SWOT Technology and Expected Performance

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**SWOT**

Interferometer/Altimeter Heritage

- **Nadir altimeters**: TOPEX/Poseidon & Jason & ERS & EnviSAT
  - **Heritage**: Error budget for propagation delays, algorithms for range corrections, water reflectivity near nadir

- **Radar Interferometers**:
  - **TOPSAR/AIRSAR**: early 1990’s-present: C-band airborne platform
  - **Star3I**: X-band airborne radar interferometer (1990’s-present)
  - **GeoSAR**: X-band P-band radar interferometer
  - **Europe**: DLR airborne IFSSAR, DLR X-band spaceborne interferometer with SRTM
  - **Shuttle Radar Topography Mission**: spaceborne land topography (2000)
    - Also imaged rivers and the ocean
  - **Wide-Swath Ocean Altimeter**: centimeter level precision concept funded by NASA past design reviews, but deferred due to budget problems
  - **Cryosat**: forthcoming studies will investigate the use of cryosat interferometric/altimeter modes for surface water.
  - **WatER**: proposal to ESA Earth Explorer.
    - **Heritage**: error budget verification, instrument design and manufacture, processing algorithms, ground system, mission management, calibration and validation

**High-frequency Radars**:

- **CloudSat**: the proposed instrument uses technology and lessons learned from the high-frequency CloudSat mission (EIK, High Voltage Power Supply)
SWOT
KaRIN: Ka-Band Radar Interferometer

- Ka-band SAR interferometric system with 2 swaths, 60 km each
- WSOA and SRTM heritage
- Produces heights and co-registered all-weather imagery *required by both communities*
- Additional instruments:
  - conventional Jason-class altimeter for nadir coverage
  - AMR-class radiometer (with possible high frequency band augmentation) to correct for wet-tropospheric delay
- No land data compression onboard (50m resolution)
- Onboard data compression over the ocean (1km resolution)
SWOT Configuration

Interferometry
SAR Antennae

CNES conceptual drawing
- 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.

\[
\Phi = 2\pi \frac{\Delta r}{\lambda} = 2\pi B \sin \frac{\Theta}{\lambda}
\]

\[
h = H - r \sin \Theta
\]
Other error sources (e.g., baseline length, yaw errors) can be controlled so that errors are smaller by an order of magnitude, or more.
• Errors can be divided into spatially correlated and uncorrelated
  – Uncorrelated: thermal/speckle noise. Precision improves linearly with the area
  – Correlated: geophysical, orbit. Precision does not improve significantly with averaging
• Slope (~velocity) is affected differently than height by spatially correlated errors
  – Relatively large height errors can result in relatively small slope errors
• For ocean, geostrophic velocity ~slope. Sea-level rise ~height. Heat content ~height
• For hydrology, velocity (discharge) ~slope (or assimilated height). Storage ~ height
## Error Budget Allocations

<table>
<thead>
<tr>
<th></th>
<th>Height Error</th>
<th>Typical wavelength</th>
<th>Typical geophysical magnitude</th>
<th>Slope error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase error</td>
<td>1cm @ 1km^2 area</td>
<td>uncorrelated</td>
<td>NA</td>
<td>0.7μrad @ 5km</td>
</tr>
<tr>
<td>Roll errors</td>
<td>2cm (max) at swath edge</td>
<td>200km</td>
<td>Depends on platform dynamics</td>
<td>0.1μrad (max)</td>
</tr>
<tr>
<td>Wet Troposphere</td>
<td>1cm (Ocean) &lt;5cm (Land)</td>
<td>&gt;100km</td>
<td>3-6cm</td>
<td>0.1μrad</td>
</tr>
<tr>
<td>Dry Troposphere</td>
<td>&lt;1cm</td>
<td>&gt;1000km</td>
<td></td>
<td>0.01μrad</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>1cm</td>
<td>&gt;900km</td>
<td>50cm</td>
<td>0.2μrad</td>
</tr>
<tr>
<td>EM Bias</td>
<td>1-2cm</td>
<td>100km</td>
<td>&lt;5cm</td>
<td>0.1μrad</td>
</tr>
<tr>
<td>Orbit</td>
<td>1cm</td>
<td>&gt;8000km</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ \delta h = \lambda \frac{r \tan \Theta}{2 \pi B} \delta \Phi \]

- Significant advantages to near-nadir geometry:
  - SRTM vs SWOT \( \tan \theta \): \(~0.09\)
- Dominant sources of phase noise:
  - Thermal noise in radar signal (random)
  - Decorrelation of the two returns due to speckle decorrelation of scattered fields (random)
- Phase imbalance between the two interferometric channels:
  - Temperature driven (slow change)
  - Can be calibrated using calibration loop.
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Random Height Error Validation

29 Palms THED Values

29 Palms Random Height Error

RMS Height Error (m)
SWOT KaRIN Random Noise Performance

The graph shows the relationship between the averaging area in km² and the height precision in cm. The graph includes different lines representing different RMS slopes:
- Surface RMS Slope: 1 deg
- Water RMS Slope: 4 deg
- Surface RMS Slope: 8 deg
- Surface RMS Slope: 16 deg
Geostrophic Speed Error

\[ \sigma_s \approx \sqrt{\frac{12}{N}} \frac{\sigma_h}{L} \]

\[ \sigma_V = \sqrt{2} \frac{g}{f} \sigma_s \]

- \( \sigma_s \): Slope std
- \( \sigma_h \): Height std
- \( L \): Distance for slope calculation
- \( \Delta x \): Sample spacing
- \( N \): Total number of samples


\[ dh = -\delta \ r \cos \Theta \]

- Similar to nadir altimeter range errors (although there is no tracker error since no estimate of the waveform leading edge is necessary).
- Sources of range error:
  - Ionospheric delay
  - Dry and wet tropo delays
  - EM Bias
Media errors and sea-state errors have scales larger than 100 km and not affecting submesoscale SSH measurement.
A determination of the spatial variability of the media delays can be made using multi-seasonal TOPEX/Poseidon data.

- No attempt has been made to remove instrument noise, and that is why the errors at 20 km are so large: wet-tropo, EM bias, and ionospheric correlation lengths are >> 20 km.

- Correcting for media effects can have significant effects on the calculation of slopes and the high frequency spectra.

- Global altimetry: accuracy
- (Sub) Mesoscale: precision
Tropospheric delays have correlation distances > 50 km. Order of magnitude slope biases: 5cm/50km ~ 1cm/10km.

Source: S. Kheim, JPL
$\delta h = r \sin \Theta \delta \Theta$

- An error in the baseline roll angle tilts the surface by the same angle.

  - This is equivalent to introducing a constant geostrophic current in the along-track direction

- As an order of magnitude, a 0.1 arcsec roll error results in a 4.5 cm height error at 100 km from the nadir point

- Roll knowledge error sources:
  - Errors in spacecraft roll estimate
  - Mechanical distortion of the baseline (can be made negligible if the baseline is rigid enough)
**Cross-Over Calibration Concept**

- Roll errors must be removed by calibration

- Assume the ocean does not change significantly between crossover visits

- 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 smooth interpolating function (e.g., cubic spline.)
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Distribution of Time Separation Between Calibration Regions

Temporal Separation Scales

Cumulative Distribution Function

- Calibration Diamond Separation
- Nadir Crossover Point Separation

Time (s)
Minimizing high-frequency motion errors can be achieved with an appropriate architecture (e.g., Grace has no moving panels).

Both CNES and JPL have determined that a feasible architecture exits where no high-frequency spacecraft component motion will occur during data collection.
• The effect of waves is to increase the observed height variance
• This is a small effect on the height precision (on a single pixel, random noise \( \sim 2\text{m SWH} \))
• SWH can be estimated by estimating the excess variance relative to the predicted variance
• To make a meaningful measurement, a large area must be used for averaging
• The area required is not that different from the altimeter area used for SWH
SWOT Wind Speed

- SWOT will measure radar sigma0 at 1km resolution
- Sigma0 can be converted to wind speed (without direction)
- Can high frequency variability of speed be used for SWOT applications?
Can KaRIn measure bathymetry?

- The slope accuracy and spatial resolution are compatible with Abyss mission requirements, for even 1 repeat cycle (not taking into account ocean mesoscale contamination).
- Using compromise orbit and expanded swath (120km -> 140km), there are no holes in the coverage.

From Sandwell et al.