

**The SWOT (Surface Water and Ocean Topography) Mission:
Spaceborne Radar Interferometry for Oceanographic and
Hydrological Applications**

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Abstract

Satellite altimetry has revolutionized the study of the global oceans for the past two decades. Precision altimetry missions like TOPEX/Poseidon, Jason-1, and OSTM/Jason-2, complemented by other missions like ERS 1 and 2, ENVISAT, and GFO, have provided unprecedented observations of the ocean surface topography at scales larger than about 200 km and made significant advances in our understanding of global ocean circulation and sea level change. However, the measurement errors have prevented resolving scales shorter than 100 km, the submesoscales that are important for understanding the dynamics of the ocean kinetic energy and the vertical transfer processes in the ocean. These processes are critical to the understanding of the role of the ocean in regulating global climate change. Altimetry measurements have also been applied to the study of the water levels of rivers and lakes, but the coarse resolution of the data has severely limited its ability in addressing key hydrological questions on the storage of water on land and its discharge. These are important questions on the distribution of fresh water on land that is being seriously affected by global climate change. A new space mission called Surface Water and Ocean Topography (SWOT) is being developed jointly by a collaborative effort of the international oceanographic and hydrological communities for making high-resolution measurement of the water elevation of both the ocean and land surface water to answer the questions about the oceanic submesoscale processes and the storage and discharge of land surface water. The key instrument payload is a Ka-band radar interferometer capable of making high-resolution wide-swath altimetry measurement. The development of the mission has been proceeding as a joint effort of NASA and CNES, following the long-lasting tradition in collaboration in radar altimetry over the past 25 years. This paper describes the science objectives and requirements as well as the measurement approach of SWOT, which is anticipated to be launched in 2016. SWOT will demonstrate this new approach to advancing both oceanography and land hydrology and set a standard for future altimetry missions.

1. Introduction

Satellite radar altimetry has revolutionized oceanography by providing close to two decades' worth of global measurements of ocean surface topography. Long-term measurements of large-scale circulation and heat storage of the global oceans have led to major advances in our understanding of the processes underlying the changes of the ocean in relation to climate cycles such as El Niño and La Niña. Radar altimetry has also provided high-precision sea level measurements with global coverage. The spatial variability of global sea level change has allowed the separation of natural from human-induced changes, as well as identifying the most vulnerable coastal areas and improving climate models used for sea level projections.

In contrast to ocean observations, land surface water measurements are limited mostly to in situ networks of gauges that record water surface elevations at fixed points along river channels. Globally, the spatial and temporal distribution of surface water stored on land and moving through river channels is known only crudely. Furthermore, water movement

in wetlands and across floodplains throughout the world is essentially unmeasured, significantly limiting our understanding of flood processes. In rivers, in situ networks are declining worldwide due to economic and political reasons.

A critical limitation of the classical nadir altimetry from space, for both ocean dynamics and land hydrology, is the 200- to 300-kilometer spacing between satellite orbital tracks, which is unable to resolve small-scale features in ocean circulation (e.g., currents and oceanic mesoscale processes that contain 90% of the kinetic energy of the oceans) and miss a large number of surface water bodies on land (small lakes and reservoirs, most rivers, etc.)

The physical oceanography and surface freshwater hydrology communities have now joined together in recognizing the potential of high-resolution, space borne measurements of water surface elevations (Alsdorf et al., 2007). They propose a new mission named SWOT (Surface Water Ocean Topography) based on the concept of wide-swath interferometric altimetry for mesoscale oceanography and land surface hydrology. The SWOT mission was recommended by the National Research Council decadal review “Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond” for implementation by NASA. The SWOT mission is a partnership between NASA and CNES.

The primary SWOT instrument is an interferometric altimeter which has a rich heritage based on (1) the many highly successful ocean observing radar altimeters, (2) the Shuttle Radar Topography Mission, and (3) the development effort of the Wide Swath Ocean Altimeter (WSOA) (Fu, 2003; Fu and Rodriguez, 2004). It is a near-nadir viewing, 120 km wide, swath based instrument that will use two Ka-band synthetic aperture radar (SAR) antennae at opposite ends of a 10 m boom to measure the highly reflective water surface. Interferometry SAR processing of the returned pulses yields a 5 m azimuth and 10 m to 70 m range resolution, with elevation precision of 50 cm. Spatial averaging over areas of 1 km² improves the height precision to less than 2 cm.

2. The oceanic submesoscale variability

Observations made by satellite altimeters since 1980s have provided progressively improved views of the global ocean mesoscale eddy field that contains most of the kinetic energy of the ocean circulation. In parallel to these observations, ocean models have also progressed from coarse-resolution, highly dissipative mesh grids to higher resolutions where mesoscale eddies dominate the solutions. We are now able to produce simulations of the present state of the ocean which compare increasingly well to observations. However, the skill of these models in making long range predictions of the ocean is still very limited, because they lack a physically-based representation of the submesoscales, i.e. scales of 1-100 km that are important for turbulent transport and energy dissipation. Ocean models running at sufficient resolutions to address submesoscale dynamics have just begun to emerge (e.g. Capet et al., 2008), but we need global observations at these scales to guide the model development.

Conventional nadir-looking radar altimeters have a footprint on the order of 2-10 km. Even with thousands of pulses averaged over 1 second, the noise level of the sea surface height (SSH) measurement is substantial, making ocean SSH signals at wavelengths less than 100 km not well observed. A typical wavenumber spectrum of SSH deviations from a time mean, sampled along a long satellite pass (from the Jason Mission) from Bering Sea to Drake Passage in the Southern Ocean, is shown in Figure 1a (from Fu and Ferrari, 2008). At wavelengths longer than 100 km, the spectrum shows a typical “redness” with power density increasing with wavelength. The spectral slope levels off at wavelengths shorter than 100 km, showing the dominance of measurement noise at the submesoscales. However, very high resolution models that resolve the submesoscale (Capet et al., 2008) show a cascade of energy from the mesoscale to the submesoscale, such that the ocean spectra remains “red” down to kilometric wavelengths (Fig. 1b).

When the noisy measurements along nadir tracks are smoothed and merged to produce two-dimensional maps, the spatial resolution is on the order of 200 km even with combined data from two altimeters (Ducet et al., 2000). This resolution is not even sufficient to resolve the details of the two-dimensional structure of ocean currents like the Gulf Stream and Kuroshio, whose cross-current dimension is on the order of 100 km. Although combined data from TOPEX/Poseidon and ERS have been used extensively to study the characteristics of ocean eddies (e.g., Chelton et al, 2007), the size of the eddies have been limited to diameters larger than 100 km.

Mesoscale eddies larger than 100 km are effective in transporting ocean properties (nutrients, heat, salt, carbon) horizontally in the upper ocean, as illustrated by Figure 2. Ocean variability at the submesoscales in the form of fronts and filaments is most effective in the vertical transport of ocean properties between the upper layers of the ocean and the deep ocean. This vertical transport of ocean properties is important for understanding the ocean’s role in climate change, in terms of the rate of oceanic uptake of heat and CO₂. The vertical transport of nutrients is important to the biogeochemical cycle of the ocean that also has important effects on climate. For example, the current generation of carbon models suggest that one third to one half of the global uptake of anthropogenic CO₂ occurs south of 30°S, yet the errors in the different model estimates are large. The highest simulated total uptake in the Southern Ocean is 70% larger than the lowest (Orr et al., 2001). SWOT measurements of the mesoscale and submesoscale dynamics, combined with state-of-the-art carbon and biogeochemical models, will greatly improve estimates of CO₂ uptake and nutrient cycles.

To make an order of magnitude advance in resolution for resolving the submesoscales, the measurement noise must be less than the signal at a wavelength of 10 km as shown by the horizontal dashed line in Figure 1a, in which the SSH spectrum is extended from the power law to wavelengths of 10 km. The threshold of noise level corresponds to a power density of 1 cm²/cycle/km, about two orders of magnitude less than that of the Jason altimeter. This performance in SSH measurement translates to a geostrophic velocity error of 3 cm/sec at 10 km wavelength at 45 degree latitude. The two dimensional SSH map from SWOT will then allow the study of the submesoscale ocean eddies, fronts, narrow currents, and even the vertical velocity at these scales.

The oceanic submesoscales happen to coincide with the scales of oceanic internal tides. These are oscillations of the ocean's internal density surfaces (the thermocline) at tidal frequencies causing surface elevations of a few centimeters at scales of 10-100 km. If not corrected, these signals would cause errors in the computation of ocean geostrophic currents with magnitude of a few cm/sec, comparable to the signals at these scales. To obtain information on internal tides so that they can be removed from the observations, we must avoid sun-synchronous orbits that will alias solar tides to zero frequency and thus contaminate the signals for studying ocean circulation. The orbit configuration must also be chosen not to alias different tidal components onto the same frequency, which would make the determination of various components of internal tides impossible. Long time series will be needed to determine the various components of the tides. We also desire to cover as much high-latitude oceans as possible where the technology of radar interferometry will provide the first opportunity to map the ocean surface topography with minimized sea-ice contamination. With these considerations, the orbit inclination has been chosen to be 78 degrees, beyond which the tidal aliasing will become a significant issue. The selected orbit provides coverage from 78S to 78N with a 22-day repeat period.

3. Hydrological processes of surface water on land

Under the threat of global climate change, one of the most urgent problems is the change in global fresh water supplies. In-situ measurements have been traditionally used to provide information on surface water storage and river discharge. However, it is important to recognize that globally, the number of in situ streamflow gaging stations is in decline. The implication of this decline is that less data will be available for hydrologic characterization in the future. Moreover, many countries do not share hydrologic data, as shown in Figure 3. For countries whose water resources and flood risk management depends on information from upstream countries, the implications of data sharing are particularly important. These issues of data decline and lack of data sharing constitute a hydrologic data problem which is difficult to solve with in-situ approaches alone; e.g., remote locations are difficult to access regularly whereas other regions suffer from significant economic decline and political instability. Remote sensing is crucial for solving this hydrological data problem.

The primary SWOT hydrology science question relates to the global water cycle: "What is the spatial and temporal variability in the world's terrestrial surface water storage and discharge? How can we predict these variations more accurately?" The ability of SWOT to provide water surface elevation (WSE), as well as freshwater discharge and storage change in lakes, reservoirs, wetlands, and rivers at the global scale, would provide a tremendous leap forward in understanding the dynamics of the land surface branch of the global water cycle. Moreover, measurements of spatial and temporal changes in water elevations along the course of rivers will complement in situ gages, and should foster advances in the understanding of fluvial processes. Additionally, the ability to derive river discharge measurements from a single global WSE dataset will certainly improve understanding of hydrological dynamics in ungaged basins (Sivapalan et al., 2003), and

other locations where data are not available due to data-sharing issues. To illustrate the use of SWOT observations in estimating river discharge, a simulation was carried out with synthetically-generated SWOT measurements assimilated into a hydrologic model for a reach of the Ohio River. (Figure 4).

The second SWOT hydrology science question is: “How much water is stored on a floodplain and subsequently exchanged with its main channel? How much carbon is potentially released from inundated areas?” As noted by Richey et al. (2002), the quantities of water exchanged between the Amazon River and its floodplain can be up to 25 % of the average annual flow. Despite the magnitude of these exchanges, they are currently unmeasured. SWOT measurements would provide the means to study the nature of the floodplain hydraulics. A better understanding of the global water cycle would allow for a detailed investigation of linkages with the global carbon cycle. Richey et al. (2002), for instance, have suggested that evasion of CO₂ from river surfaces may be of the same order of magnitude as terrestrial carbon fluxes. Better estimation of this term in the global carbon balance requires better time-varying measurements of global inundated area than can produced by any current sensors.

The third SWOT hydrology science question is: “What policy implications would freely available water storage data have for water management? Can health issues related to waterborne diseases be predicted through better mappings?” For transboundary rivers where water resources and flood risk management are international in nature, SWOT measurements of upstream reservoir levels could prove useful. Remote sensing of surface water bodies has been used to study water-related infectious diseases such as schistosomiasis (e.g., Clennon et al., 2007). The utility of SWOT measurements will be explored in this context.

These science questions lead to the following mission requirements: a) all lakes greater than 250 m x 250 m must be measured with a temporal resolution of at least 10 days, and a vertical precision of at least 10 cm; b) in order to observe most global lakes and rivers, the SWOT measurements must be made to at least to 74 degrees latitude; c) in order to observe global fluvial processes, rivers with widths greater than 50 – 100 m must be measured. The vertical precision of WSE measurements must be at least 10 cm, and river slope must be measured to within 10 μ rad (1 cm km⁻¹).

5. Other applications

In addition to the core mission goals discussed in the previous two sections, the SWOT data will be useful for a variety of other scientific applications. These applications will not drive the mission requirements or cost, but the mission design development will not preclude them, assuming that enabling these science applications will have small or no impact on the mission design or cost.

Although it is impossible to foresee all the applications that could be made of the SWOT data, the following is a list of applications being considered:

1. SWOT can be a complementary data set to the operational oceanographic altimeters in the Topex/Poseidon, Jason series, to continue the monitoring of global sea level rise and the ocean's response to climate variations, primarily for scientific and not operational purposes.
2. SWOT can improve the estimates of barotropic and internal tides, globally in the deep ocean, coastal regions, and underneath sea ice and ice shelves.
3. SWOT can collect data over coastal regions that will be of significant benefit to coastal oceanography and estuary hydrology, possibly after assimilation into regional models, and improve storm surge models.
4. SWOT can collect data over the tidally affected portions of rivers, and estuaries and wetlands, to help better understand the dynamics of freshwater/marine interaction dynamics.
5. SWOT data can provide an accurate distribution of the upper ocean heat content, which affects the overlying atmospheric circulation, and is important for weather forecasting, including cyclone and hurricane prediction.
6. The SWOT data can be used to estimate the global ocean mean sea surface and surface slopes. These data can be used to improve estimates of the ocean bathymetry at higher resolution and accuracies than currently possible. In conjunction with gravity missions, it can also be useful for estimating the marine geoid and absolute geostrophic currents
7. SWOT surface water extent data can be useful for estimating CO₂, CH₄, and other biogeochemical fluxes and their changes from inundated regions.
8. SWOT data could potentially provide useful target of opportunity information for flood events, both in near-real time and post-event analysis.
9. SWOT data can potentially be used for measuring the topography of part of the Greenland and Antarctic ice sheets, and their changes.
10. SWOT data can potentially be used for mapping the thickness of floating sea ice by measuring sea ice freeboard.
11. SWOT data can be used to improve the Earth's mean land/ice topography, its changes and potential land-cover classifications, at a higher resolution, an enhanced accuracy, and uniformly referenced to a well-defined International Terrestrial Reference Frame (ITRF).

5. The measurement approach

Displayed in Figure 5 is a schematic illustration of the measurement configuration of the SWOT Mission. The major instrument is a Ka-band radar interferometer (KaRIN). Other instruments include those from a standard payload of a precision radar altimeter system (e.g., Jason-2): a 3-frequency microwave radiometer; a nadir looking, dual-frequency C- and Ku-band radar altimeter; and three orbit determination systems including a microwave tracking receiver called DORIS, a GPS receiver, and a laser retroreflector. The nadir gap between KaRIN's swaths will be filled with the nadir looking altimeter, similar to the Jason-2 altimeter. In addition to providing nadir coverage, the nadir-looking instrument will be able to collect during rain and provide data for the calibration of the Ka-band interferometer. The 3-frequency radiometer will be used for the estimation of the wet tropospheric delay along the nadir direction, as has been done for the

TOPEX/Poseidon and Jason altimeters. The precision orbit determination system will obtain a centimeter level precision orbit. The combined KaRIN and nadir altimeter configuration will allow us to resolve the full spectra of submesoscale to large-scale ocean dynamics.

The Ka-band radar interferometer

Conventional altimeters use ranging measurements, which require additional *a priori* assumptions (e.g., the first return is from the nadir direction) in order to obtain heights and location measurements. In addition, because altimeters are nadir looking instruments, they can only provide along-track one-dimensional measurements. These limitations of radar altimetry can be overcome by the introduction of a second antenna to achieve triangulation by measuring the phase difference between the two radar returns (Rodriguez and Martin, 1992; Rosen et al., 2000), a technique called synthetic aperture radar interferometry (IFSAR). This technique is quite mature and has been demonstrated from airborne platforms, and most notably from space by the SRTM, where two IFSARs (at C and Xbands) produced global data with an accuracy of a few meters.

In order to achieve centimeter accuracies, a few changes to the SRTM design are required. The major contributor to height errors is the lack of knowledge of the interferometric baseline roll angle: an estimation error of $\delta\theta$ will result in a height error $\delta h = x\delta\theta$, where x is the cross track distance. Clearly, the error will be reduced if the swath cross-track distance, or, equivalently, the radar look angles are reduced. In SRTM, the look angle varied from about 20° to about 60° . We propose to limit KaRIN's maximum look angle to about 4.5° , which will reduce the outer swath error by about 14 times, compared to the SRTM outer swath attitude error. A similar reduction applies to errors due to phase, since the two errors have similar angular signatures [Rodriguez and Martin, 1992]. The reduction in look angles entails a reduction in swath, from 220 km for SRTM, to about 60 km (from 10 km to 70 km in cross-track distance), for the KaRIN instrument. In order to mitigate this loss in coverage, the instrument looks to both sides of the nadir track to achieve a total swath of 120 km. The isolation between the two swaths is accomplished by means of offset feed reflect array antennas which produce beams of orthogonal polarizations for each swath. This technology was developed for WSOA, and the antennas have been prototyped and their performance demonstrated.

The height noise of the instrument is proportional to the ratio between the electromagnetic wavelength (λ) and the interferometric baseline (B). For SRTM, a 63 m baseline was required to achieve the desired height accuracy using a wavelength of 5.6 cm ($\lambda/B \sim 8.9 \times 10^{-4}$). Such a large structure entails large costs. In order to reduce the instrument size, KaRIN uses a smaller wavelength (Ka-band, $\lambda=0.86$ cm), and reduces the interferometric mast size to 10 m ($\lambda/B \sim 8.6 \times 10^{-4}$). The technology for a 10 m interferometric mast capable of meeting the stringent mechanical stability required for centimetric measurements has been developed by Able Engineering (SRTM mast manufacturer) in support of the WSOA technology development. Height noise can be

reduced by averaging neighboring image pixels. SRTM averaged about two pixels in order to achieve a 30 m spatial resolution with a meter level height noise. To achieve centimetric height noise, and also to produce images of the water bodies, an increase in the intrinsic range resolution of the instrument is required. Using a 200 MHz bandwidth system (0.75 m range resolution) achieves ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. A resolution of about 5 m (after onboard data reduction) in the along track direction is derived by means of synthetic aperture processing. Noise reduction is achieved by averaging over the water body.

Note that to achieve the desired resolution, SAR processing must be performed. On board processing to 1 km x 1 km pixels for ocean applications is achievable. However, the large volume of the high-resolution data for hydrological applications must be downlinked for ground processing. Therefore, after passing through a data reduction presuming filter, the raw data are stored and subsequently downlinked to the ground. The data downlink requirements can be met with four 300Mbit/sec X-band receiving stations.

Conclusions

Observing and understanding the oceanic submesoscale processes is critically important to understanding the role of the ocean in regulating climate change. Measurements of WSE provide an important opportunity for advancing understanding of the spatial and temporal distribution of surface water, one of the major issues facing society resulting from global climate change. Thus, the SWOT Mission will address two key questions on future climate change. First, what is the role of the oceanic mesoscale and submesoscale processes in the ocean's capacity for regulating the rate of climate change? Second, what is the consequence of climate change on the distribution of water on land? The collaboration of the oceanographic and hydrological communities has been very productive in the development of SWOT. Taking advantage of the legacies from the long-lasting partnership between the US and France in developing the series of precision altimetry missions as well as WSOA, both technical and scientific aspects of the development of SWOT have been progressing in a rapid phase towards the formulation of a flight mission. The current concept for the development of the mission leads to an anticipated launch in 2016.

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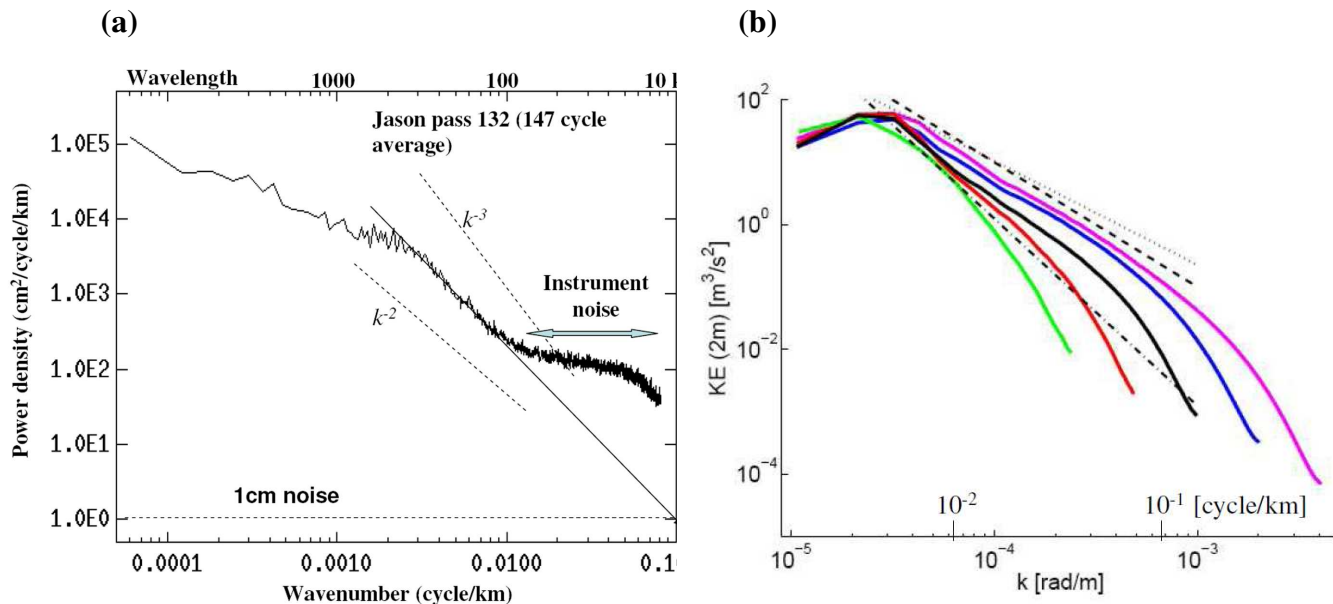


Figure 1 (a) Spectrum of sea surface height anomaly from Jason altimeter data (solid line). The two slanted dashed lines represent two spectral power laws with k as wavenumber. The horizontal dashed line represents the threshold of measurement noise at 1/km sampling rate. The slanting solid straight line represents a linear fit of the spectrum between 0.002 and 0.01 cycles/km. It intersects with the threshold noise level at 10 km wavelength. (from Fu and Ferrari, 2008). (b) Wavenumber spectra for simulated kinetic energy at 10- m depth. Straight lines indicate $-5/3$ (dotted), -2 (dashed), and -3 (dot-dash) spectrum slopes. The five other lines correspond to different simulations whose resolutions increase from 12 (green), 6 (red), 3 (black), 1.5 (blue) to 0.75 km (purple). (From Capet et al., 2008)

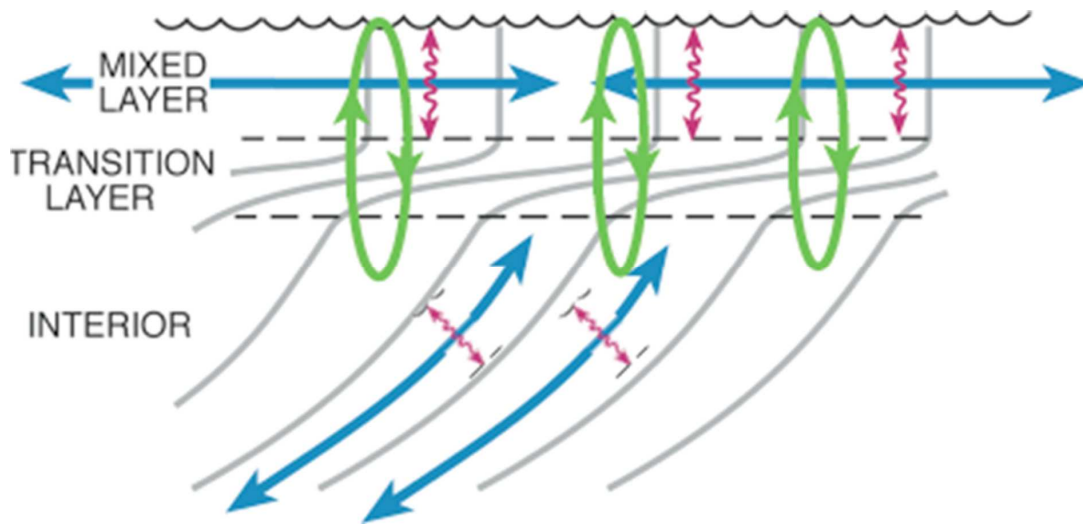


Figure 2. The oceanic motion at submesoscales (1-100 km, in green color) are effective in transferring heat, carbon dioxide, and other water properties from ocean surface to the deep ocean. Blue color represents motions at mesoscales (100-500km) transferring ocean properties mostly horizontally and red color represents mixing processes at scales less than 1 km (courtesy of R. Ferrari of MIT).



Figure 3. Countries that share hydrologic data (pink) and which do not (blue); courtesy of Vladimir Smakhtin, International Water Management Institute.

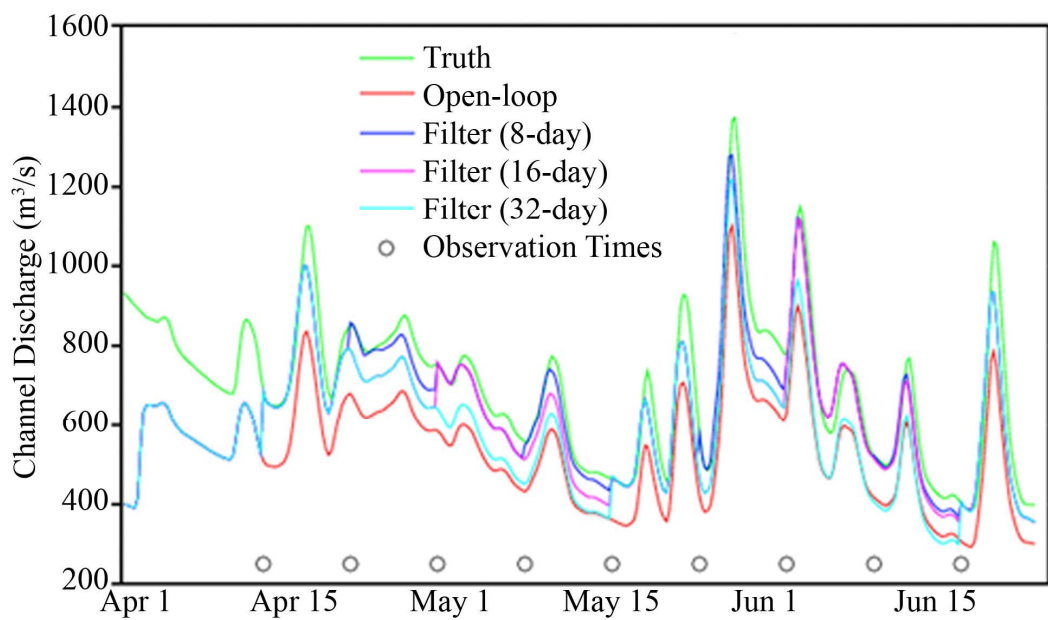


Figure 4. Discharge estimates from assimilating synthetic SWOT observations into a hydrodynamic model of the Ohio River for different repeat times (top; from Andreadis et al., 2007).

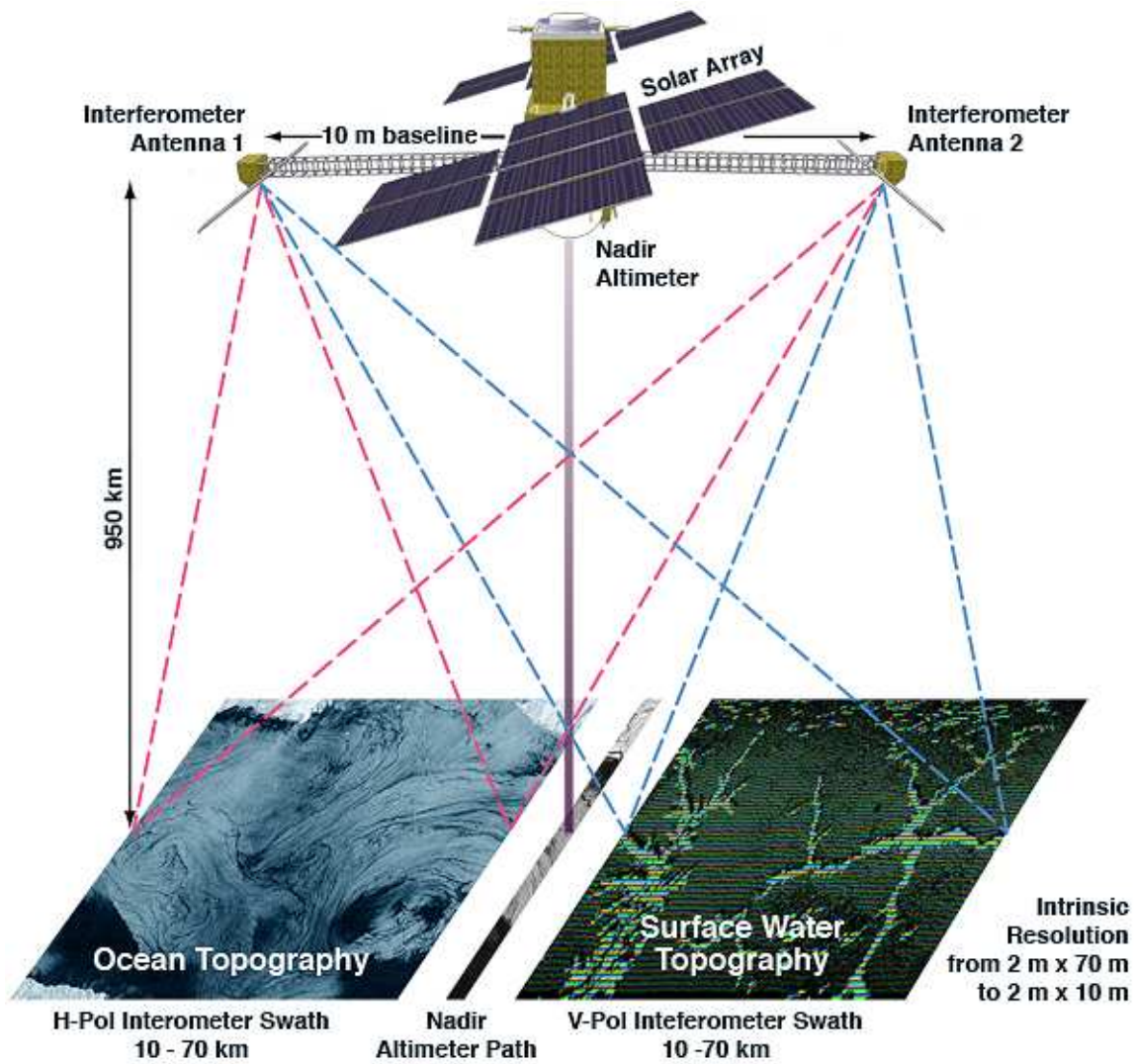


Figure 5. A schematic illustration of the measurement configuration of the SWOT Mission.