Centimetric Sea Surface Height Accuracy Using the Wide-Swath Ocean Altimeter

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***Abstract*—In this paper, we present error sources and predicted performance of the Wide-Swath Ocean altimeter, an instrument which has been proposed as an experiment for the NASA/CNES Ocean Surface Topography Mission. The data obtained by this instrument will allow the detailed study of ocean mesoscale phenomena, with a space-time resolution which cannot be achieved by a single conventional nadir altimeter.**

Keywords –radar interferometry; altimetry; ocean circulation;

I. INTRODUCTION

The goal of the Wide-Swath Ocean Altimeter (WSOA) is to extend the coverage of the nadir point sea surface height, as provided by conventional altimeters, to heights measured over a large swath on either side of the satellite track. Conventional altimetry measures only one variable related to topography: the round trip delay to the nearest point on the surface. Because geometry constrains the nearest surface point to be the nadir point, it is straightforward to determine the location of the height measurement if the satellite position is known.

In order to determine the location of the measurements that are not from the nearest point on the surface, it is clear that additional information is required. One possible approach to measuring off-nadir heights is the scanning radar altimeter [1]. While this concept has been used successfully for laser altimeters, centimetric height accuracy requirements lead to antenna sizes that cannot be realized with currently available technology.

An alternate method for obtaining additional geometric information is radar interferometry [2], a technique that uses a measurement of the relative delay between the signals from two antennas separated by a "baseline distance", together with the system ranging information, to form a triangle which can be used for geolocation in the plane of the observation. The measurement triangle is made up of the baseline B, and the range to the two antennas, r1 and r2. The baseline is known by construction and knowledge of the spacecraft attitude. The range r1 is determined by the system timing measurements. The range difference between r1 and r2 is determined by measuring the relative phase shift Φ between the two signal, which is related to the range difference Δ by the equation $\Phi = 2\pi\Delta/\lambda$. The additional information required for geolocation, the incidence angle θ, and be obtained from the range difference by means of the relationship $\Delta = 2\pi B \sin(\theta)/\lambda$. Given these measurements, the height h above the a reference plane can be obtained using the equation $h = H - r1 \cos(\theta)$. (The formulas given here are appropriate for mapping heights relative to a reference plane. A detailed treatment of mapping heights relative to a curved surface is given in [3]. The formulas relating to the height errors, given below, remain essentially identical for both cases and the near-nadir WSOA geometry).

A major difference between conventional altimetry and interferometry is that the interferometric measurements rely on the complex phase information, which is available for each imaged pixel in the scene. In contrast, the altimeter measurement relies on the power and the specific shape of the leading edge of the return waveform, which is only available for the nadir point. Thus, the interferometric measurement is intrinsically a finer measurement for range and is available for all imaged points in the scene.

The WSOA instrument is an implementation of the interferometer measurement concept as a complement of a Jason-class altimeter mission. The WSOA instrument suite would complement the standard Jason altimeter package, Ku and C band altimeters, a three-frequency radiometer, a DORIS transponder and GPS receivers, with a Ku-band interferometric system using a deployable 6.4 m baseline. The interferometric antennas have beams illuminating both sides of the nadir track to produce a total swath of 200 km when optimally oriented.

The instrument spatial resolution characteristics are determined by the size of the antenna beam in the direction perpendicular to the baseline direction, and by the system bandwidth (or intrinsic range resolution) in the direction parallel to the baseline direction. For the WSOA system, the first resolution is 11 km, while the initrinsic range resolution varies from about 500 m in the inner swath to about 100 m in the outer swath. The height estimates measured at these

resolutions are noisy, so noise is reduced by averaging all measurements within a box. The topographic results are posted on a 15 km grid. An additional advantage of wide-swath coverage is that the revisit time between observations is reduced, on average, to half a cycle, since most points are imaged by both ascending and descending satellite.

II. Instrument Errors

Random errors in the interferometric measurements are introduced through measurement noise of the interferometric phase difference. This noise has two sources: thermal noise in the two interferometric channels; and differences in the return signal speckle from distributed targets. The first source of noise decreases with increasing signal brightness, while the second is independent of brightness, but depends on the geometry.

Given a phase error, $\delta\Phi$, the resulting height error is given by $\delta h = \lambda r \tan(\theta)/(2 \pi B)\ \delta\Phi$ where r is the range from the platform to the imaged point on the ground, θ is the look angle, λ is the wavelength, and B is the baseline length. For small look angles, as in the WSOA case, this can be written as $\delta h = \lambda x/(2 \pi B)\ \delta\Phi$, where x is the cross-track distance. The errors increase linearly with cross track distance and, when generated by random sources such as thermal noise, are independent from pixel to pixel. Spatial averaging will reduce the random errors by the square root of the number of pixels averaged.

There are three different kinds of systematic errors: range errors; roll errors; and systematic phase errors. We will examine each of these in turn in the following paragraphs.

1. **Range Errors:** Given an error in the estimated range, the resulting error in height is given by $\delta h = -\delta r/\cos(\theta)$, which, for the angles of incidence in the WSOA (<4 degrees), can be approximated by $\delta h = -\delta r$. These errors are identical with the altimeter media errors and are due to the fact that the speed of light varies in the atmosphere and troposphere depending on the medium condition. The EM bias also produces a range error, as in the nadir altimeter measurement. The only additional error source for the WSOA is the fact that corrections across the swath are assumed to be identical to the nadir correction. In order to assess the spatial variability of the media and EM bias corrections, we examined the TOPEX data and computed the average change in the correction for varying distances. The results are latitude dependent, but show a worst case error of about 2.2 cm at the swath edge. A more typical value is about 1 cm.
2. **Roll Errors:** These errors are induced by lack of knowledge in the roll angle of the interferometric baseline. The effect of an error in the roll knowledge of $\delta\theta$ is to introduce a tilt to the measured surface of $x\ \delta\theta$, where x is the distance from the nadir track. As an order of magnitude, a roll error of 0.1 arcsec will result in a height error of 4.5 cm at the edge of the swath. The main source of roll error is knowledge errors in the spacecraft attitude. Current attitude measurement systems have the precision appropriate for measuring the roll to the desired tolerance, but they suffer from long term (fractions of a revolution) drifts which must be corrected by the calibration process described in the next section.
3. **Systematic Phase Errors:** These errors are due to changes in the delays in the electronic system. As discussed above, for the small look angles in WSOA, their effect is identical to the roll error: they induce linear tilts over the swath. The changes in the system delay are driven by temperature changes, which change slowly over an orbit, so the systematic phase errors can be calibrated in the same fashion as the roll errors, as described in the next section. A further reduction in the systematic phase error can be accomplished by introducing a calibration tone into the return signal, monitoring the phase of that tone, and making the appropriate phase correction during processing.

III. Calibration Simulation Results

The accuracy of the WSOA instrument, prior to calibration, is governed by the systematic errors. As discussed in the previous section, these errors vary slowly over the orbit and have known geometric signatures. In order to significantly reduce these errors, we have developed a calibration process which uses the fact that the nadir altimeter accompanying the WSOA is not affected by the roll in the same way as the WSOA. If the ocean did not move, the systematic errors could be estimated by taking height differences between the ascending and descending tracks and solving for the spacecraft roll (or equivalent phase error) by least squares inversion at the cross-over diamonds. The value of the roll between cross-over diamonds can then be interpolated using a smooth interpolator. This interpolation step is valid since the maximum time separation between cross-over diamonds is 80 seconds, while the mean separation is about 20 seconds. This period is significantly smaller than the expected variations in either roll drift or instrument temperature.

In order to validate the cross-over calibration scheme, and to study the impact of the ocean motion, we have used the Los Alamos 0.1 degree eddy resolving model as an input to a measurement and calibration simulator. The resulting error for the North Atlantic, which includes the effects of ocean and spacecraft roll motion, is presented in Fig. 1. The RMS residual error for this experiment was 3.2 cm, and included random and systematic errors.

With the aid of the previous experiment and using the height error models described above, we predict the expected single pass height error budget for the WSOA instrument to be given by Table 1.

One of the primary advantages of a WSOA system is that it produces sea surface height maps in two dimensions, not just along the nadir track. This implies that both the surface gradient (which can be converted to the geostrophic vector velocity) and the surface Laplacian (which can be converted to the relative geostrophic vorticity) can be computed at every point. The vector velocity can be computed using standard altimetry only at the cross-over points, and the accuracy of the computed vector velocity degrades with latitude, since the angle between the cross-over tracks approaches zero. Furthermore, the ascending and descending data are collected at two different times, and the vector velocity will be in error for regions with short correlation times compared to the cross-over period. It is not possible to obtain an accurate estimate of the relative geostrophic vorticity using nadir altimeter tracks. Fig. 2 shows examples of the velocity magnitude retrieved from the simulated data discussed previously.

TABLE I. WIDE-SWATH ERROR BUDGET

Error Source	WSOA Cross-track Error		
	Near Swath	*Mid Swath*	*Far Swath*
Interferometer Precision	1.9 cm	1.8 cm	2.5 cm
Residual Systematic Error	1.6 cm	2.6 cm	2.9 cm
EM Bias	2.0 cm	2.0 cm	2.0 cm
Wet Tropo	1.2 cm	1.2 cm	1.2 cm
Dry Tropo	0.7 cm	0.7 cm	0.7 cm
Ionosphere	0.5 cm	0.5 cm	0.5 cm
Cross-Track Media Decorrelation	1.0 cm	1.4 cm	1.8 cm
Total Height Error	3.7 cm	4.0 cm	4.9 cm

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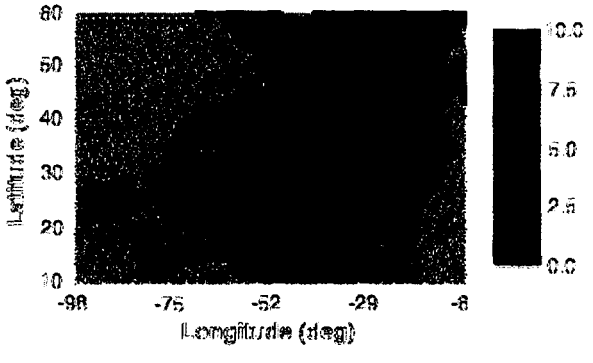

Figure 1- Residual height errors from the simulation using the Los Alamos circulation model as input. Errors increase near the Gulf Stream, but are much smaller than the dynamic topography signature there

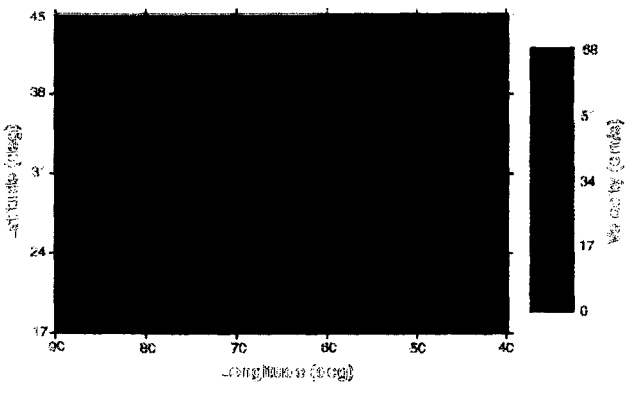

Figure 2- Estimated geostrophic velocity magnitude obtained by computing the vector magnitude of the two-dimensional (u,v) vector geostrophic velocities. Note that the wide-swath coverage allows for the calculation of the vector velocity at all swath points, not just bthe altimeter cross-over points.