The Surface Water and Ocean Topography (SWOT) Mission

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http://swot.jpl.nasa.gov
The SWOT mission is a joint NASA/CNES mission

- Within the last month, NASA and CNES have reached an understanding on partnering and launch date

The estimated launch date is 2019

Mission lifetime: 3 years (5 years goal)

970 km, 78° inclination orbit

- ~3 day fast sampling phase 1st 3 months
- ~22 day repeat cycle for nominal mission
Responding to the Challenge of Climate and Environmental Change:

NASA’s Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space

June 2010

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### Accelerated ESD Missions

| Missions       | Launch Readiness Date | FY10 Plan | FY11 Plan |
|----------------|-----------------------|-----------|-----------|
|                |                       | Development | Primary Operation | Extended |
| SMAP           | FY10: 2015, FY11: 2014| Orange     | Purple     | Yellow    |
| DESDynl Radar  | FY10: 2019, FY11: 2017| Orange     | Purple     | Blue      |
| DESDynl Lidar | FY10: 2019, FY11: 2017| Orange     | Purple     | Blue      |
| CLARREO-1      | FY10: 2019, FY11: 2017| Orange     | Purple     | Blue      |
| Venture (Satellite EV2) | FY10: NET 2022, FY11: 2017 | Orange     | Purple     | Blue      |
| ASCENDS        | FY10: NET 2023, FY11: 2019 | Orange     | Purple     | Blue      |
| CLARREO-2      | FY10: 2019, FY11: 2020 | Orange     | Purple     | Blue      |
| SWOT           | FY10: NET 2025, FY11: 2020 | Orange     | Purple     | Blue      |

**FIGURE 2:** Accelerated Missions—This figure compares the timelines for mission development associated with the FY2010 and FY2011 budgets. The FY11 budget request substantially accelerates the development and launch of Decadal Survey-recommended missions.
The SWOT Mission and Payload

Mission Science

Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and greater.

Hydrology: To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250 \text{m})^2$ (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (requirement) (50 m goal) (rivers).

- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

Mission Architecture

- Ka-band SAR interferometric (KaRIn) system with 2 swaths, 50 km each (goal of 60 km)
- Produces heights and co-registered all-weather imagery
- Use conventional Jason-class altimeter for nadir coverage, radiometer for wet-tropospheric delay, and GPS/Doris for POD.
- On-board data compression over the ocean (1 km$^2$ resolution). No land data compression onboard.

Orbit: 970 km Alt, 78 deg Incl, 22 day repeat
Baseline Payload Concept (I)

- **Spacecraft**
- **Instrument GPS**
- **KaRIn Feeds**
- **Payload Module**
- **Direction of Flight**
- **KaRIn Reflectarray**
- **Radiometer**
- **Nadir Altimeter**
- **LRA**
- **Doris**

**Nadir**
• Conventional real-aperture altimeter spatial resolution is determined by iso-range annuli and antenna beamwidth
  – Left/right/front/back ambiguity
  – Pulse limited circle gives geolocation
• Synthetic aperture processing narrows the along-track (azimuth) cell size
  – Left/right ambiguity is not resolved
  – Clutter from land is reduced
• Interferometer resolves left/right ambiguity by illuminating only one side of the swath
Conventional altimetry measures a single range and assumes the return is from the nadir point.

For swath coverage, additional information about the incidence angle is required to geolocate.

Interferometry is basically triangulation.

Baseline B forms base (mechanically stable).

One side, the range, is determined by the system timing accuracy.

The difference between two sides ($\Delta r$) is obtained from the phase difference ($\Phi$) between the two radar channels.

$$\Phi = 2\pi \frac{\Delta r}{\lambda} = 2\pi B \sin \Theta/\lambda$$

$$h = H - r \cos \Theta$$
Step 1: Transmit 1
Delay 1: $2 \frac{r_1}{c}$

Step 2
Receive 1

$B$

$r_1$
Step 3
Transmit 2

Delay 1: \(2 \frac{r_1}{c}\)

\(r_1\)

\(r_2\)

B
Delay 1: \(2 \frac{r_1}{c}\)
Delay 2: \(2 \frac{r_2}{c}\)

\[\Delta r = B \sin \theta\]
SWOT

KaRIN Interferometry: Nominal Mode

Step 5
Form Phase Difference

\[ \Delta r = B \sin \theta \]

Delay 1: \( 2 \frac{r_1}{c} \)
Delay 2: \( 2 \frac{r_2}{c} \)
Differential delay: \( dt = 2 \frac{(r_1 - r_2)}{c} = 2 \Delta r / c \)
\[ \Phi = \omega dt = k(2\Delta r) \]
Example SWOT Image

Color represents interferometric phase (modulo $2\pi$)

Brightness is radar normalized cross section

Spatial resolution:

Land: 2.5m x 10m – 70m

Ocean: 1 km x 1km
The SWOT Error Spectrum

The driving requirement is to measure sea surface heights at all scales, from 10 km to basin scale. The requirements are derived by requiring that the errors be one order of magnitude smaller than the extrapolated Jason spectrum.
Step 1: Transmit 1

\[ r_1 \]
Delay 1: \((r_1 + r_0)/c\)

Step 2
Receive 0
Step 3
Transmit 2

Delay 1: \( \frac{r_1 + r_0}{c} \)

B
KARIN Interferometry: Near-Nadir Mode

Delay 1: \( (r_1 + r_0)/c \)
Delay 2: \( (r_2 + r_0)/c \)

\[ \Delta r = B \sin \theta \]
KaRIN Interferometry: Near-Nadir Mode

Step 5
Form Phase Difference

Delay 1: \((r_1 + r_0)/c\)
Delay 2: \((r_2 + r_0)/c/c\)
Differential delay: \(dt = (r_1 - r_2)/c = \Delta r/c\)
\(\Phi = \omega dt = k(\Delta r)\)

The effective baseline is \(1/2\) nominal baseline
There is enough KaRIn power in the near-nadir direction?

- Getting appropriate signal to noise ratio over the swath up to and past 10 km probably requires separate tilted feeds for each (right/left) swath.
- There is significantly more power in the near swath compared to KaRIN nominal mode
- However, there is only ½ the baseline
KaRIN Near-nadir Performance

KaRIN Altimeter Performance

Estimation Interval: 1 second

- AltiKa
- Poseidon

Height STD (cm)

- boresight: 0.0 deg
- boresight: 0.2 deg
- boresight: 0.4 deg
- boresight: 0.6 deg

Cross-Track Distance (km)

- 0
- 2
- 4
- 6
- 8
- 10

Height Noise (cm)

- 0
- 1
- 2
- 3
- 4
- 5

SWHSTD (m)

- 0.01
- 0.02
- 0.03
- 0.04
- 0.05
- 0.06

σ STD (dB)

- 0.001
- 0.002
- 0.003
- 0.004
- 0.005
- 0.006

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October 22, 2010
What are the Basic KaRIN Products?

**Hydrology**
- Water surface elevation for all water bodies
  - Geolocated elevations reported on an irregular grid conformal to the water body shape
  - Order of magnitude resolution: 50 m
- Water extent gelocated mask on irregular grid conformal to water body shape
- Elevation and classification updated every revisit (~10 days)
- DEM of floodplain derived over the mission

**Oceanography**
- SSH in repeat pass along-track grid
  - Allows automatic pass-pass differencing
- Grid spacing: 1km x 1km
- Co-registered radar cross section
- SWH estimate
- SSH random error estimate
- Wind speed estimate
• >74N is OK
• 66N is not

Courtesy D. Alsdorf, OSU
Tidal Aliasing: \( i = 78^\circ \)

78 degrees

Tidal Aliasing Frequency (cpy)

Repeat period (days)

Courtesy S. Nerem et al.
22-Day Repeat, 3-Day Subcycle

Base Interval
~25° or ~3000 km

Courtesy S. Nerem et al.
Base Interval
≈25° or ≈3000 km

Courtesy S. Nerem et al.
10 days of 22-Day Repeat, Aghulas
SWOT

4-Days of 22-Day Repeat, Aghulas
SWOT

4-Days of 22-Day Repeat, Amazon

Number of Observations/Cycle

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4 Days of 22-Day Repeat, Lena

Number of Observations/Cycle

1 2 3 4 5 6 7 8 9 10
SWOT

22-Day Repeat

Latitude: 0 deg

Latitude: 20 deg

Latitude: 40 deg

Latitude: 60 deg

Time (days)

Longitude (deg)
Cross-Track Distance: 10 km \( \sigma = 0.5 \) m

\[ \rho - \rho_0 \text{ (m)} \]

\[ \text{Height (m)} \]

\[ \text{Phase (deg)} \]
Cross-Track Distance: 35 km $\sigma = 0.5$ m
Cross-Track Distance: 60 km $\sigma = 0.5$ m
Effect on Interferometric Correlation

Pierson-Moskowitz Simulation

Geometric Correlation vs. Cross-Track Distance (km)

- SWH: 0 m
- SWH: 1 m
- SWH: 2 m
- SWH: 3 m
- SWH: 4 m
- SWH: 5 m
Correlation Ratio (land less correlated than water)

$$\langle v_1 v_2^* \rangle = P_{\text{Water}} \gamma_{\text{Water}} \exp[i\Phi_{\text{Water}}] + P_{\text{Land}} \gamma_{\text{Land}} \exp[i\Phi_{\text{Land}}]$$

$$\delta \Phi = \arg \left[ 1 + \frac{P_{\text{Land}} \gamma_{\text{Land}}}{P_{\text{Water}} \gamma_{\text{Water}}} \exp[i(\Phi_{\text{Land}} - \Phi_{\text{Water}})] \right]$$

Brightness Ratio (land darker than water)
**Vegetation Effects**

**Canopy attenuation:** weaker signal but no height bias

**Canopy Layover:** no attenuation, but height bias.
\[ \delta \Phi = \text{arg} \left[ 1 + \frac{\mu \nu}{\beta + i\kappa_z T} \left( \exp \left[ i\kappa_z (T - z_1) \right] e^{-\beta_1 / T} - \exp \left[ i\kappa_z (T - z_2) \right] e^{-\beta_2 / T} \right) \right] \]

\[ \kappa_z = \frac{kBT}{H \sin \theta} \quad \beta: \text{attenuation constant. } T: \text{tree height. } \mu: \text{brightness ratio.} \]

\[ \nu = \frac{\beta}{1 - e^{-\beta}} \]
Height errors as a function of cross-track distance (from near swath (bottom) to far swath (top)), tree/water brightness contrast, and distance between the water pixel and the start of the vegetation patch along the range direction. The tree stand has a range extent of 50 m and was assumed to be 50 m tall.
Amazon vegetation/water mask courtesy of L. Hess, UCSB
Amazon Tree Layover Simulation

- Assumed tree height: 20 m
- Fraction of land which is tree covered: 100%
Cross-Over Calibration Concept

- Roll errors are the dominant error source for WSOA and must be removed by calibration. Residual range and phase errors are also removed.

- Assume the ocean does not change significantly between crossover visits (<5 days)

- For each cross-over, estimate the baseline roll and roll rate for each of the passes using altimeter-interferometer and interferometer-interferometer cross-over differences, which define an over-constrained linear system.

- Interpolate along-track baseline parameters between calibration regions by using optimal interpolation given gyro drift correlation function (similar for phase)
Cross-over technique demonstrated for WSOA

- New orbit has new geometry and longer repeat times between cross-overs
- Results show that changes in cross-over geometry have not affected the calibration accuracy
- Results also show that interferometer only calibration is sufficient for roll restitution
- Interferometer-Altimeter cross-calibration required for range calibration to altimeter global frame
Simulations with ocean motion

- Ocean motion between cross-over revisits is the dominant contributor to the roll calibration error budget.
- In general, the calibration parameters are well behaved, but the distribution has large tails.
  - 68% error < 1.5 cm
  - 80% error < 2.0 cm
  - 90% error < 5.0 cm
- These large tails are due to cross-overs with long time separations or over active regions.
- Improved estimates can be obtained by editing and optimal interpolation.
Ocean cross-over calibration leads to roll calibrations over the ocean at each cross-over point.

Gyro+star-tracker may have absolute errors or drifts, but the errors are slowly varying, so once calibrated over the ocean cross-overs they have a long memory.

Worst case example: assume that land crossing is bracketed by only two ocean points, roll is estimated (with error) and propagated using optimal interpolation (correlation function based) over land.

In practice, additional ocean information could be used to estimate gyro drift, etc.
How long are the land crossings?
How does the error grow?

Error at coast: 2.0 cm. Apriori error: 5.0 cm

- 20% duration: 1 minute
- 40% duration: 2 minutes
- 60% duration: 3 minutes
- 80% duration: 4 minutes
- Max duration: 23 minutes
How does it look globally?

Optimal interpolation can reduce roll RMS errors by 1-3 cm

\[ \sigma_{\text{coast}} = 2 \text{ cm} \quad \sigma_{\text{Giro}} = 5 \text{ cm} \]
A challenging mesoscale eddy

SSH contours are 1 cm
A bad case...
Effective roll 10x worse than expected
Swot
Smoothing does not help much...
• Cross-track surface slopes have very small power at high density.
• The effective roll angle (roll + phase) can be estimated for each range line by removing a best guess *a priori* surface and estimating from the flattened interferogram (or fitting a slope).
• The resulting estimate of effective roll is contaminated by the unknown height.
• **However**, the high-frequency part of the correction can be extracted and applied with little surface contamination.

Spectra from high-resolution ROMS ocean model at 1km sampling.
But removing the estimated high frequency roll does...

When the errors are smaller than 10x, it works even better…