On the Transition from Profile Altimeter to Swath Altimeter for Observing Global Ocean Surface Topography

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ABSTRACT

Conventional radar altimeter makes measurement of sea surface height (SSH) in one-dimensional profiles along the ground tracks of a satellite. Such profiles are combined via various mapping techniques to construct two-dimensional SSH maps, providing a valuable data record over the past two decades for studying the global ocean circulation and sea level change. However, the spatial resolution of the SSH is limited by both coarse sampling across the satellite tracks and the instrument error in the profile measurements. A new satellite mission based on radar interferometry offers the capability of making high-resolution wide-swath measurement of SSH. This mission is called Surface Water and Ocean Topography (SWOT), which will demonstrate the application of swath altimeter to both oceanography and land hydrology. This paper presents a brief introduction to the design of SWOT, its performance specification for SSH, and the anticipated spatial resolution and coverage, demonstrating the promise of SWOT for fundamental advancement in observing SSH. A main objective of the paper is to address issues in the anticipated transition of conventional profile altimetry to swath altimetry in the future—in particular, the need for consistency of the new observing system with the old for extending the existing data record into the future. A viable approach is to carry a profile altimeter in the SWOT payload to provide calibration and validation of the new measurement against the old at large scales. This is the baseline design of SWOT. The unique advantages of the approach are discussed in the context of a new standard for observing the global SSH in the future.

1. Introduction

Satellite altimetry has become an essential component of a global ocean observing system for a variety of applications (Fu and Cazenave 2001). By mapping the height of sea surface along satellite ground tracks, satellite altimetry has produced a continuous record of the global ocean surface topography since 1991. This record allows oceanographers to study the circulation of the ocean and sea level change from the mesoscale to the basin and global scales for a time span of more than 20 years (Fu et al. 2010; Willis et al. 2010; Hamlington et al. 2012). This data record is the driver of the new enterprise of ocean state estimation that produces estimates of the physical state of the ocean from ocean models constrained by a variety of observations (Wunsch and Heimbach 2013). The resulting knowledge of the state of the global ocean and its evolution over decadal scales has provided a framework for assessing the role of the ocean in climate change and the feasibility of predicting future climate. It is imperative to continue this data record into the future with consistency and integrity.

While a radar altimeter measures the sea surface height (SSH) along the satellite’s ground tracks, it produces a one-dimensional profile of SSH. This profile has relatively high-resolution along-track sampling (6–7 km) but leaves large cross-track gaps (200–300 km). In the event of multiple simultaneous altimetric satellites in orbit, data from different satellites were merged for producing two-dimensional maps at moderate resolution (Ducet et al. 2000). Fortunately, there have been at least two altimeters flying simultaneously since 1992 when the Ocean Topography Experiment (TOPEX)/Poseidon, the first of a series of high-precision altimetric missions, was launched. The “merged” data products from multiple altimeters have been providing the database for the majority of the research using altimeter data (e.g., Dussurget et al. 2011; Escudier et al. 2013).

Because the merged data products are primarily based on observations from only two altimeters, their spatial...
resolution after two-dimensional gridding is limited to wavelengths larger than about 150 km (Ducet et al. 2000), resolving only relatively large eddies. However, the unresolved scales of ocean circulation play important roles in the dynamics of ocean circulation and mixing. For example, Lapeyre and Klein (2006) estimated that about 50% of the vertical transfer of nutrients in the ocean takes place at scales of 10–100 km. Nonlinear transfer of energy through scales in this range is shown to be important to the understanding of the energy balance of ocean circulation (Capet et al. 2008).

Although the along-track data have small sampling intervals, the noise level of the data limits the resolution of ocean signals to wavelengths longer than about 70–100 km (Xu and Fu 2012). Therefore, the resolution of the present altimetry record is not sufficient for addressing small-scale ocean circulation of great importance to both scientific and practical objectives. This recognition provides a basis for the development of wide-swath altimetry (Fu and Rodriguez 2004), leading to the establishment of the Surface Water and Ocean Topography (SWOT) mission (Durand et al. 2010). SWOT will make high-resolution measurement of the elevation of land surface water and ocean topography for both hydrologic and oceanographic applications.

The basic measurement of SWOT is to be made by a radar interferometer that will produce high-resolution observation of the water elevation over a swath on the order of 120 km wide centered along the nadir tracks of the spacecraft. This approach promises high-precision measurement over both land surface water and the ocean. The sampling capability of SWOT will enable the measurement of ocean surface topography at scales not resolvable by profile altimeters. However, radar interferometer measurement is sensitive to the stability of the spacecraft and is prone to large-scale errors. To address this issue, the SWOT payload includes a conventional profile altimeter for calibration and validation of the interferometer measurement for its large-scale performance. This approach would enable the demonstration of the transition of profile altimeter to swath altimeter for observing ocean surface topography over a wide range of scales. If successful, SWOT will then establish swath altimeter as the standard for future measurement of ocean surface topography.

The purpose of the paper is to provide a brief description of the SWOT mission in terms of its sampling capability for oceanography and expected performance. The emphasis is placed on the need for calibration and validation of the measurement at large scales and the need for carrying a profile altimeter as part of the payload to achieve this objective.

2. Swath measurement from radar interferometry

Shown in Fig. 1 is the configuration of the baseline design of the SWOT mission. The primary instrument is a Ka-band (35 GHz) radar interferometer (or KaRIN) consisting of two radar antennas 5 m long separated by a 10-m boom. Signals received by the two antennas from a surface target away from the nadir have a phase difference that allows the determination of the look angle of the target. In a band (20 km wide) centered at the nadir, the phase difference becomes too small for accurate determination of the look angle. Inside this band the phase difference between signals (shown by the green dashed lines) received by the nadir antenna and one of the interferometer antennas will be used instead. The range of the target from the spacecraft is determined from the round-trip travel time of the radar signal via pulse compression technique. Then the elevation of the target from a reference surface is determined from the knowledge of the location of the spacecraft in orbit. A brief but more detailed description of the technique can be found in Durand et al. (2010) and Fu and Rodriguez (2004).

Because the elevation error increases with the look angle, KaRIN must have a near-nadir look angle for making accurate measurement, leading to a relatively narrow swath of 50 km wide on each side of the nadir with a gap of 20 km in the center, where the small phase difference makes the measurement uncertain. A relatively long orbit repeat period of 22 days is needed to provide nearly complete zonal coverage of the earth between ±78° latitude dictated by the 78° inclination of the orbit chosen to minimize tidal aliasing and maximizing latitudinal coverage. The nadir measurement will be provided by the conventional profile altimeter carried on board, as shown in Fig. 1. The role of the profile altimeter, however, is more than just providing the nadir observation. This is the main point of the paper to be addressed in a later section after the description of the expected performance of KaRIN.

Shown in Fig. 2 is the performance specification (or requirement) of KaRIN expressed in wavenumber spectrum overlaid on a spectrum of SSH measurement from Jason-1 (from Fu and Ferrari 2008). At wavelengths shorter than 100 km, the Jason-1 measurement is dominated by instrument noise. Extrapolation of the Jason-1 spectral slope to shorter wavelengths is an attempt to estimate the signals at the unresolved scales where theories of ocean dynamics predict an extension or power laws (e.g., Capet et al. 2008). The spectral specification of KaRIN was established to detect the unresolved short-scale signals and to produce observations with errors significantly less than the signals. The
driving requirement for the design of KaRIN is its noise level. To detect SSH signals to wavelengths on the order of 10 km, the KaRIN noise level must be less than that of Jason-1 by two orders of magnitude.

As opposed to a real aperture radar of the Jason-1 altimeter, KaRIN is based on a synthetic aperture radar (SAR) system. Its pixel size is on the order of 10 m. Over an area of 1 km², there are a large number of independent measurements to reduce the noise level to $2 \text{cm}^2 \text{cycle}^{-1} \text{km}^{-1}$ (Fu et al. 2012), shown by the red line at the high-wavenumber end in Fig. 2. This is the noise requirement that KaRIN will be designed to meet, called the baseline requirement. To allow flexibility in mission development, a threshold requirement, shown by the blue line, is also specified to allow a somewhat higher noise level. The threshold requirement represents the upper bound of measurement error that would still allow significant advance in the mission’s science. The intersections of the specified noise levels with the SSH spectrum represent roughly the spatial resolution of KaRIN: 15 km for the baseline performance and 20 km for the threshold performance in the particular case.

At wavelengths longer than 30–50 km, the error spectrum is dominated by systematic measurement errors from various sources, including the effects of water vapor in the atmosphere and ocean waves (Fu et al. 2012). The performance of KaRIN at these wavelengths must be compared with conventional nadir altimeter measurement for consistency. At wavelengths longer than 1000 km, the systematic errors are expected to level off until reaching the scales of the radius of Earth where the orbit errors will dominate. The red line at the long wavelengths is a schematic representation of the long-wavelength errors that are not driving the mission design.

As reported in Xu and Fu (2012), the wavenumber spectrum of SSH has a high degree of geographic variability. The expected resolution of KaRIN should be evaluated geographically. We simply applied the noise specification to the SSH spectrum at every position of the $2^n \times 2^n$ grids as in Xu and Fu (2012) and found the
intersections of the noise level with the SSH spectrum, which was computed from all the data from TOPEX/ Poseidon, Jason-1, and Jason-2. Displayed in Fig. 3 is a map of the spatial resolution based on the baseline specification (noise at $2 \text{ cm}^2 \text{ km}^{-2} \text{ cycle}^{-1}$). The resemblance to the pattern of the SSH spectral slopes (Fig. 3b in Xu and Fu 2012) is not surprising. At midlatitudes away from energetic boundary currents, the resolution is about 15 km, in agreement with the result from Fig. 2 based on a typical spectrum in these regions. As the SSH spectrum becomes steep in the regions of energetic ocean currents, such as the Gulf Stream and the Antarctic Circumpolar Current, the expected resolution is in the range of 20–30 km even though the mesoscale energy is very high.

In the tropics and other regions where the mesoscale SSH variability is extremely low and the spectral slopes are flat (close to $k^{-2}$, where $k$ is the wavenumber), the resolution becomes high and to a level less than 10 km. However, the spectral slopes in these regions are not consistent with our understanding of ocean circulation. In particular, ocean general circulation model simulations have shown consistently steeper slopes in the tropics and in other low-eddy-energy regions than altimeter observations (Richman et al. 2012). The expected high resolution from KaRIN in these regions might prove to be an artifact caused by altimetry errors not accounted for in the Jason measurement or related to physical processes not accounted for in the model simulations.

3. Simulated SWOT observations

With the spatial resolution depicted in Fig. 3, the SWOT mission will sample the global ocean surface topography with unprecedented details. To illustrate the impact of SWOT relative to the coordinated tandem sampling by the combination of Jason-1 and Jason-2, we conducted modeling experiments in which the ocean surface topography was simulated by a high-resolution ocean general circulation model configured off the
Oregon coast. We used a regional configuration of the Oregon coast with the Regional Ocean Modeling System (ROMS) model (Shchepetkin and McWilliams 2005). The horizontal resolution was set up at 2 km and the vertical resolution at 50 levels, over a domain of 600 km (zonal) and 800 km (meridional) off the coast of Oregon. We then simulated observations of SWOT and Jason-1 / Jason-2 by sampling the model-produced data and compared the results.

Figure 4a represents the SSH from the model at a particular time, serving as the reference “truth” to be observed. Figure 4b shows the simulated Jason-1 and Jason-2 observations gathered over a repeat cycle (10 days), from 5 days before to 5 days after the reference time. As shown in Fig. 2, Jason-1 is not able to resolve ocean signals at wavelengths shorter than 80 km because of the effects of instrument noise. The model simulations were low-pass filtered to remove variability at wavelengths shorter than 80 km to simulate the Jason observations. This is why eddies are attenuated along the tracks on Fig. 4b.

Figure 4c represents the results after mapping the along-track data using a Gaussian correlation function with a decorrelation scale of 120 km. No temporal interpolation was applied because the time variability of the eddies is quite small within ±5 days for the reference time. Figure 4c is qualitatively similar to typical maps of SSH anomaly produced by Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data in terms of spatial resolution and eddy attenuation. Figure 4d shows the simulated SWOT observations gathered over a repeat cycle (22 days), from 11 days before to 11 days after the reference time. Here again,
the instrumental noise is implicitly taken into account by smoothing over 20-km scales. Note that a much more detailed map is obtained. Without resorting to any mapping operations, some discontinuities can be noted in the map arising from the time lag between observations, but the finescale features of the reference truth field (Fig. 4a) are captured by the simulated SWOT observations.

Figure 4e is the reference surface current speed derived from SSH based on geostrophy. Shown in Figs. 4f and 4g are the speeds of the geostrophic velocities derived from the SSH observed by Jason-1/2 (Fig. 4c) and from the SSH observed by SWOT (Fig. 4d), respectively. As the velocity is a derivative of SSH, the difference in resolution is even more striking. The short mesoscale eddies not observable in the Jason observations are clearly resolved in the SWOT simulations. These results have underscored those from the study by Pujol et al. (2012), which demonstrated the potential superiority of SWOT in sampling the mesoscale ocean processes relative to the performance of a constellation of conventional altimeters.

4. The role of the profile altimeter on SWOT

As discussed in the preceding section, the sampling capability of the SWOT mission has the potential for making measurement of ocean surface topography from the mesoscale to the global basin scales. This new capability may retire the need of a constellation of multiple altimeters for covering a wide range of scales of ocean variability. Furthermore, the noise level of conventional altimetry is not able to resolve wavelengths of 10–20 km no matter how many altimeters are flying in formation. We are thus having an opportunity of transitioning the conventional profile altimetry to swath altimetry in the future by providing observations of global ocean surface topography.

A challenge is to ensure consistency of the new approach with the old approach for continuing the climate data record of ocean surface topography established over the three decades before the launch of SWOT, scheduled for the year of 2020. According to the monitoring principles governing the continuity of climate data record issued by the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO), we should adhere to the following principles in making the transition from an old observing system to a new observing system (http://gosic.org/gcos/GCOS-climate-monitoring-principles.htm):

- The impact of new systems or changes to existing systems should be assessed prior to implementation.
- A suitable period of overlap for new and old observing systems is required.

The benefits of overlap between new and old systems have been demonstrated by the tandem missions of TOPEX/Poseidon with Jason-1 and of Jason-1 with Jason-2 (Fu and Haines 2013). During the tandem missions, the two altimeters were flown over the same ground tracks with only 1-min difference in overflight times. In such a short time, most sea-state and overlying atmospheric conditions remain the same and cannot cause significant differences in the SSH measurement. Shown in Fig. 5 is the wavenumber spectrum of the differences between Jason-1 and Jason-2 SSH observations in the tandem mission. The computation was made to 19 cycles (190 days) of data from the two satellites along a long pass in the eastern Pacific Ocean from the central North Pacific to the Drake Passage. The error bar of the spectrum is comparable to the wiggles of the noise floor at the high-wavenumber end. The spectrum of the difference is essentially white noise.

The slight dip at the high-wavenumber end is caused by the process of gridding the data to the same locations for difference analysis. However, during the tandem mission of TOPEX/Poseidon and Jason-1, the spectrum of the SSH difference between the two altimeter measurements was dominated by variance at long wavelengths (Vincent et al. 2003). These differences were correlated to the observed wave height, indicating problems in the instrument algorithms that were affected by wave height differently between TOPEX/Poseidon and Jason-1. In-depth analyses revealed that
the source of the problem was from Jason-1. After re-processing of the Jason-1 data, the wave-height-dependent problems were resolved and the difference between Jason-1 and Jason-2 data shows the dominance by instrument noise as expected. Without the overlapping observations from the two successive missions, such systematic errors would be difficult to detect and to correct for maintaining consistency between successive missions in building a climate data record.

There have been arguments for the utility of a constellation of profile altimeters for calibration and validation of SWOT after its launch. There will certainly be benefits from these altimeters in evaluating the performance of SWOT over large scales. Their utility for calibration and validation will be limited through the analysis of crossover differences with the SWOT observations. The time differences of the crossover differences will not be limited to short periods in which the sea-state and atmospheric conditions would remain nearly identical as in the case of the tandem missions. The growing magnitude of crossover difference with increasing time difference (Fig. 6) would make it not particularly useful for understanding the differences between altimeter and KaRIN measurements. Both systematic errors and geophysical signals make the matter of separating signals from errors very complicated. Furthermore, the spatial extent of crossover is on the order of the 120-km swath width, making analysis over a wide range of scales as conducted for the altimeter tandem mission not possible. However, simultaneous flight of KaRIN with an altimeter would provide cross calibration/validation to achieve understanding of any systematic differences between the two measurements and to enable necessary steps for ensuring consistency of the two measurements.

5. An approach to calibration/validation of SWOT

As shown in Fig. 5, the magnitude of the signal in the altimeter measurement dominates the instrument noise (about one-half of the noise level of the difference) at wavelengths longer than 100 km. At 120-km wavelength, the width of the SWOT swath, the signal-to-noise ratio is about 5. From the discussion in the preceding section, carrying a profile altimeter on board SWOT will then provide effective calibration and validation of KaRIN at wavelengths longer than 120 km in the same way in which Jason-1 and Jason-2 were calibrated and validated.
At wavelengths shorter than 120 km, we will need a different approach that is able to provide two-dimensional high-resolution SSH observations for calibration/validation. An airborne radar interferometer, called AirSWOT (http://swot.jpl.nasa.gov/airswot/), is being developed by the SWOT mission as a tool for calibration/validation. AirSWOT will produce SSH observations over a swath of only 5 km using the same technique as SWOT. However, over the period of one day, AirSWOT is able to make measurements over a square of 120 km$^2$ from zigzag flight paths. Such observations will need calibration/validation through comprehensive comparison to in situ observations (from current profilers, floats, and gliders, etc.) and modeling analysis. These efforts will allow the characterization of the measurement and sampling errors of AirSWOT in constructing a synoptic map for comparison to the SWOT observations. After such efforts, the calibrated/validated AirSWOT observations will be used for the calibration/validation of SWOT measurement at the scales of the swath width. Shown in Fig. 7 is a schematic configuration for the approach.

To evaluate the KaRIN performance at scales larger than the swath width, we consider performing along-track two-dimensional low-pass filtering to retain variance at wavelengths (along track) longer than 120 km. Consistency between KaRIN and altimeter measurements will be analyzed for identifying any systematic errors. These errors must be understood with possible mitigation identified to demonstrate the feasibility of KaRIN for replacing the profile altimeter for monitoring large-scale ocean surface topography.

6. Conclusions

The swath altimeter to be flown on the SWOT mission will transform the sampling of ocean surface topography from one-dimensional, along-track profiling to two-dimensional mapping. The spatial resolution will be improved from 70–100 km limited by the profile altimeter instrument noise to 10–30 km owing to the averaging of a large number of high-resolution observations offered by radar interferometry. The improvement in sampling of SSH and surface geostrophic current velocity is illustrated by simulations from a high-resolution ocean general circulation model. However, radar interferometer measurement is sensitive to the stability of the spacecraft and prone to large-scale errors. To address this issue, the SWOT payload includes a conventional profile altimeter for calibration and validation of the interferometer measurement for its large-scale performance. The experience of cross calibration of profile altimeter using nearly simultaneous measurements from successive missions has illustrated the potential efficacy of the flight of a profile altimeter with the new swath altimeter for calibration and validation of the new measurement at large scales. This approach is in accord with the monitoring principles of the GCOS for maintaining climate data records from evolving observing systems.

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