Second Surface Water and Ocean Topography Science Team Meeting

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Introduction

The second Surface Water and Ocean Topography (SWOT) Science Team Meeting was held in Toulouse, France, June 26-28, 2017.[1] The meeting was immediately followed by the SWOT Calibration/Validation Workshop, which took place on June 29. The meeting was planned and convened by the mission's science leads: **Tamlin Pavelsky** [University of North Carolina, Chapel Hill] and **Jean-François Cretaux** [Centre National de la Recherche Scientifique/Laboratoire d'Études en Géophysique et Océanographie Spatiales, France] for hydrology, and **Rosemary Morrow** [Centre National d'Études Spatiales (CNES), French Space Agency] and **Lee-Lueng Fu** [NASA/Jet Propulsion Laboratory (JPL)] for oceanography.

SWOT is designed to make the first-ever global survey of Earth's surface water. SWOT will provide essential information on large rivers, lakes, and reservoirs—along with high-resolution measurements of our global ocean—on average twice every 21 days. Its data will aid in freshwater management worldwide while improving ocean circulation models and predictions of weather and climate. NASA and CNES are jointly developing and managing SWOT, with contributions from the Canadian Space Agency and the United Kingdom Space Agency. Now in Phase C of its Mission Life Cycle (final design and fabrication), all major mission elements (flight, ground, system) are heading towards the project's Critical Design Review (CDR) in early 2018. In November 2016 NASA selected Space Exploration Technologies (SpaceX) of Hawthorne, CA, to provide launch services for SWOT. Launch is targeted for April 2021 on a SpaceX Falcon 9 rocket from Vandenberg Air Force Base in California.

The second SWOT Science Team Meeting lasted three days to accommodate the contributions of 160 participants, 90 oral presentations, and 38 posters. This report summarizes the big picture ideas discussed at the meeting; all of the individual presentations from the plenary, splinter, and poster sessions, are available from the SWOT website at *https://swot.jpl.nasa.gov*.

[1] For a summary of the first meeting, which includes useful general background on the SWOT mission, please reference "The Surface Water and Ocean Topography Science Team Meeting" in the September–October 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 5**, pp. 18-23—*https://go.nasa.gov/2g8tqxE*].

Getting Ready for SWOT

With launch approaching, it is important for SWOT to engage and grow its user community. Towards this end, simulated data products will continue to be developed and improved for user training purposes. In addition, based on input from stakeholders who attended the workshop, *Engaging the User Community for Advancing Societal Application of SWOT*[2] (at the U.S. Geological Survey, April 4-6, 2017 in Reston, VA), the project is assessing the development of specific data products with short latency (i.e., two-to-three days). These *short-term* or *quick-look* products would have lower performance than SWOT's nominal science and research products, which will be released within 60 days of data acquisition.

Major activities of the SWOT Calibration/Validation Team include collecting ground-truth data using various support instruments (e.g., *in situ* sensors; aircraft-mounted interferometer, AirSWOT, for hydrology; Modular Aerial Sensing System lidar for oceanography). The SWOT Calibration/Validation Plan, scheduled for final release prior to the project's CDR, will identify key calibration parameters and approaches for their estimation; validation approaches for both key error-budget terms[3] and science products; and instrumentation for specific sites. Prelaunch field campaigns for hydrology have begun in North America and France, with plans to expand to South America, Africa, Asia, and other European sites.

Oceanography: From "Noise" to Signal

The SWOT mission builds upon the capabilities of the *Jason series* (which includes Jason-1, launched in 2001 and decommissioned in 2013, the Ocean Surface Topography Mission (OSTM)/Jason-2, launched in 2008, and Jason-3, launched in 2016). Data from these three missions have contributed to a satellite ocean altimetry data record that began with the launch of the U.S./French Ocean Topography Experiment (TOPEX)/Poseidon satellite in 1992. SWOT's K_a-band Radar Interferometer (KaRIn)—shown in **Figure 1** on the next page—will have increased spatial resolution as

[2] The second SWOT Applications User Workshop report is available at *https://swot.oceansciences.org/meetings.htm?id=19*.
[3] Details about the SWOT project, mission performance, and error budget are available at *https://swot.oceansciences.org/documents.htm*.

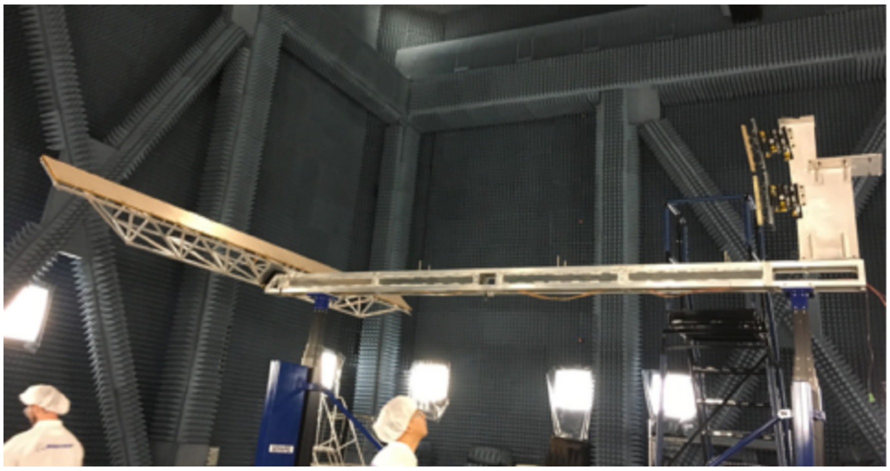

Figure 1. [*Left to right*] Antenna structure, boom, and K_a-band Radar Interferometer (KaRIn) in a NASA/JPL clean room. Using two antennas separated by 10 m (32.8 ft), KaRIn's synthetic aperture radar (SAR) data will be processed into sets of *interferograms* (i.e., amplitude, phase, coherence) to determine the elevation of water surfaces. **Photo credit:** JPL

compared to the altimeter that has flown on the Jason series—see **Table 1** for comparison. This will provide a significant opportunity to study ocean dynamics at scales previously undetectable by satellite altimeters.

SWOT will provide global observations of small *mesoscale eddies* (ubiquitous, relatively short-lived, swirling currents) and *fronts* (boundaries between two distinct water masses) at wavelengths of 15 to 200 km (9.3 to 124.3 mi). These dynamical scales are poorly observed today, but are important for their impact on horizontal and vertical currents in the ocean; in the transport of heat, carbon and nutrients; and to understand the ocean's energy budget and dissipation.

SWOT will also detect *internal waves* (IW), i.e., *gravity waves*[4] that propagate within the ocean rather than on its surface, at scales similar to the smaller mesoscale eddies. Thus, many science team members are focusing their efforts on understanding sea surface height (SSH) variability at these scales. For example, *in situ* observations from deep-ocean moorings and gliders—in conjunction with ocean general circulation models—are providing information on IW signals and ocean eddies for SWOT calibration/validation planning and data-product development. Other investigators are looking at various types of satellite data—e.g., sea surface temperature, salinity, and synthetic aperture radar (SAR)—to characterize the impact of IWs on SSH at small scales.

Internal tides (IT)—internal waves at a tidal frequency—can contribute several centimeters to the SSH signature and thus need to be corrected in SWOT data to distinguish other features (e.g., ocean eddies). With wavelengths ranging between 50 and 250 km (~31 and 155 mi), IT are generated in the ocean interior as surface tides move stratified water along sloping topography such as mid-ocean ridges and continental slopes. Several IT models, including those of Science Team members **Brian Arbic** [University of Michigan], **Richard Ray** [NASA's Goddard Space Flight Center], and **Edward Zaron** [Portland State University] are being analyzed to provide an initial correction for SWOT. Moreover, SWOT's IT data themselves may provide information on changes in ocean heat content over time, as has been demonstrated with altimeter-derived IT data.

Understanding how to accurately model IW and IT in ocean general circulation models (e.g., HYCOM,[5]

[4] In this context, gravity waves are waves that propagate at the interface between the atmosphere and the ocean as the force of gravity or buoyancy tries to restore equilibrium.

[5] HYCOM stands for HYbrid Coordinate Ocean Model. The HYCOM consortium is a multi-institutional effort sponsored by the National Ocean Partnership Program (NOPP), as part of the U.S. Global Ocean Data Assimilation Experiment (GODAE). Learn more at *https://hycom.org*.

Table 1. Comparison of Jason series and SWOT mission characteristics.

	Jason series	SWOT
Altitude	1336 km	891 km
Orbit Type	10-day repeat	21-day repeat
Inclination	66°	77.6°
Swath	N/A	120 km
Frequency	K_u-band	K_a-band
Height Precision	2 cm @ 6 km (Jason-3)	0.4 cm @ 6x6 km^2
Spatial Resolution	6.2 km, along track; 300 km, cross track	<100 m, imaging
Instrument	Nadir altimeter	Nadir altimeter and interferometer

MITcgm[6]) will be key to revealing dynamics at scales from 10 to 200 km (~6 to 124 mi) in SWOT data. Of particular interest are mesoscale eddies (defined above) for which SWOT will provide more information than conventional altimeters (e.g., Jason-2 and Jason-3). Mesoscale eddies have been shown to move around as much ocean water as wind or deep-water currents, as demonstrated[7] by SWOT investigator **Bo Qiu** [University of Hawaii at Manoa].

Some SWOT Science Team members are investigating ocean features such as surface currents and fronts at even finer scales [< 20 km (< ~12 mi)]. These studies use data from multiple sources including the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) on Terra, the MEdium Resolution Imaging Spectrometer (formerly on the European Space Agency's Envisat), and other airborne instruments (e.g., DopplerScatt). Overall, these studies show promising results in terms of resolving the fine-scale ocean features that drive vertical currents, transporting heat up and down the water column.

SWOT's collection of high-resolution data—acquired to differentiate among internal and surface waves, tides and internal tides, eddies, and fronts—will provide additional value for oceanography studies. A related challenge, however, will be managing and distributing such large volumes of oceanographic data. In preparation, sample oceanographic data products based on simulations—and prototype user software—will be generated for testing by the community before the third SWOT Science Team Meeting in 2018. In parallel, significant efforts are underway to assess the impact of SWOT data assimilation into regional ocean analysis and forecasting systems such as France's *Mercator Ocean* (*https://www.mercator-ocean.fr/en*).

[6] MITgcm stands for the Massachusetts Institute of Technology's General Circulation Model, which is a numerical model designed for study of the atmosphere, ocean, and climate. Learn more at *http://mitgcm.org*.

[7] The abstract is at *http://science.sciencemag.org/content/early/2014/06/25/science.1252418*. American Association for the Advancement of Science subscribers may view the full article.

Hydrology: Going With the Flow

Given that SWOT will provide NASA's first-ever global survey of land-based water levels from satellite, the project's hydrology team has focused on defining processes to create hydrological data products. The term *pixel cloud* is used to describe how interferometric phase data will be processed into vector products to compute mean water heights, slopes, and area based on the shapes of rivers and lakes. Pixel cloud data consist of georeferenced interferogram pixels with latitude, longitude, height, classifications, and flags, thus serving as a *water mask* for SWOT.

Prior to and after launch, SWOT river data products will be constructed by attaching the pixel cloud to a *centerline*, which is fixed from pass to pass, but may be updated annually—see **Figure 2**. *Node locations* are defined at regular intervals [e.g., every 200 m (~656 ft)] along the centerline. The average length of *reaches*—sections of rivers along which there are similar hydrologic conditions, such as discharge, depth, area, and slope—are computed from nodes. Some example node and reach data are currently being distributed as shapefiles, maximizing the ease of bringing SWOT-like data into processing programs such as *ArcGIS* or *Google Earth*. Official hydrology test products will begin production in mid-to-late 2018.

In addition, geolocated, pixel-based (i.e., raster) data products are being developed to provide SWOT height and inundation-extent data, along with appropriate errors and flags, resampled onto a uniform grid. This will provide a means to study complex flow environments not effectively captured by other SWOT data products (e.g., wetlands, estuaries). Raster data products will also measure internal variability in river reaches and

Figure 2. [*Left*] Aerial view of a river with SWOT centerline in red. [*Right*] Blue circles show example *node locations* defined at fixed intervals along the centerline. See text for more details. **Image credit:** Michael Durand [Ohio State University]

lakes not captured by the vector products. The raster product will be available for all locations that the pixel cloud is produced.

The Discharge Algorithm Working Group is responsible for estimating river discharge from SWOT measurements. They have made excellent progress by accumulating about 40 community datasets, based on the "Pepsi Challenge"[8] and other experiments. Key challenges that still need to be addressed include standardizing assessment of algorithms and reporting uncertainty.

SWOT water detection will rely heavily on distinguishing land versus water pixels, which is challenging due to *speckle noise*[9] and variable water/land contrast as well as the near-nadir radar look angle. A *prior water probability map* is being developed for use in several processing steps, such as for definition of zones within the pixel cloud (e.g., always include floodplains and wetlands while excluding areas where the presence of water is very unlikely). Another challenge for SWOT is mitigating the impact of *dark water*, which can be caused by calm water, signal attenuation due to rain, vegetation, and low signal-to-noise ratios in some parts of the swath. The project is currently testing a dark-water flag algorithm based on an analysis of 30 years of Landsat data. Likewise, the SWOT Project is developing strategies for mitigating radar geometric distortion effects (e.g., flagging, theoretical models, simulation). An example of when such strategies might be helpful is when analyzing radar returns from higher terrain adjacent to rivers or from lakes that appear to overlay water pixels.

Accessible and accurate *a priori* lake, river, and geoid data will be key to SWOT's success. To accommodate this requirement, the Project is creating an easily used database that allows users to search and retrieve information by lake name. Several SWOT investigators are analyzing the applicability of existing lake and river datasets for use with SWOT. For example, **Tamlin Pavelsky** has created a database to support SWOT river vector data products, consisting of a combination of Landsat-derived centerlines, Shuttle Radar Topography Mission-derived drainage areas, and modeled mean river discharge. It has been used to generate continental-scale statistical estimates for SWOT. These statistics do not include rivers north of 60° N outside of Europe—since no suitable digital elevation models exist for these areas. Analysis shows that, for river reaches with minimum widths of 100 m (~328 ft) that are sampled by two SWOT passes every 21 days, data will be collected globally along 327,843 km (203,712 mi) of river length. By decreasing the minimum river reach width by half [i.e., to 50 m (164 ft)], the total length of rivers sampled by SWOT twice every 21 days increases to 663,984 km (412,580 mi), which is equivalent to 95 times the length of the Amazon River.

A large-scale simulator is being used to generate SWOT-like pixel cloud files for hydrologic modeling purposes. Some investigators are conducting experiments with theoretical SWOT observations to construct basin-wide river discharge estimations while others are developing frameworks for assimilating SWOT's global water surface elevations into hydrodynamic models.

Recently converted to open source software, the *RiverObs* package from JPL takes in pixel cloud data from the SWOT Hydrology Simulator to estimate key parameters such as water slope and height. *RiverObs* has been used to estimate discharge for the Po and Sacramento Rivers (in Italy and California in the U.S., respectively) with promising results—emphasizing SWOT's potential application to estimate discharge for rivers without gauges. A similar computing challenge still exists for determining lake volume (i.e., developing *LakeObs*); however, a general lack of bathymetry data necessitates that SWOT software developers focus on approximating lake water storage volume change over time.

Wrap Up and Summary

The final session began with reports on tides and currents in estuarine, coastal, and shelf environments (e.g., U.S., France, Canada, Brazil, and Southeast Asia) using *in situ*, model, and simulated SWOT water-level data. Anticipated outcomes of these studies include using SWOT to better understand river plume transport and to determine the potential impact of storm surges, among others. A number of presentations described unique applications of SWOT data to study the cryosphere, such as the feasibility of retrieving *sea ice freeboard*—the height of ice above the local sea surface—and thickness, along with the prospective ability to infer properties of ice-sheet beds and seasonal ice streams in Greenland and Antarctica. The meeting concluded with a presentation on the importance of having high-resolution mean sea-surface and slope-correction data for SWOT, made possible thanks to new products based on 20 years of satellite altimetry data.

The meeting achieved all its objectives, and demonstrated a high degree of interaction among SWOT Science and Project Team members, setting the stage for important work to be completed prior to the project CDR. The next SWOT Science Team Meeting will take place during June 2018 in Montreal, Canada. ■

[8] The Discharge Algorithm Working Group's *Pepsi Challenge* is an activity that tests discharge results from different inversion algorithms, all of which use the same assumptions and multiple-river hydraulic model dataset (width, height, slope).

[9] Speckle noise degrades the quality of active radar, synthetic aperture radar (SAR), medical ultrasound, and optical coherence tomography images. In this context, it refers to the impact it has on interferometric SAR images, where coherence of waves reflected from many elementary scatterers degrades the quality of the interferogram.