Participation in the SWOT Science Team: Marine Geophysics

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1. Introduction & Objectives

One of the secondary objectives of the SWOT mission is marine geophysics. Over the past 4 years we have worked with SWOT scientists and engineers to clarify the scientific payoffs of the SWOT mission for understanding the geological structures and roughness of the seafloor. In addition, we continue to improve mean sea surface height and slope models using conventional radar altimetry (Figure 1). SWOT, with its smaller footprint and additional cross-track slope measurement, could improve the gravity accuracy by perhaps an order of magnitude and also improve spatial resolution especially on the shallow continental margins. These improvements are critical for a large number of basic science and practical applications, including:

- Understanding the geologic processes responsible for ocean floor features unexplained by simple plate tectonics, such as abyssal hills, seamounts, microplates, and propagating rifts.
- Improving tsunami hazard forecast accuracy by mapping the deep ocean topography that steers tsunami wave energy.
- Determining the effects of bathymetry and seafloor roughness on ocean circulation, mixing, climate, and biological communities, habitats, and mobility.
- Mapping the marine gravity field to improve inertial navigation and provide homogeneous coverage of continental margins.
- Providing bathymetric maps for numerous other practical applications, including reconnaissance for submarine cable and pipeline routes, improving tide models, and assessing potential territorial claims to the seabed under the United Nations Convention on the Law of the Sea. Because ocean bathymetry is a fundamental measurement of our planet, there is a broad spectrum of interest from government, the research community, industry, and the general public (e.g. Google Earth).

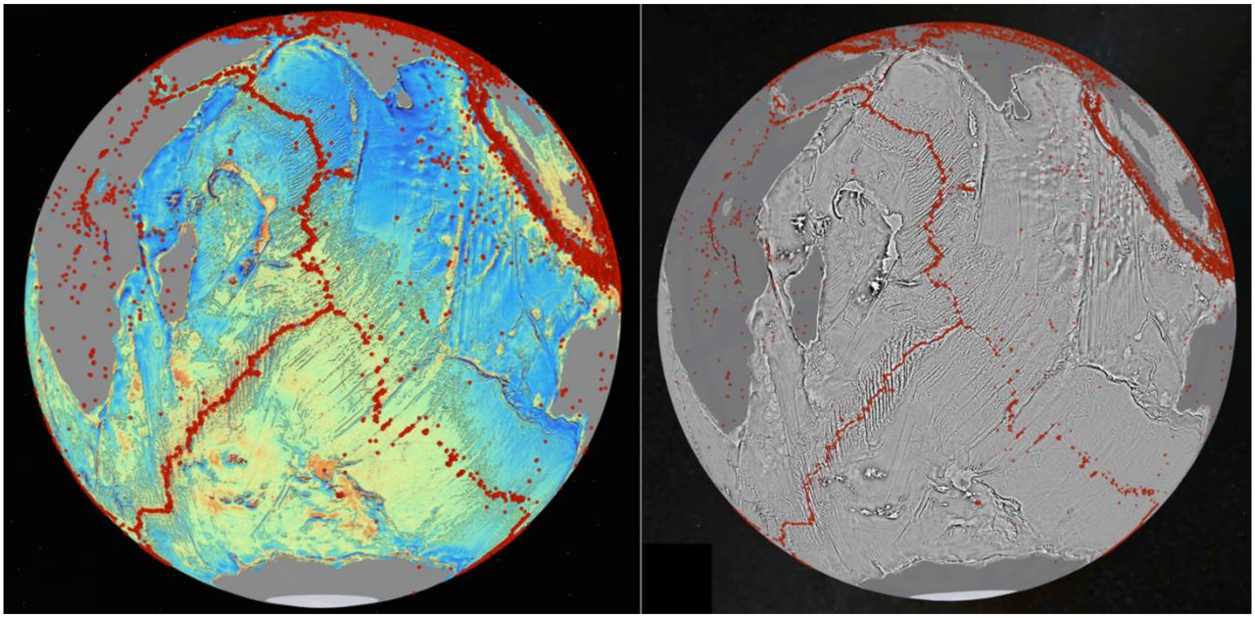


Figure 1. Global marine gravity (left) and vertical gravity gradient (VGG – right) for the Indian Ocean. Red dots (earthquakes M>5) highlight the three spreading ridges forming the Indian Ocean Triple Junction. The gravity fields were derived from all altimeter data available in 2014 (Sandwell et al., 2014) and are available in a variety of formats [here](#).

Our contribution to the SWOT mission will come in three main areas:

1. We will continue to **refine ocean gravity and bathymetry models** using conventional radar altimetry and early SWOT data. Our analysis will focus on the large amplitude, short wavelength (6-40 km) gravity signals. Working in this band will help the science community to understand the small spatial scale errors in the SWOT measurements.
2. We will collaborate with CNES/CLS to make the best possible **mean sea surface height (MSS) model** having both long-wavelength accuracy and high spatial resolution. CLS will contribute the long-term average sea surface height along the repeating tracks of the Topex/Jason series and the ERS/Envisat/SARAL/AltiKa series. SIO will contribute the along-track sea surface slope data from the non-repeat altimeters to fill the gaps between the repeat tracks. The combined model will provide a reference surface for extracting oceanographic signals early in the SWOT mission.
3. We will interpret and model the small scale variations in the gravity field derived from SWOT and other altimeters to **improve our understanding of marine geophysics** (e.g., abyssal fabric and the global distribution of small seamounts). This will include the production of a global predicted depth grid at 15 arcsecond resolution.

2. Approach

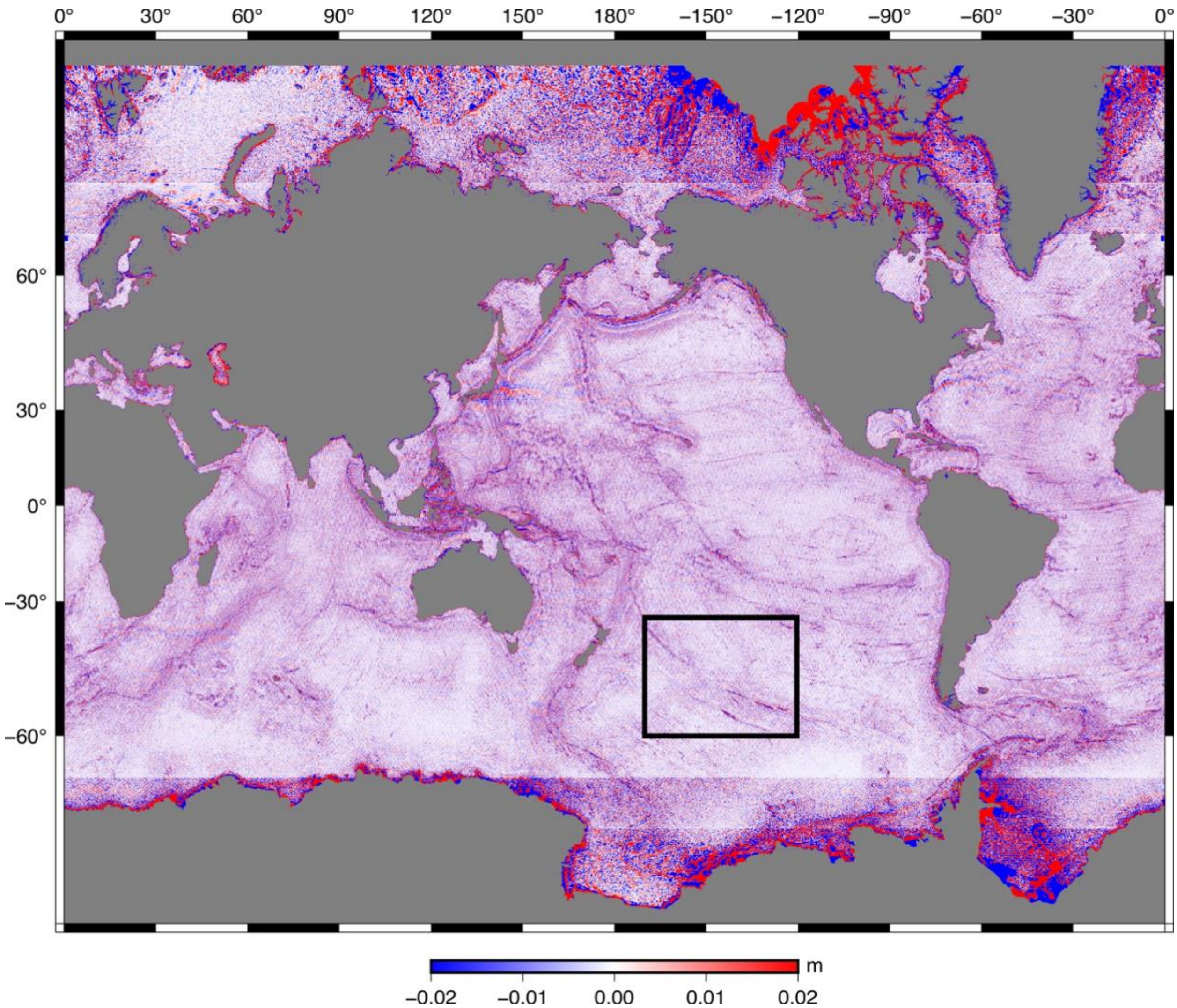
Waveform Retracking — Over the past two decades our group has worked with raw radar waveform data from Geosat, ERS-1, Jason-1, Envisat, CryoSat-2, and AltiKa to reduce the small spatial scale noise in the altimeter range measurements due to altimeter bandwidth limitations and ocean waves (Table 1 from Zhang and Sandwell, 2016). Ocean swell produces one of the largest errors in standard radar altimetry because the sharp radar chirp emitted by the satellite is blurred by reflection from the irregular ocean surface. The length of the blurring is related to the significant wave height so it is typically 1-2 m. Recovery of sea surface slope to an accuracy of 1 microradian (μrad) over a horizontal distance of 10 km requires a range precision of 1 cm, which is 100 times smaller than the rise length of the leading edge of the return echo. This 100-fold improvement in range precision is achieved by averaging thousands of independent pulses both along-track and from near repeat cycles. Recovery of 1 μrad at 1 km length scale will require millimeter range precision. Through modeling and consultation with the SWOT engineers we propose to achieve a better understanding of the fundamental limitations placed by the ocean swell signal on the recovery of the sea surface slope at the smallest scales in both the along-track and cross-track directions. This will help to guide the measurement requirements for ocean applications.

Table 1. Altimeter noise at 20 Hz (mm)

Altimeter	3-para	2-para
Geosat	88.0	57.0
ERS-1	93.6	61.8
Envisat	78.9	51.8
Jason-1	75.9	46.4
CryoSat-2 LRM	64.7	42.7
CryoSat-2 SAR	49.5	49.7
AltiKa	**34.3**	**20.5**

Standard deviation of altimeter waveforms with respect to the 1 Hz average. The non-AltiKa analysis was published in Garcia et al. (2014).

Mean Sea Surface — We are working with SWOT scientists at CLS/CNES (Phillippe Schaeffer and Yannice Faugere) to produce a new mean sea surface grid (MSS) at one-minute spatial resolution. High spatial resolution and good accuracy in coastal areas will be needed at the start of the SWOT mission for CAL/VAL as well as to produce oceanographic results. The method combines the accurate MSS along tracklines of repeat altimeters (e.g., Topex, Jason-1/2, ERS-1/2, Envisat and Sentinel-3) with the retracked waveforms from the geodetic missions (Geosat, ERS-1/GM, Jason-1/GM, and Cryosat-2). An example of the difference between the new MSS grid and the original CLS grid is shown in Figure 2. The CLS group is currently evaluating this model.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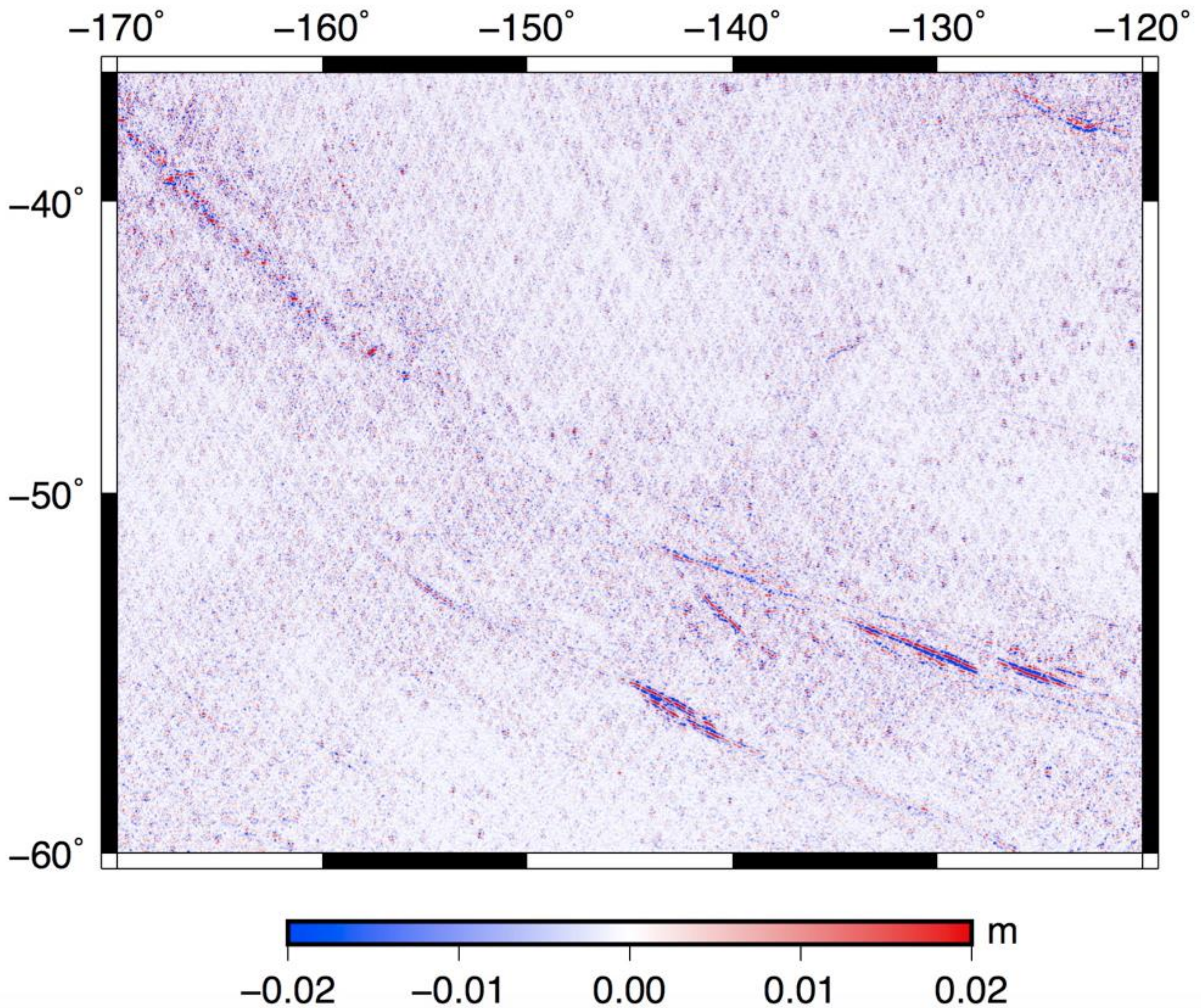

Figure 2. Top: The difference between the new MSS grid and the original CLS grid. Bottom: Zoom of an area in South Pacific has mean and standard deviation of -1.0 mm and 5.1 mm, respectively. Larger differences occur in the diamond shaped areas that are not well sampled by the repeat-track altimeters. Differences are greatest in areas of high sea surface slope such as the Eltanin Fracture Zone and Louisville Ridge.

Contributions to SWOT CAL/VAL — There are two areas where we propose to contribute to the calibration and validation of the SWOT data to be collected along the 1-day repeat ground track during the first 90 days of the mission; these are the Foundation seamounts and the California mooring site.

Foundation Seamounts - The analysis of SWOT data over the Foundation seamounts is central to our investigation and also an important validation site for SWOT. The crossover of interest is in the South Pacific at ~35˚S (Figure 3) in a region of relatively low ocean variability (< 1 μrad RMS). This remote region of very large seamounts was originally discovered in Seasat and Geosat altimetry data and eventually surveyed in 1997 by French scientists aboard the RV L'Atlante. The complete multibeam coverage enables the construction of a sea surface slope model having an accuracy of better than 1 μrad at wavelengths as small as 10 km. Using the known small-scale signal, we propose to evaluate the along-track and across-track slope from SWOT as a function of the number of repeats. We expect that the accuracy of the SWOT data will primarily depend on the SWH. If SWOT can achieve better than 1 μrad accuracy at 10 km wavelength resolution then it will have the ability to detect all of the uncharted seamounts in the oceans taller than 1 km. This is estimated to be more than 100,000 (*Wessel, 2001*). Even more important scientifically will be the vastly improved resolution of the detailed tectonics of the ocean basins and improved bathymetric estimation – the ultimate focus of our investigation

Figure 3. High-resolution (500 m) bathymetry of the Foundation Seamounts in the South Pacific from extensive multibeam surveys of the R/V Sonne and R/V L'Atalante (Devey et al., 1977). Also shown are the swaths of the SWOT altimeter during the commissioning phase of the mission. Many of these large seamounts have crests shallower than 1000 m so produce high amplitude, high-resolution geoid slopes. This is also a region of low significant wave height and low mesoscale variability so it is optimal for exploring the ultimate resolution of the SWOT altimetry.

Offshore California Mooring Site - As part of this proposal we will also contribute to the offshore California pre-launch mooring experiment [Jinbo Wang, Lee Fu, personal communication] by updating our sea surface slope maps with the latest altimetry including Sentinel-3 data. These GNSS equipped moorings are constrained to drift over a circular area having a ~2 km diameter (Figure 4). The geoid height will vary over this area so a sea surface slope model will be needed to correct for the changing position and geoid height of the buoy. We are working with this CAL/VAL group to reduce the uncertainty in the slope by adding repeat altimeter data from Sentinel-3 (Figure 4, orange lines).

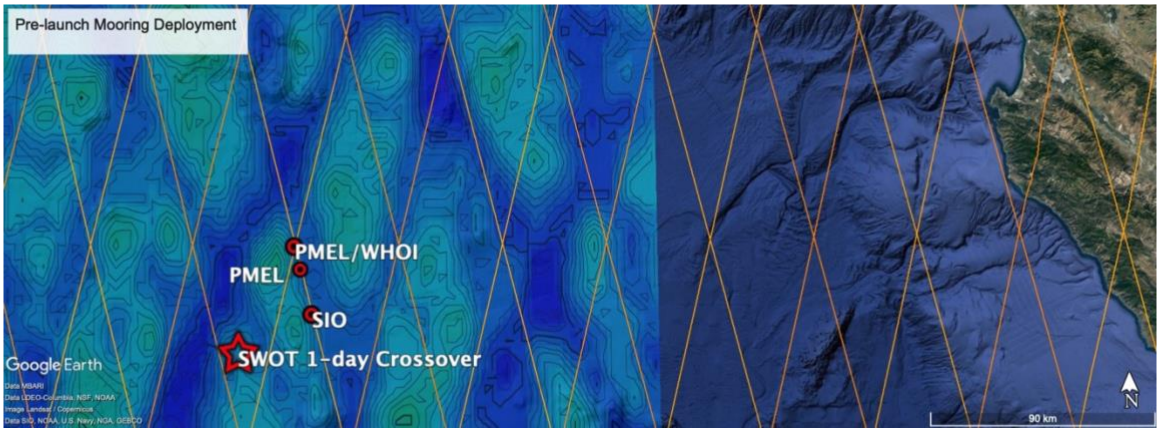

Figure 4. Location of three moorings deployed within ascending and descending swaths of the 1-day repeat of the SWOT calibration orbit. The slope uncertainty map has 0.1 μrad contours. Maximum errors of 2 μrad occur in areas where there are few repeats of conventional altimetry. The moorings are deployed along Sentinel-3 tracks (orange lines) so the slope error should be well below 1 μrad by the time SWOT is launched.

3. Anticipated Results

These three analyses will be most valuable to the SWOT mission during the commissioning phase. The high spatial resolution, mean sea surface can be used to understand the cross-track accuracy of the SWOT data. The super resolution sea surface slope models will be useful in evaluating the performance of SWOT as well as to tune the algorithms and spatial filters for production of higher-level products. Following the commissioning phase, we will work with the SWOT team to achieve the marine geophysics objectives.

4. References

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