KARIN: THE KA-BAND RADAR INTERFEROMETER FOR THE PROPOSED SURFACE WATER AND OCEAN TOPOGRAPHY (SWOT) MISSION

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1. INTRODUCTION

Over the last two decades, several nadir profiling radar altimeters have provided our first global look at the ocean basin-scale circulation and the ocean mesoscale at wavelengths longer than 100 km. Due to sampling limitations, nadir altimetry is unable to resolve the small wavelength ocean mesoscale and submesoscale that are responsible for the vertical mixing of ocean heat and gases and the dissipation of kinetic energy from large to small scales. The proposed Surface Water and Ocean Topography (SWOT) mission would be a partnership between NASA, CNES (Centre National d'Etudes Spatiales) and the Canadian Space Agency, and would have as one of its main goals the measurement of ocean topography with kilometer-scale spatial resolution and centimeter scale accuracy. In this paper, we provide an overview of all ocean error sources that would contribute to the SWOT mission.

2. THE SWOT MISSION

The core technology for the proposed SWOT mission would be the Ka-Band Radar Interferometer (KaRIn) instrument, originally developed from the efforts of the Wide Swath Ocean Altimeter (WSOA)\(^1,2\). While conventional altimetry relies on the power and the specific shape of the leading edge of the return waveform, which is only available for the nadir point, the interferometric technique relies on the measurement of the relative delay between the signals measured by two antennas separated by a known distance (hereafter termed “baseline”), together with the system ranging information, to derive the height for every imaged pixel in the scene. For a given point on the ground, a triangle is thus formed by the baseline B, and the range distance to the two antennas, which can be used to geolocate in the plane of the observation. Using two consecutive radar pulses, one from each antenna, to form the

interferometric pair (this operation mode is commonly referred to as “ping-pong mode”), the range difference between the two antennas is determined by the relative phase difference between the two signals.

The KaRIn instrument would be complemented with the following suite of instruments: a Jason-type (C- and Ku-band) nadir-looking conventional altimeter, a three-frequency microwave radiometer, similar to the Advanced Microwave Radiometer (AMR) flown on the Ocean Surface Topography Mission (OSTM), as well as GPS receivers and a DORIS transponder for precise orbit determination (POD).

For the SWOT concept, the ocean measurement would drive the required performance of the payload system, where accuracies approaching 1 cm at 1 km$^2$ would be required to resolve sub-mesoscale processes. In contrast, the hydrology requirements in order to resolve surface water features are relatively less stringent, for a total height error budget of 10 cm. The high accuracy requirements for ocean topography measurements imply that the measurement error budget must be well understood and properly sub-allocated. Several sources of errors limit the accuracy of the final height$^{2,3}$:

1. Random errors, most notably the measurement noise of the interferometric phase difference. These errors are zero mean, uncorrelated in space and time, and destructive in nature, i.e. they cannot be overcome after signals are acquired. The random error contribution depends on several factors, most remarkably the system signal-to-noise ratio (SNR), the length of the interferometric baseline, and the processing algorithm.

2. Platform and instrument systematic errors, such as (unknown) roll, baseline, range and phase drift errors. These are not zero mean, but not destructive in nature, and could be corrected in theory if adequate knowledge existed. Lack of knowledge in the spacecraft roll angle, changes in the baseline due to thermal contraction or expansion, system timing errors, and phase errors introduced by the antennas or the electronics will induce height errors.

3. Orbit, media and sea-state errors. These errors are related to orbit errors, target and echo path characteristics, and expected to be temporally and spatially correlated, at least on local scales. Media errors include tropospheric and ionospheric propagation delays, electromagnetic (EM) bias. While KaRIn would not directly measure tropospheric and ionospheric corrections, the proposed SWOT altimeter/radiometer suite would be used to perform each range correction at nadir. The POD suite of instruments would be used to correct orbit errors.

3. THE OCEAN MEASUREMENT ERROR BUDGET

The primary oceanographic objective of the proposed SWOT mission is to characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and larger. Mapping of mesoscale and sub-mesoscale phenomena at 10 km resolution requires that the measurement noise be smaller than or equal to the signal for the resolved wavelengths. We define the Sea Surface Height (SSH) error spectrum, $E_{SSH}(f)$, as a function of the spatial frequency $f$ (i.e., $f=1/$wavelength$=1/\lambda$). The key oceanographic requirement for the SSH is specified as the following error, defined in the preliminary SWOT Science Requirement Document\(^4\) in units of cm\(^2\)/cycle/km as:

$$E(f) = \begin{cases} 
1000 \text{ cm}^2/(\text{cycle/km}) & , 1,000 \text{ km}<\lambda<10,000 \text{ km} \\
0.001 f^2 \text{ cm}^2/(\text{cycle/km}) & , 35 \text{ km}<\lambda<1,000 \text{ km} \\
1.5 f^2 \text{ cm}^2/(\text{cycle/km}) & , 1 \text{ km}<\lambda<35 \text{ km}
\end{cases}$$

The error spectrum is defined as an “ensemble average” requirement, such that the expected SSH error variance in a wavelength interval $[\lambda_{\text{min}}, \lambda_{\text{max}}]$ is given by the integral of $E_{SSH}(f)$:

$$\langle \left( \delta h \right)^2 \rangle = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} E(f)df$$

It is important to note that for the SWOT concept, the science requirements define the error as a swath-average performance requirement, rather than specifying the performance at some point in the swath. Also, the spectral form of the science requirements allows for different error budgets over different time scales, as given by the SSH error spectrum. Therefore, the allocation rationale that will be applied throughout the error budget discussion in this paper is as follows: 1) We first define the spectrum level of all errors (the direct sum of the random, systematic, media, and POD error spectra) at 1 km\(^2\) sampling resolution, after cross-over calibration, which shall meet the required science error envelope. 2) The KaRIn instrument random error allocation (at 1x1 km\(^2\) sampling) is 0.9 cm. This translates into a random spectral density of 0.32 cm\(^2\)/cycle/km. By subtracting the random error from the overall science requirement, one is left with the residual error that will be allocated to all the remaining errors (systematic, media, and POD). 3) We bound all the media, wave state, and POD errors by using error spectral envelopes. By subtracting all these spectral envelopes from the previous residual, one obtains the residual error that will be allocated to the following systematic errors: 1) Roll errors: the lack of

knowledge in the interferometric roll angle induces height errors. As an example, a roll knowledge error of only 1/10,000 deg (0.36 arc seconds) would result in a height error of roughly 6 cm for a point situated at 35 km in the cross-track direction. It is thus clear that in order to meet centimetric accuracy, a very accurate knowledge of the roll would be required for KaRIn; 2) Phase errors: Systematic phase errors arise due to changes in the effective delay of the interferometer system; 3) Baseline errors: as with any interferometer, a change in the baseline length would directly impact the precision of the height measurements that could be obtained; and 4) Timing errors: a system timing error would also introduce a height error.

4. THE OCEAN MEASUREMENT ERROR BUDGET

Characterization of ocean submesoscale processes is critically important in order to understand physical oceanographic processes. The proposed SWOT mission represents a unique opportunity towards understanding the role of the oceans in the global energy cycle. The SWOT payload concept would achieve the measurement needs for submesoscale ocean surface topography, providing 1 cm height accuracy at a spatial resolution of 1 km to resolve ocean wavelengths down to 10 km. The payload concept would utilize synthetic aperture radar interferometry as the primary measurement technique. The key performance and functional requirements, and error budget presented throughout this paper lay the groundwork towards understanding, quantifying, and sub-allocating the requirements for this mission for oceanography. The current concept for the development of the mission would lead to an anticipated launch in the 2019-2020 time frame.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

