Surface Water and Ocean Topography Mission (SWOT)

Science Requirements Document

Initial Release

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CHANGE LOG

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1- SWOT Mission Objectives

The Surface Water and Ocean Topography (SWOT) mission has been recommended by the National Research Council decadal survey "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 two communities, physical oceanography and hydrology, to share high vertical accuracy and high spatial resolution topography data produced by payload configuration, whose principal instrument is the Ka-band Radar Interferometer (KaRIN). The broad scientific objectives specified by the NRC decadal review have been refined by community involvement in open workshops and the guidance of an informal science team. A summary of the scientific objectives for each community is given below:

1.1 Oceanography Objectives

The primary oceanographic objectives of the SWOT mission are to characterize the ocean mesoscale and submesoscale circulation at spatial resolutions of 10 km and larger.

Current altimeter constellations can only resolve the ocean circulation at resolutions larger than 300 km. Fundamental questions on the dynamics of ocean variability at scales shorter than 300 km, the mesoscale and submesocale processes, such as the formation, evolution, and dissipation of eddy variability (including narrow currents, fronts, and quasi-geostrophic turbulence) and its role in air-sea interaction, are to be addressed by the new observations.

Kinetic energy and tracer transports

Global study of the circulation in the scales between 10 and 300 km are essential for quantifying the kinetic energy of ocean circulation and the ocean uptake of climate relevant tracers such as heat and carbon. Tracers are transported into the ocean by the large-scale mean circulation, as well as by the mesoscale and submesoscale eddies. Traditional altimeters revealed the fundamental role of mesoscale eddies in the horizontal transport of tracers. The uptake of heat and carbon by the ocean is complete only after these properties are transported away from the surface turbulent boundary layer into the ocean interior. The vertical transport is confined to submesoscale fronts with horizontal scales between 10 and 50 km. The SWOT mission is the only available option to open a window on these dynamics.

Climate change and ocean circulation

The new knowledge of the kinetic energy of the ocean circulation and the vertical transport of carbon and heat is crucial for understanding the role of the ocean in regulating climate change through the interaction of the mesoscale and submesoscale variability with the large-scale circulation. Accurate knowledge of the large-scale circulation is thus required to achieve these objectives.

Coastal tides and internal tides

The new capability of mapping sea surface height down to 10 km scales will improve the knowledge of coastal tides as well as internal tides that have not been well sampled by conventional altimetry. This new information is not only crucial for achieving the ocean circulation objectives, but is also important for a wide range of applications in both coastal and open oceans.

1.2 Hydrology Objectives

The SWOT mission will provide measurements of water storage changes in terrestrial surface water bodies and will provide estimates of discharge in large (50 m-100 m width) rivers, globally. NASA has envisioned missions for the global measurement of the water cycle: the Global Precipitation Mission (GPM) will measure precipitation globally while the Soil Moisture Active Passive mission (SMAP) will do the same for near-surface soil moisture. The SWOT measurements will provide a key complement to these measurements by directly measuring the surface water (lakes, reservoirs, rivers, wetlands) component of the water cycle. The hydrologic science objectives of the SWOT mission are:

1. **`To provide a global inventory of all terrestrial surface water bodies whose surface area exceeds $(250m)^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100m (requirement) (50m goal)**
2. **To measure the global storage change in terrestrial surface water bodies (for man-made reservoirs, total storage) at sub-monthly, seasonal, and annual time scales.**
3. **To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.**

These data sets will provide a quantum improvement on our current understanding of global fresh water dynamics. Beyond improved characterization of the water cycle, meeting these science objectives will enable numerous applications of great scientific, social, and political importance.

1.3 Additional Science Applications

In addition to the mission objectives listed above, the SWOT data will be useful for a variety of scientific applications. Although these applications will not drive the mission requirements or cost, it is useful to keep some of them in mind so that mission design decisions 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, a number of applications are natural candidates for consideration:

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, primarily for scientific and not operational purposes.
2. SWOT can collect data over coastal regions that might be of significant benefit to coastal oceanography and estuary hydrology, possibly after assimilation into regional models, and improve storm surge models.
3. 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.
4. 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 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
5. SWOT surface water extent data can be useful for estimation of CO_2, CH_4, and other biogeochemical fluxes and their changes from inundated regions.
6. SWOT data could potentially provide useful target of opportunity information for flood events, both in near-real time and post-event analysis.
7. SWOT data can potentially be used for measuring the topography of part of the Greenland and Antarctic ice sheets, and their changes.
8. SWOT data can potentially be used for mapping the thickness of floating sea ice by measuring sea ice freeboard.
9. 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).

2- SWOT Science Specifications

2.1 Key Terms and Definitions

2.1.1 Requirement.

A "requirement" as used in this document specifies a condition, parameter, or capability with which the system design must be compliant, verifiable, and have a demonstrated achievement during the mission. All requirement statements are preceded by the word "Requirement" and use the verb "shall".

2.1.2 Goal.

A "goal" as used in this document specifies a condition, parameter, or capability with which the system design will strive to be compliant but it is not mandatory that such compliance be verifiable or have a demonstrated achievement during the mission. Mandatory compliance or demonstrated achievement are not required because the capabilities in the SWOT systems limit the performance, because the inherent technical difficulty with the achievement is too great, or because cost of achievement is too large. Nevertheless, a goal is tracked like a requirement so if resources or capabilities permit compliance, better system performance will result. All goal statements are preceded by the word "Goal" and use the verb "will".

2.2 Nominal/Minimum Science Missions

Science requirements for the SWOT mission are categorized into three levels: Science Goals (SG), Nominal Science Mission (NSM) Requirements and Minimum Science Mission (MSM) Requirements. The Nominal Science Mission forms the basis for the initial Project Implementation Plan and the requirements shall be achieved unless the resources of the Project are insufficient to accomplish them. Descoping to the Minimum Science Mission requirements will be exercised only when the resources of the Project are insufficient to implement the NSM and only after other descope options have been explored. Science Goals are defined here so that the SWOT engineering team can decide how to make trades and where to apply resources that might otherwise go unused.

Unless otherwise indicated, requirements are written to reflect the Nominal Science Mission.

2.3 Mission Payload

2.3.a [Requirement] The core SWOT payload shall consist of KaRIN, a Ka-band radar interferometer capable of meeting the swath topographic measurements with the precision and resolution given below.

2.3.b [Requirement] The payload shall include a precision orbit determination (POD) system enabling orbit determination to an accuracy comparable to that of the Jason-series altimeters (1.5 cm rms in the radial component).

2.3.c [Requirement] In order to meet the long wavelength calibration accuracy requirements, profile topography measurements shall be available with an accuracy equal or better than the Jason series of altimeters and radiometers (3.0 cm rms for corrected altimeter range over a typical sea of 2 m significant waveheight and 11 dB sigma0 at 1/sec along-track data rate) and with a sampling compatible with the SWOT calibration needs.

The nominal mission scenario envisions that these measurements would be collected by a Jason-class altimeter/radiometer combination located on the same platform as KaRIN. In addition, it may be possible to use profiling ocean topography measurements from another mission flying at the same time. A nominal complimentary payload suite is meeting these requirements is assumed to be:

1. *A dual-frequency (Ku and C-band) altimeter with capabilities similar to the Poseidon altimeter on OSTM/Jason-2.*
2. *A 3-frequency radiometer with capabilities similar to the Advanced Microwave Radiometer (AMR) on OSTM/Jason-2.*

However, other solutions from non-sun-synchronous orbits may exist that provide the required calibration performance.

2.3.d [Goal] An enhancement to the AMR-like radiometer capabilities including additional channels, that would enhance wet troposphere corrections enabling additional science applications or improving science performance for the mission science objectives.

2.4 Mission Lifetime

2.4.a [Requirement] The Nominal Science Mission shall operate for 40 months, including three annual cycles (36 months), a 1-month instrument checkout phase and a 3-month fast-sampling calibration/validation phase.

A minimum of three years is required to sample seasonal and inter-annual variability for both the ocean and surface water height changes appropriately. The 36 months do not include the data calibration and validation phases. It is expected that these phases will produce valid science data after suitable reprocessing with the calibrated instrument parameters.

2.4.b [Requirement] The Minimum Science Mission shall operate for 16 months, including one annual cycle (12 months), a 1-month instrument checkout phase and a 3-month fast-sampling calibration/validation phase.

The Minimum Science Mission is required to sample the seasonal variability for one year.

2.5- Space-Time Sampling Requirements

2.5.a [Requirement] The SWOT sampling for the Nominal Science Mission shall minimize aliasing of ocean tidal signals.

Tidal signals must be removed from the ocean topography data in order to meet the mesoscale and submesoscale measurement requirements and associated annual and interannual variability. This requirement precludes the use of a sun-synchronous orbit, which aliases solar tides into a very long period signal.

2.5.b [Requirement] The SWOT orbit inclination for the Nominal Science Mission shall be equal to 78º.

A minimum of 74 deg inclination is required to cover all important hydrology land targets. Extending the inclination to 78 deg is required to cover important polar ocean areas and still meet the tidal aliasing requirement. This will also cover a large part of the Greenland and Antarctic ice sheets, particularly in the highly variable coastal regions.

2.5.c [Requirement] The SWOT orbit shall be an exact repeat orbit with a maximum repeat period of 22 days.

With swath coverage, ascending and descending pass swath coverage implies an average revisit time on the order of 11 days at low latitudes. This temporal sampling is similar to that obtained by OSTM/Jason-2 and better than the GEOSAT and GFO ocean altimeter missions. For surface water, an 11-day revisit period guarantees appropriate sampling of river dynamics in the tropics. At high latitudes, the swath sampling will produce shorter revisit periods, compatible with arctic river dynamics. This temporal sampling choice is a required trade-off for maintaining global coverage including the high-latitude regions and for minimizing the tidal aliasing.

2.5.d.1 [Requirement] SWOT shall collect data over a minimum of 90% of all ocean and land areas covered by the orbit inclination for 90% of the operation time. This requirement does not apply to the fast sampling calibration/validation phase described in 2.5e.

This requirement is similar to that levied for Topex/Poseidon and Jason time series. The requirement ensures that geographic gaps in coverage shall be smaller than 10% of the Earth's surface available to the mission. The requirement can only be met by a swath instrument if one takes into account the temporal sampling requirement.

2.5.e [Requirement] SWOT shall have a calibration/validation phase after the instrument check out phase for at least 3 months, in which SWOT shall fly in a 3-day repeat orbit.

SWOT will demonstrate the first interferometry measurement of water elevations. We will need to understand, calibrate and validate the new measurement at the beginning of the mission to get ready for subsequent science studies. During this cal/val phase, we will need sufficient amount of data collected in exact repeating coverage for evaluation and comparison to other independent observations from both in-situ and spaceborne platforms. A 3-day repeat orbit represents a compromise between the required data volume and adequate spatial coverage.

Three-day repeat sampling is also valuable for sampling some submesoscale and mesoscale phenomena appropriately. The 3-day sampling will give us better temporal coverage of the evolving submesoscale filament structures and fronts in the ocean. It will also be necessary for investigating certain dynamical structures in the tropics, including tropical instability waves, and the filament structures surrounding them. Coastal currents and propagating waves, and offshore squirts and jets, will also benefit from the higher frequency sampling. Measuring these phenomena is part of the SWOT ocean science objectives.

2.5.f [Goal] The fast-sampling phase will coincide with Northern hemisphere spring.

Fast data collection during the arctic spring is desired for monitoring the dynamics associated with ice breakup of arctic rivers and lakes. This will also provide an unprecedented view of the role of mesoscale and submesoscale dynamics in the formation of intermediate and deep waters in the northern hemisphere. These water masses form in late winter-early spring, and are important for the uptake of heat and carbon at mid-to-high latitudes.

2.6 Science Data Products and Data Product Delivery

2.6.1 [Requirement] Level-1B data products shall be produced from the payload data.

2.6.2.a [Requirement] The following Level-2 standard data products shall be produced for the ocean data:

1. **Ocean sea surface heights (SSH) in a latitude/longitude grid defined by the payload measurement sampling (including the nadir measurements according to 2.3c).**
2. **Estimated sea surface height uncertainties (1σ) on the same grid as the SSH measurements.**
3. **Radar σ_0 measurements on the same grid as the SSH measurements.**
4. **Wind speed (but not direction) estimates derived from the radar σ_0 on the same grid as the SSH measurements.**

5. **Standard deviation of SSH prior to averaging from the high resolution onboard processor data to the Level 2 resolution, on the same grid as the SSH measurements.**
6. **Estimated Sea Surface Slope vector on the same grid as the SSH measurements.**

The sea surface slope computed prior to averaging from the high-resolution onboard processor data will be lost if not downloaded. The slope computed from the averaged data is less accurate than from the original high-resolution data.

2.6.2.b [Goal] Estimates of ocean significant wave height on the same grid as the SSH measurements.

2.6.2.c [Goal] Lower accuracy data with the same sampling characteristics as the level 2 ocean data, but with degraded accuracy, will be produced in near real time (1 day-1 week) in support of operational applications.

2.6.3 [Requirement] The following Level-2 standard data products shall be produced for the surface water data:

- **A geolocated water mask of all water bodies meeting the minimum size criteria set in the science objectives: water bodies with area greater than $(250m)^2$, or rivers of width greater than 100m (goal, 50m). The water mask may be sampled on an irregular grid conformal to the shape of the water body, as long as the spatial sampling requirements described below are met. Only water bodies in regions of moderate topographic relief (i.e., where layover contamination is negligible) shall be included in the water mask.**
- **Estimated surface water elevations with the same sampling as the water mask.**
- **Estimated surface water elevation uncertainties (1σ) with the same sampling as the water mask.**

2.6.3.b [Goal] A Level-2 standard data product will be a topographic map of the floodplain surrounding the mapped surface water areas, and channel cross-sections.

2.6.4 [Requirement] With the exception of the floodplain topographic map and channel cross sections, all Level-2 products shall be produced for each pass of data collection. The floodplain topography and channel cross-sections map shall be updated yearly and a final floodplain map shall be produced at the end of the mission, excepting areas where floodplain and/or channel topography is dynamic on shorter time scales.

While floodplain topography is not required to estimate storage changes and river discharge, such floodplain Digital Elevation Models (DEMs) are a key data set for understanding flood dynamics and channel cross-sections are needed for estimation of stream discharge. The floodplain and cross-section maps are produced by using the *varying river stage and extent to contour the channel topography. The floodplain and channel topography maps cannot be produced for each pass since it requires the observation of the river stage history over the mission lifetime*

2.6.5 [Requirement] After the calibration phase, Level-2 products shall be available to the science team within three months of data collection. The Level-2 data production rate shall keep up with the data acquisition rate during the rest of the mission so that no data backlog results.

2.6.6 [Goal] The project will allow a limited set of users access to small amounts of Level 1 data to support near real time monitoring needs. In addition to *ad hoc* access related to flood monitoring, or other events requiring emergency response, routine access in near real time (<2 weeks) for a limited (<1000) number of large reservoirs will be allowed.

This capability is foreseen as a response to near real-time disasters, such as floods, coastal storm surge prediction, and cyclone and hurricane prediction. Routine access to reservoir levels will serve societal needs for cross-boundary water storage monitoring of the Earth's major reservoirs.

2.6.7 [Requirement] After the initial calibration phase (approximately Launch +120 days), all Level-2 Standard data products shall be made available for distribution to the general scientific community within 6 weeks after they are made available to the SWOT Science Team.

It is expected that data collected during the calibration phase can be used for the production of valid data products.

2.6.8 [Requirement] For distribution to the general scientific community, Level 2 products shall be accompanied by an assessment of the quality of the product relative to the measurement requirements. The quality assessment is provided by the Science Team.

2.6.9 [Goal] Reprocessing will be conducted on the SWOT Standard data products to correct for known errors and/or improved algorithms, in parallel with normal processing of incoming data.

2.6.10 [Requirement] All Level 0, 1 and 2 Standard data products shall be delivered to NASA to be placed in a permanent archive at the end of the mission.

2.7- Minimum Ocean Science Performance Specifications

In order to achieve the ocean science objectives, the following minimum measurement science requirements and goals for the SWOT mission are imposed:

2.7.1.a [Requirement] The spatial posting of sea surface height measurements shall be no coarser than 2 km.

2.7.1.b [Goal] The spatial posting of height measurements will be no coarser than 500 m.

A measurement posting shall be defined as the location of the geographical center of a set of higher spatial resolution instrument height measurements which are merged to form an estimate of the sea surface height.

In order to achieve a resolution of 10 km, as set in the science objectives, a sampling of 5 km is required by the Nyquist sampling criterion. In order to calculate geostrophic velocities and relative vorticity, derivatives of the height field must be computed. To reduce errors in estimating these derivatives, it is required to oversample the height field relative to instrument resolution. A 2km over-sampling will achieve this requirement.

For coastal, estuarine, and ice applications, it is desirable to have the higher spatial sampling of 500 m.

2.7.2.a [Requirement] The sea surface height error spectrum in the wavelength range smaller than 1,000 km shall not exceed the spectrum envelope given in Figure1 and the formulas below.

2.7.2.b [Requirement] The sea surface height error spectrum provided by the nadir altimeter system described in 2.3c in the wavelength range between 1,000 km to 10,000 km shall not exceed the spectrum envelope given in Figure 1 and the formulas below.

Mapping of mesoscale and submesoscale phenomena at 10 km resolution (for a nominal spectrum) requires that the measurement noise be smaller than or equal to the signal for the resolved wavelengths. It is desirable to have the signal strength be at least one order of magnitude greater than the measurement noise. Achieving basin scale(~1,000 km to 10,000 km) SSH consistency is not required in order to meet the science objectives, but will enable basin scale oceanography, as a complement to the Topex/Jason altimeter series.

Define the SSH error spectrum, E(f), as a function of the spatial frequency f *(i.e., f=1/wavelength=1/λ) (the same as the term of "wavenumber" used in some oceanographic literature) such that the expected SSH error variance in the wavelength interval [λ_{min},λ_{max}] is given by the integral of E(f):*

$$\left\langle (\delta h)^2 \right\rangle = \int_{1/\lambda_{\max}}^{1/\lambda_{\min}} E(f)\, df \qquad (1)$$

Then the SSH spectrum in the ranges defined above is given by

$$E(f) = \begin{cases} 1\ [cm^2/cycle/km] & 1km<\lambda<30km \\ 0.001f^{-2}\ [cm^2\ cycle/km] & 30km<\lambda<1000km \\ 1000\ [cm^2/cycle/km] & 1000km<\lambda<10000km \end{cases}$$

Due to the inherent noise in estimating the spectrum of a noisy process, validation of this requirement shall be understood in an ensemble sense, to insure that the estimation errors associated with the error spectral power for any given frequency are suitable to insure that the requirement has been met with a probability greater than 68%.

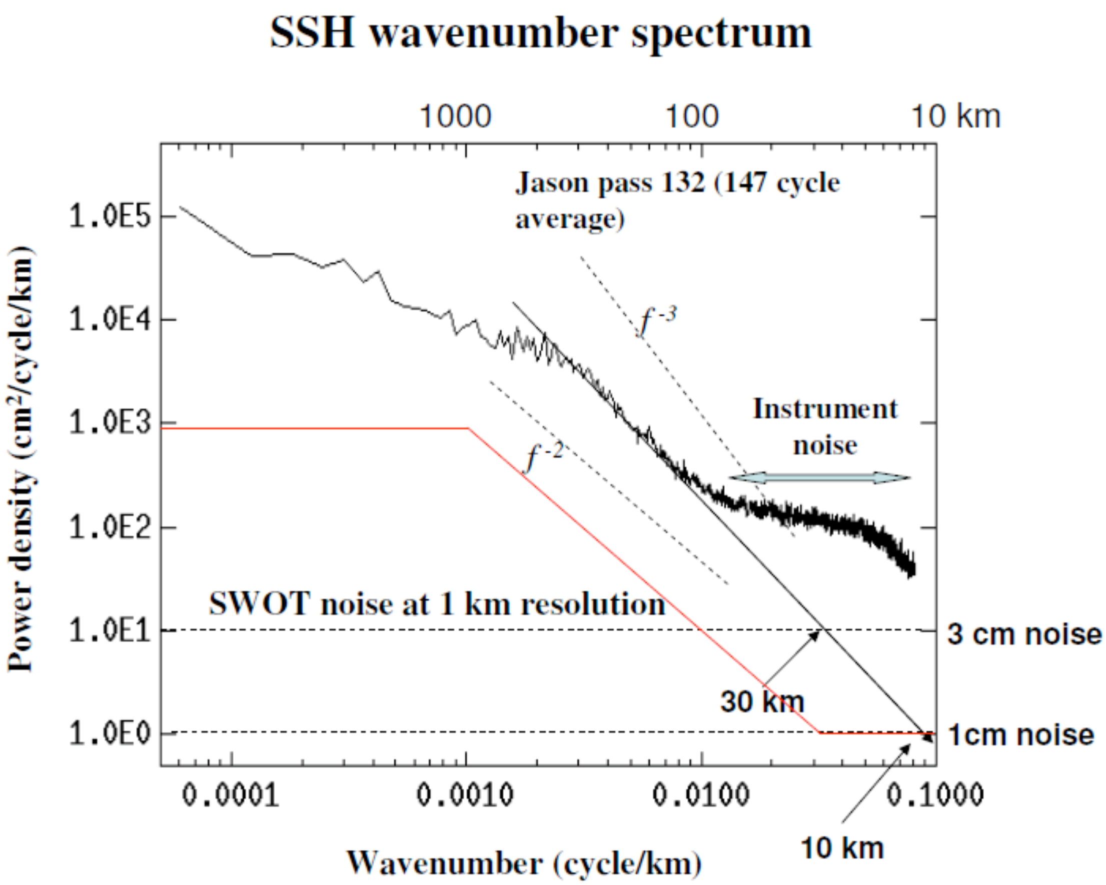

Figure 1: *SSH error spectrum (red curve) as a function of spatial frequency. Shown, for reference is the SSH spectrum for a reference Jason pass (pass 132) (jagged line). Also shown as the solid black line is the expected spectral continuation. The intersection of the spectral signal with the noise floor at 10km determines the resolving capabilities for the SWOT instrument.). As can be seen, instrument noise dominates the signal for wavelengths smaller than ~100km.*

2.7.3 [Requirement] The height postings shall be geographically fixed, and independent of spacecraft position and attitude. The absolute height error introduced by interpolation to a geographically fixed grid shall not exceed 0.5 cm for 68% of all posts. Errors include errors due to geoid variations.

The measurement geographic grid needs to remain constant over the mission to minimize geoid errors and enable the construction of a mean sea surface and variability studies.

2.7.4 [Requirement] SWOT shall provide flagging of height postings affected by rain. The accuracy of the rain flag shall be 68%. (More than 68% of rain-contaminated data must be correctly flagged)

Rain cells significantly distort Ka-band radar measurements due to signal attenuation. An estimated 5%-10% of all data (depending on latitude) will be affected by rain events. This specification is inherited from the OSTM mission requirements for rain flagging.

2.7.5 [Requirement] SWOT shall provide flagging of sea ice over the ocean. The accuracy of the sea ice flag shall be 68%. (More than 68% of sea-ice-contaminated data must be correctly flagged.)

2.7.6 [Requirement] The SWOT ocean performance shall be verified by payload independent measurements or analysis during a post-launch calibration/validation period.

2.8- Minimum Surface Water Science Performance Specifications

In order to achieve the surface water science objectives, the following minimum measurement science requirements and goals for the SWOT mission are imposed:

2.8.1 [Requirement] The average post separation for surface water Level-2 geolocated data products (described in 2.6.3) shall be 50m. The worst-case separation shall be no greater than 70m.

This posting is required to sample 100m river widths with an average of two points.

2.8.2 [Requirement] The lake, reservoir, and wetland areas estimated using the water mask shall have a relative error smaller than 20% (1σ) of the total water body area.

2.8.3 [Requirement] The lake, reservoir, and wetland height accuracy relative to the surrounding topography shall be 10 cm (1σ) or better.

To measure storage change, only relative changes in water level are required.

2.8.4 [Requirement] After processing elevations over an area of 1 km^2 inside the river mask, river height accuracy relative to the surrounding floodplain topography shall be 10 cm (1σ) or better.

All river requirements assume that the elevations are processed to average height and slope by fitting a polynomial of suitable order to the irregularly sampled elevation data.

The requirement applies for any given location along the river reach where the minimum width requirements are met. Elevations and slopes relative to surrounding floodplain topography are sufficient for estimating relative changes in discharge.

2.8.5 [Requirement] After processing elevations over downstream distance of 10 km inside the river mask, river downstream slope accuracy relative to the surrounding floodplain topography shall be 1cm/1km (10 μrad) (1σ) or better.

2.8.6 [Requirement] SWOT shall provide flagging of height postings affected by rain. Affected postings should not be used for height or slope estimates. The accuracy of the rain flag shall be 68%.

Rain cells significantly distort Ka-band radar measurements due to signal attenuation. An estimated 5%-10% of all data (depending on latitude) will be affected by rain events.

2.8.7 [Requirement] SWOT shall provide flagging of height postings affected by topographic layover. Affected postings should not be used for height or slope estimates. The accuracy of the layover flag shall be 68%.

Topographic layover (radar energy from surrounding topography or vegetation and arriving at the same time as the water signal) can significantly affect the height error, if the layover radar energy is sufficiently great compared to the water return.

2.8.8 [Requirement] SWOT shall provide flagging of frozen surface water. Affected postings should not be used for height or slope estimates. The accuracy of the frozen water flag shall be 68%.

2.8.9 [Requirement] The SWOT surface water performance shall be verified by a payload independent measurement or analysis during a post-launch validation period.