National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CENTRE NATIONAL D'ÉTUDES SPATIALES

http://swot.jpl.nasa.gov

The Surface Water and Ocean Topography (SWOT) Mission

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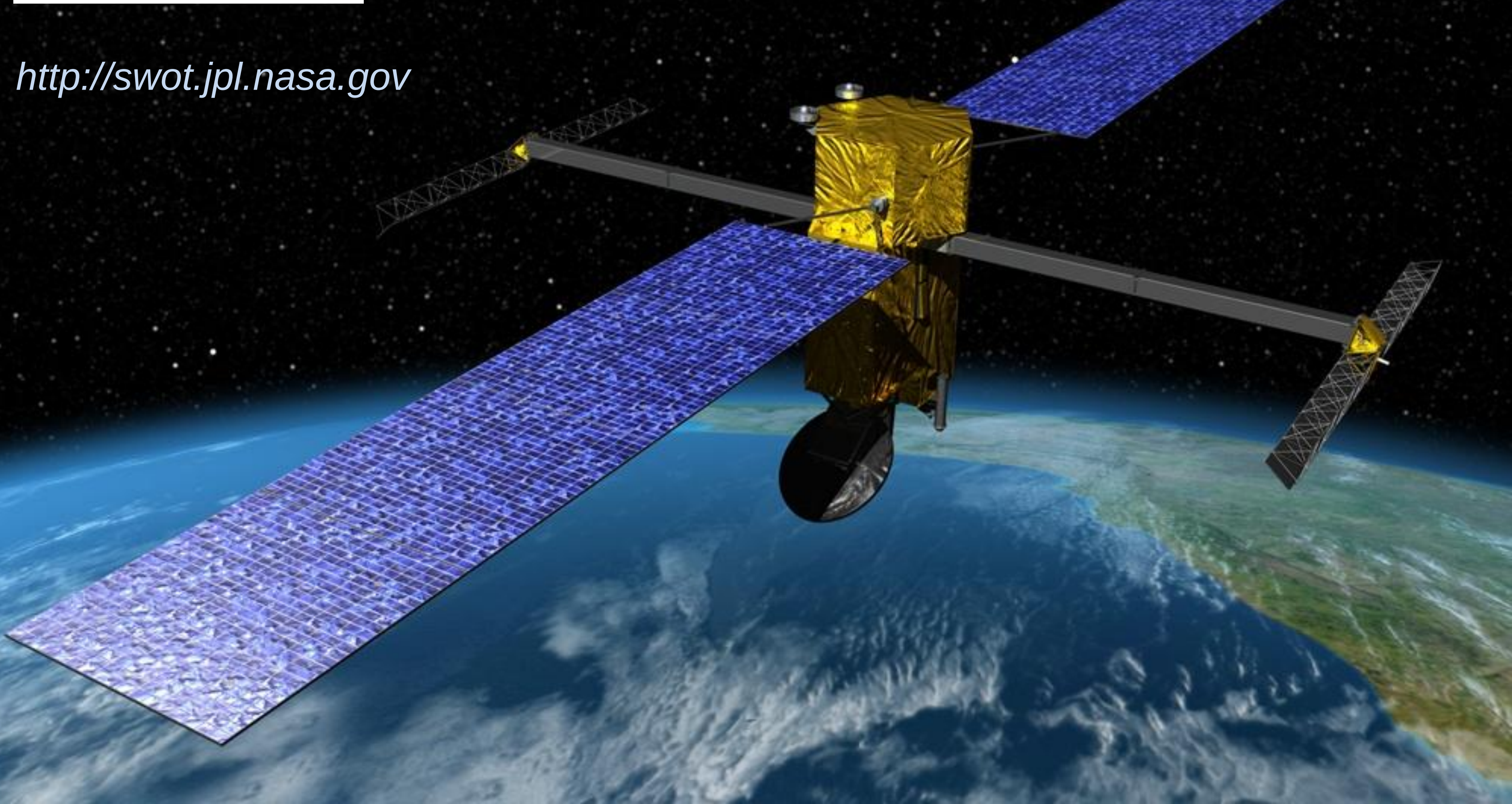


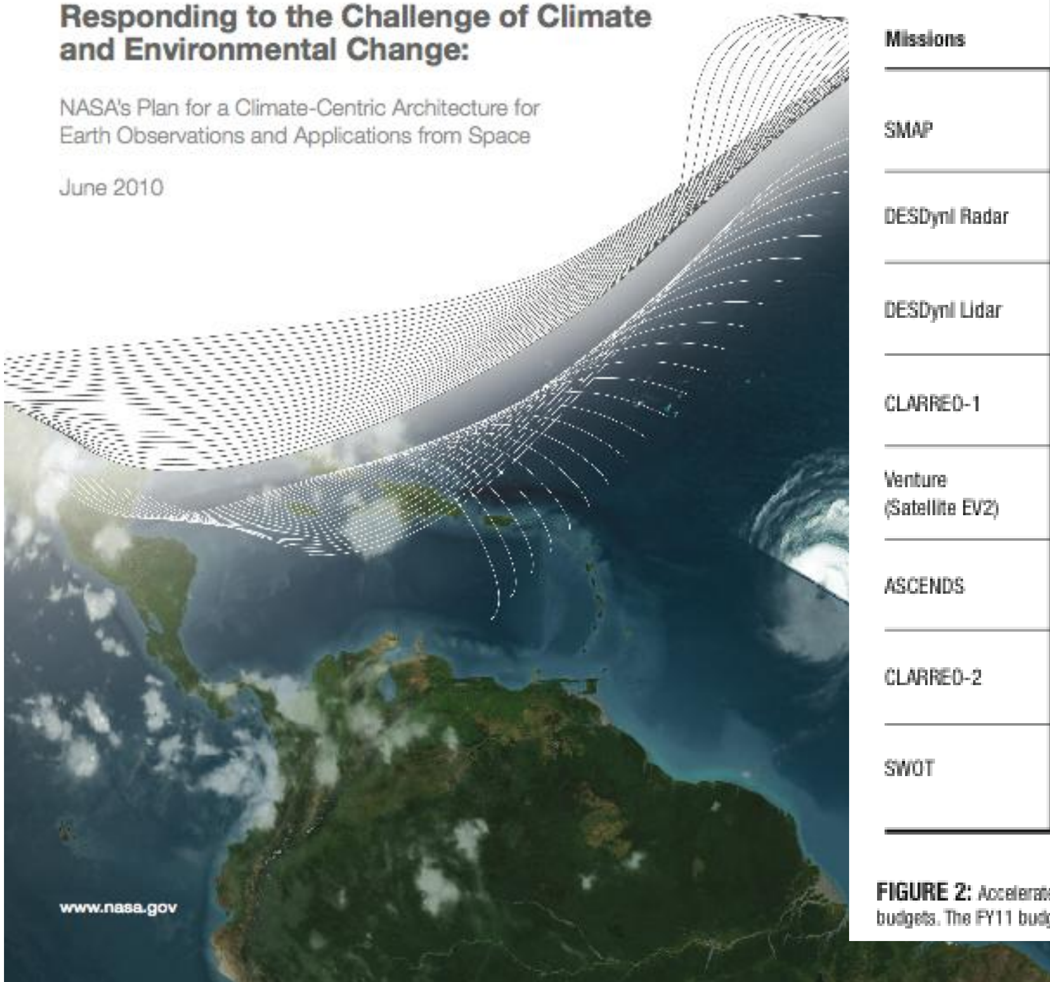
- The SWOT mission is a joint NASA/CNES mission
  - Within the last month, NASA and CNES have reached an understanding on partnering and launch date
- The estimated launch date is 2019
- Mission lifetime: 3 years (5 years goal)
- 970 km, 78º inclination orbit
  - ~3 day fast sampling phase 1st 3 months
  - ~22 day repeat cycle for nominal mission

National Aeronautics and Space Administration

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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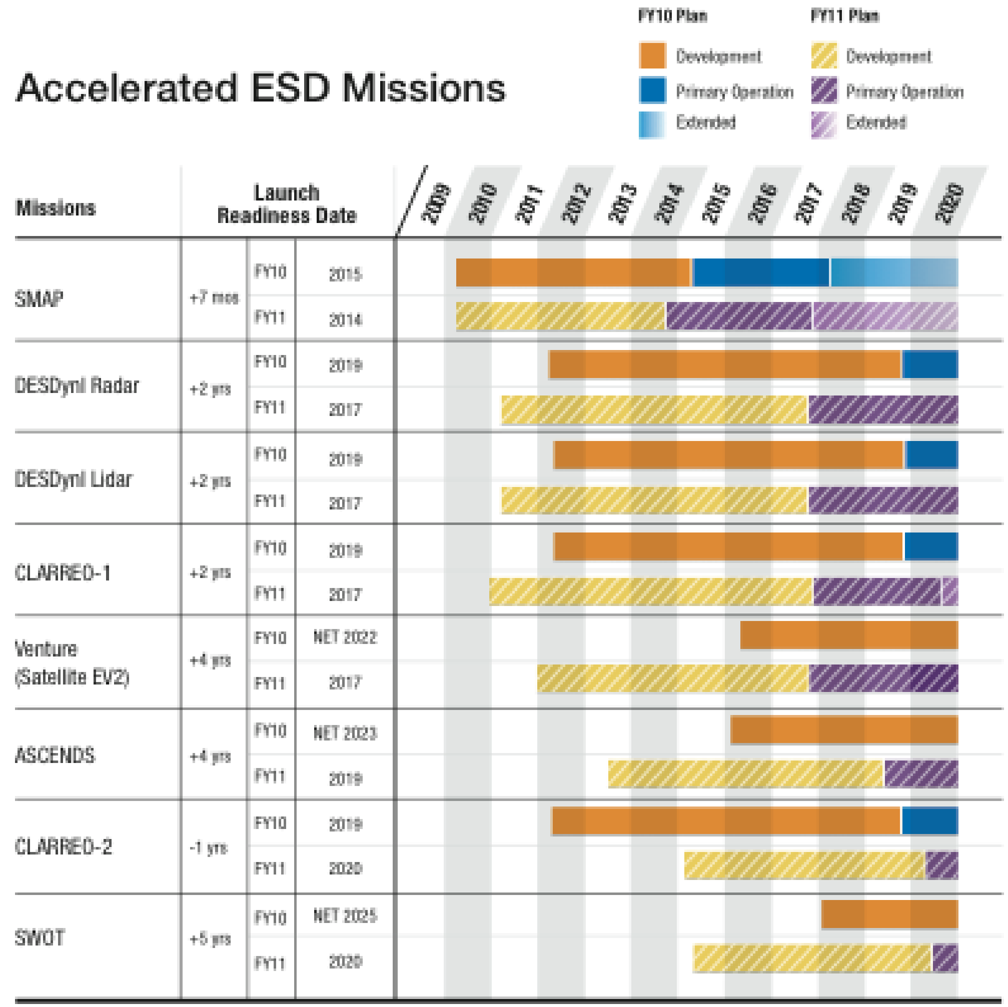


FIGURE 2: Accelerated Missions—This figure compares the timelines for mission development associated with the FY2010 and FY2011 budgets. The FY11 budget request substantially accelerates the development and launch of Decadal Survey-recommended missions.

SWOT The SWOT Mission and Payload

Mission Science

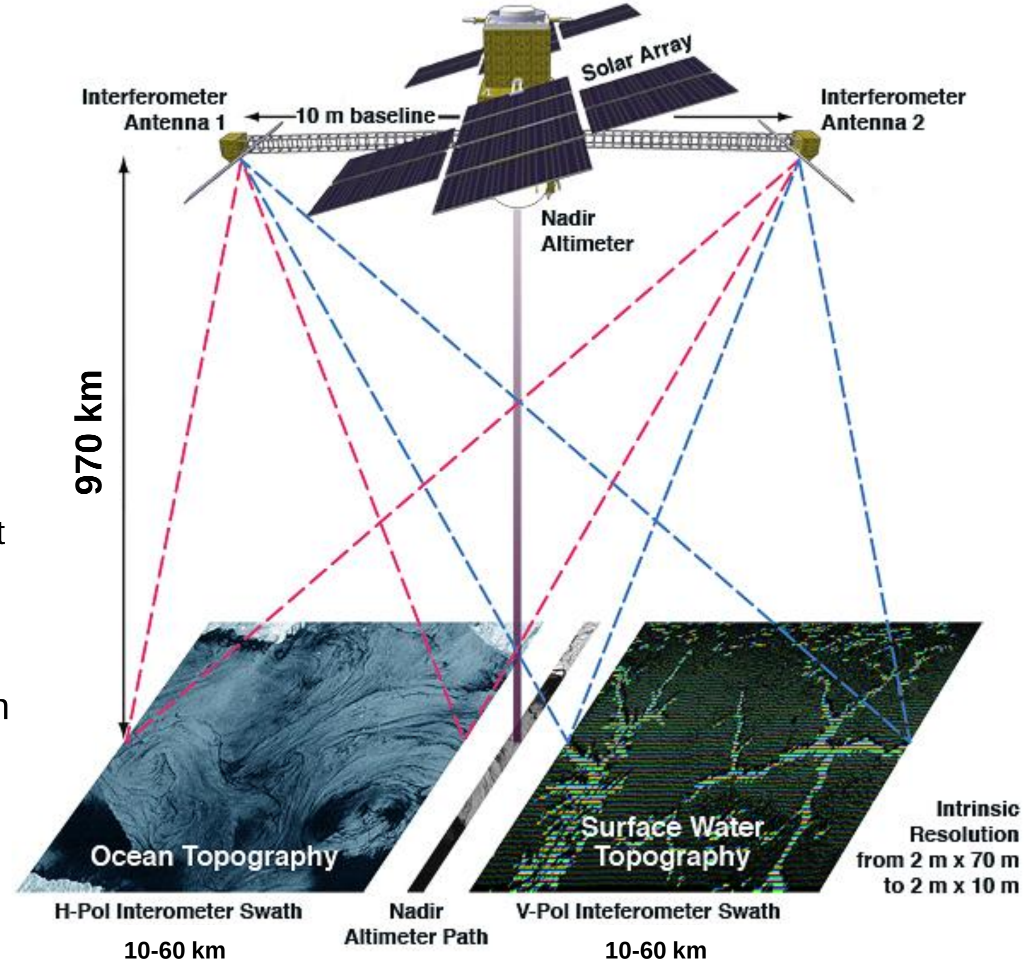
Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and greater.

Hydrology: To provide a global inventory of all terrestrial water bodies whose surface area exceeds $(250m)^2$ (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.

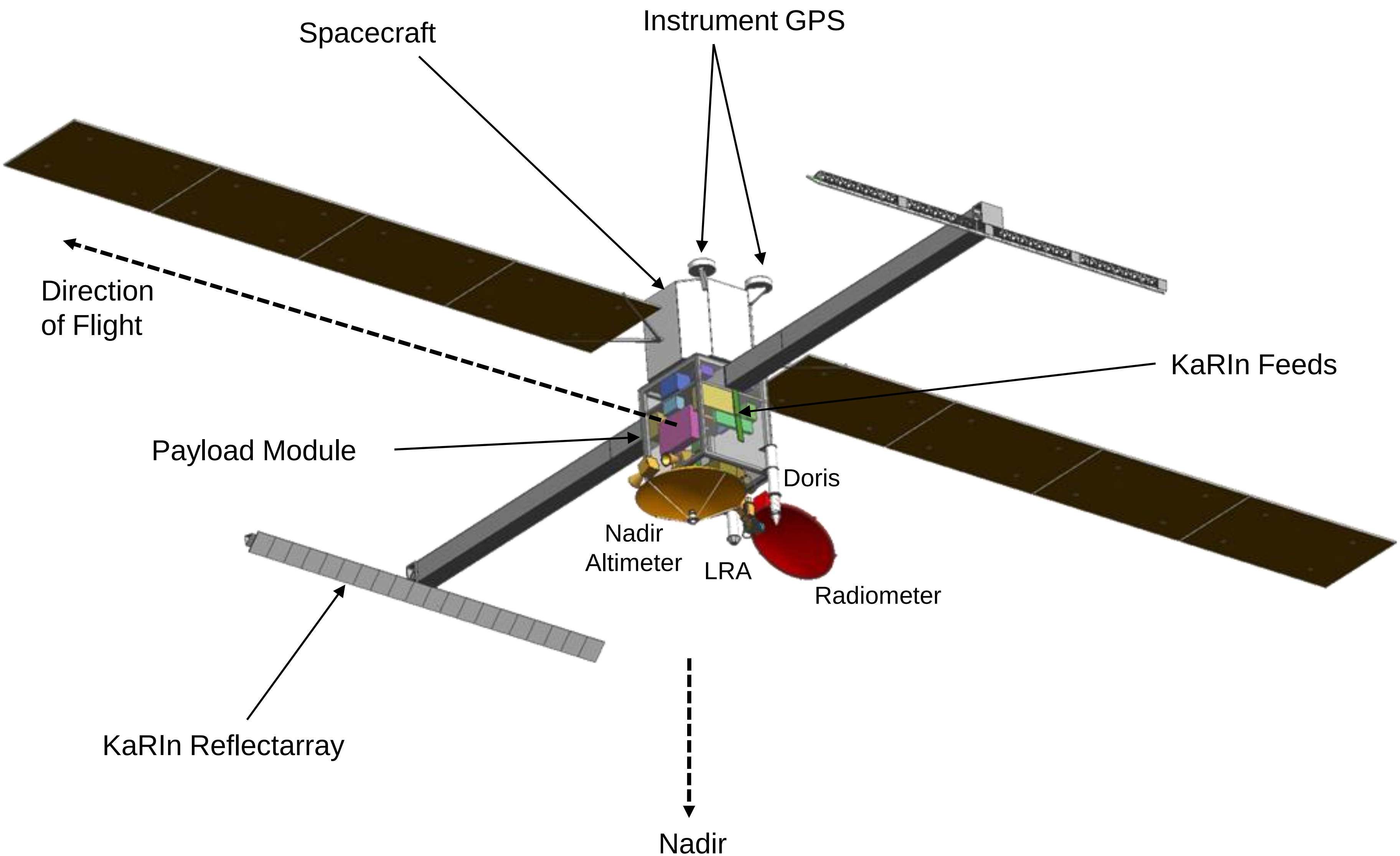
Mission Architecture

- 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.

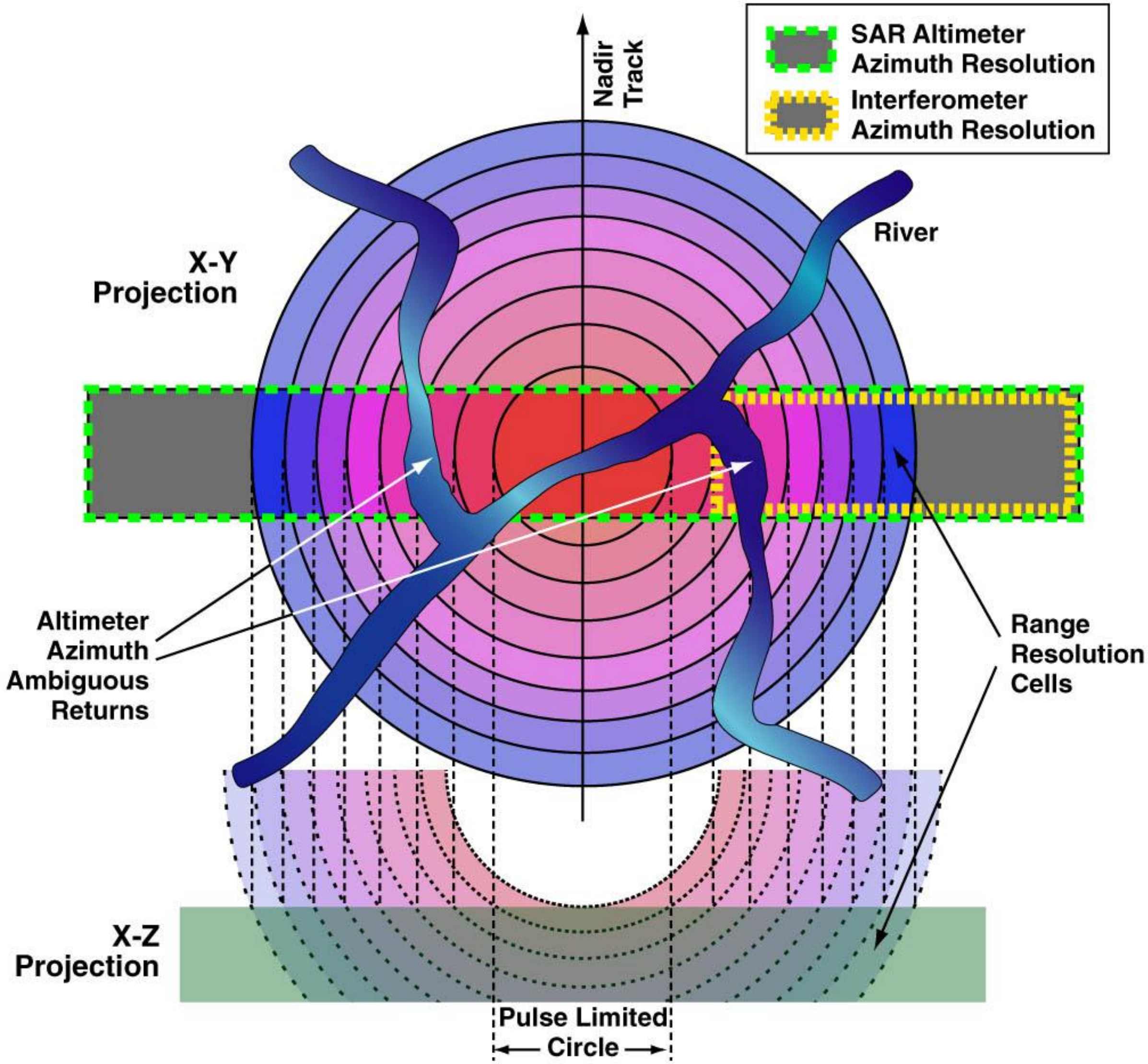


Orbit: 970 km Alt, 78 deg Incl, 22 day repeat

Baseline Payload Concept (I)

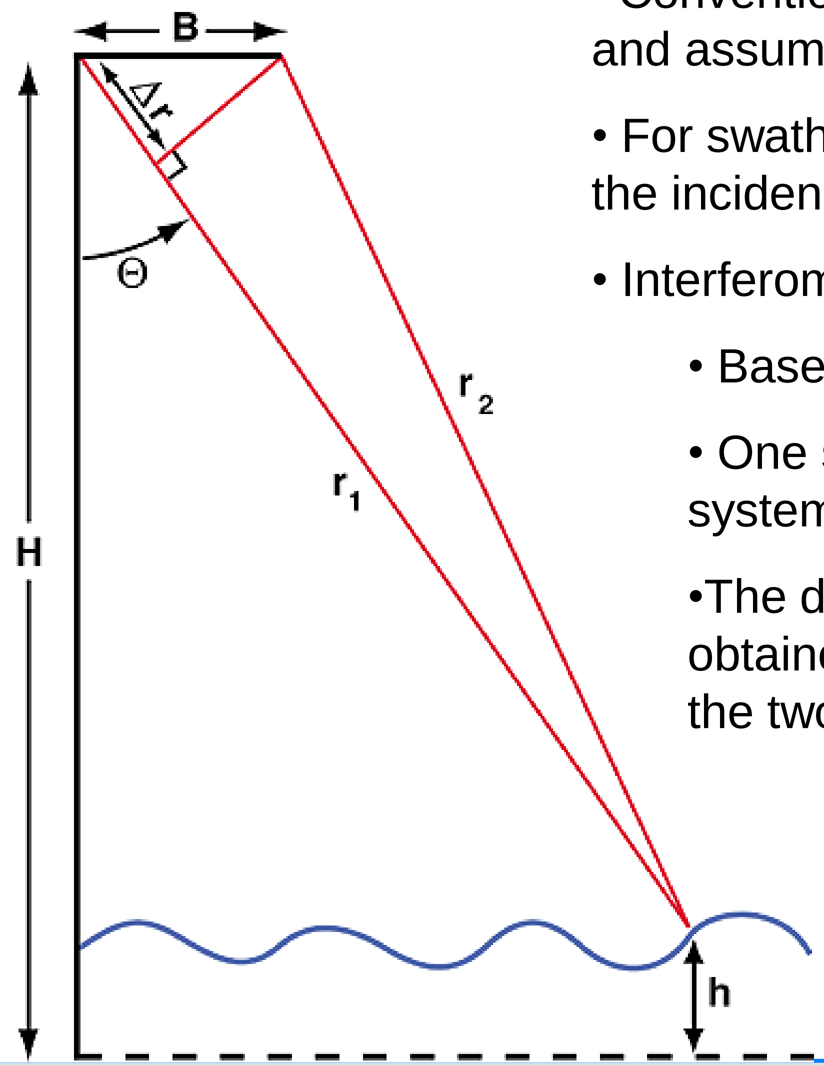


Radar Spatial Resolution



- 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

Interferometric Measurement Concept

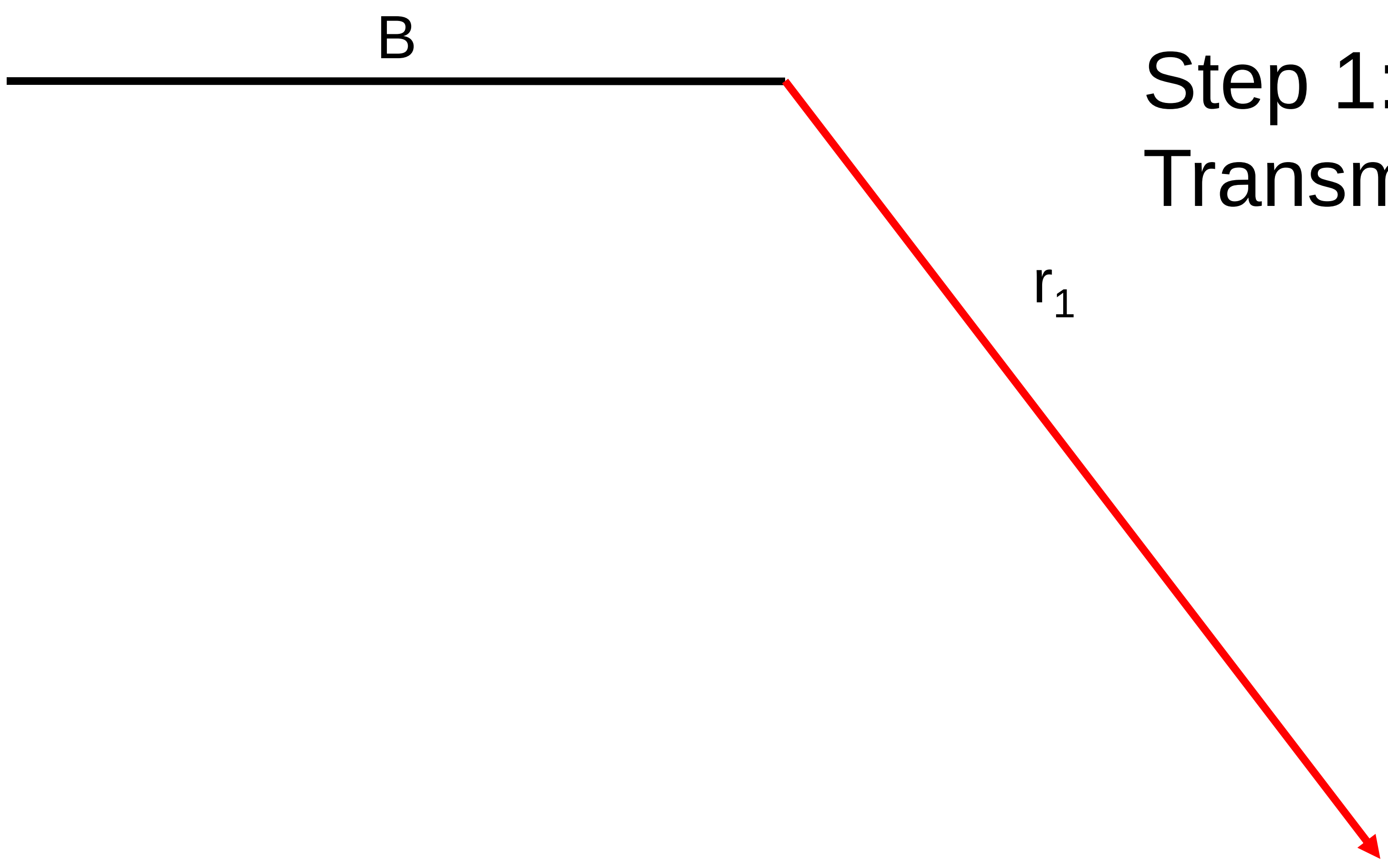


- Conventional altimetry measures a single range and assumes the return is from the nadir point
- For swath coverage, additional information about the incidence angle is required to geolocate
- Interferometry is basically triangulation
  - Baseline B forms base (mechanically stable)
  - One side, the range, is determined by the system timing accuracy
  - The difference between two sides (Δr) is obtained from the phase difference (Φ) between the two radar channels.

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

$$h = H - r \cos \Theta$$

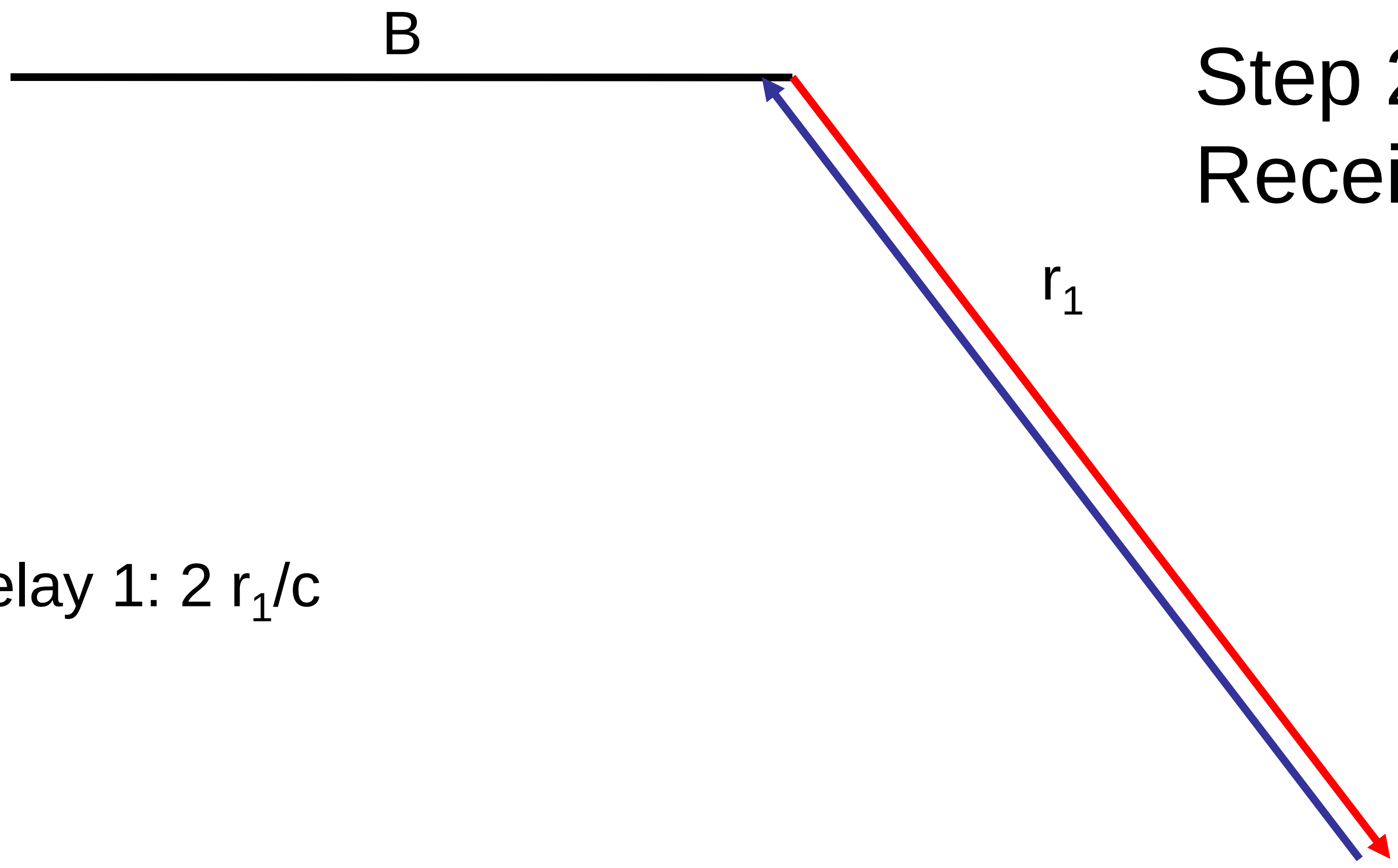
KaRIN Interferometry: Nominal Mode



Step 1:
Transmit 1

KaRIN Interferometry: Nominal Mode

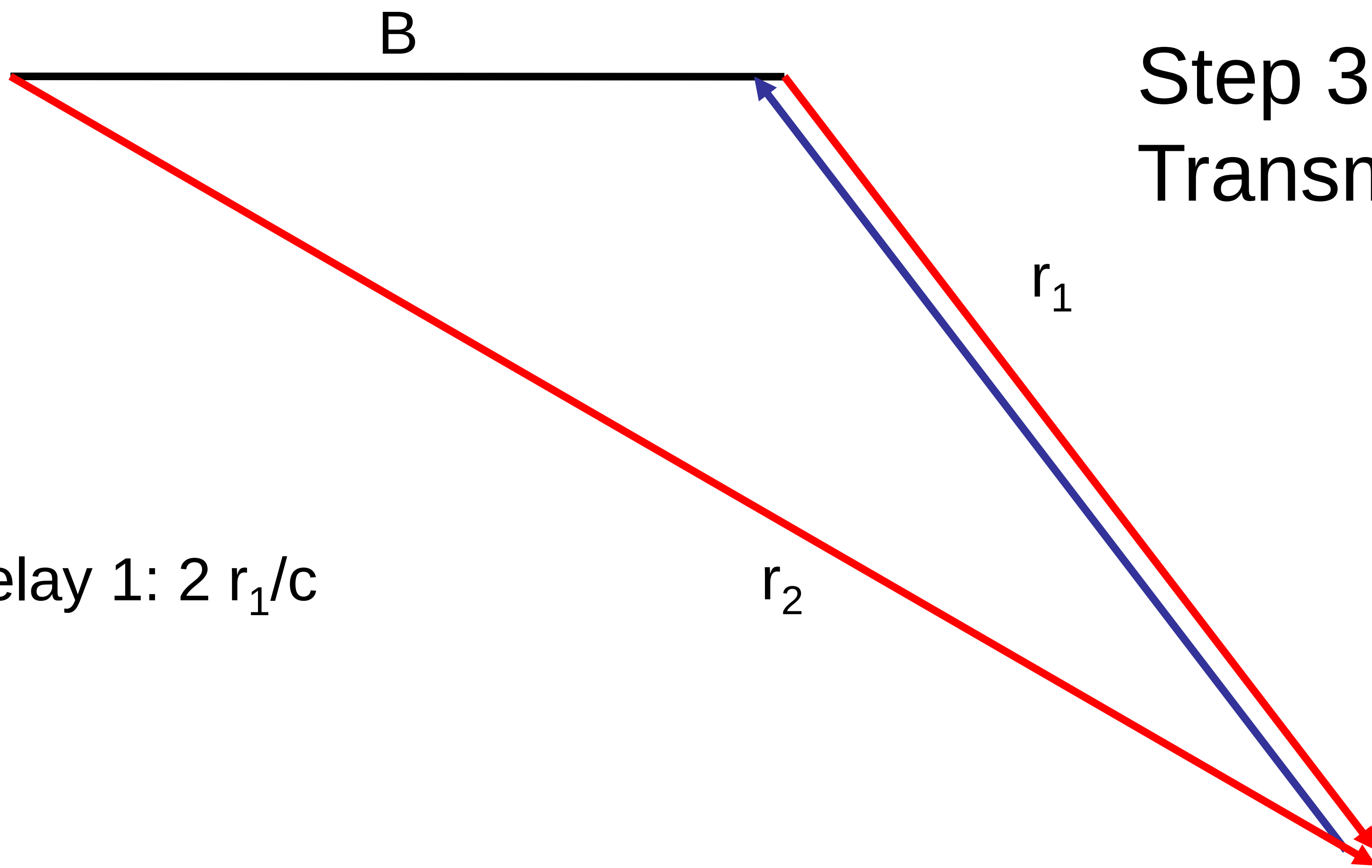
Step 2
Receive 1



Delay 1: $2\ r_1/c$

KaRIN Interferometry: Nominal Mode

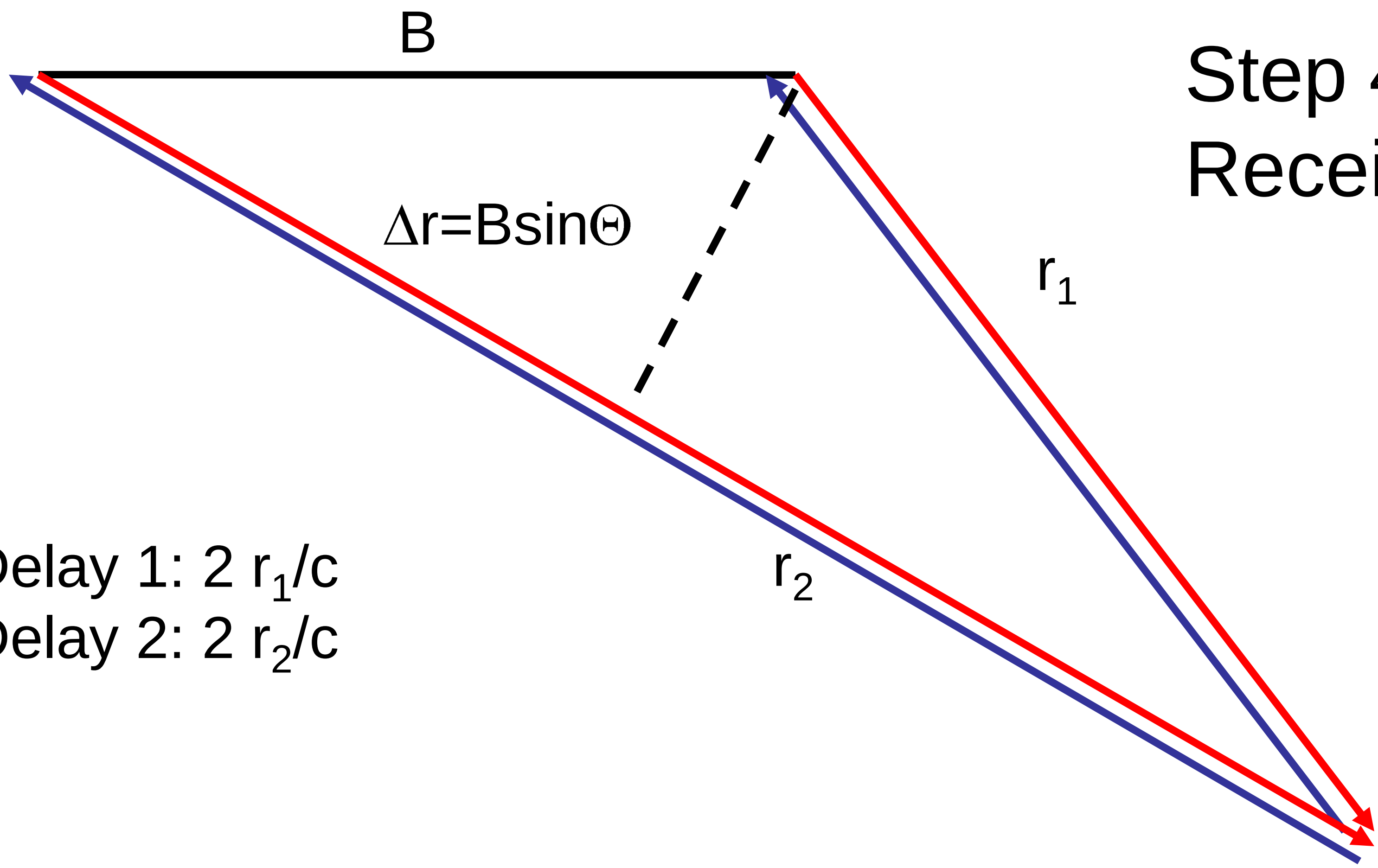
Step 3
Transmit 2



Delay 1: 2 r_1/c

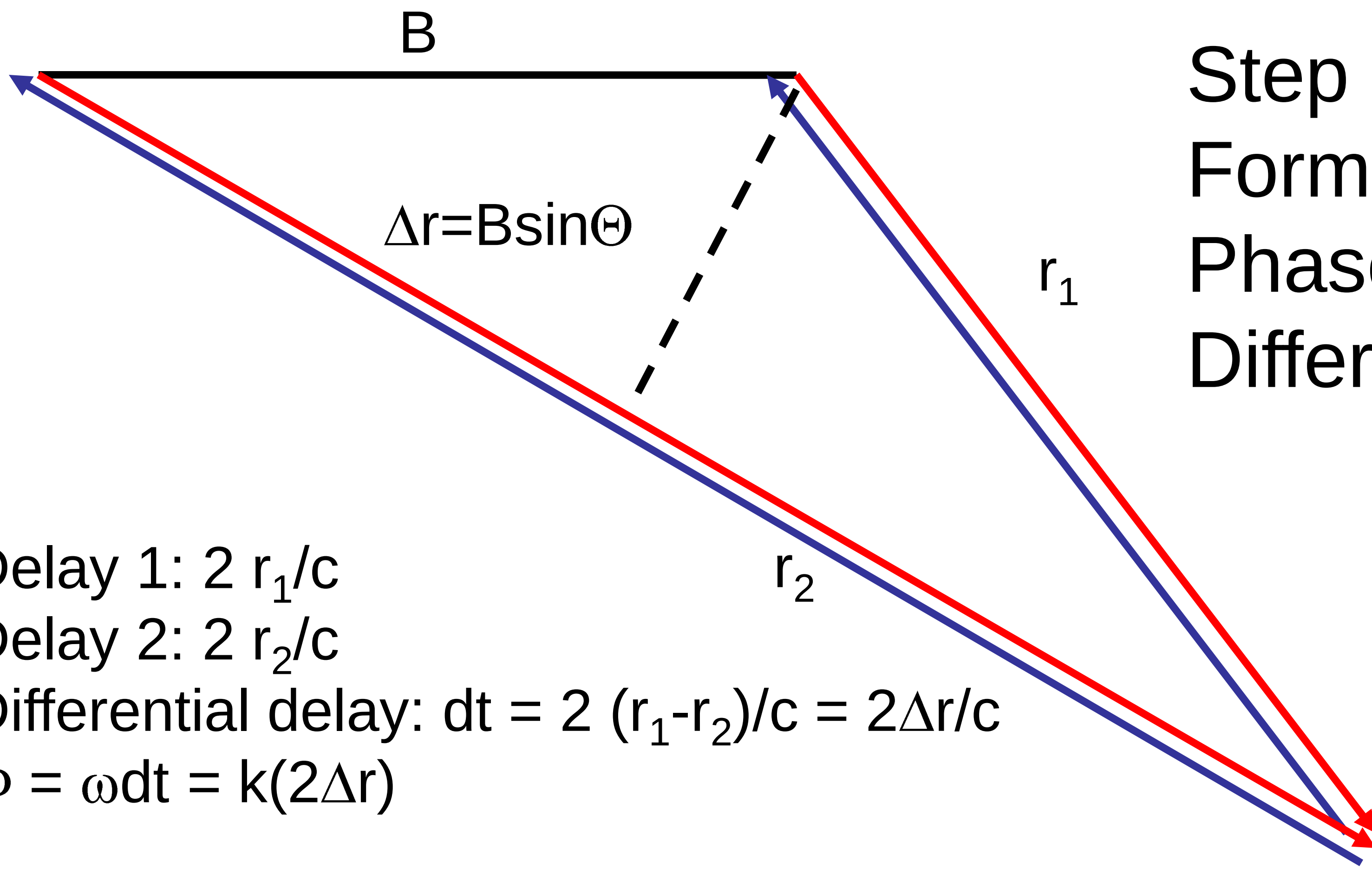
KaRIN Interferometry: Nominal Mode

Step 4
Receive 2



Delay 1: 2 r_1/c
Delay 2: 2 r_2/c

KaRIN Interferometry: Nominal Mode

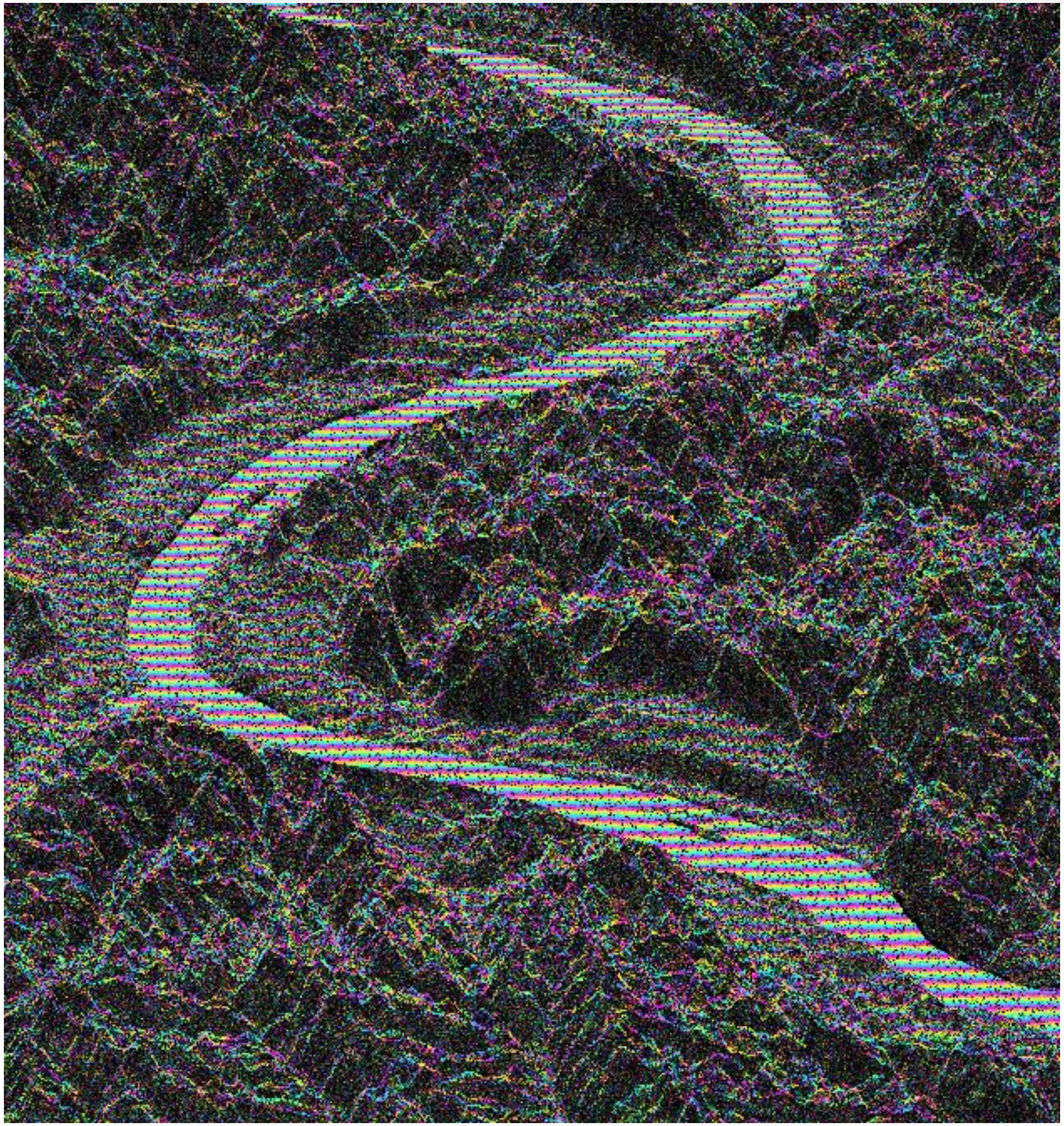


Step 5
Form
Phase
Difference

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

SWOT

Example SWOT Image



Color represents interferometric phase (modulo 2π)

Brightness is radar normalized cross section

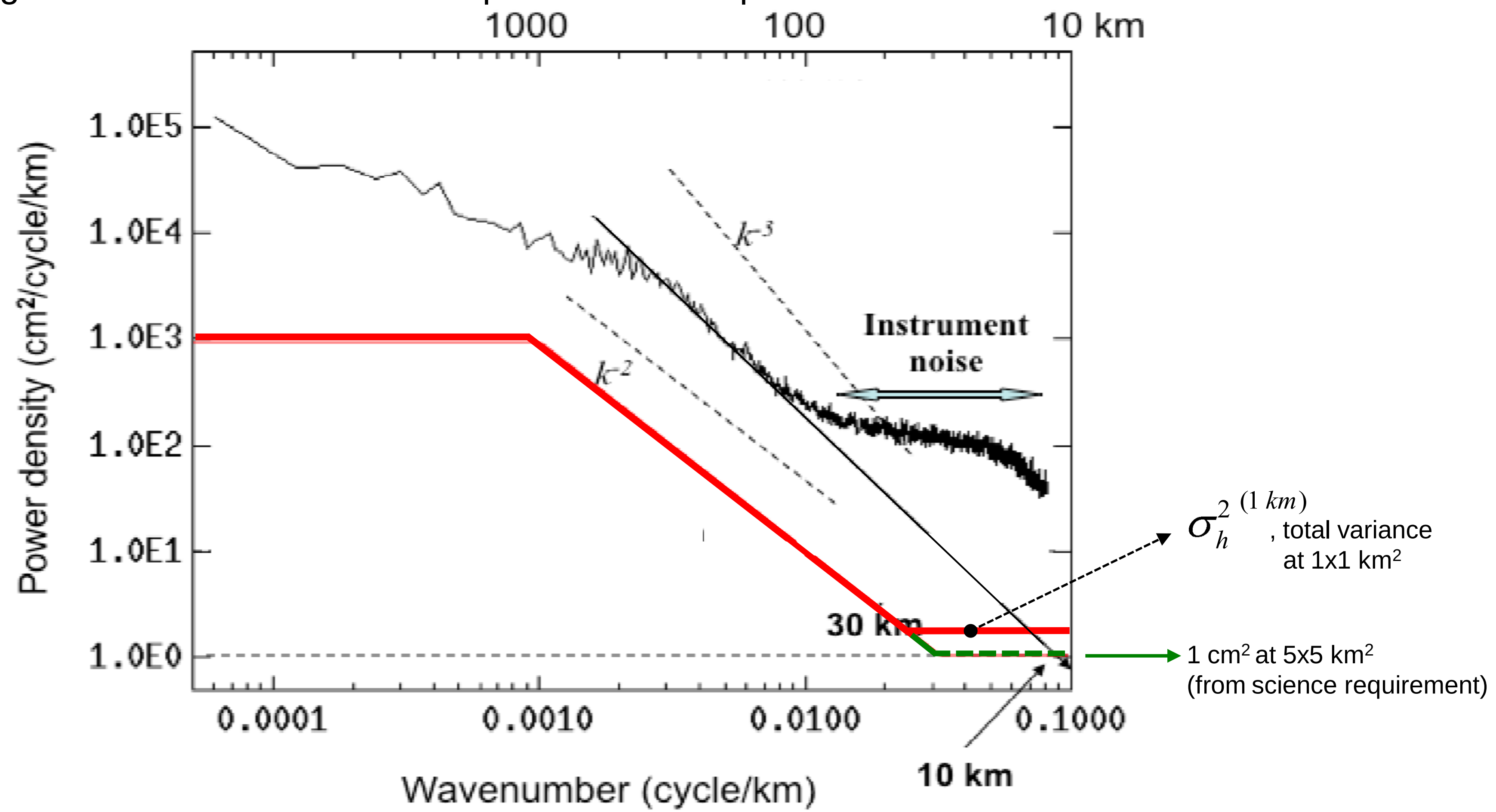
Spatial resolution:

Land: 2.5m x 10m – 70m

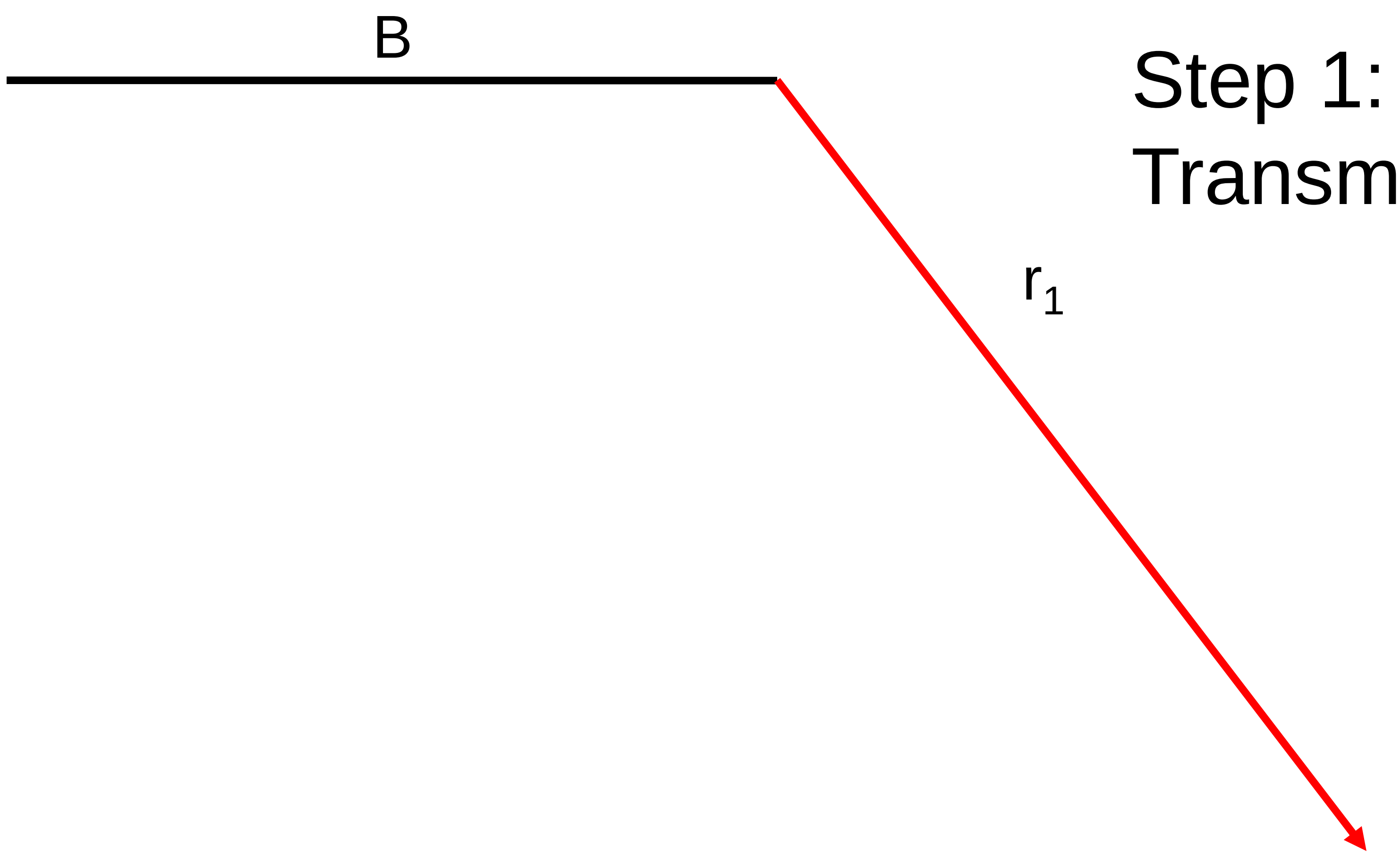
Ocean: 1 km x 1km

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.

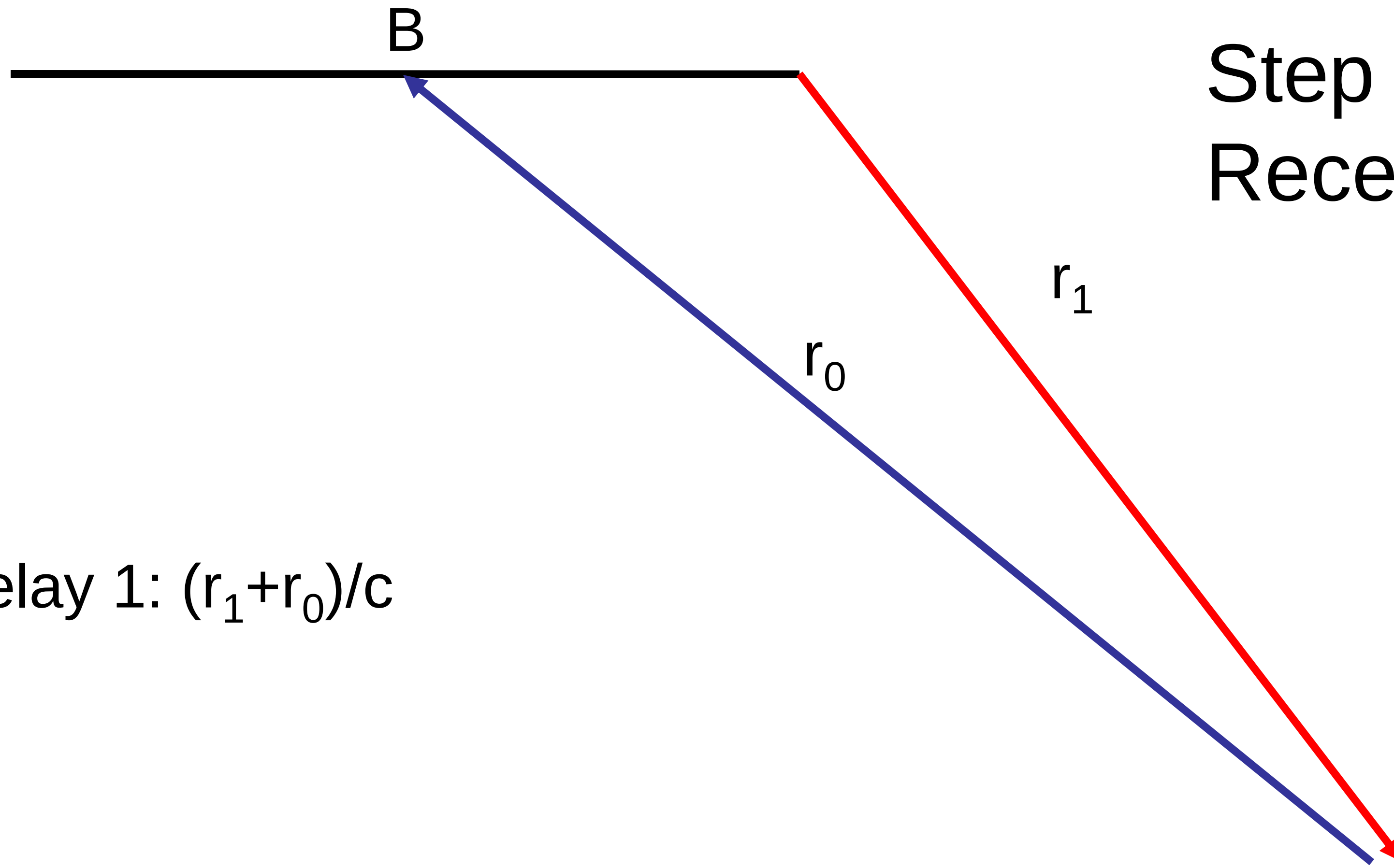


KaRIN Interferometry: Near-Nadir Mode



Step 1:
Transmit 1

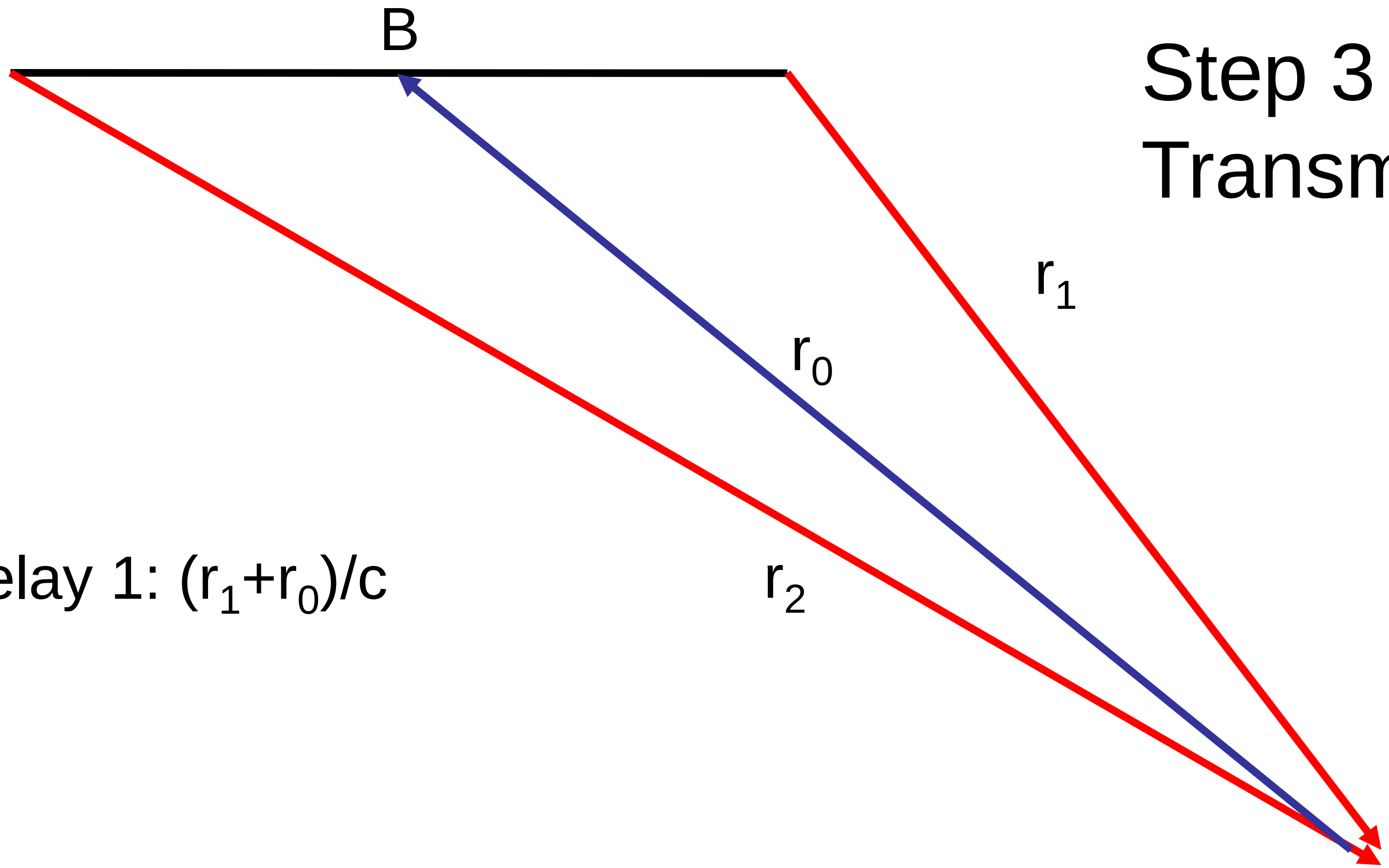
KaRIN Interferometry: Near-Nadir Mode



Step 2
Receive 0

Delay 1: $(r_1+r_0)/c$

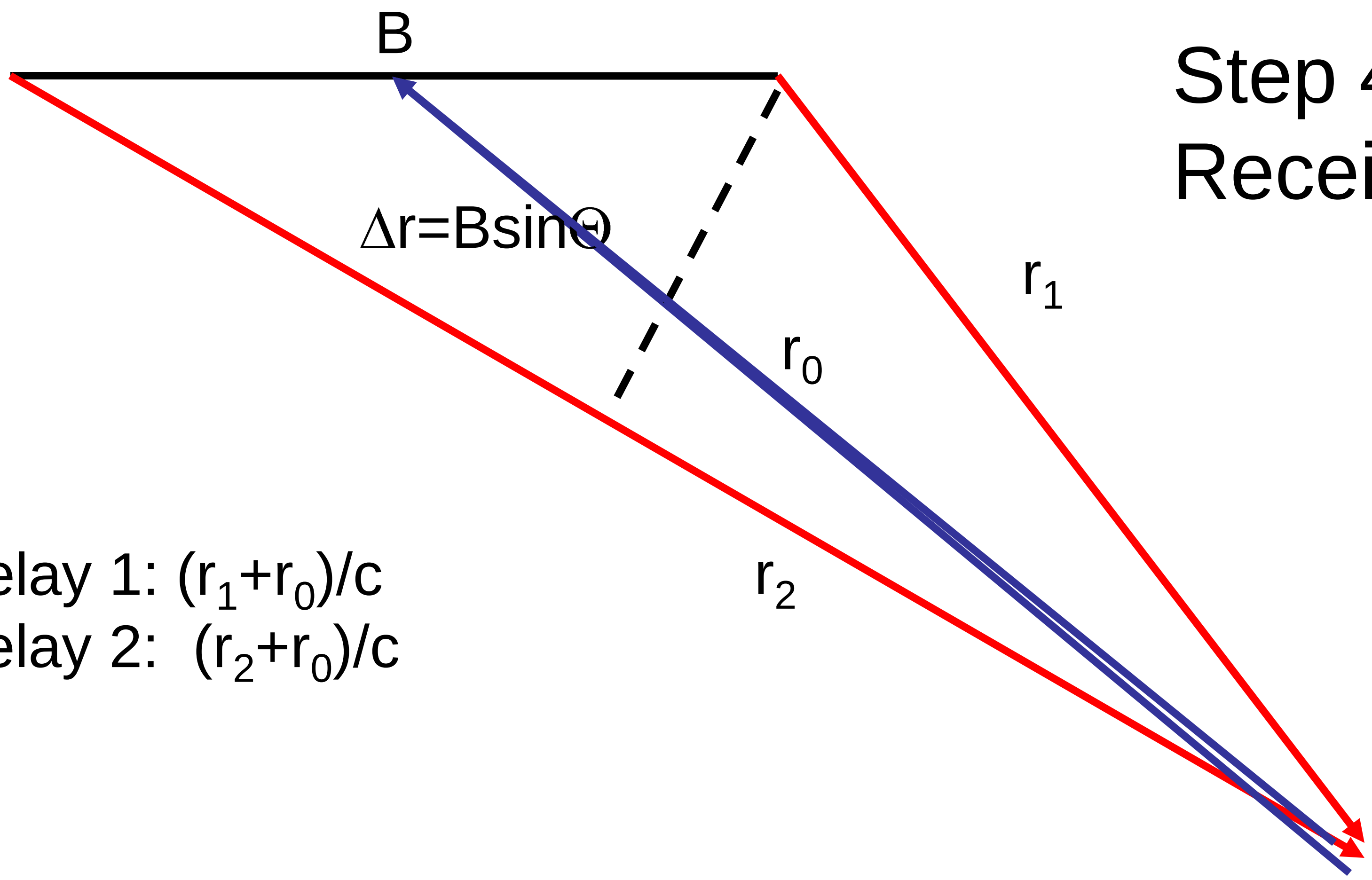
KaRIN Interferometry: Near-Nadir Mode



Step 3
Transmit 2

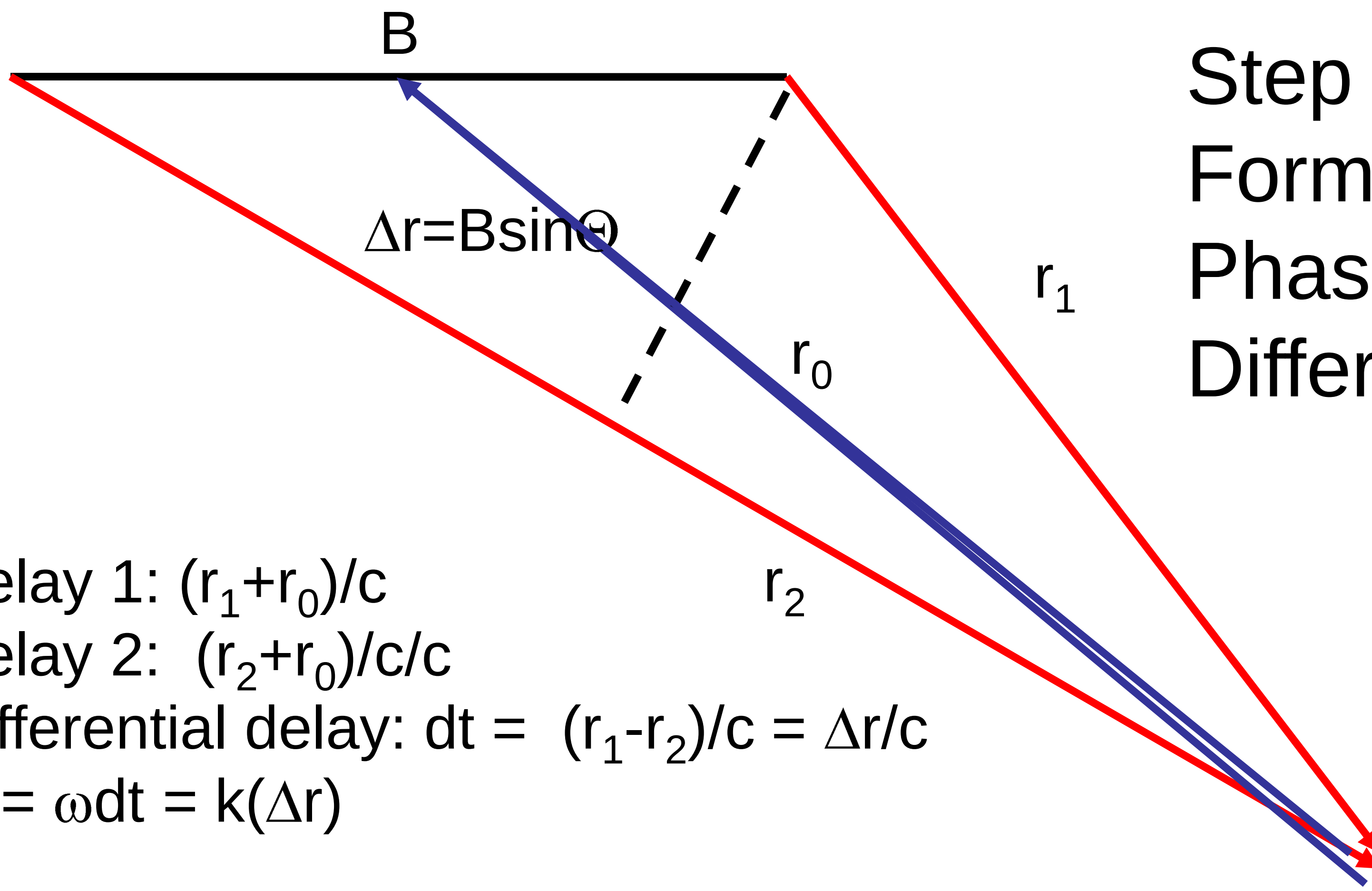
Delay 1: $(r_1+r_0)/c$

KaRIN Interferometry: Near-Nadir Mode



Step 4
Receive 0

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

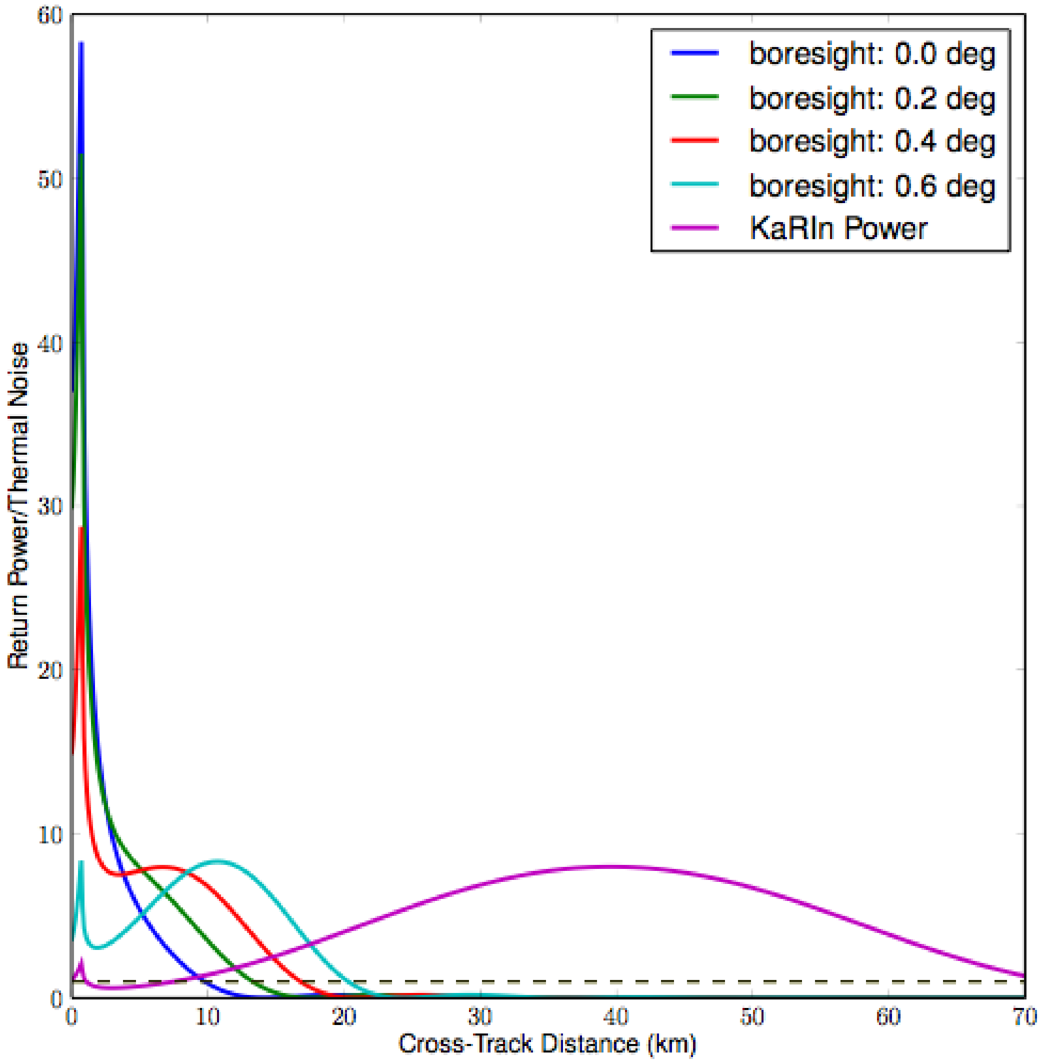


Step 5
Form
Phase
Difference

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

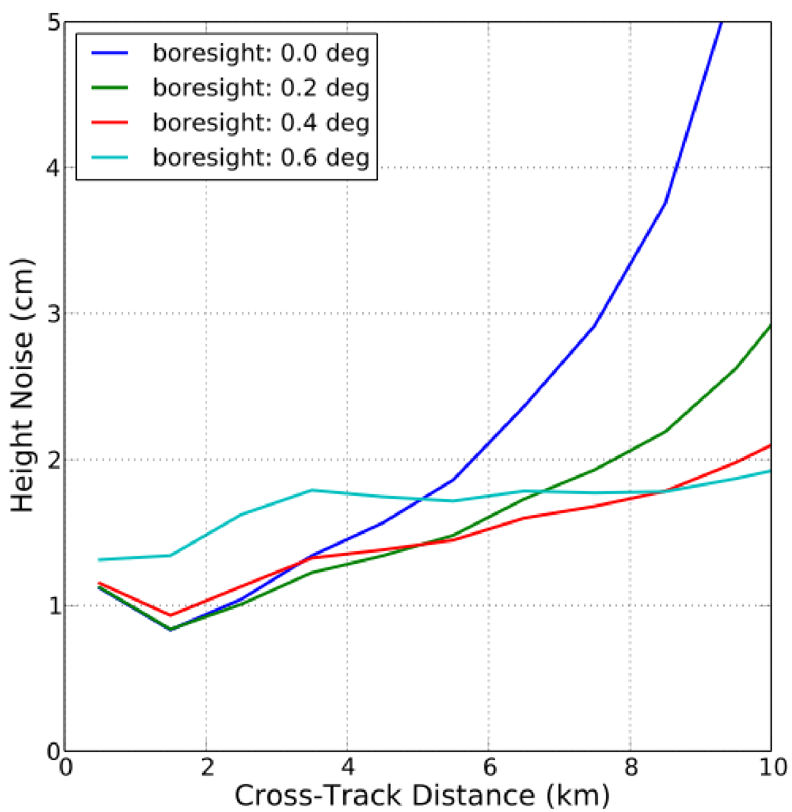
The effective baseline is ½ nominal baseline

There is enough KaRIn power in the near-nadir direction?

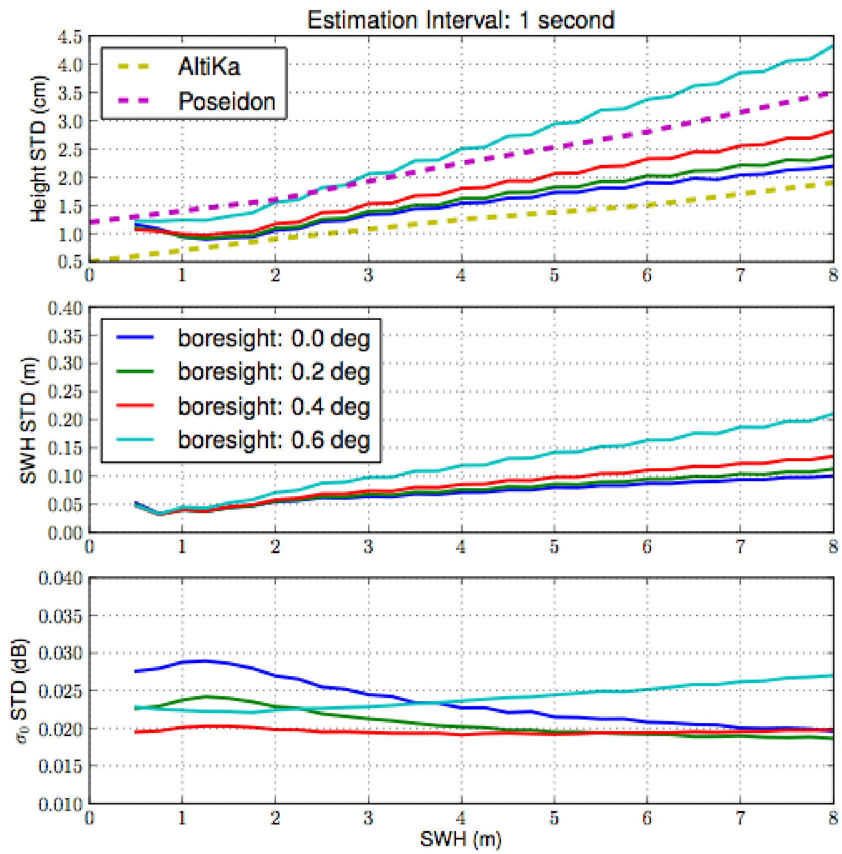


- Getting appropriate signal to noise ratio over the swath up to and past 10 km probably requires separate tilted feeds for each (right/left) swath.
- There is significantly more power in the near swath compared to KaRIN nominal mode
- However, there is only ½ the baseline

KaRIN Near-nadir Performance



KaRIN Altimeter Performance



What are the Basic KaRIN Products?

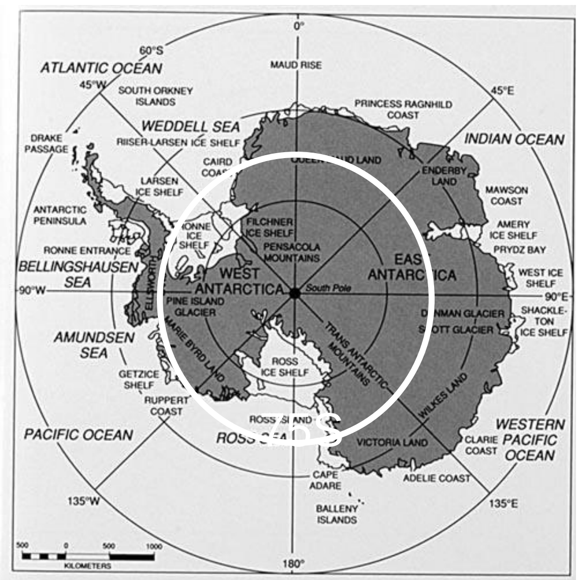
Hydrology

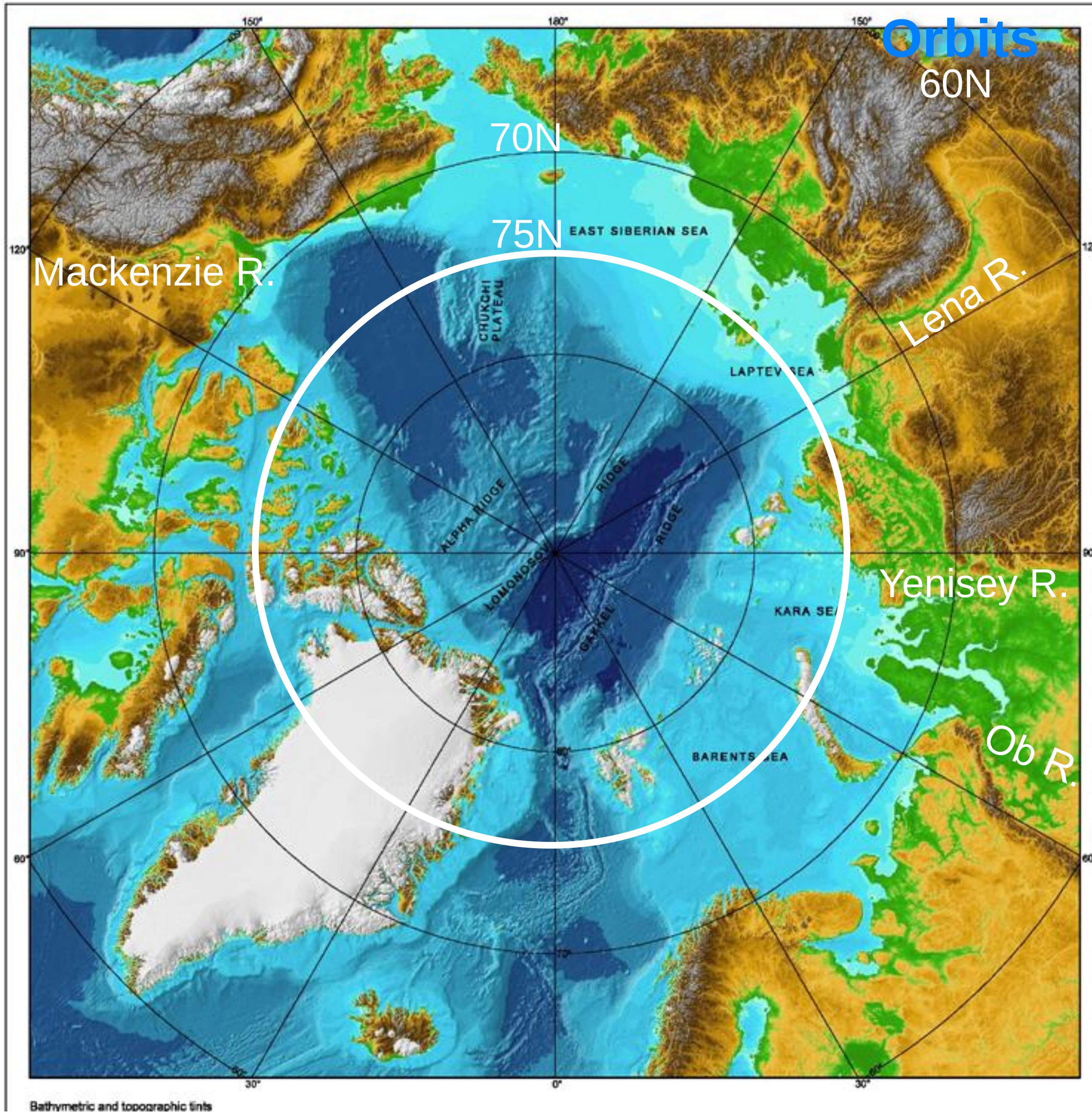
- Water surface elevation for all water bodies
    - Geolocated elevations reported on an irregular grid conformal to the water body shape
    - Order of magnitude resolution: 50 m
- Water extent gelocated mask on irregular grid conformal to water body shape
- Elevation and classification updated every 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

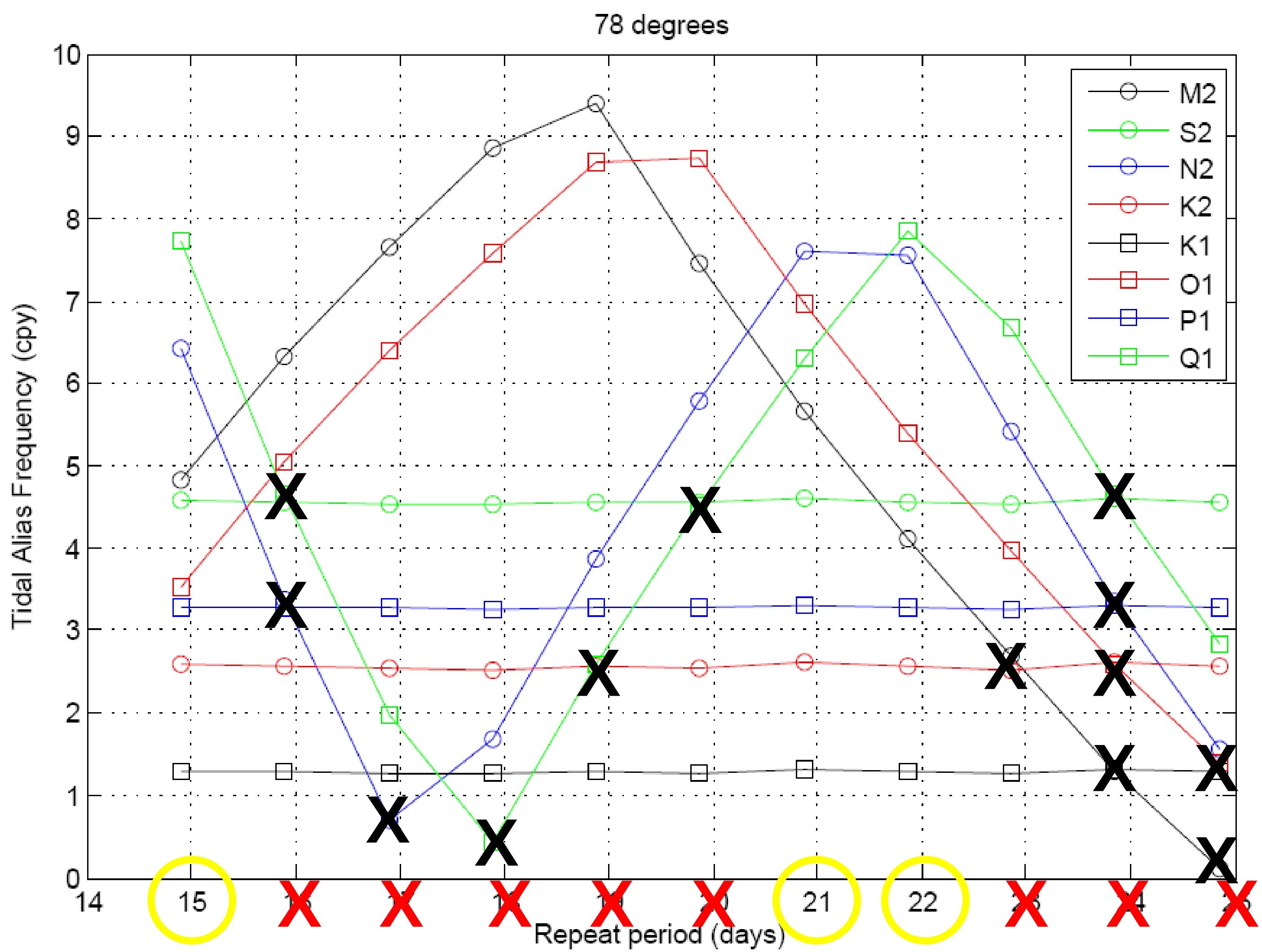
- >74N is OK
- 66N is not





Courtesy D. Alsdorf, OSU

Tidal Aliasing: i = 78°



Courtesy S. Nerem et al.

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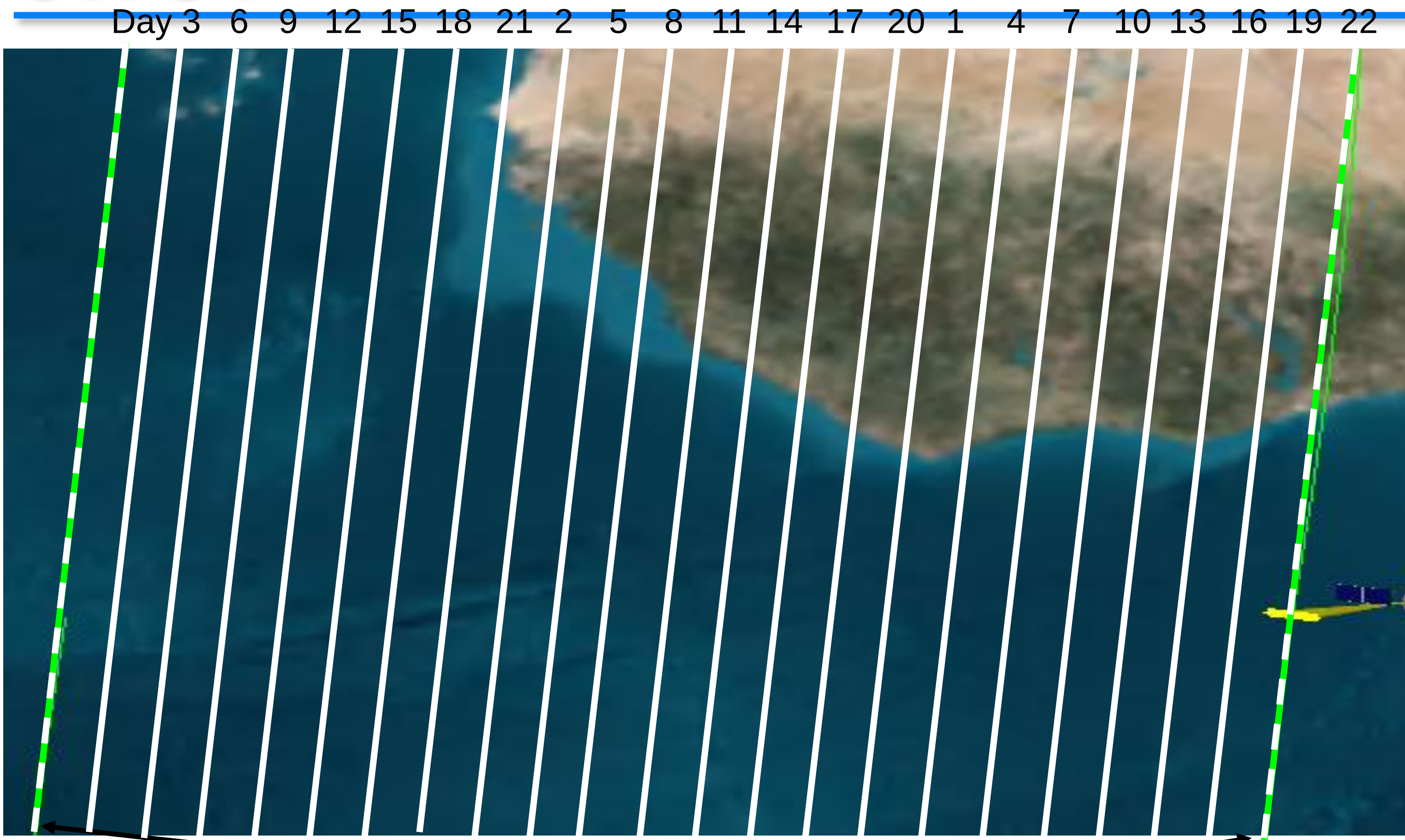
22-Day Repeat, 3-Day Subcycle

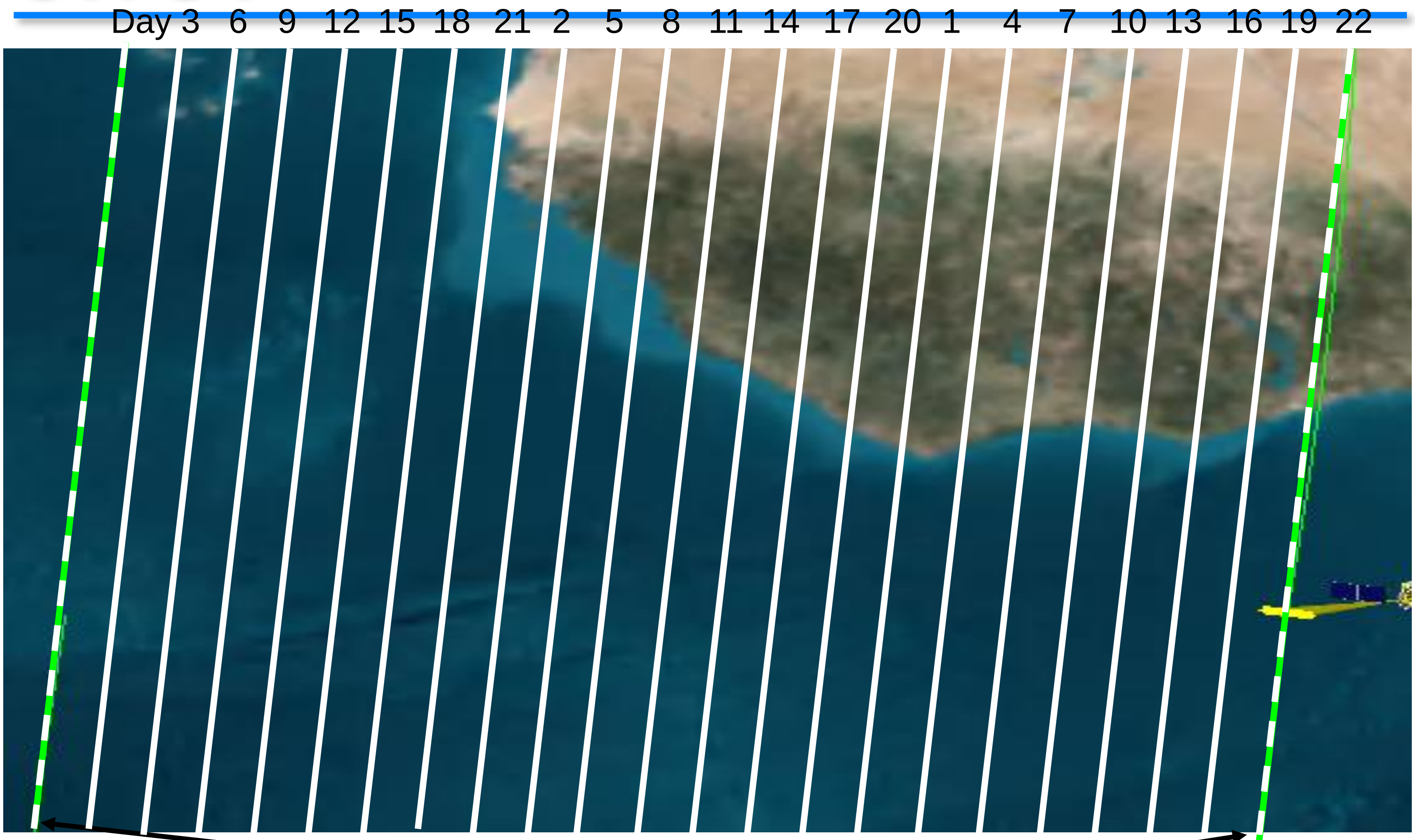


Base Interval
~25° or ~3000 km

Courtesy S. Nerem et al.

SWOT

3-Day Repeat

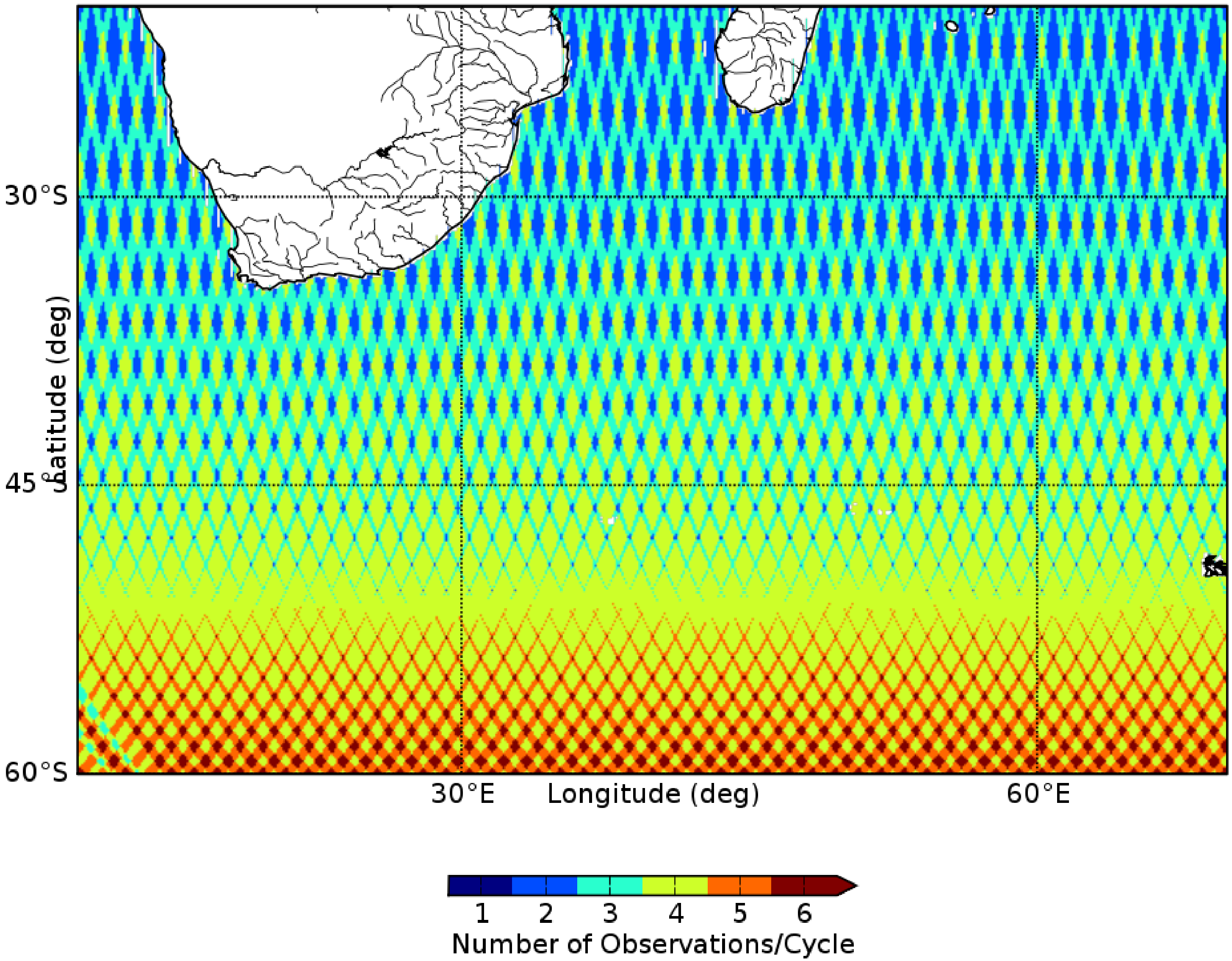


Base Interval
~25° or ~3000
km

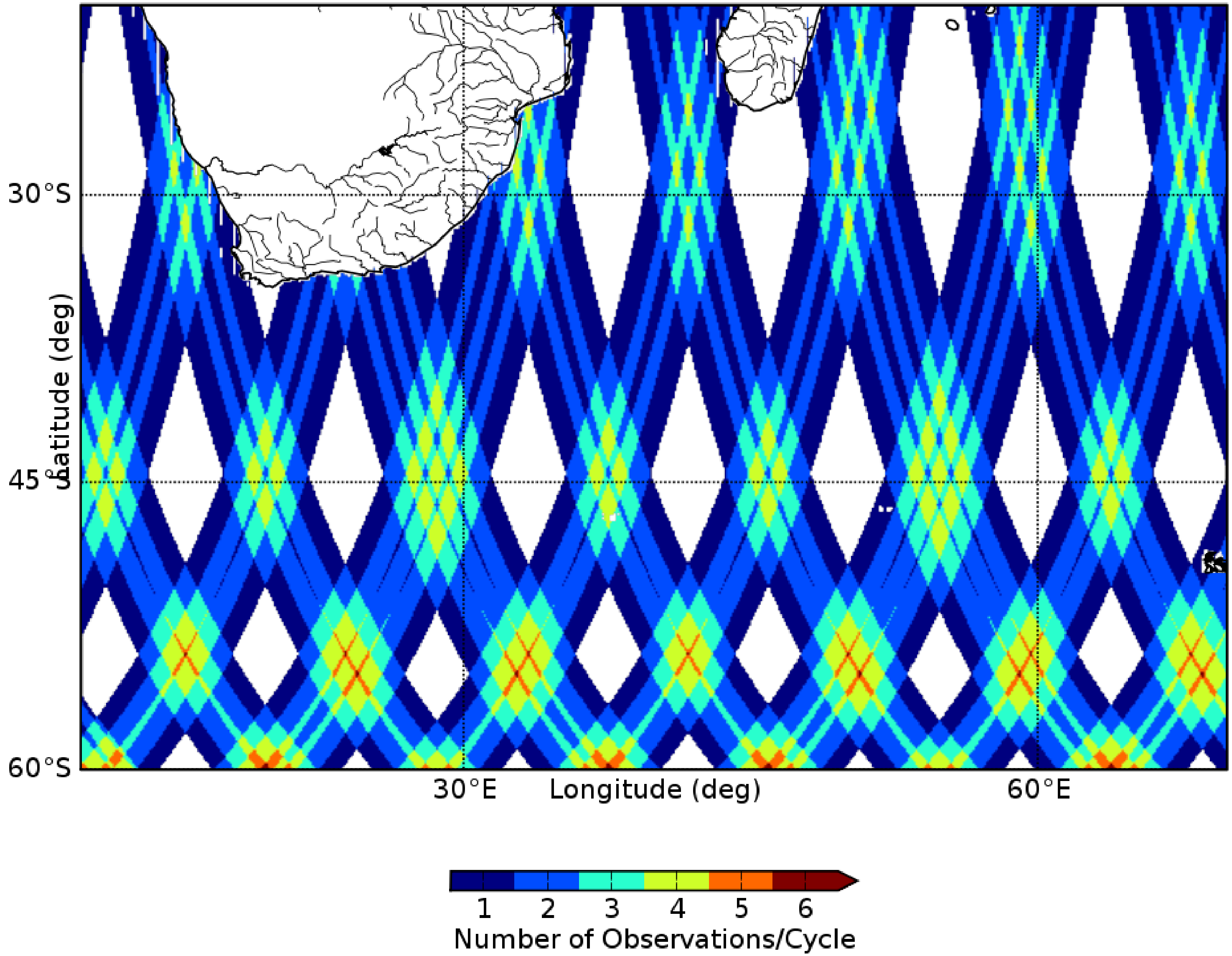
Courtesy S. Nerem et al.

SWOT

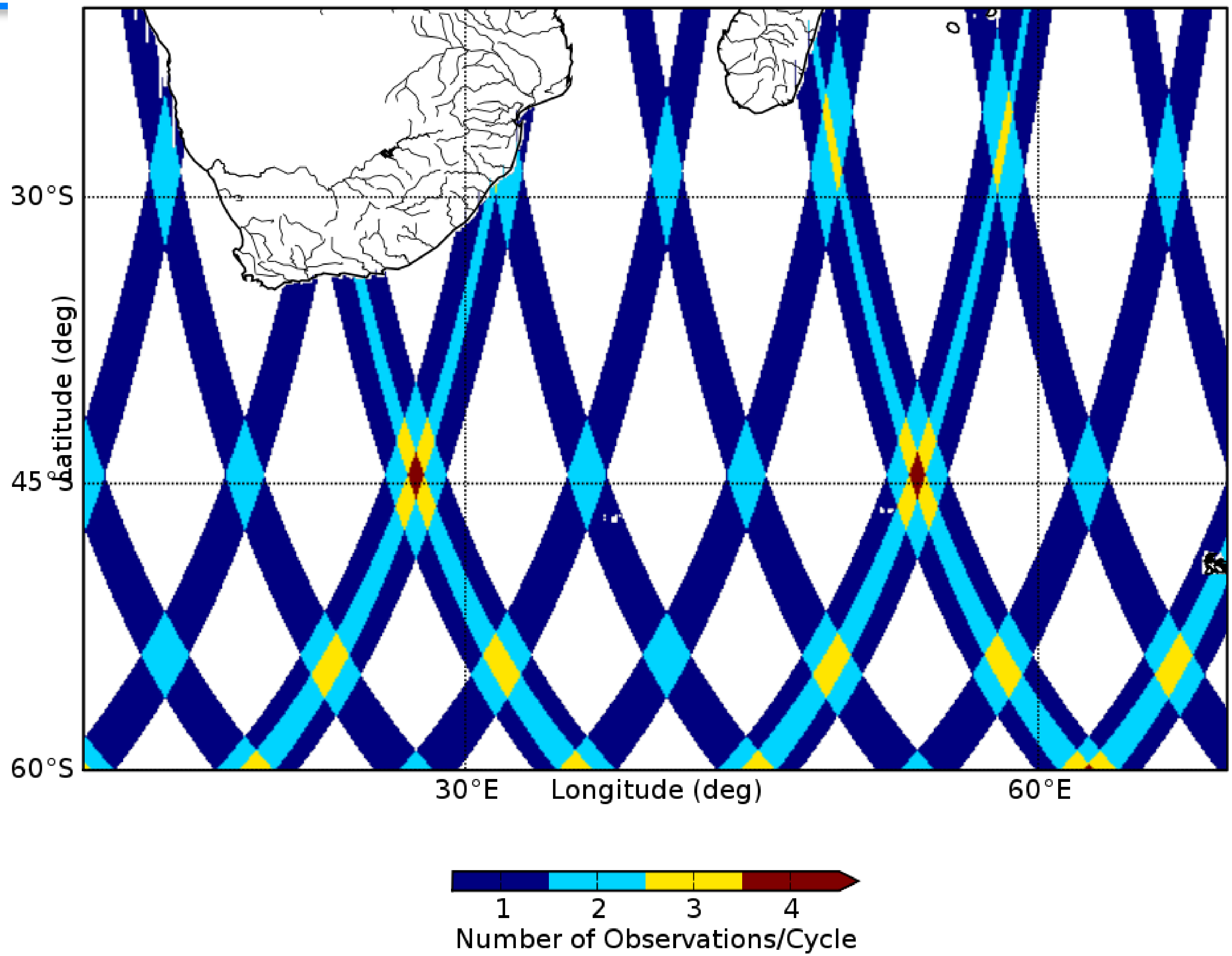
22-Day Repeat, Aghulas



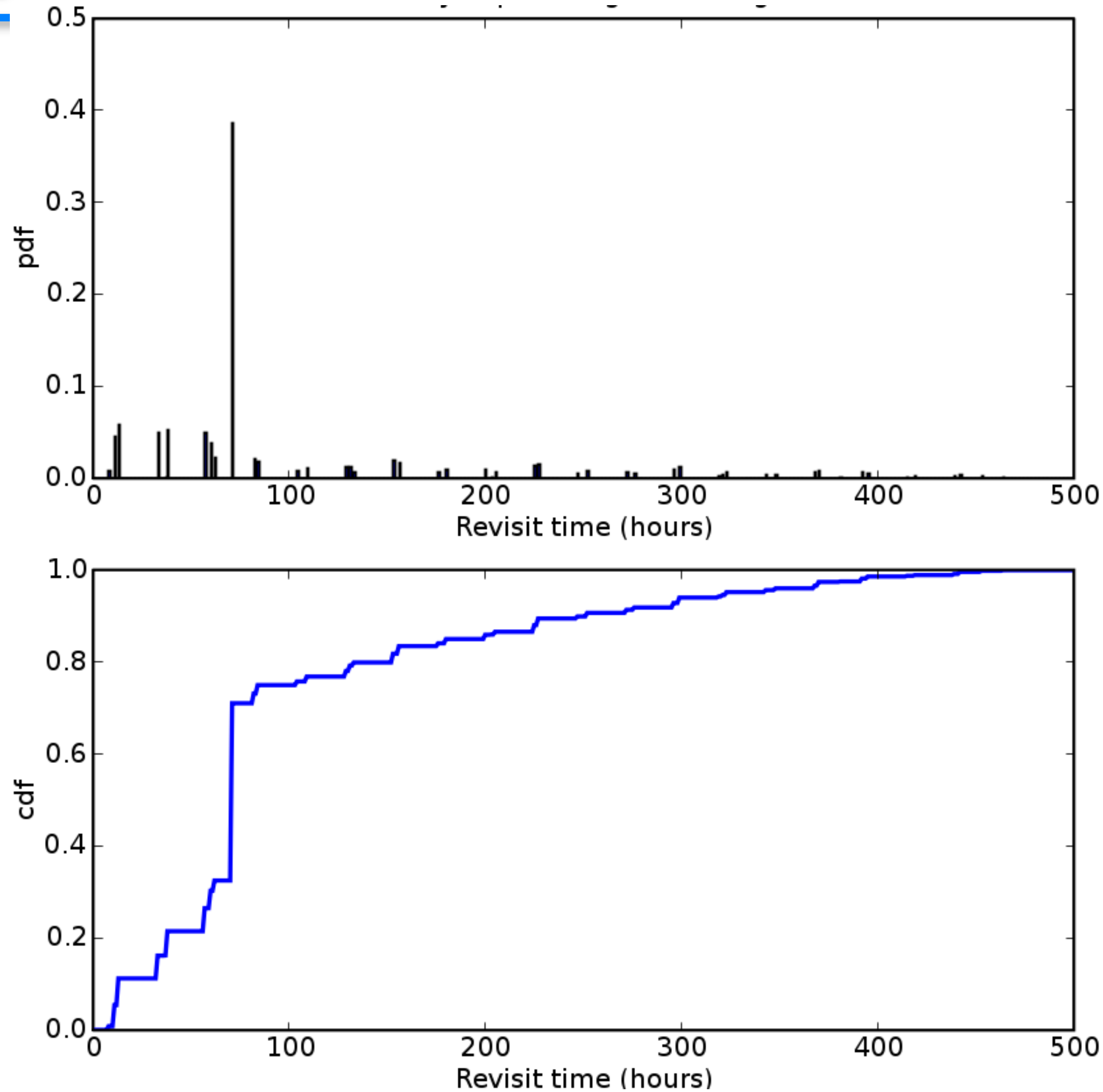
10 days of 22-Day Repeat, Aghulas



4-Days of 22-Day Repeat, Aghulas

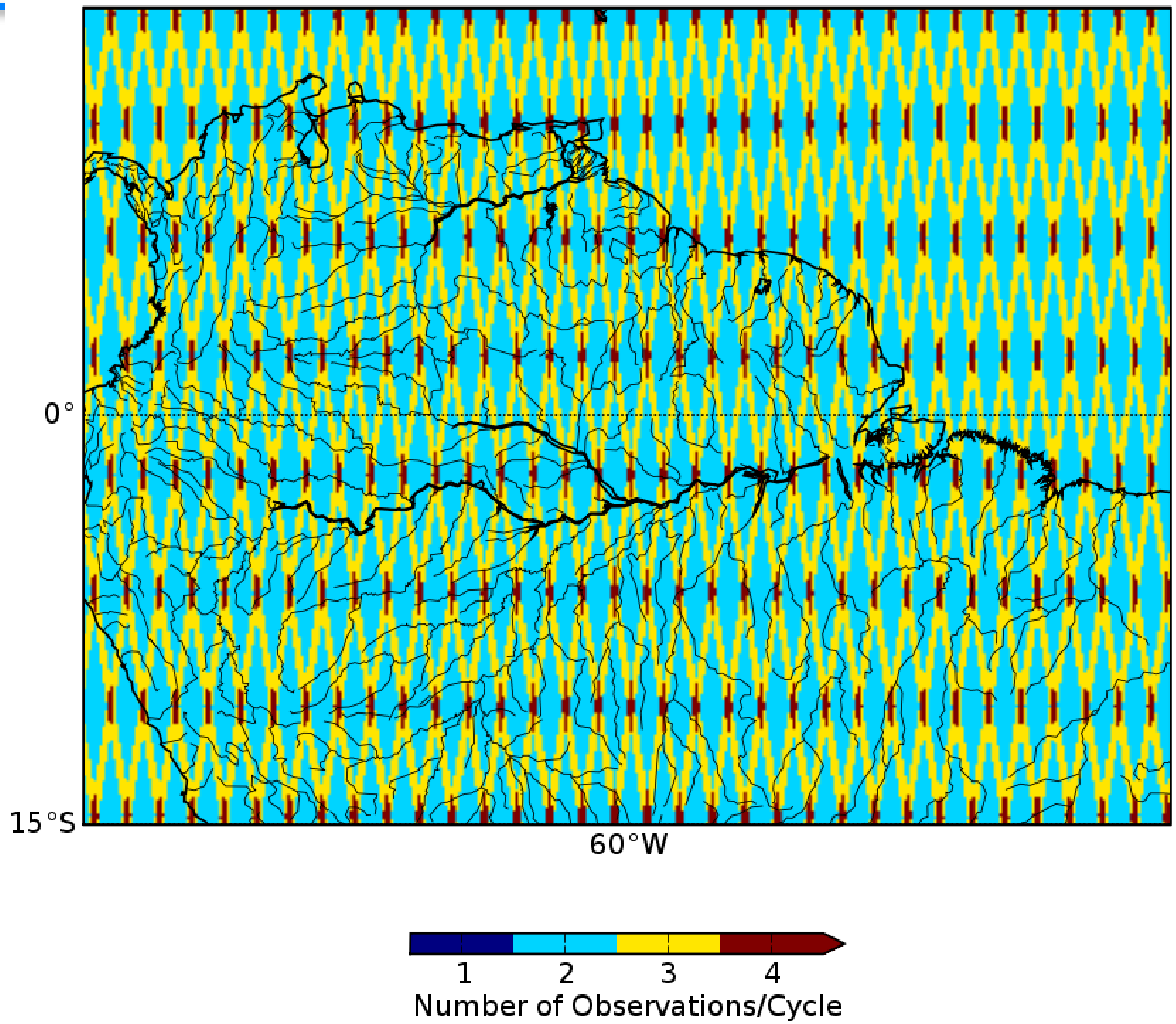


22-Day Repeat, Aghulas



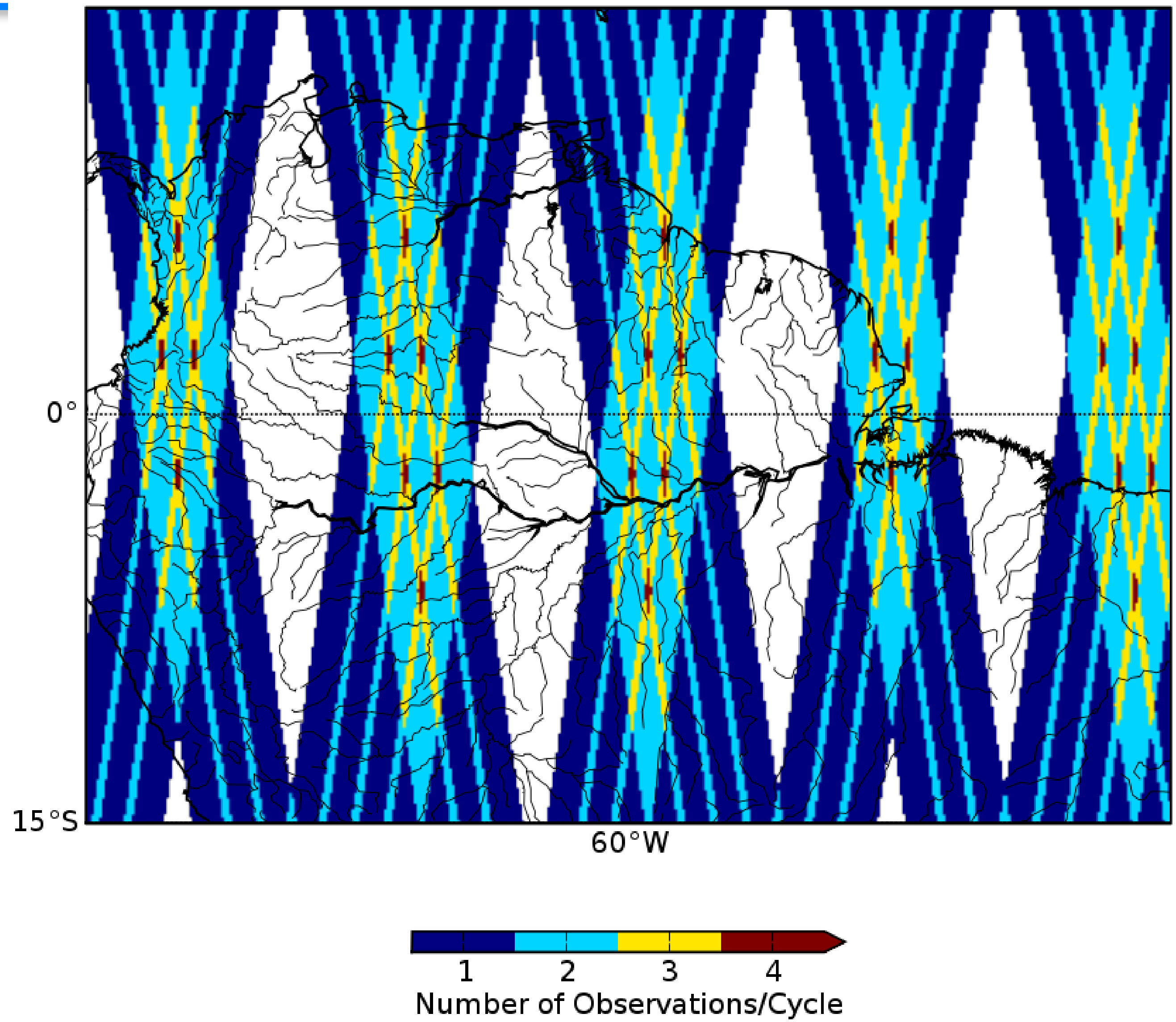
SWOT

22-Day Repeat, Amazon



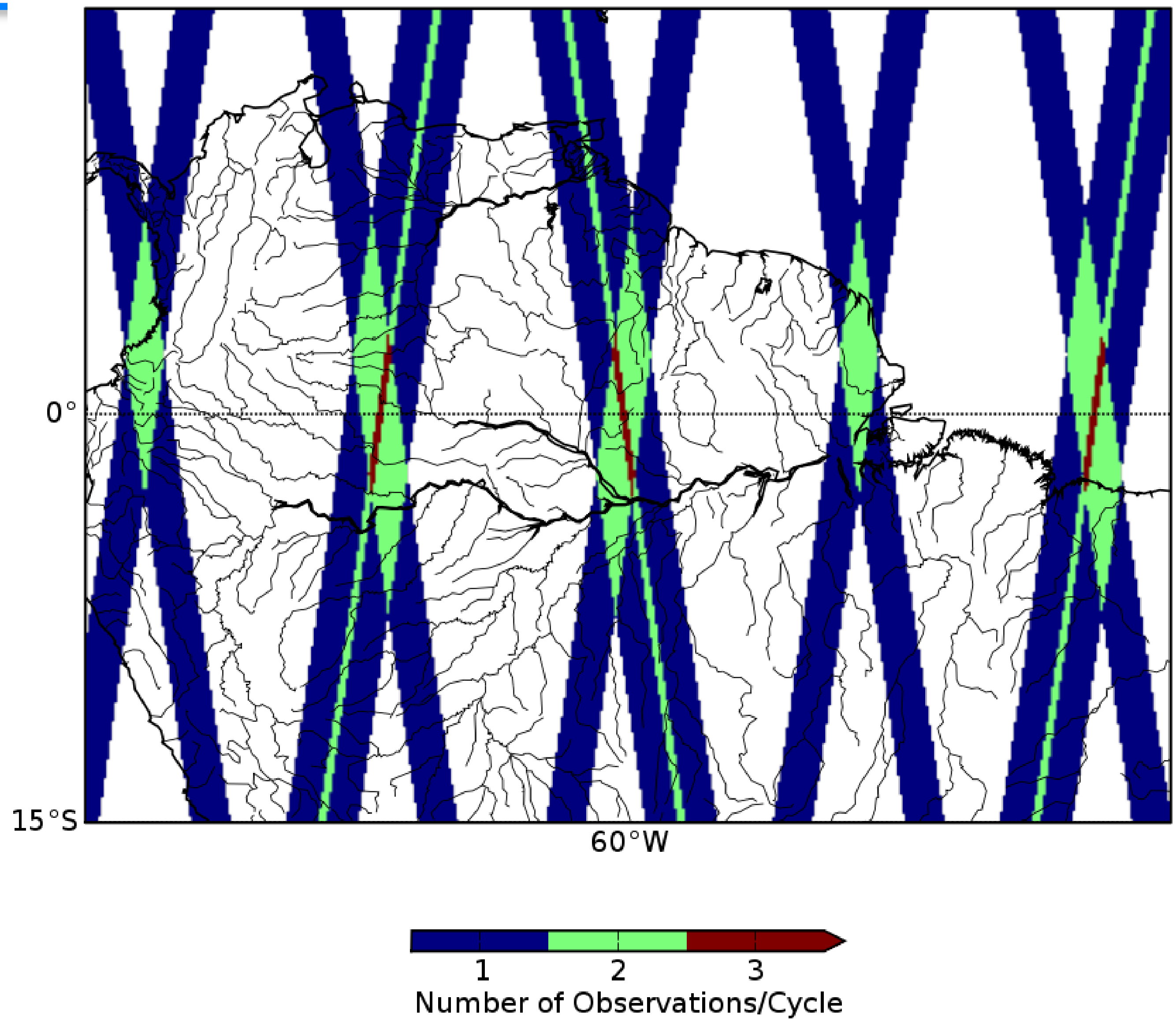
SWOT

10 Days of 22-Day Repeat, Amazon



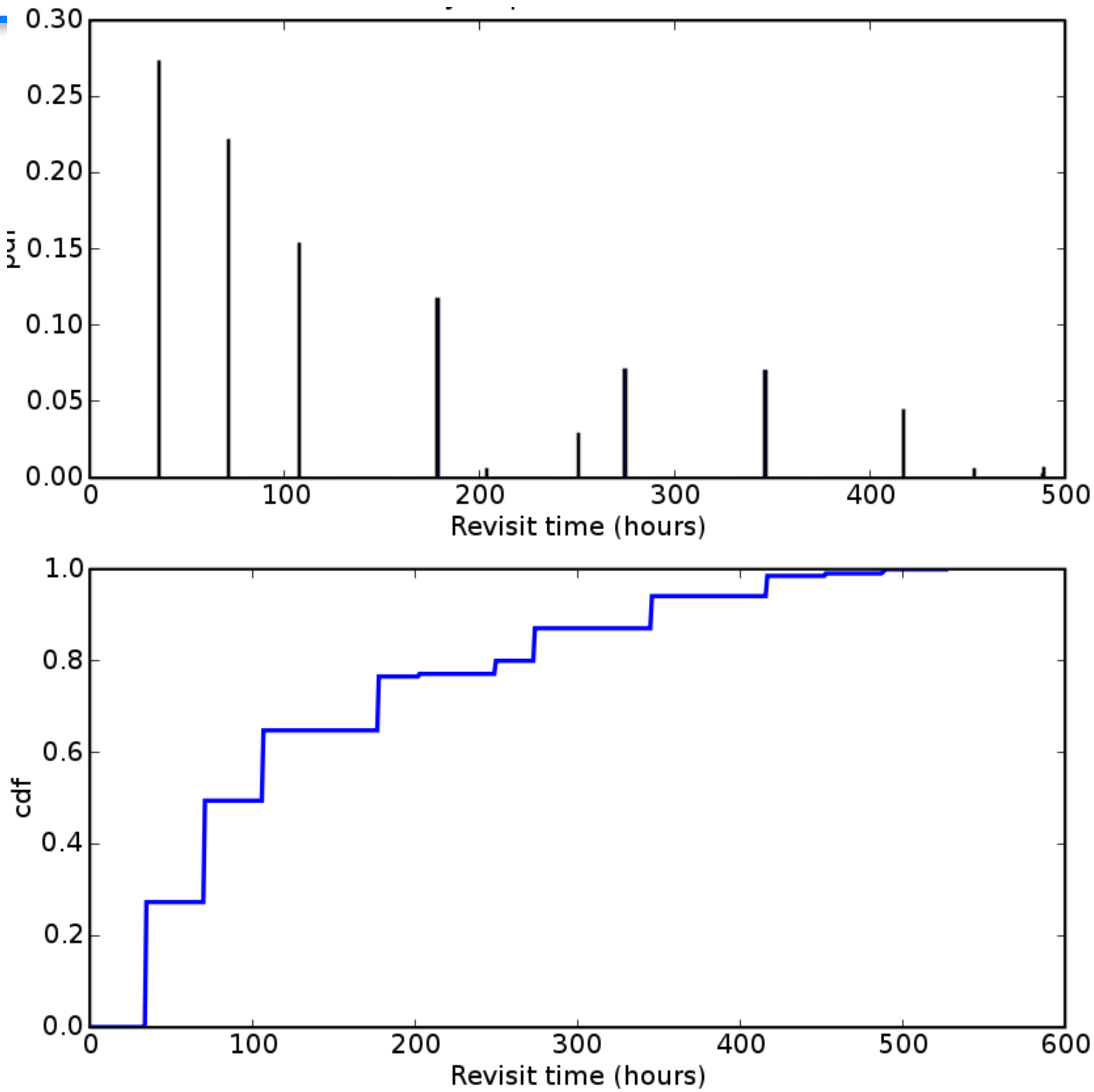
SWOT

4-Days of 22-Day Repeat, Amazon

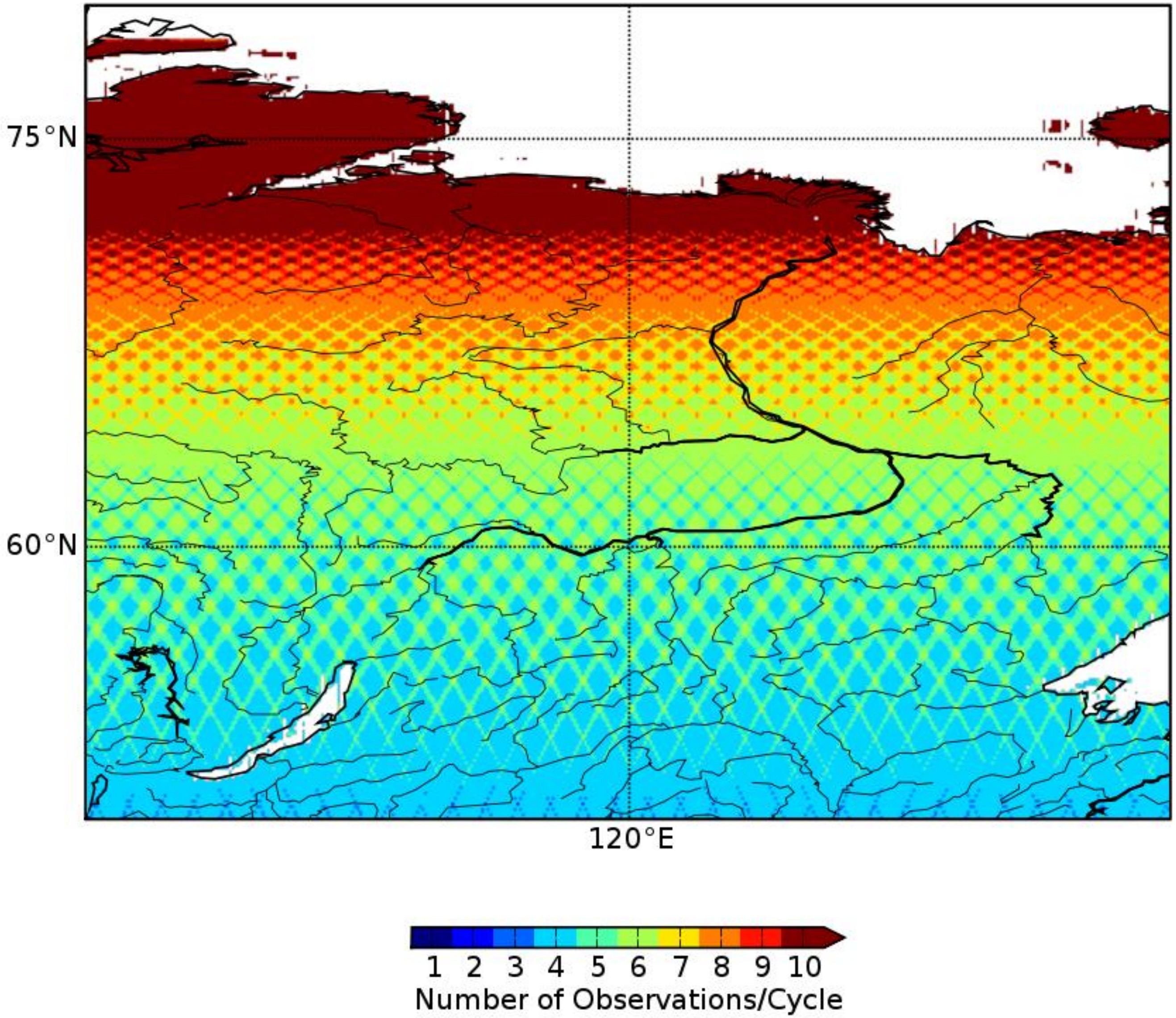


SWOT

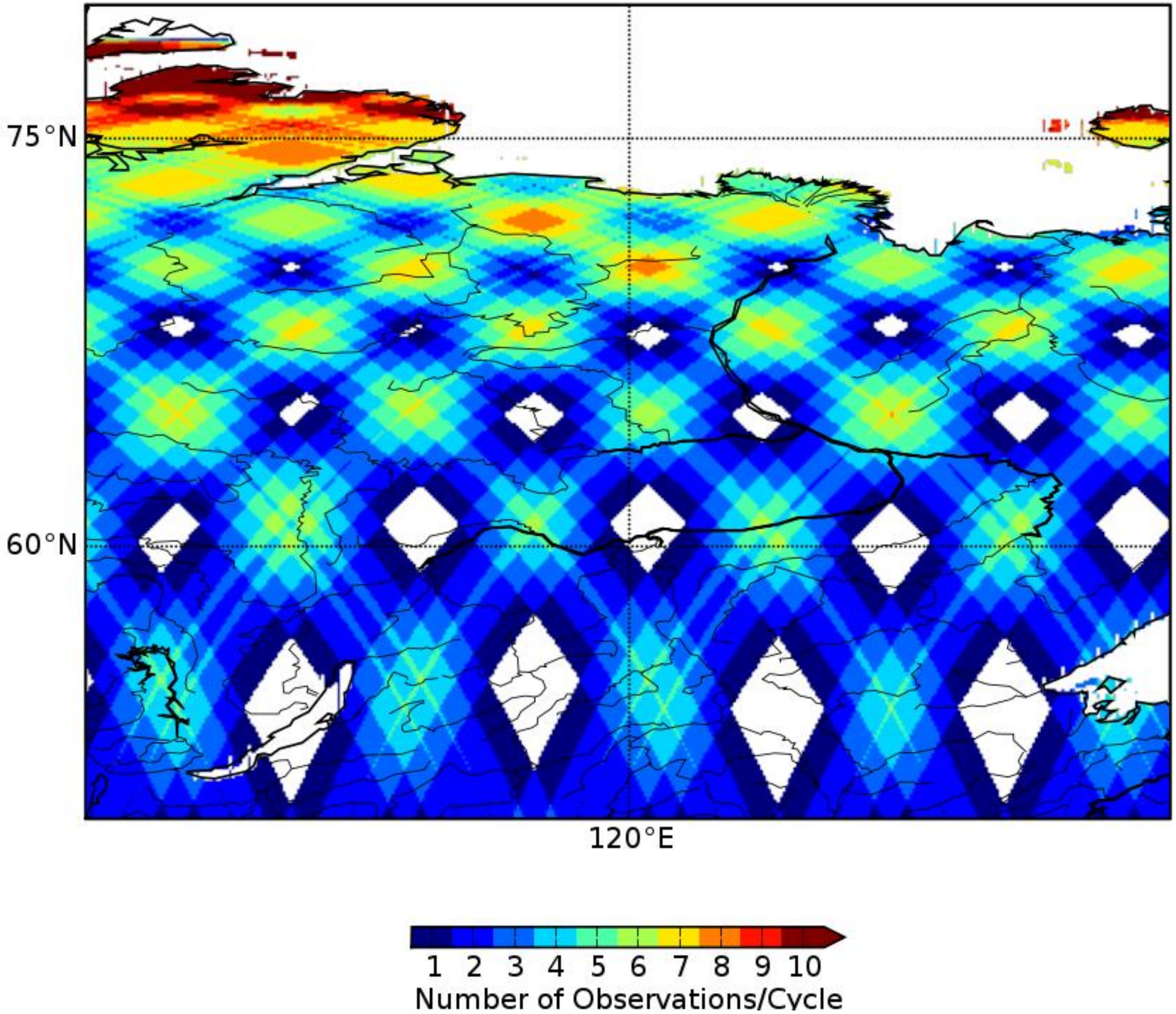
22-Day Repeat, Amazon



22-Day Repeat, Lena

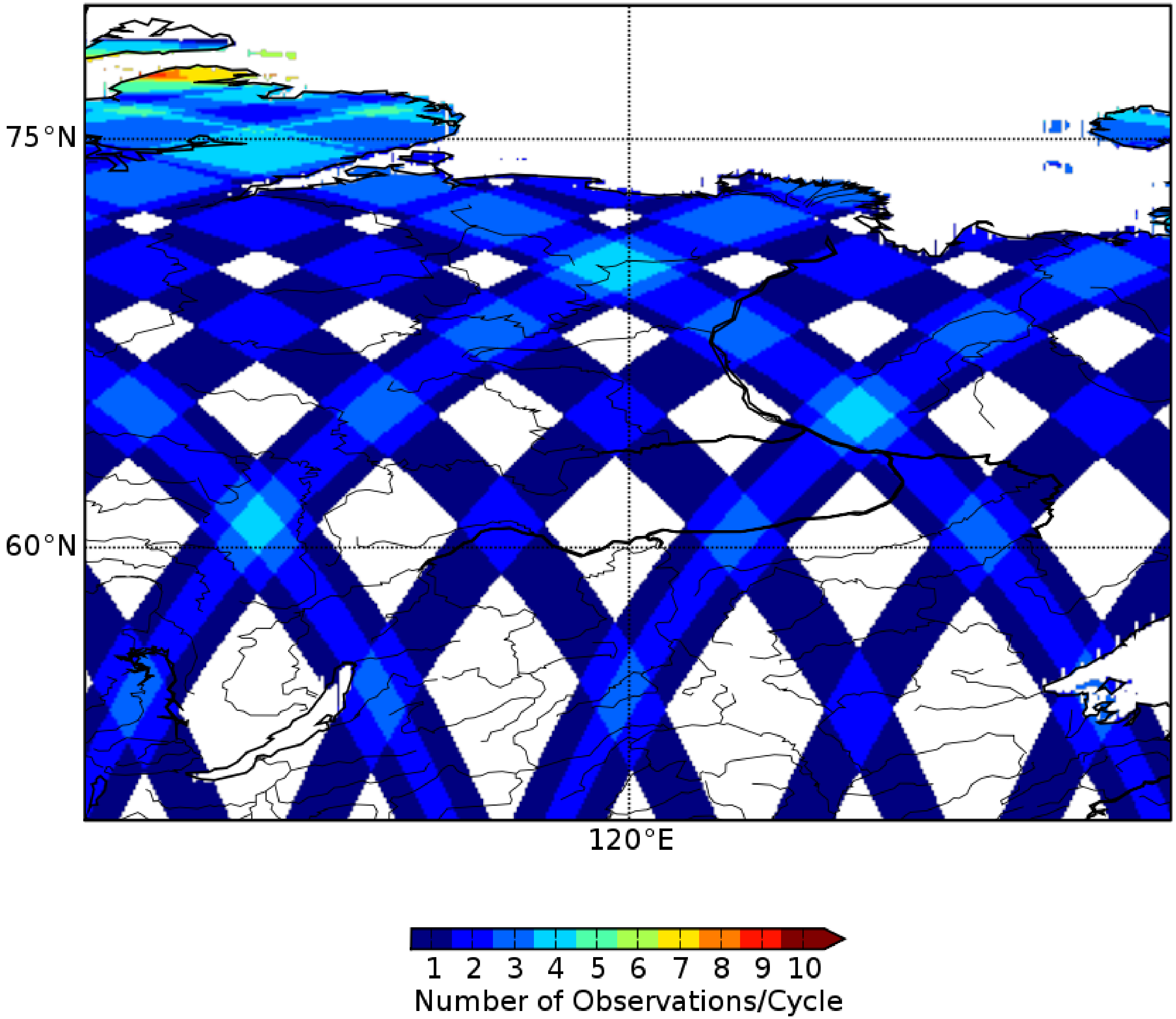


10 Days of 22-Day Repeat, Lena

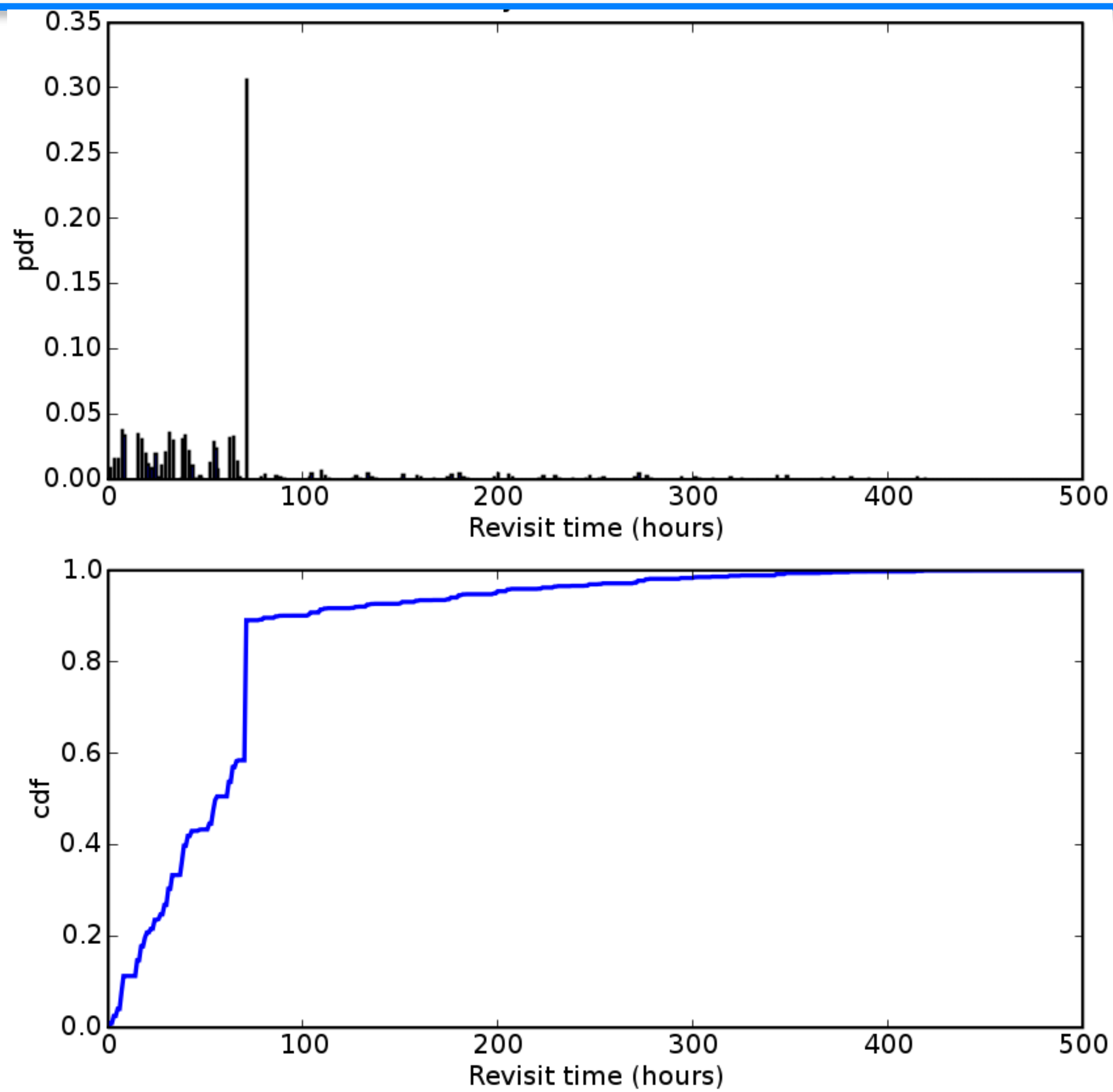


SWOT

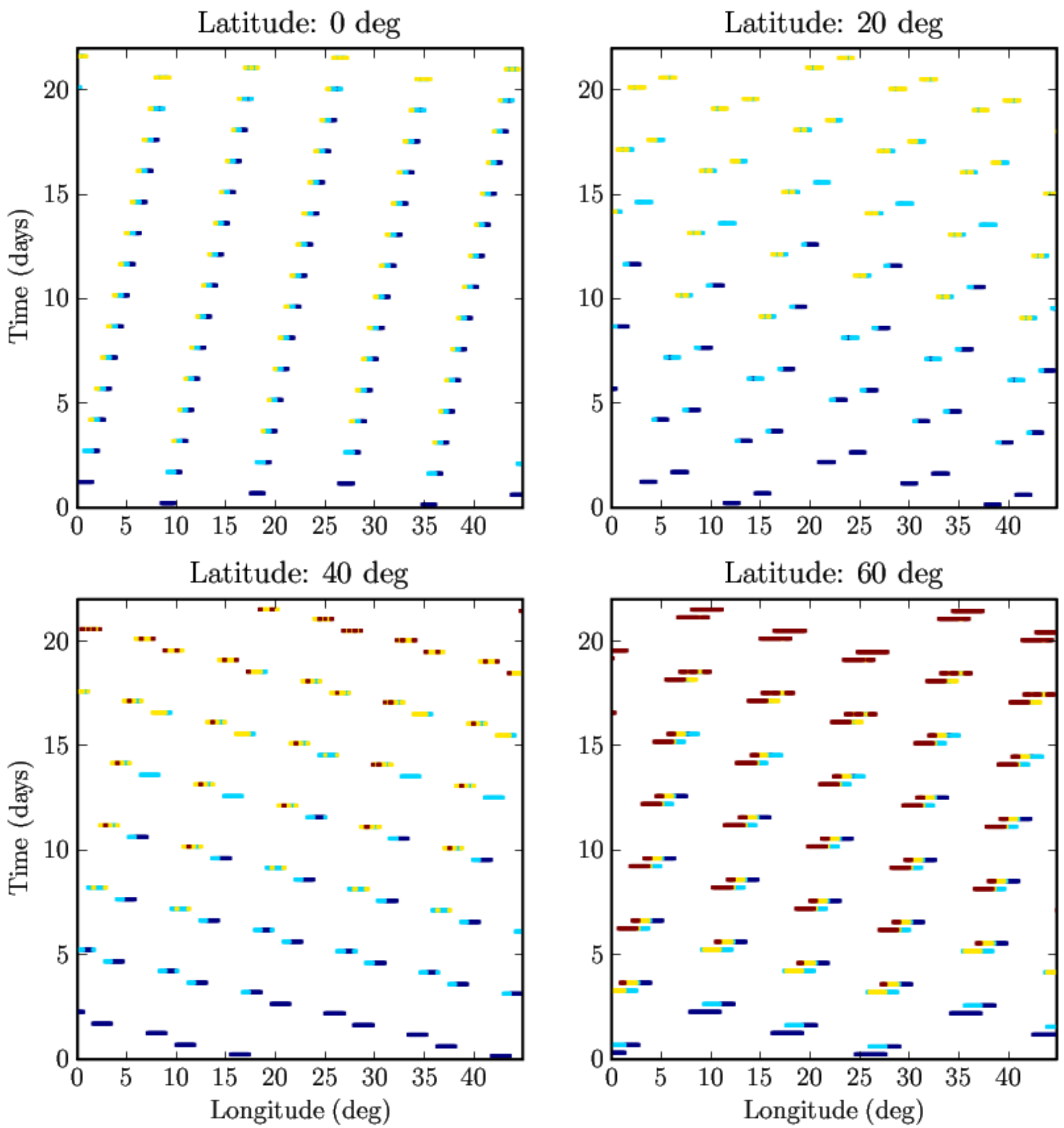
4 Days of 22-Day Repeat, Lena



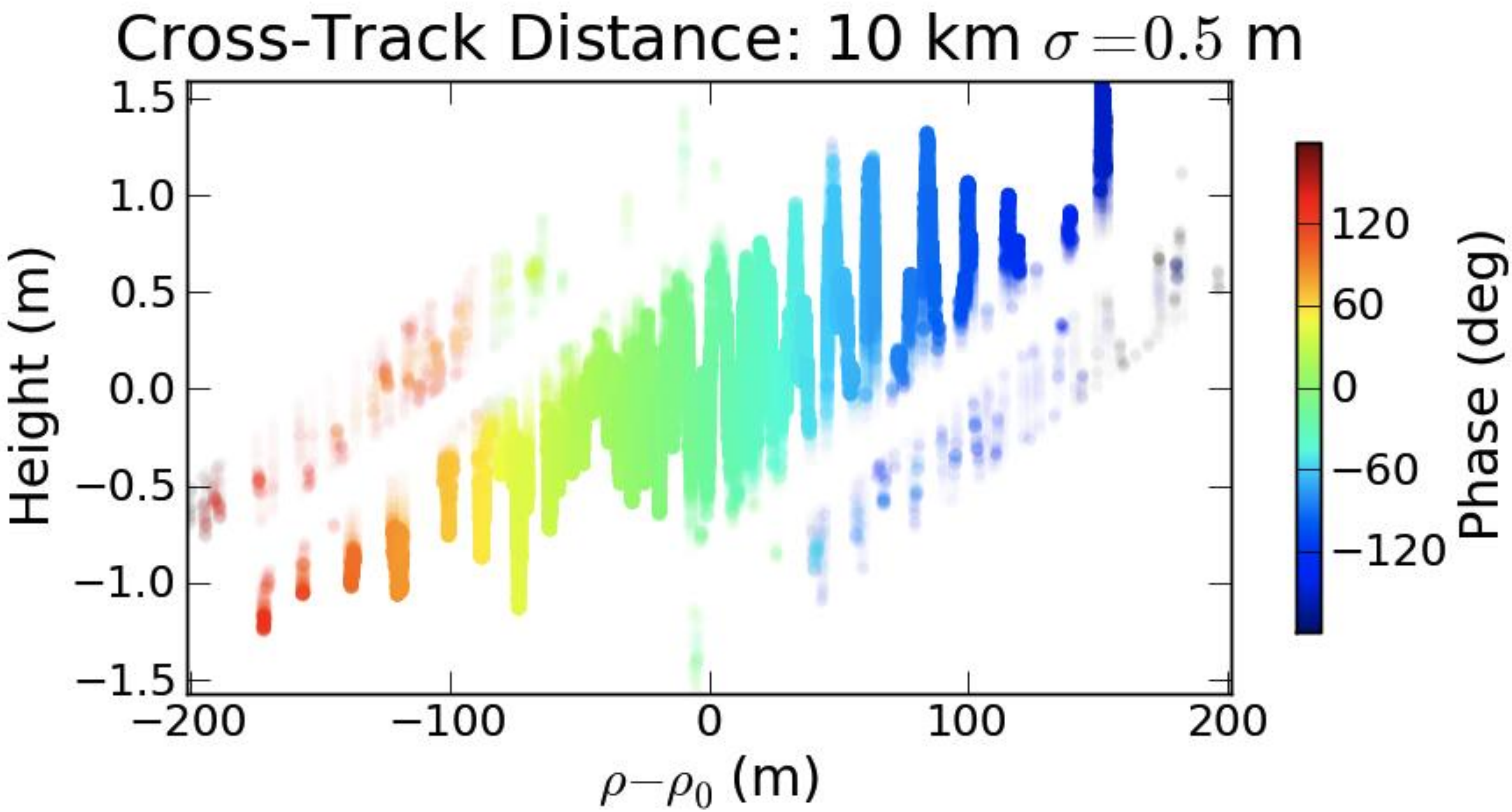
22-Day Repeat, Lena



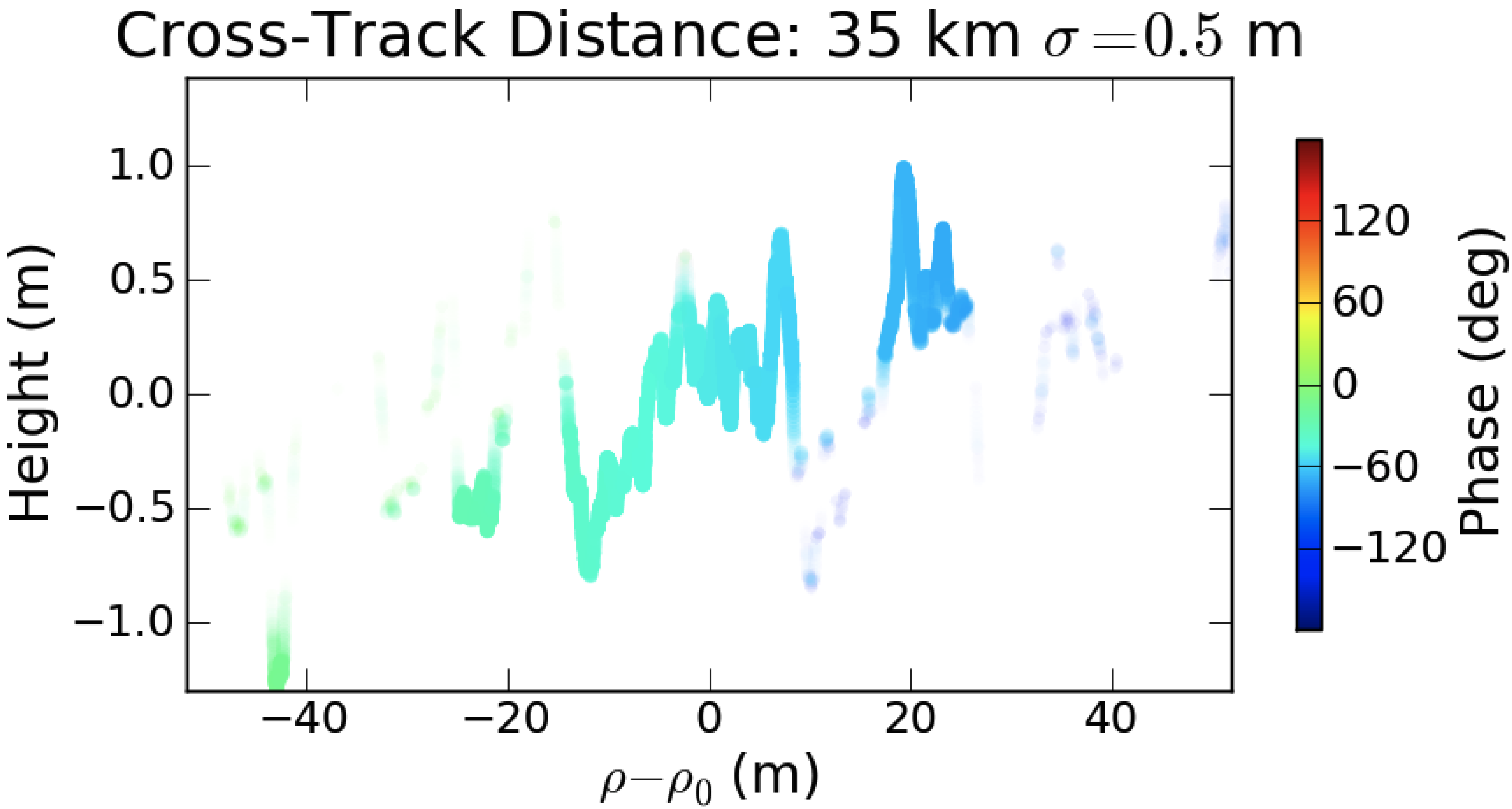
22-Day Repeat



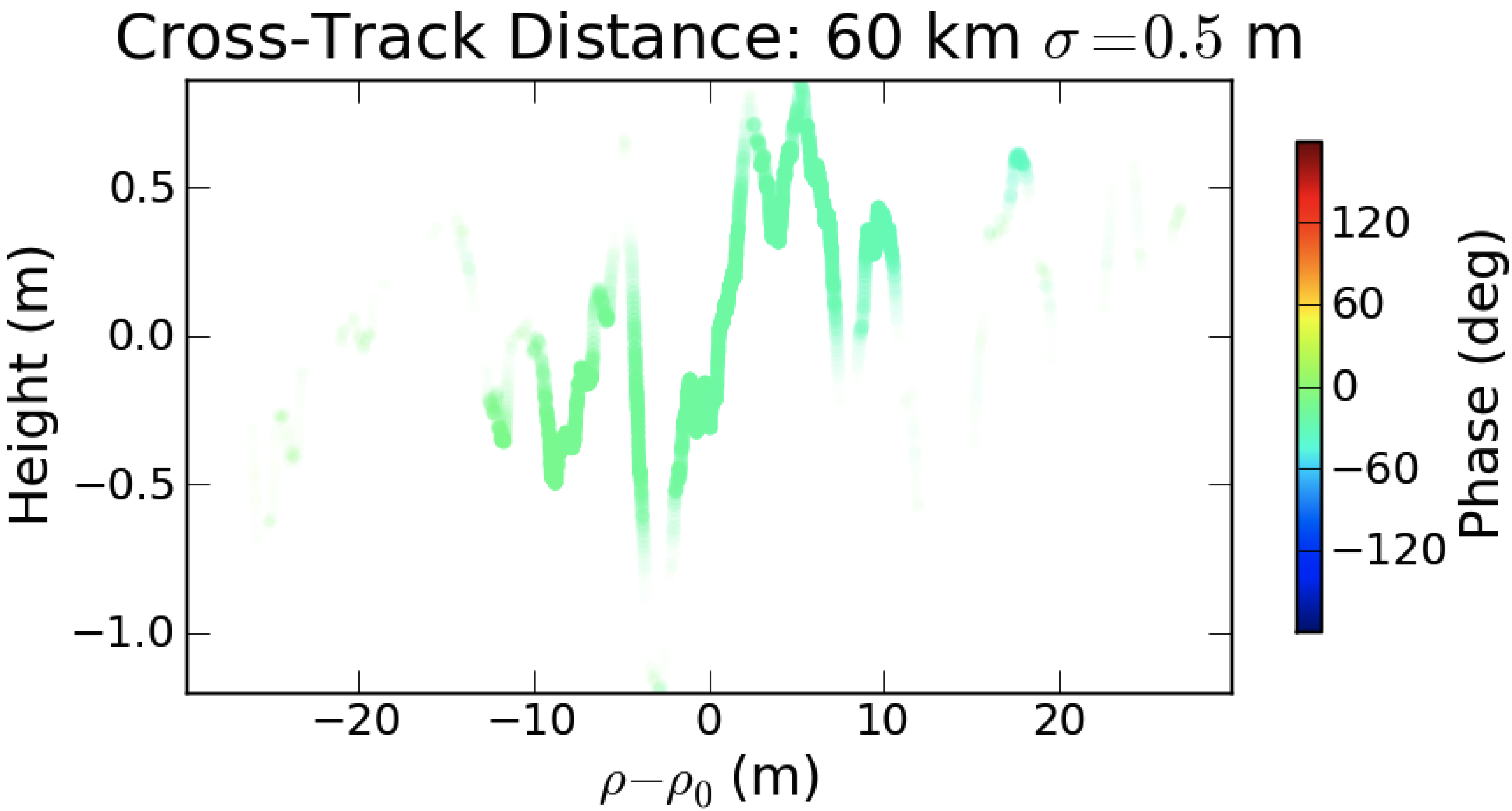
Wave Effects (10 km Cross-track)



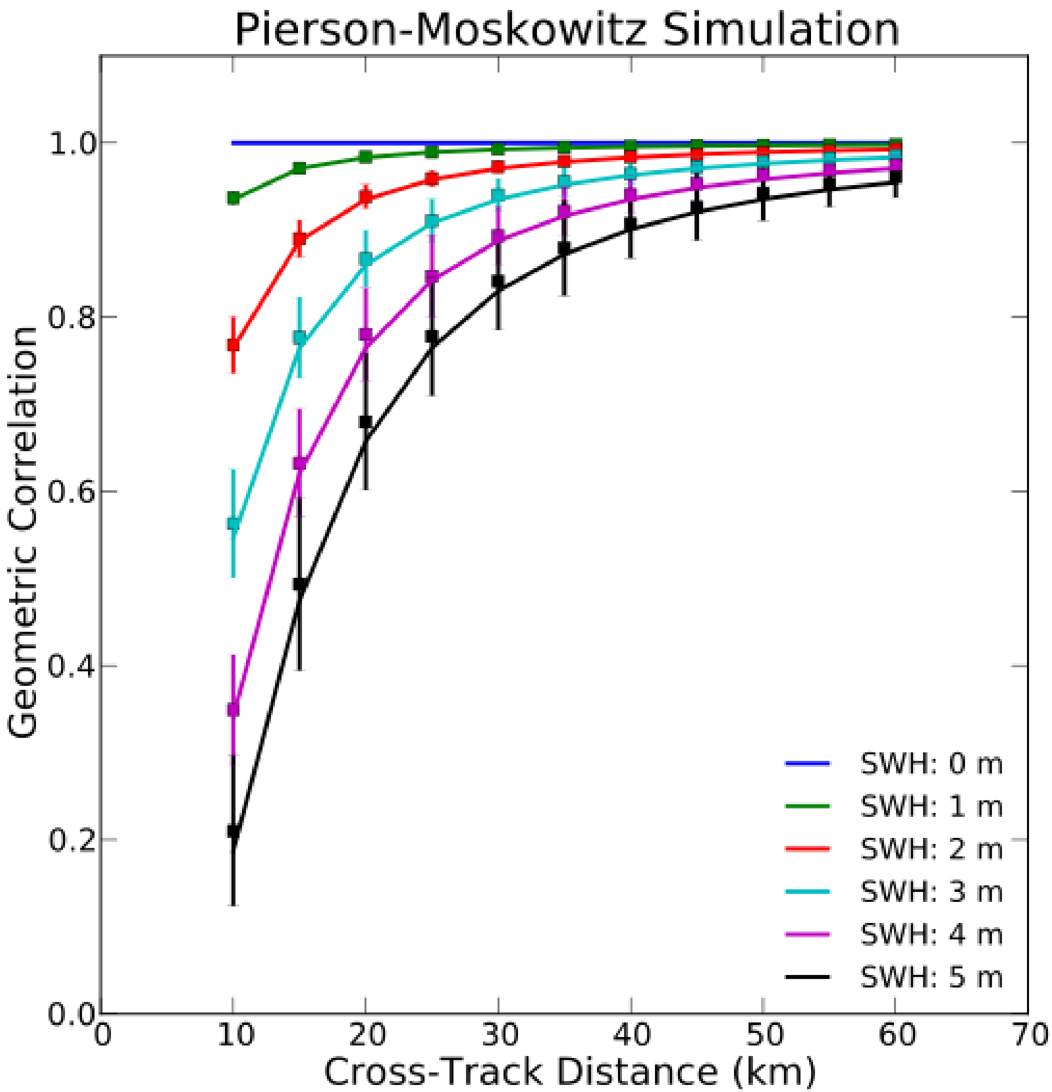
Wave Effects (35 km Cross-track)



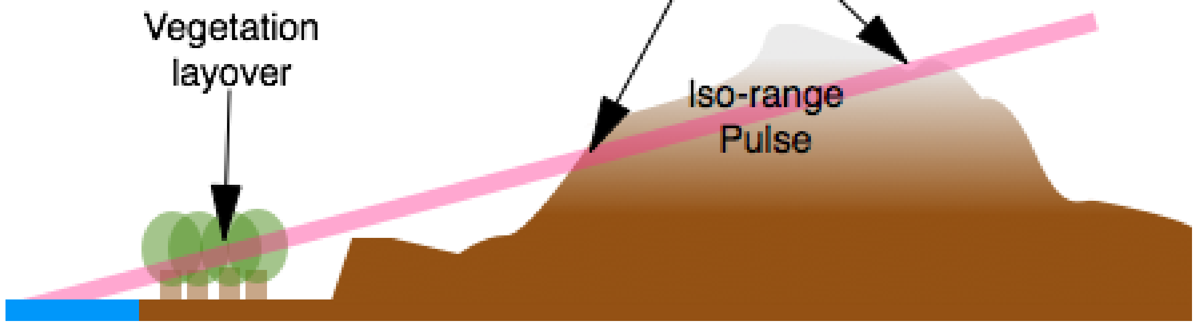
Wave Effects (60 km Cross-track)



Effect on Interferometric Correlation



Radar Layover and its Effect on Interferometry



Points on dashed line arrive at the same time

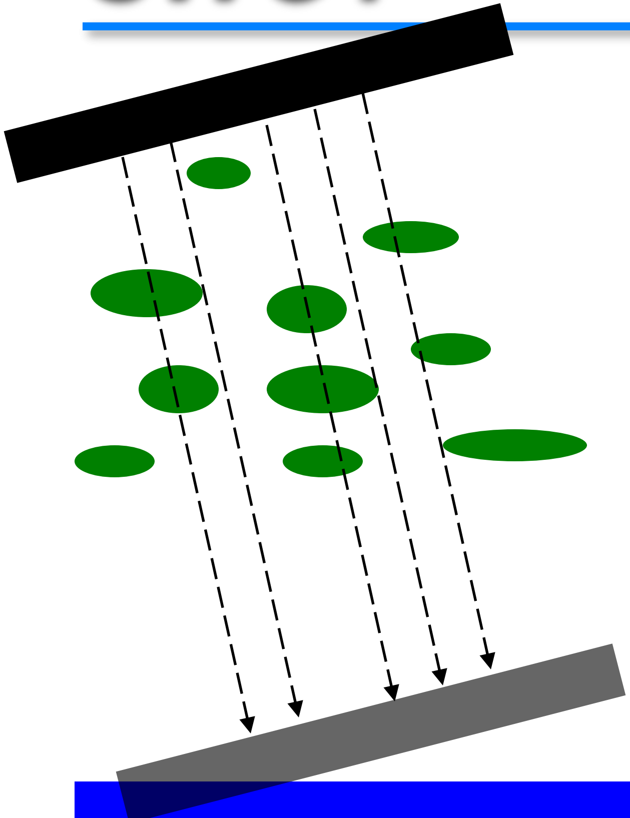
Correlation Ratio (land less correlated than water)

$$\langle v_1 v^*_2 \rangle = P_{Water}\gamma_{Water}\exp[i\Phi_{Water}] + P_{Land}\gamma_{Land}\exp[i\Phi_{Land}]$$

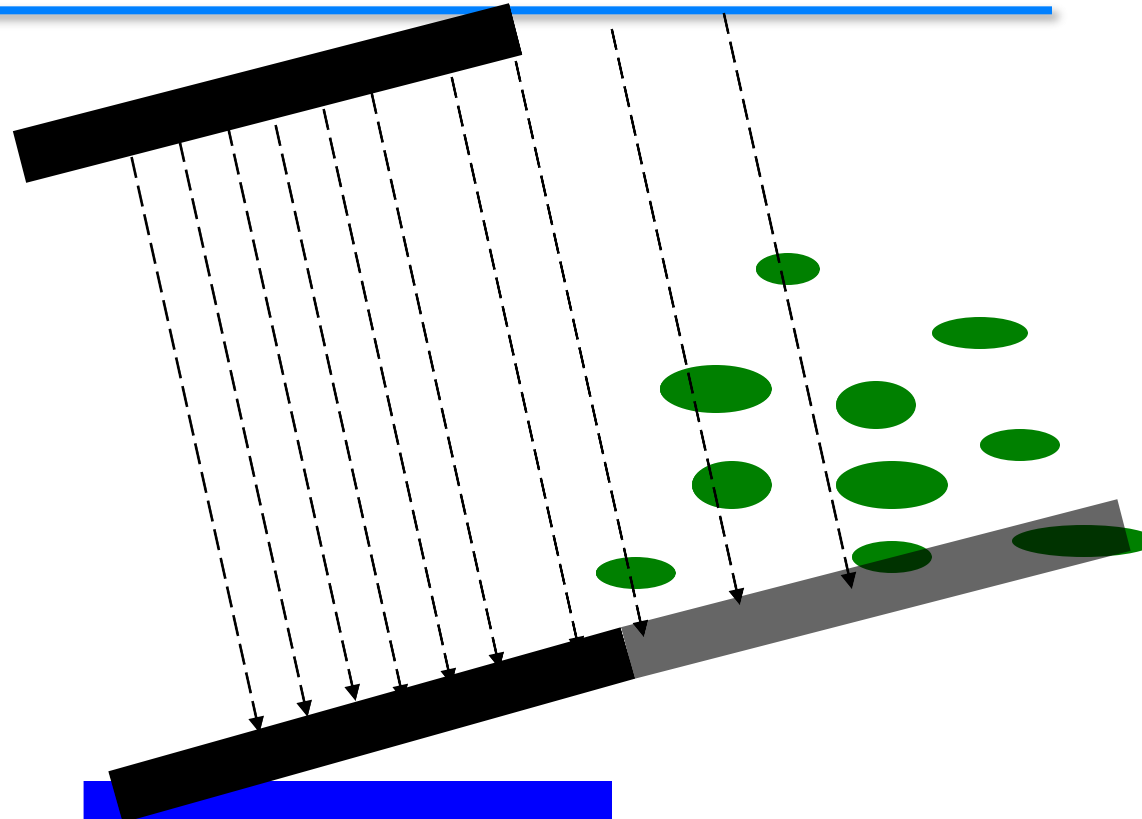
$$\delta\Phi = \arg\left[1 + \frac{P_{Land}}{P_{Water}}\frac{\gamma_{Land}}{\gamma_{Water}}\exp\left[i\left(\Phi_{Land} - \Phi_{Water}\right)\right]\right]$$

Brightness Ratio (land darker than water)

Vegetation Effects

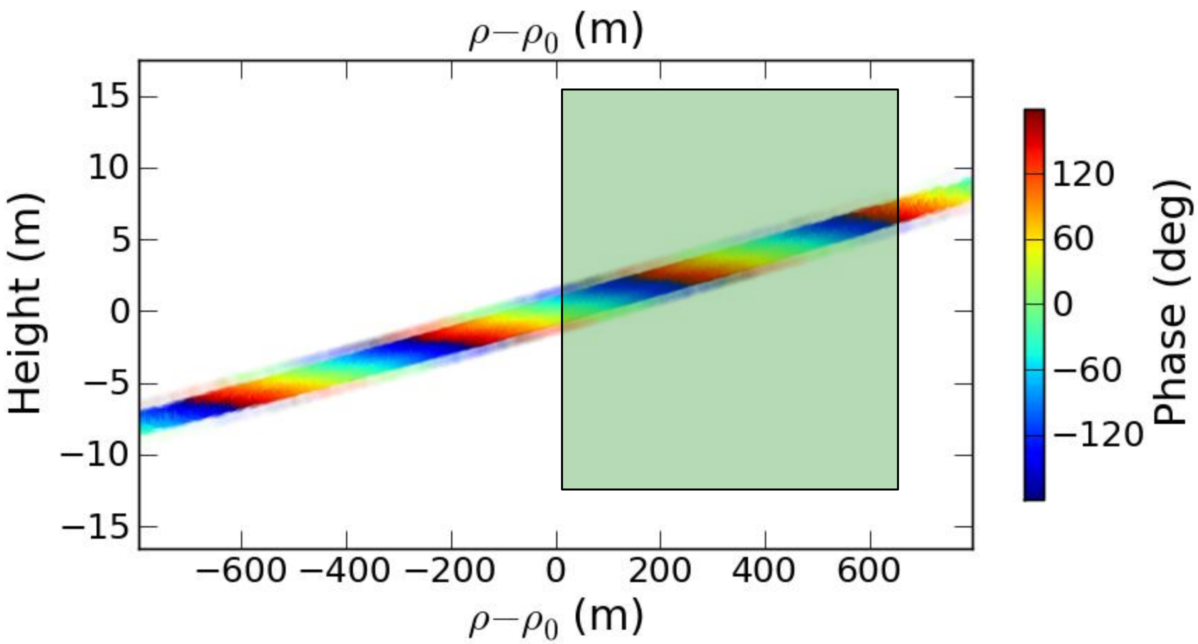


Canopy attenuation: weaker signal but no height bias



Canopy Layover: no attenuation, but height bias.

Effect of Exponentially Attenuating Trees



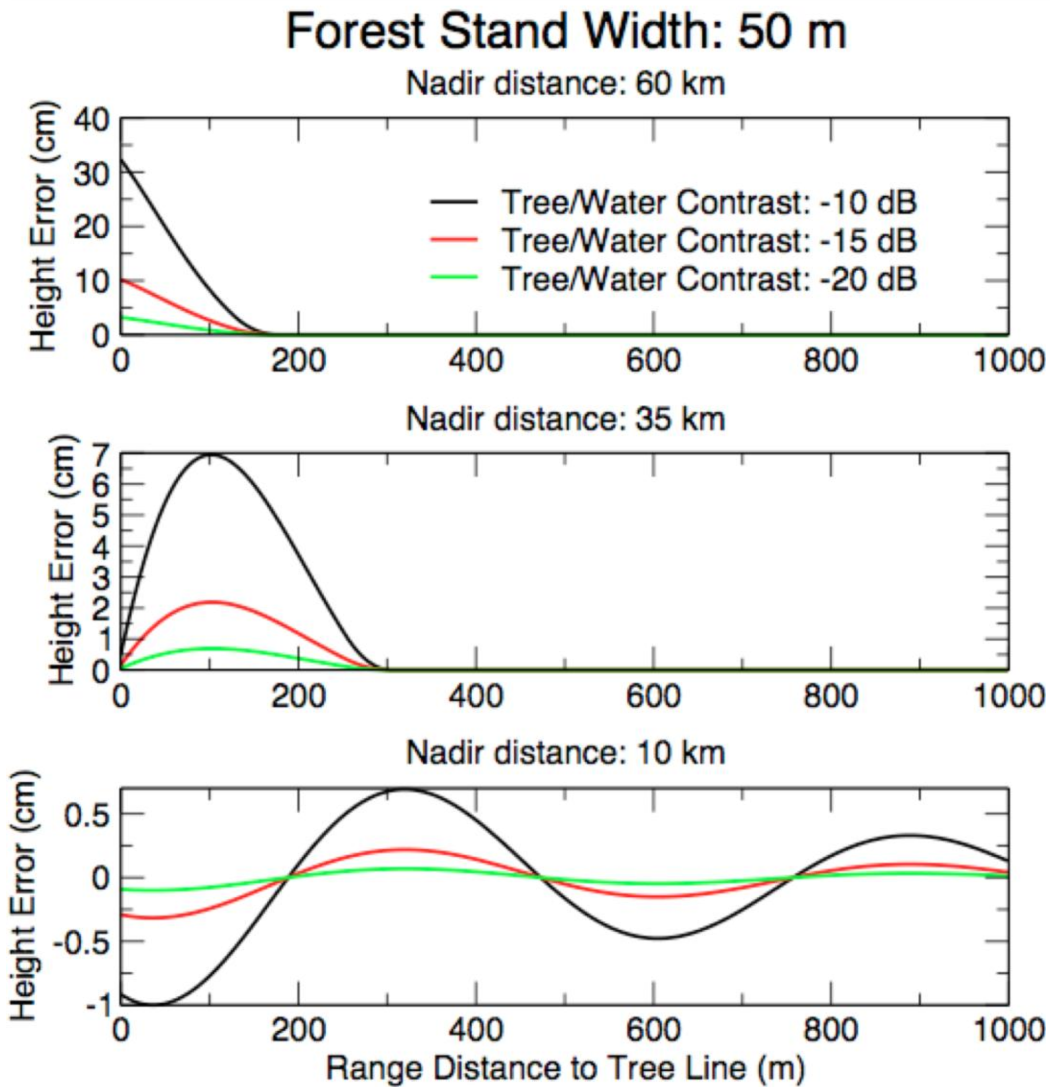
$$\delta\Phi = \arg\left[1 + \frac{\mu\nu}{\beta + i\kappa_z T}\left(\exp\left[i\kappa_z(T - z_1)\right]e^{-\beta z_1/T} - \exp\left[i\kappa_z(T - z_2)\right]e^{-\beta z_2/T}\right)\right]$$

$$\kappa_z = \frac{kBT}{H \sin\theta}$$

$$\nu = \frac{\beta}{1 - e^{-\beta}}$$

β: attenuation constant. T: tree height. μ: brightness ratio.

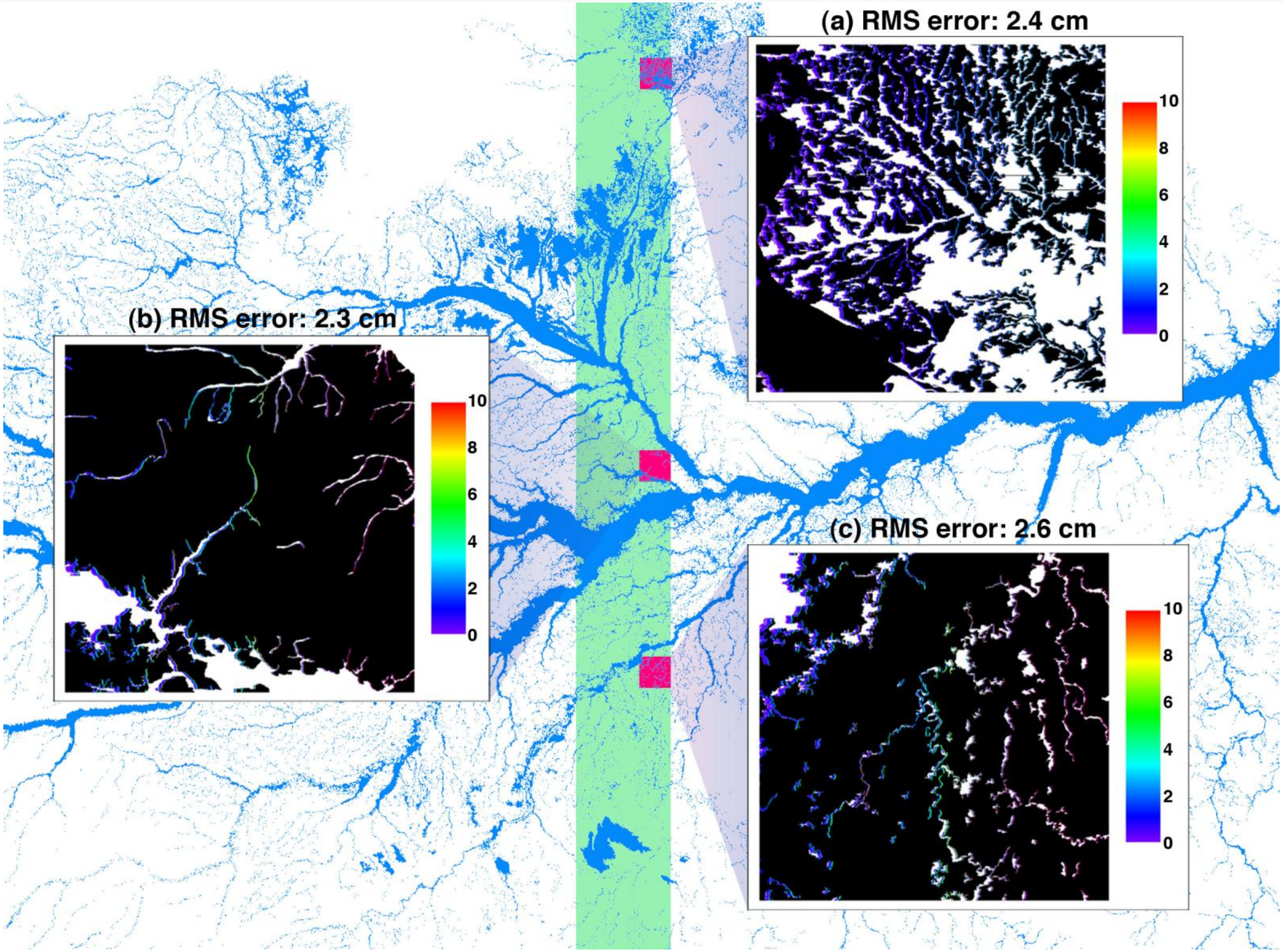
Effects of a tall stand of trees



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.

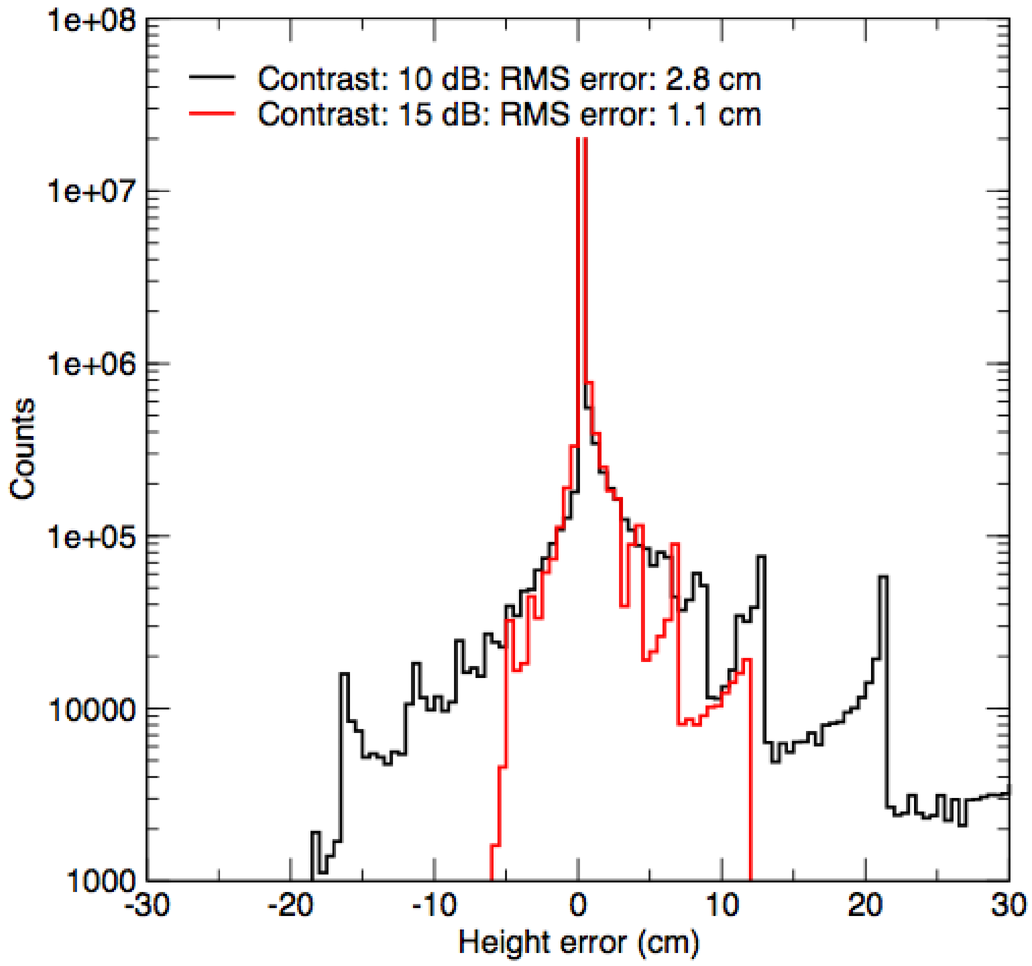
SWOT

Amazon Tree Layover Simulation



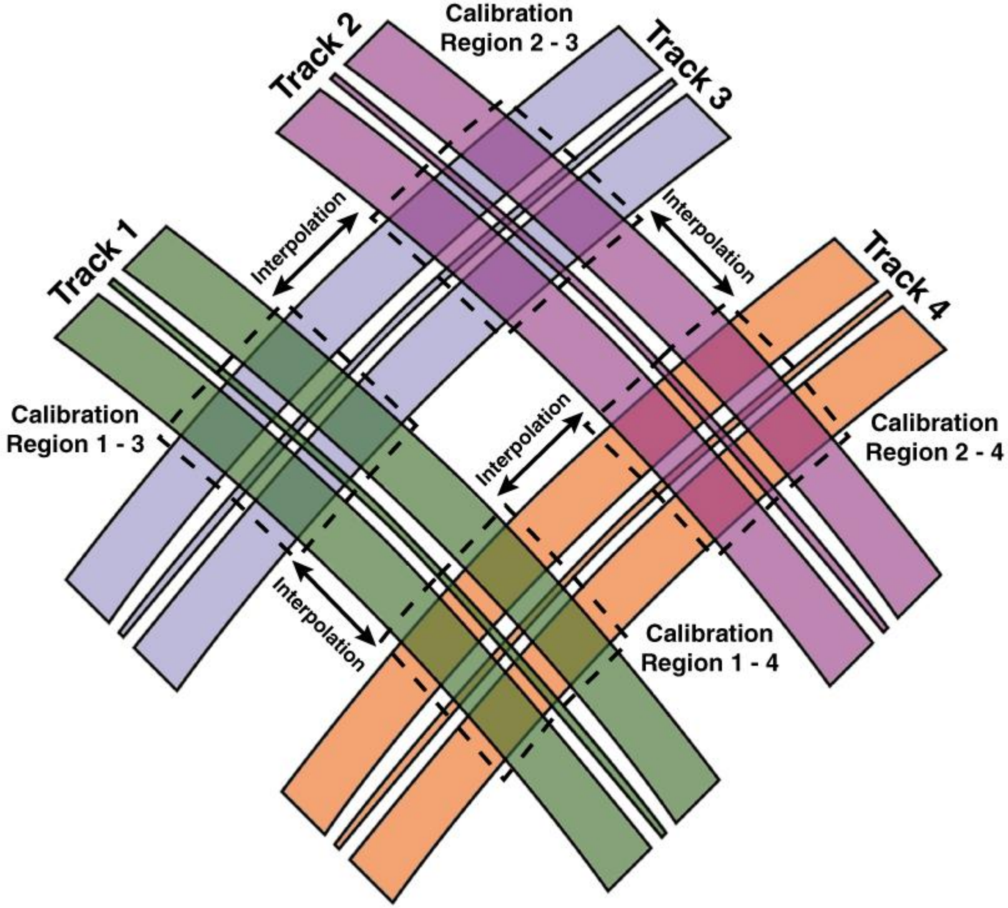
Amazon vegetation/water mask courtesy of L. Hess, UCSB

Amazon Tree Layover Simulation



- Assumed tree height: 20 m
- Fraction of land which is tree covered: 100%

SWOT 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.

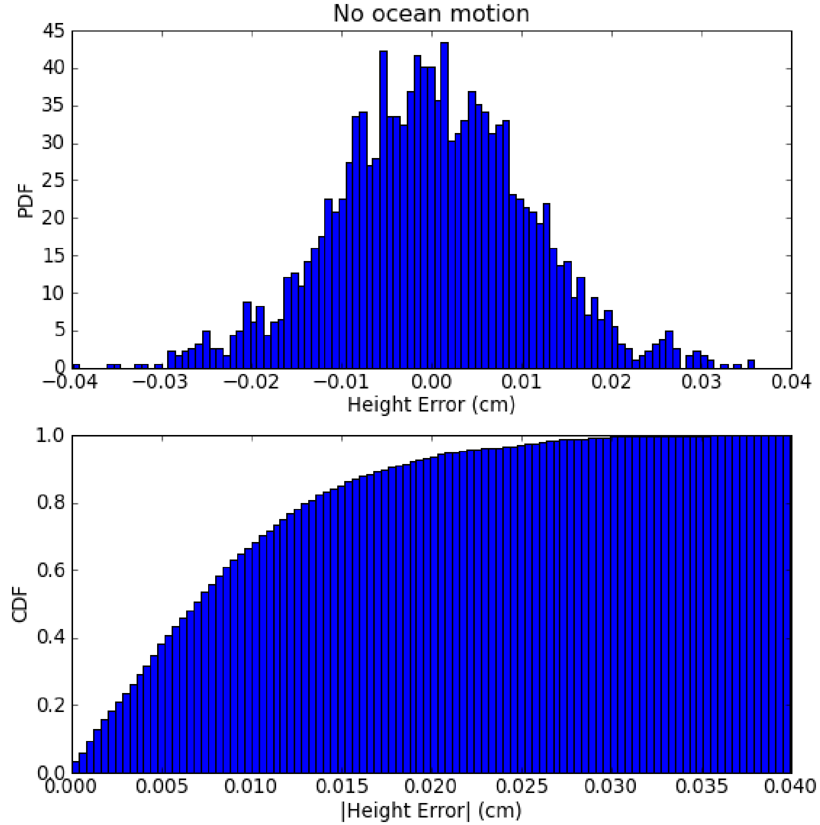
- Interpolate along-track baseline parameters between calibration regions by using optimal interpolation given gyro drift correlation function (similar for phase)

SWOT

Cross-over Calibration
Results without ocean motion

- Cross-over technique demostrated 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

Error represents swath average error

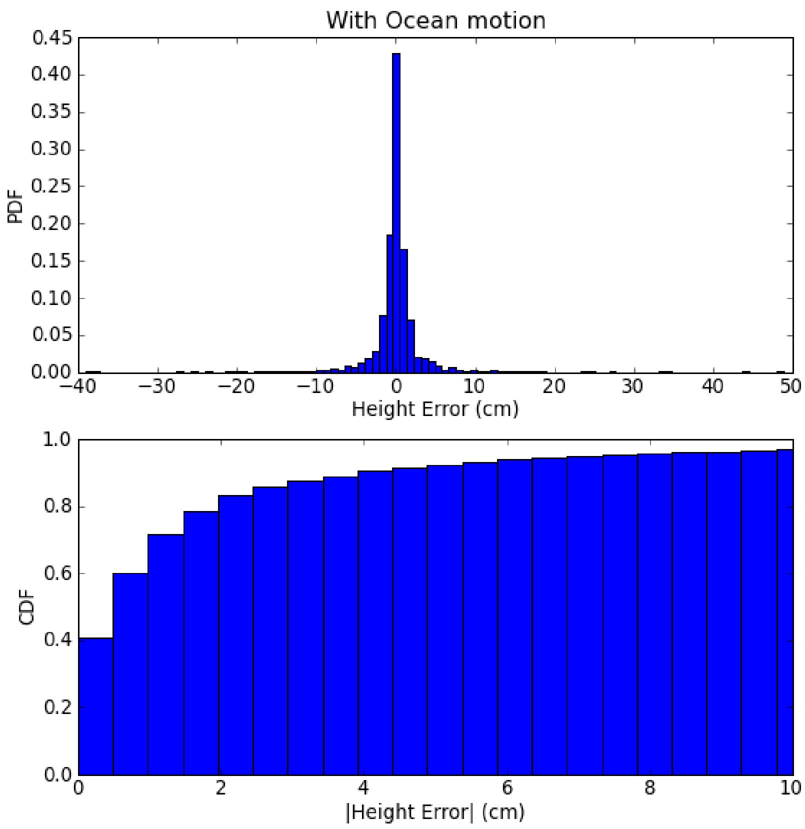


SWOT

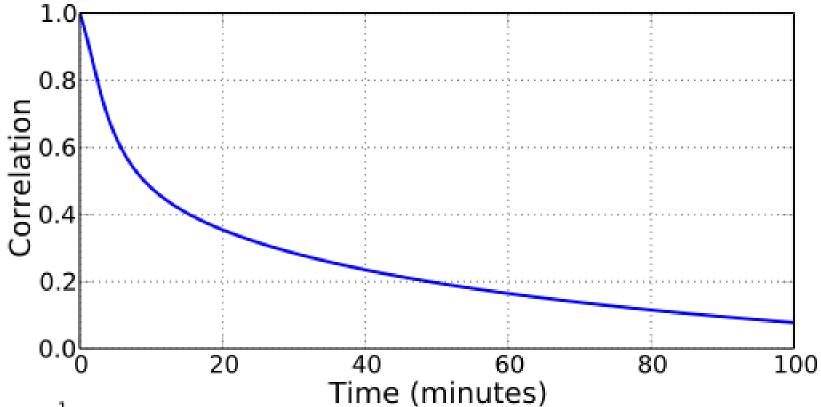
Simulations with ocean motion

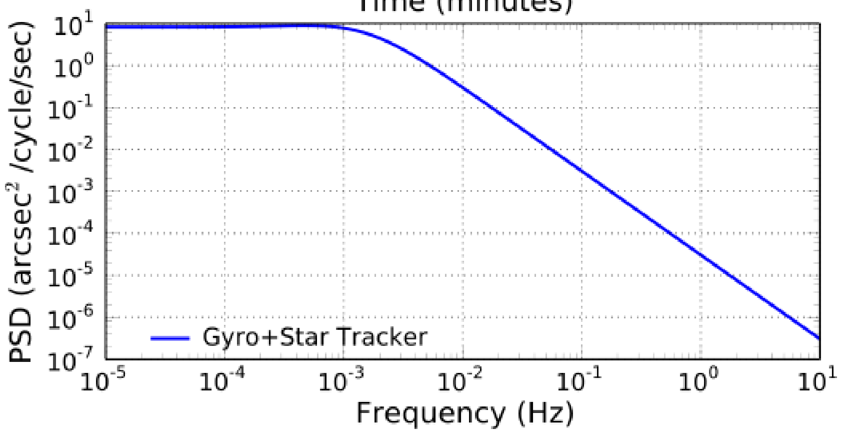
- Ocean motion between cross-over revisits is the dominant contributor to the roll calibration error budget
- In general, the calibration parameters are well behaved, but the distribution has large tails
- 68% error < 1.5 cm
- 80% error < 2.0 cm
- 90% error < 5.0 cm
- These large tails are due to cross-overs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

Error represents swath average error



Ocean Calibration Propagation Across Cross-Overs or Land

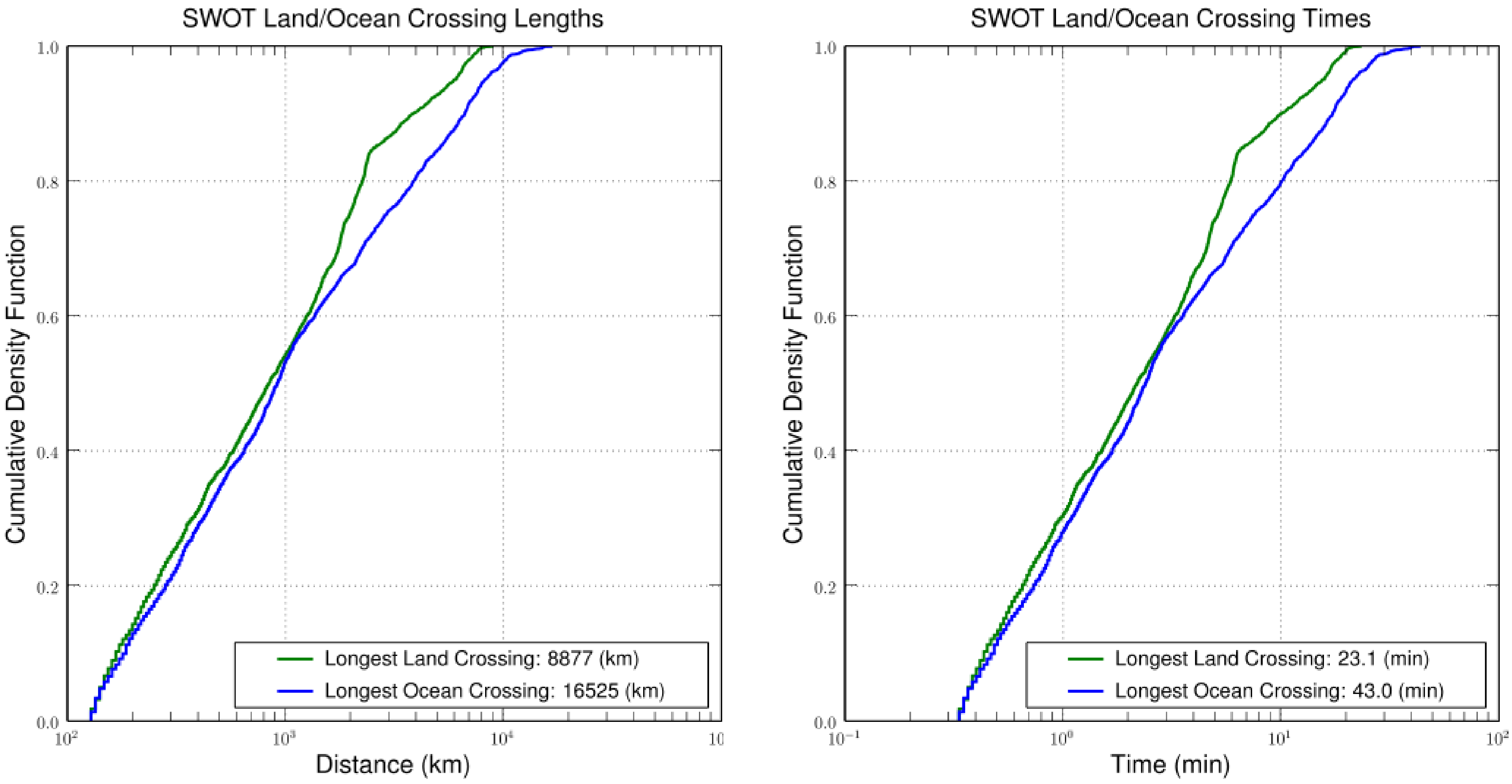




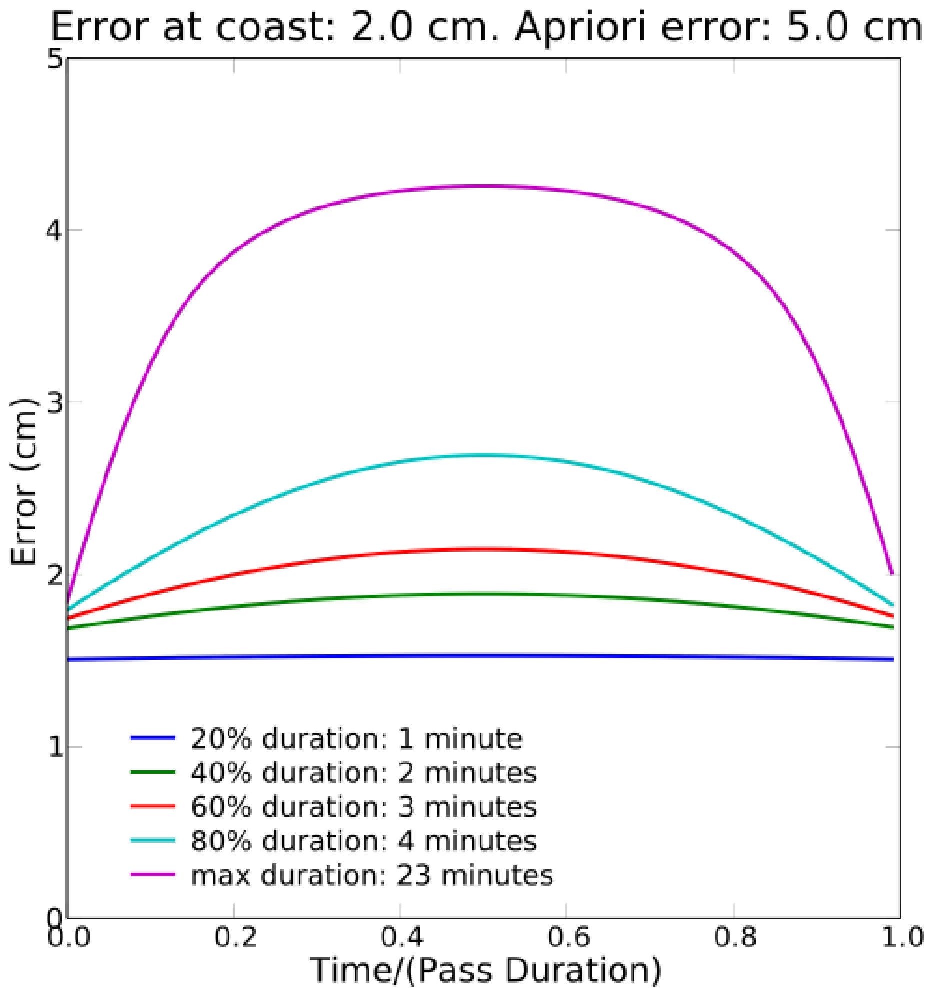
- Ocean cross-over calibration leads to roll calibrations over the ocean at each cross-over point
- Gyro+star-tracker may have absolute errors or drifts, but the errors are slowly varying, so once calibrated over the ocean cross-overs they have a long memory
- Worst case example: assume that land crossing 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.

SWOT

How long are the land crossings?



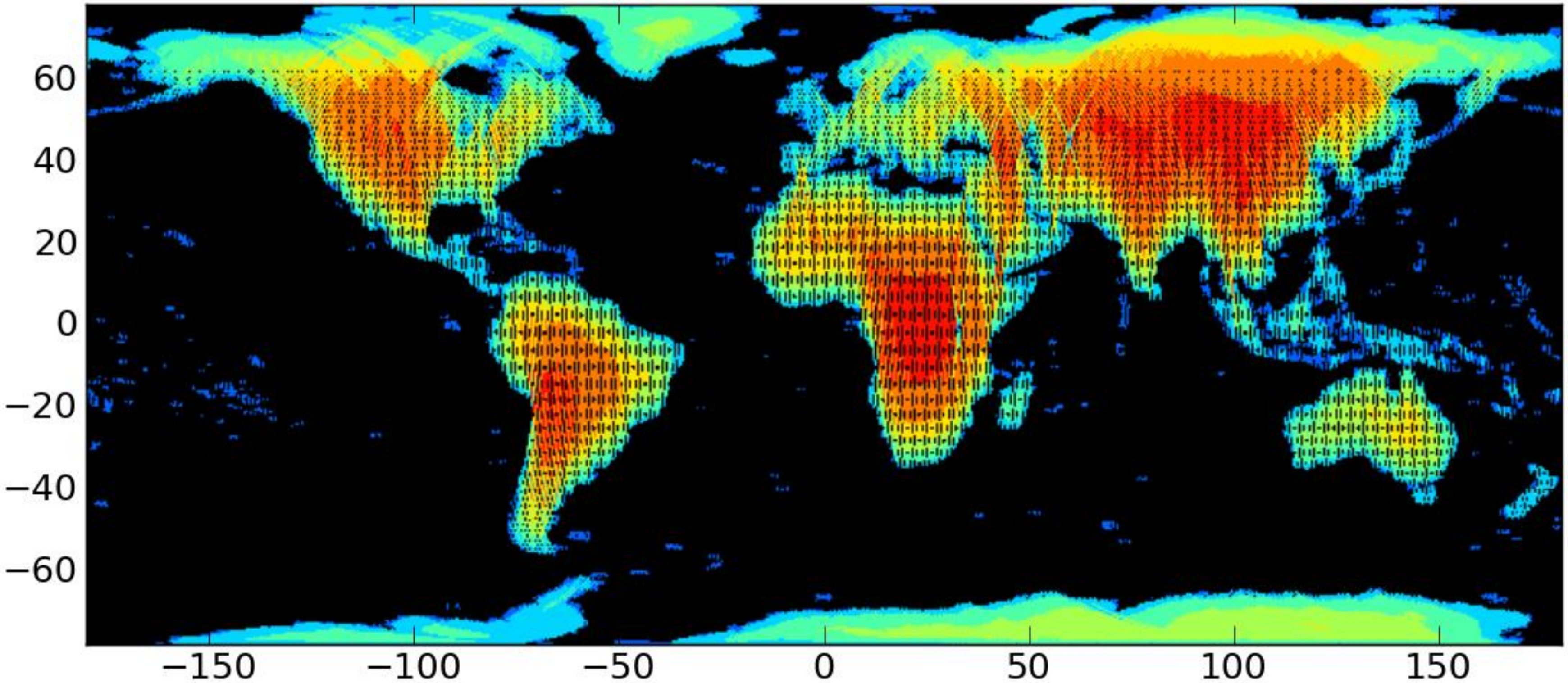
How does the error grow?



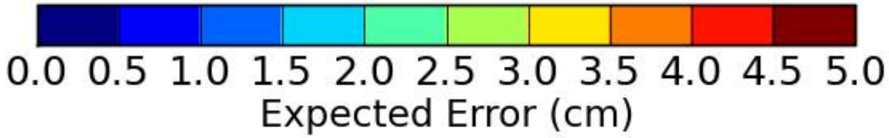
SWOT

How does it look globally?

$\sigma_{coast} = 2$ cm $\quad \sigma_{Giro} = 5$ cm

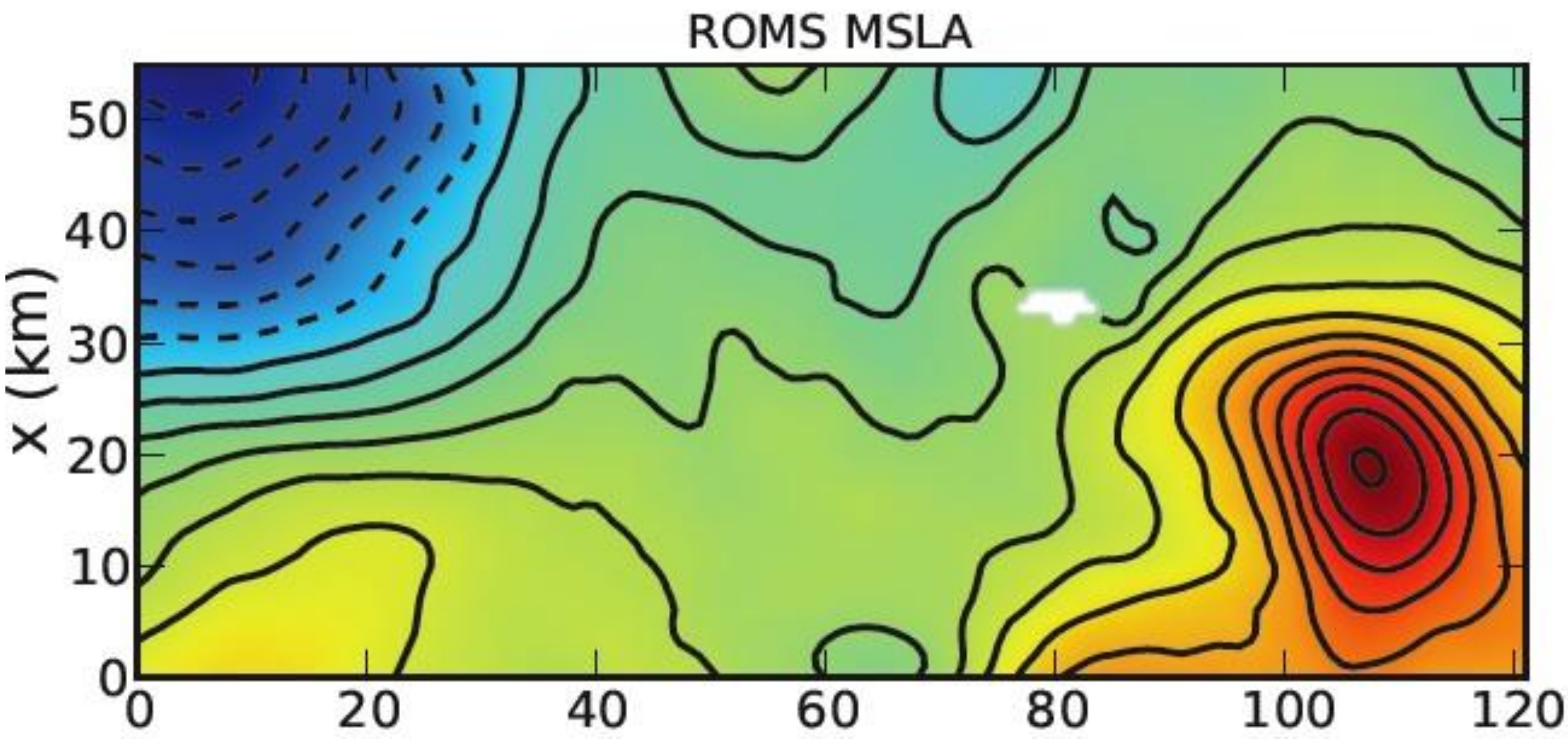


Optimal interpolation can reduce roll RMS errors by 1-3 cm



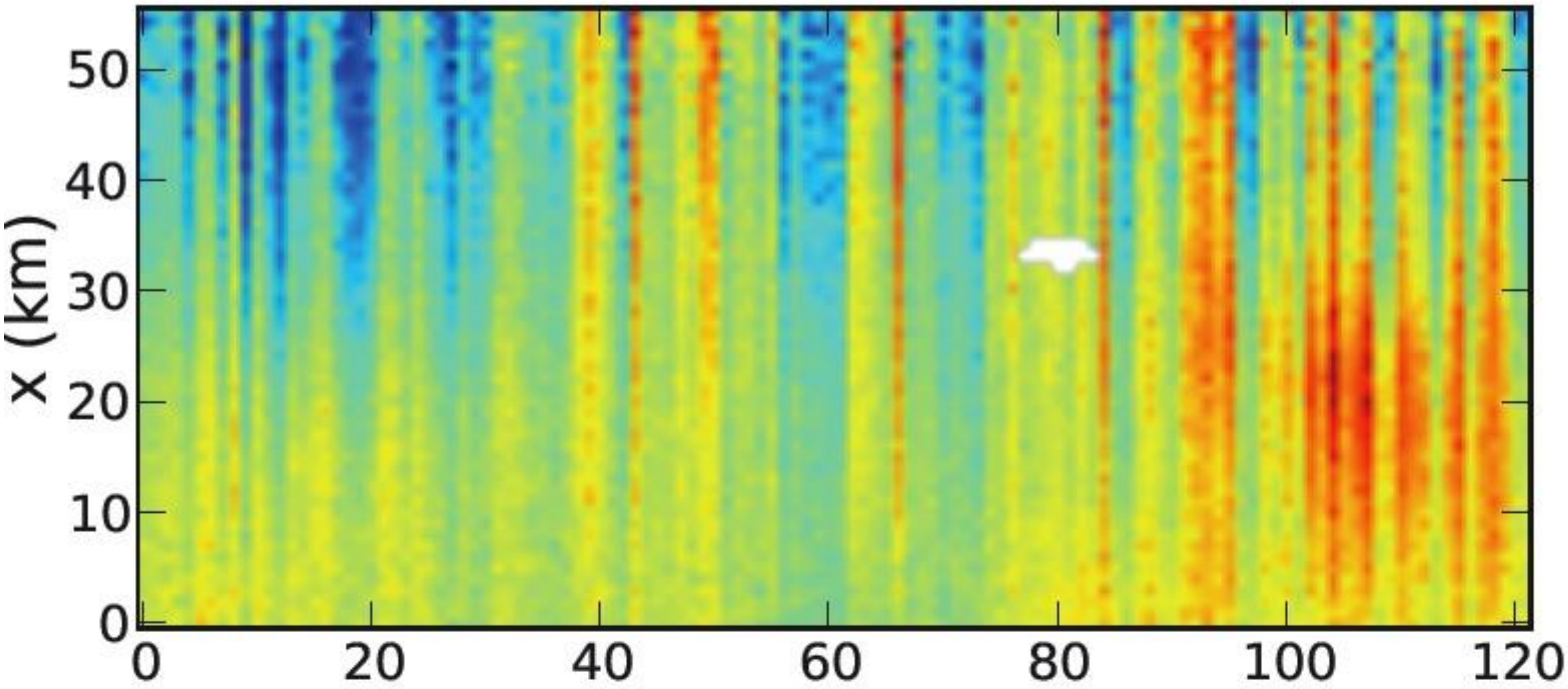
SWOT

A challenging mesoscale eddy



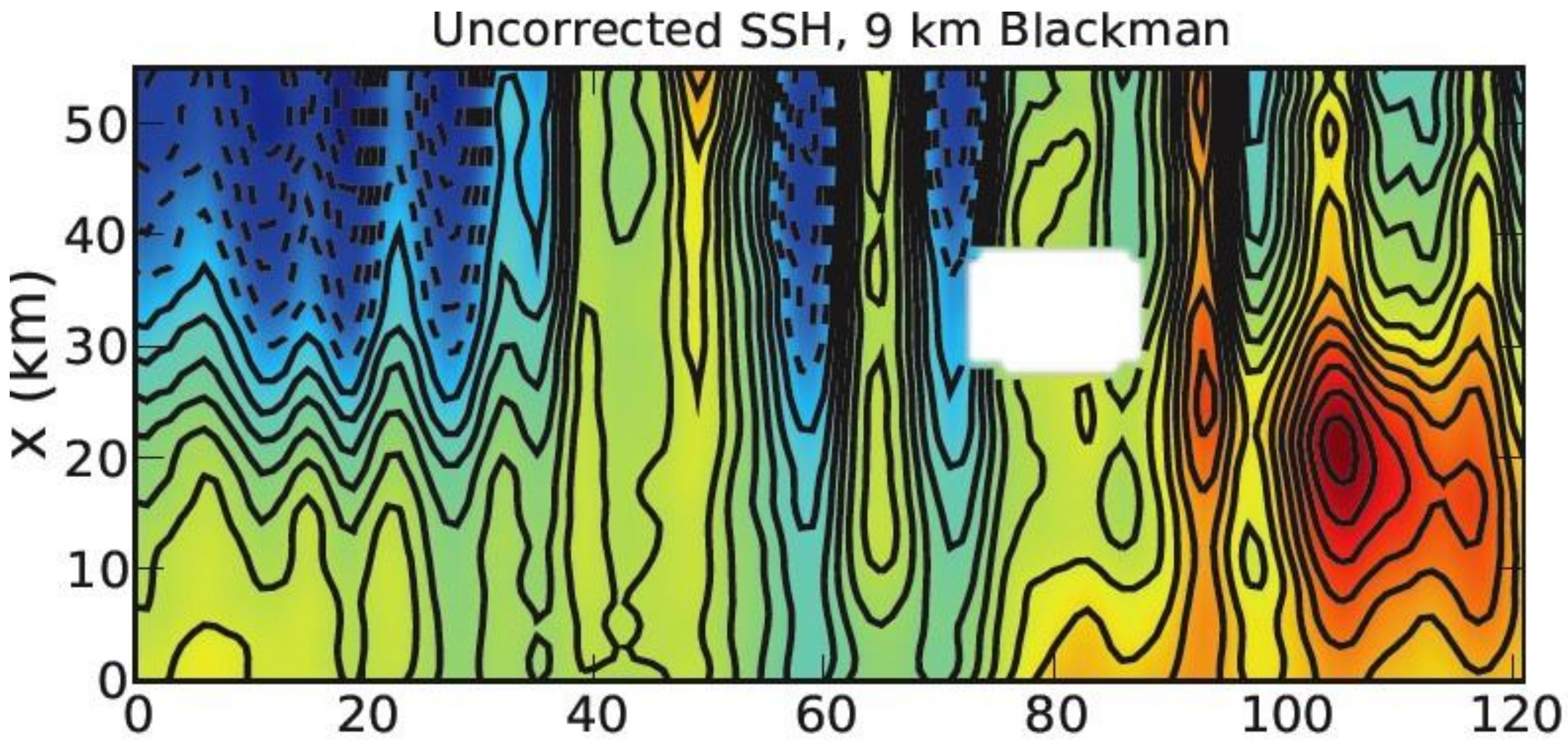
SSH contours are 1 cm

A bad case…
Effective roll 10x worse than expected



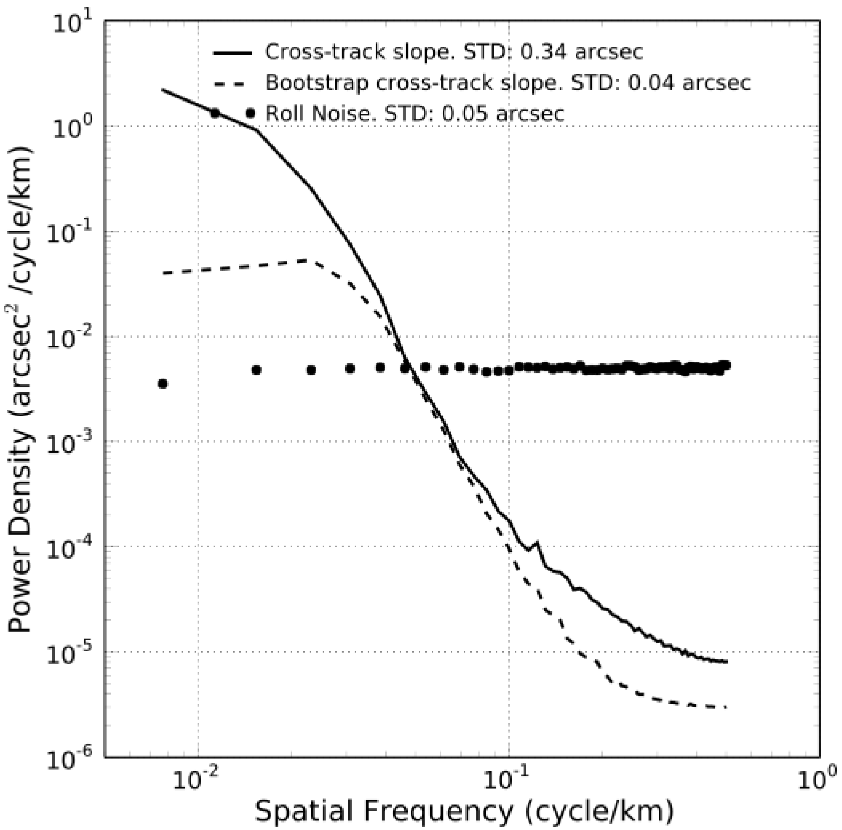
SWOT

Smoothing does not help much…



OSTST Lisboa
October 22, 2010

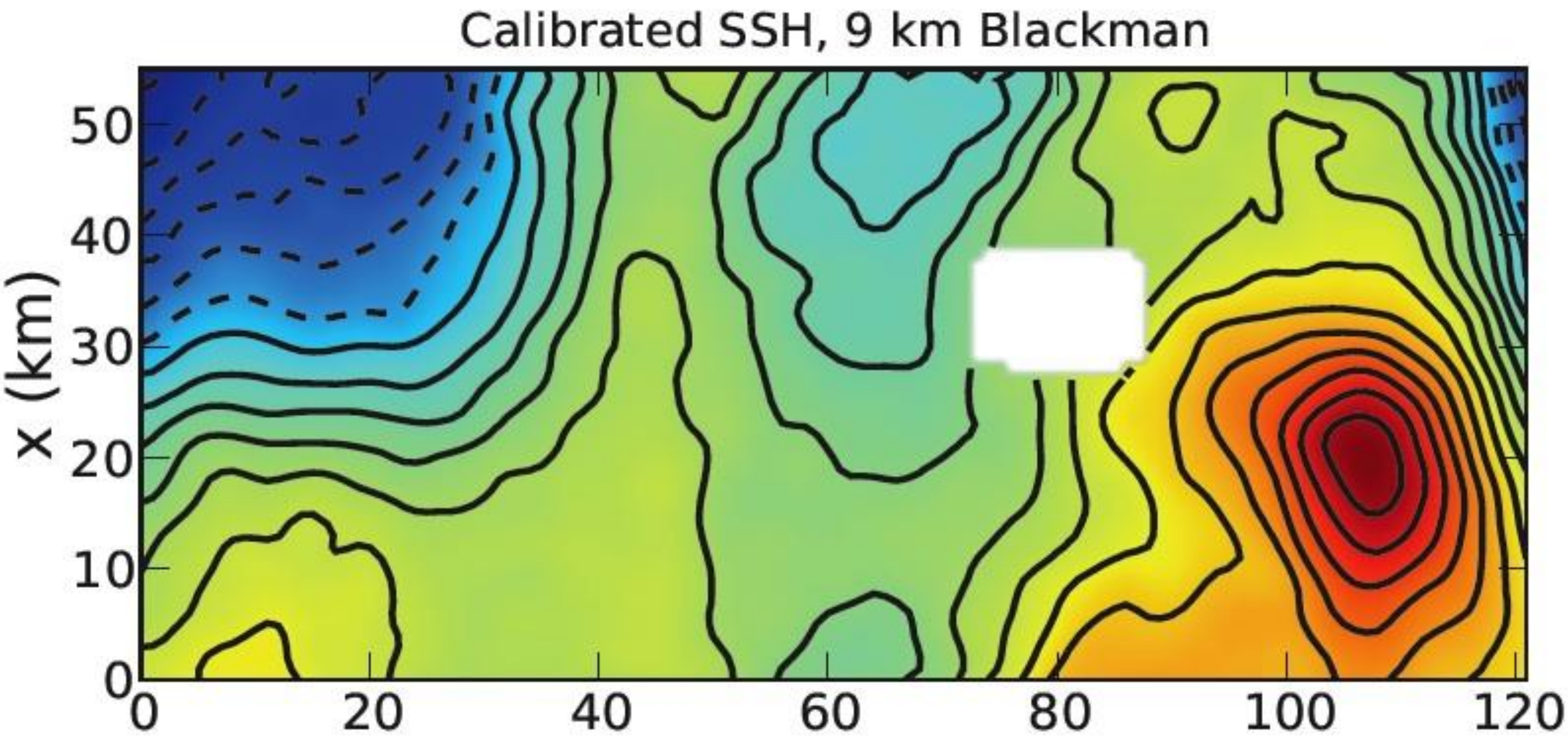
Separating the signals



Spectra from high-resolution ROMS ocean model at 1km sampling.

- 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.

But removing the estimated high frequency roll does…



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