It has been shown that the IB correction is strongly correlated with the SSB [9]; hence, the improved accuracy obtained thanks to the MOG2D correction should also improve the quality of the derived SSB correction. For all the altimeters, the MOG2D correction reduces the SSB magnitude by about 3 cm for strong sea states and the improvement is mainly correlated with the waves. It points out that SSH data corrected with inaccurate IB correction yield corrupted SSB estimates by a few centimetres.

The orbit errors are now well reduced, especially with gravity field models derived from GRACE data. Nevertheless, some systematic biases can still exist (bias between ascending and descending tracks or between North and South hemispheres). Such errors induce biased crossover SSH differences which have an impact in the SSB estimation. References [6] have assessed the effect of such error on the resulting SSB correction, through simulations on the NP process. They also showed the effects of a time tag bias error, which happened to be significant using crossover data.

More generally, one critical issue is to check carefully how SSH errors can correlate with the SSB correlatives, even if it is not a real physical relation but rather through spatial correlation. For instance, the waves exhibit a strong meridional distribution which can correlate with atmospheric and oceanic signals. Nevertheless, errors do not have the same impact on the SSB correction, depending if direct SLA data or SSH differences are considered. Hence, the choice of the method should also be guided by the knowledge of the errors affecting the SSH observations.

3. COMPARISON OF KU BAND SSB ESTIMATES FROM SEVERAL ALTIMETERS

3.1. Data sets and estimation approach

Thanks to all the improvements made on the methodology used to estimate the SSB from SSH data and on the data themselves, we are now in a position to better quantify the SSB signal for various altimeters. The SSB was estimated for different altimeters: ERS2, EnviSat, GFO, TOPEX and Jason-1. The SSH observations have been computed with the same up to date geophysical corrections, including the MOG2D correction.

TOPEX and Jason-1 SSB have been estimated with 10-day SSH differences (collinear data) for several reasons. Indeed, the TOPEX altimeter exhibits hemispheric signals at crossovers on the three altimeter parameters (range, waves and backscatter coefficient) which can corrupt the SSB estimation. These hemispheric signals seem to be due to leakages in the TOPEX waveforms. This feature was detected when comparing the SSB estimated with crossover differences between side A and side B. While NP estimate calculated for side A yields expected variations as a function of (U, SWH), the SSB obtained on side B exhibits a weird signature showing a constant value for the waves below 2 m. This feature happened to be due to hemispheric signals that leak into the crossover SSH differences and which were inverted between side A and side B altimeters. In order to cancel such errors, the SSH differences between collinear tracks are preferred for TOPEX altimeter.

The Jason-1 altimeter also exhibits a significant time tag bias estimated at -170 µs, for the GDR-A products. It was shown in [6] that it induces a spurious SWH gradient of 1.5 cm on the SSB, for the waves below 3 m. Forming SSH differences with collinear data naturally eliminates such time tag bias. The GFO SSB has also been estimated with collinear SSH differences because of a large time tag bias of about -800 µs which would affect a SSB estimate at crossovers.

The EnviSat and ERS2 SSB have been estimated with crossover SSH differences. For both missions, forming 35-day SSH differences would introduce too much oceanic variability into the correction. Note that, for ERS2 altimeter, crossover SSH differences have been corrected for a time tag bias of -1 ms.

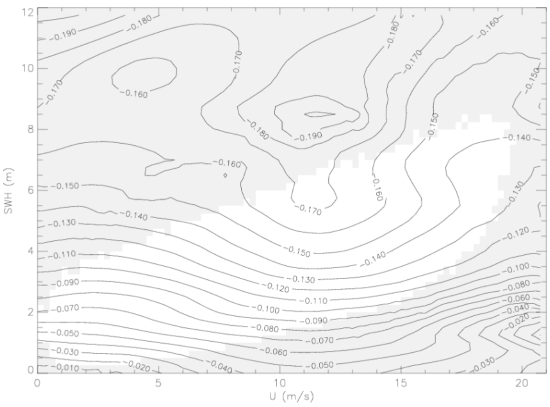

Figure 1. TOPEX A SSB

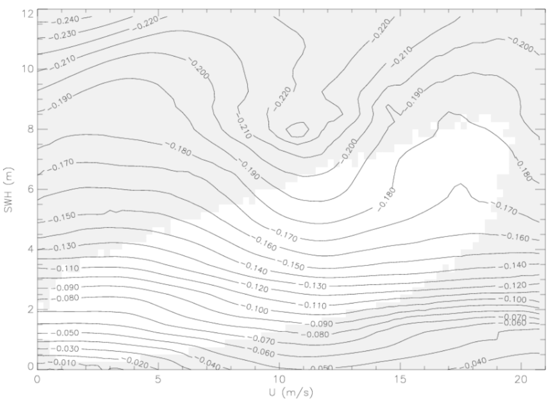

Figure 2. TOPEX B SSB

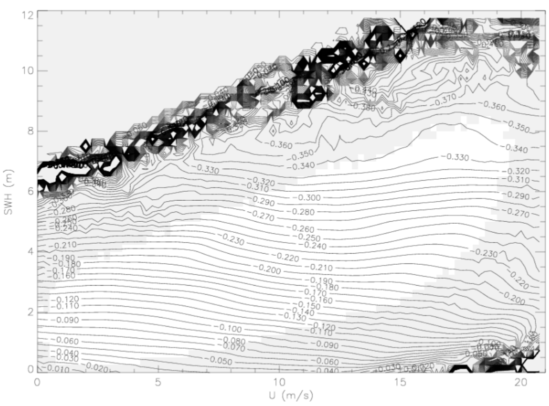

Figure 3. GFO SSB

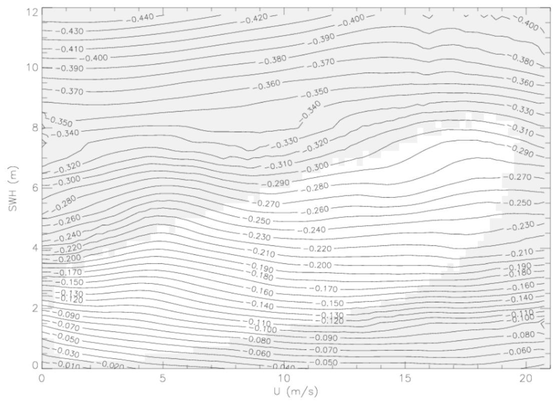

Figure 4. Jason-1 SSB

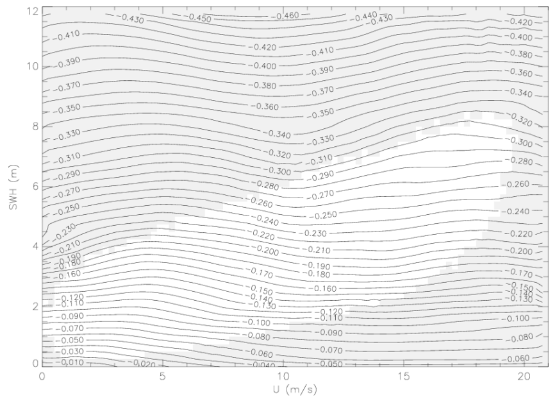

Figure 5. EnviSat SSB

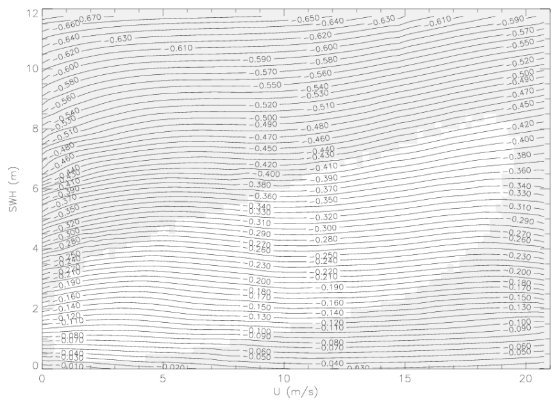

Figure 6. ERS2 SSB

3.2. Results and discussion

Figs. 1 to 6 display the NP estimates obtained in Ku-band for TOPEX side A, TOPEX side B, GFO, Jason-1, EnviSat and ER2 altimeters, respectively

The first striking feature is the difference in behaviour and magnitude of both TOPEX SSB models with respect to all the other altimeter solutions. The SSB value associated to the peak of the distribution, at SWH=2m and U=8m/s, varies between -9 cm and -10 cm for TOPEX, whereas it is close to -12 cm for GFO and -13 cm for both Jason-1 and EnviSat. Furthermore,

the SSB magnitude increases (in absolute value) with the waves for all of them, except for TOPEX SSB which values are quite stable around 20 cm for the waves greater than 6 m. This discontinuity in the TOPEX SSB at SWH of 6m is attributed to discontinuities in the gate index corrections [10].
The first most realistic explanation that comes to mind to interpret such a difference in the magnitude is the presence of different tracker biases that are combined with the electromagnetic bias. Indeed, this latter depends solely on the physical processes of the interaction between the sea surface and the altimeter radar echo and should be identical for any instrument. Hence, the differences into the sea state related signal can only come from differences between the waveform tracking. Indeed, there is a difference between the tracking procedures for all the analyzed altimeters. However, one can also note that there is a very good agreement between GFO, Jason-1 and EnviSat SSB signal even though their tracking modes are completely different. The fact that TOPEX SSB is the only one to show a so low magnitude is puzzling and is still under investigation.
The EnviSat and Jason-1 models show a very good agreement both in variations and magnitude, with a difference lower than 1 cm, without any particular structure depending on the correlatives. For comparison, the GFO estimate exhibits a larger magnitude at high waves. Another difference in behaviour can be noticed for pairs of low wind speed (below 5m/s) and waves close to 4 m. GFO shows a very linear structure with the wind speed whereas, Jason and EnviSat models present small variations with a minimum at 5 m/s wind speed. The difference between ERS2 and EnviSat SSB is close to 1.5% of SWH, with ERS2 SSB being higher.

4. QUALITY ASSESSMENT OF THE SSB CORRECTION

One of the most critical issues dealing with empirical determination of the SSB is the quality assessment of the estimated correction. On one hand, classical test on the regression residuals can be performed, but it is only a simple way to verify that the chosen regression method has correctly extracted the entire signal as a function of the used correlatives. It does not provide any indication on the accuracy of the sought sea state bias itself. On the other hand, the performance of the correction can also be assessed by computing the variance reduction on the sea surface height after applying the tested correction. In this case, the analysis can be tricky due to spurious correlations between SSB and other SSH corrections or between SSB and oceanic signals. Anyway, both analyses must be performed all together in order to provide the most careful assessment for a given SSB correction. They are detailed and discussed in the following section. A few words are also given on the theoretical error derived with the NP method.

4.1. Empirical assessment

The quality of the SSB estimated either with SSH crossover differences or collinear differences can be assessed by the analysis of the regression residuals as a function of the correlatives difference ΔSWH and ΔU. Such residuals are relatively small with values below 5 mm, which indicates that the regression extracts major part of the sea state related signal.

Another measure of the SSB accuracy is the variance explained by the correction, both globally and regionally. The regional analysis is more delicate to interpret because of the correlation between the SSB correction and the oceanic variability. Another mean is to analyse the correlation between the SSB correction and the 'true' SSH (corrected for all effects). The covariance can be expressed using the ratio between the explained variance (variance gain between *SSH',* the sea surface height not corrected for the SSB, and *SSH,* the one corrected for the SSB) and the SSB variance, as shown with Eq. 1.

$$D = \frac{Var(SSH') - Var(SSH)}{Var(SSB)}$$
$$D = 1 + 2 * \frac{Cov(SSH, SSB)}{Var(SSB)} \tag{1}$$

If the estimated SSB correction is very close to the true SSB signal, the covariance term tends to zero and the ratio between the explained variance and the SSB variance should be close to 1. Figs. 7 and 8 show the spatial distribution of this ratio for the TOPEX mission, in two different configurations. The first case exhibits the ratio for SSH corrected for the IB correction and with a SSB model estimated on the same data set. The second one shows the same ratio, but for SSH corrected for the MOG2D correction and with a SSB model estimated on this same data set. The analysis is performed on collinear SSH differences instead of the SSH itself. On both maps, the ratio varies between 0 and 2. The map in Fig. 7 exhibits clearly positive structures (45°S-260°E,50°S-85°E), correlated to regions of IB inaccuracies. Once, the MOG2D correction is applied, these features disappear and the map reveals a more homogeneous ratio, varying between 0.8 and 1.2. It suggests that the MOG2D correction does remove IB inaccuracies in the SSH data and thus in the derived SSB model. The map in Fig.8 shows that the SSB correction is globally not correlated to the SSH observations, except for the equator band which exhibits dramatic low values, meaning that the estimated SSB correction explains less variance than the exact SSB signal. However, this region often presents a variance increase when assessing other corrections. It is an area of particular behaviour and the variance increase can not be surely related to a bad performance of the examined SSB correction.

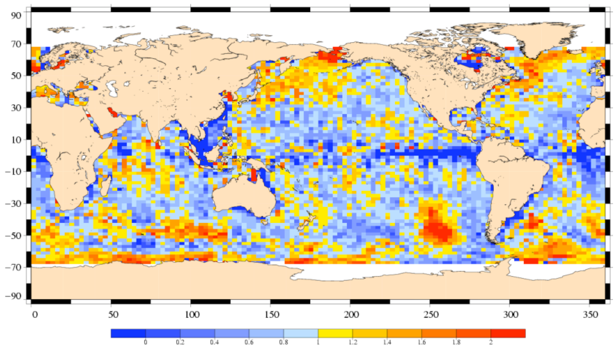

Figure 7. Ratio D for TOPEX data (cycles 21-131), the SSH are corrected with IB and the SSB is derived with IB

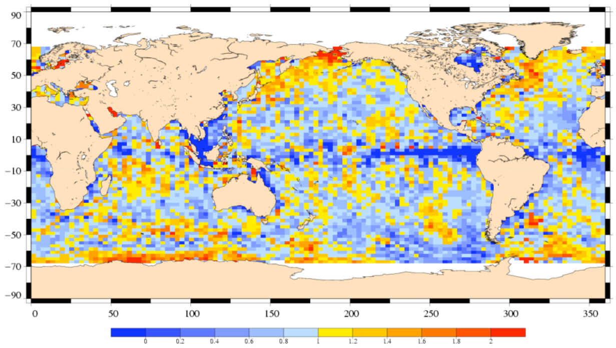

Figure 8. Ratio D for TOPEX data (cycles 21-131), the SSH are corrected with MOG2D and the SSB is derived with MOG2D

4.2. Theoretical error

A formal error can be derived within the NP formalism. A useful measure of the error associated to a regression estimator $\hat{r}(\mathbf{x})$, where $\mathbf{x}$ is the correlatives vector, is the point wise Mean Squared Error (MSE):

$$\text{MSE}\,(\mathbf{x}) = \text{E}\,\left\{\left[\hat{r}(\mathbf{x}) - r(\mathbf{x})\right]^2 \middle| X\right\} = \left\{E\left[\hat{r}(\mathbf{x})\middle|X\right] - r(\mathbf{x})\right\}^2 + \text{var}\left[\hat{r}(\mathbf{x})\middle|X\right] \qquad (2)$$

One often refers to the first term of the decomposition as the square of the bias and to the second term as the variance of the regression estimator. In the one-dimensional case (i.e. for a scalar x), the leading term in the asymptotic expansion of the bias of the locally linear regression (LLR) estimator $\hat{r}_{LLR}$ is:

$$Bias\left[\hat{r}_{LLR}(x)\right] = \frac{h^2}{2} r''(x) \int_{-\infty}^{+\infty} u^2 K(u)\,du \qquad (3)$$

Eq. (3) shows that the bias only depends on the second derivative value $r''(x)$ linked to the curvature of the SSB term and on the smoothing bandwidth *h*, with the integration term being a constant value. The calculation of the bias value is difficult, since one needs the $r''(x)$ term. Nevertheless, this quantity can be approached if the estimator is developed at least to the second order. Such a refinement has not been performed but the LLR estimator gives access to the SWH and U first derivatives. Their variations in the (U, SWH) domain are shown respectively in Fig 9 and 10 for the Jason-1 SSB. The SWH derivative exhibits a nearly constant value of 4% for all the pairings below (10m/s,4m), which indicates that the $r''(SWH)$ quantity is very close to zero. This means that the estimator yields unbiased SSB correction, depending on SWH. The U derivative shows more variations with a minimum value at 7 m/s, separating decreasing and increasing linear trends, with different slopes. The largest slope values are found between 10 m/s and 12 m/s, delimiting the region where the bias is the highest. However, one can note that the wind speed derivative is 10 times smaller than the SWH derivative, which suggests that the bias related to the wind speed, is smaller than the one depending on SWH.

5. FREQUENCY DEPENDENCE OF THE SSB

The Jason-1 and EnviSat altimeters are dual-frequency sensors; the second frequency being respectively a C-band (5.3 Ghz) and a S-band (3.2 GHz) for Jason-1 and EnviSat. The SSB corrections in C-band and S-band have been estimated for each mission. Figs. 11 and 12 show the difference between Ku-band and C-band SSB for Jason-1 and the difference between Ku-band and S-band for EnviSat. An expected result is that the SSB magnitude increases as the frequency decreases. It is confirmed by both figures which exhibit positive difference for most of the (U, SWH) values. The difference between Ku-band and S-band is strictly positive whereas the SSB(Ku)-SSB(C) difference is slightly negative for wind speed values lower than 8 m/s. These negative values can represent a real physical signature but they may also be explained by inclusion of errors due to data inaccuracies. Nevertheless the S-band SSB is greater than the C-band one for strong wind speed above 15 m/s. On both figures, the SSB difference is constant for moderate wind speed up to 10 m/s; above, the trend is mainly correlated with the wind speed.

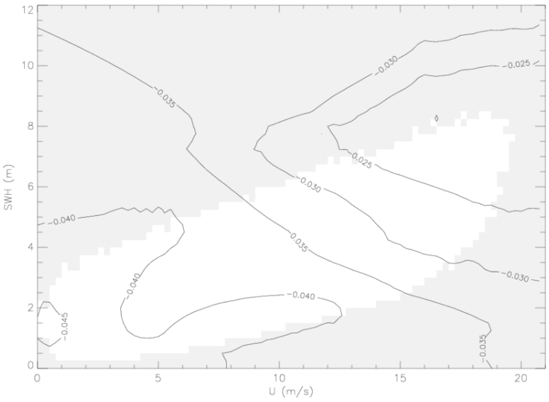

Figure 9. SWH first derivative for Jason-1SSB

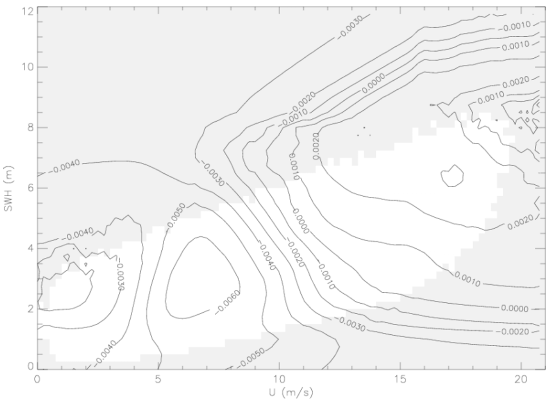

*Figure 10. Wind speed first derivative for Jason-1SS*B

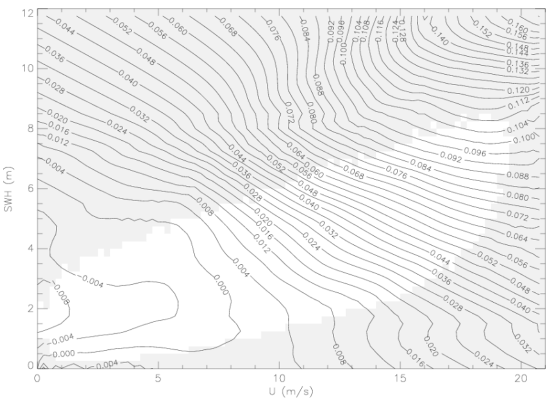

Figure 11. SSB(Ku)-SSB(C) for Jason-1

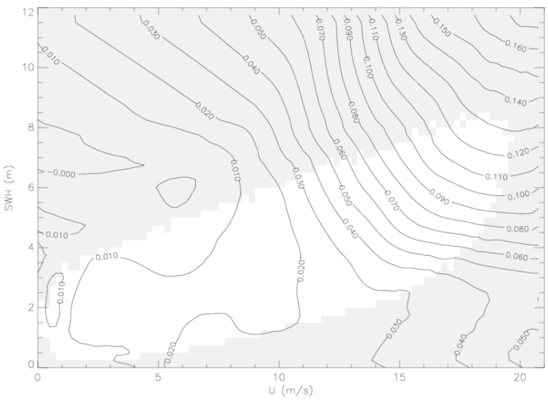

Figure 12. SSB(Ku)-SSB(S) for EnviSat

6. CONCLUSION

Evolution of the empirical determination of the SSB has shown that improvements in the data accuracy have motivated developments of new estimation methods (parametric models, NP technique, direct approach, hybrid method). In the meantime, these new methods have allowed exploring further the relations between the data and the SSB signal, especially with the NP estimation technique. Indeed, this latter has proved to be an efficient tool for the empirical determination of the SSB and all the sensitivity studies linked to this topic. The NP SSB estimates obtained for several altimeters will allow understanding more deeply the SSB and tracker differences between all the altimeters. The results shown for the C-band and S-band will certainly help in further modelling of the sea state frequency dependence.

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