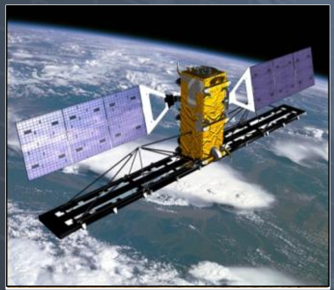
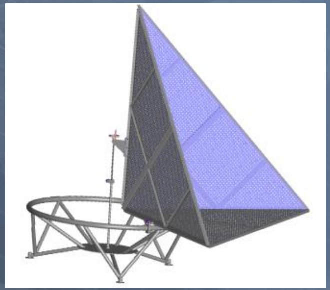
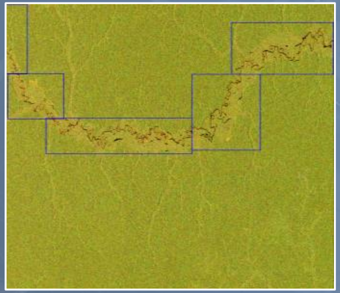
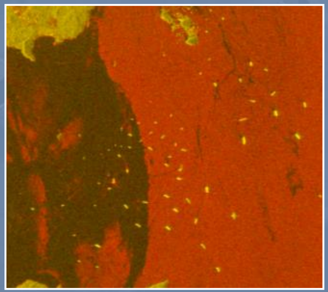
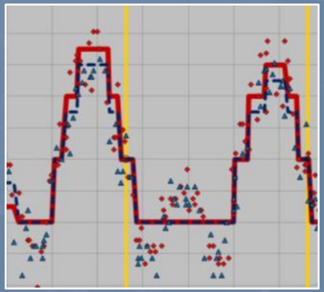
    

INFORMATION SYSTEMS

RADARSAT-2
Image Quality and Calibration Update

by Dan Williams, Yiman Wang, Gordon Fitzgerald, Marielle Chabot, Pierre Le Dantec,
Robert Fiset, Yan Wu, Ron Caves, Kenny James, Alan Thompson, Cathy Vigneron

September 7, 2016

www.mdacorporation.com

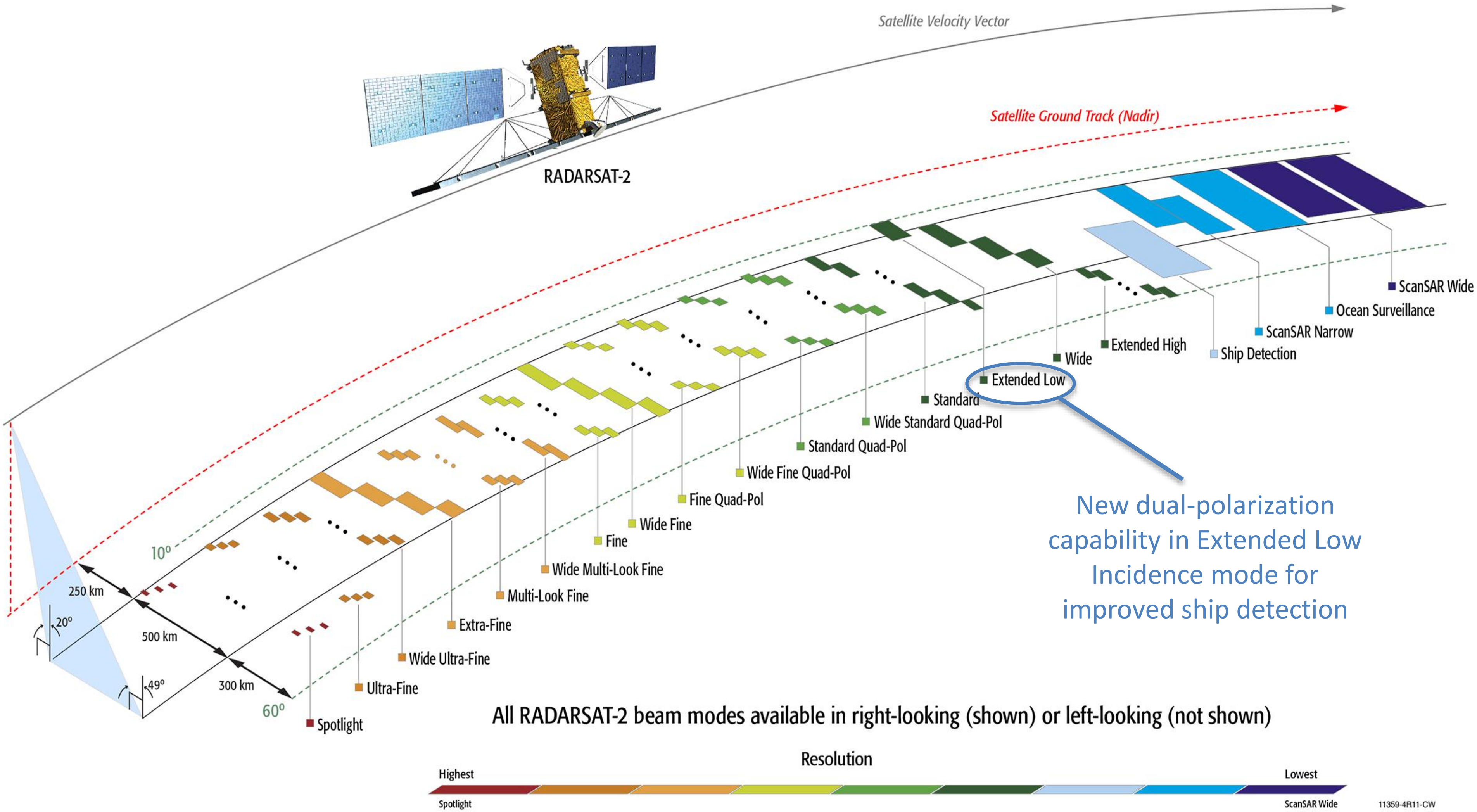
Image Credits and Disclaimer Language

GENERAL ACKNOWLEDGEMENTS
Certain images contained in this document are property of third parties:
Image on P. 31. COPYRIGHT © Copernicus Sentinel data for sentinel data.

Outline

- Overview of RADARSAT-2 commercial SAR modes
- RADARSAT-2 Image Quality Monitoring and Calibration Status
  - Overview
  - Geolocation
  - Resolution
  - Radiometric Accuracy
  - Beam Pointing
  - Inter-Wing Phase Balance
  - Polarimetric Corrections
  - Noise Levels
  - Other
- Sentinel-1 Mutual Interference
- New Extended Low Incidence Dual-Polarized mode
- Conclusion

RADARSAT-2 Commercial SAR Modes

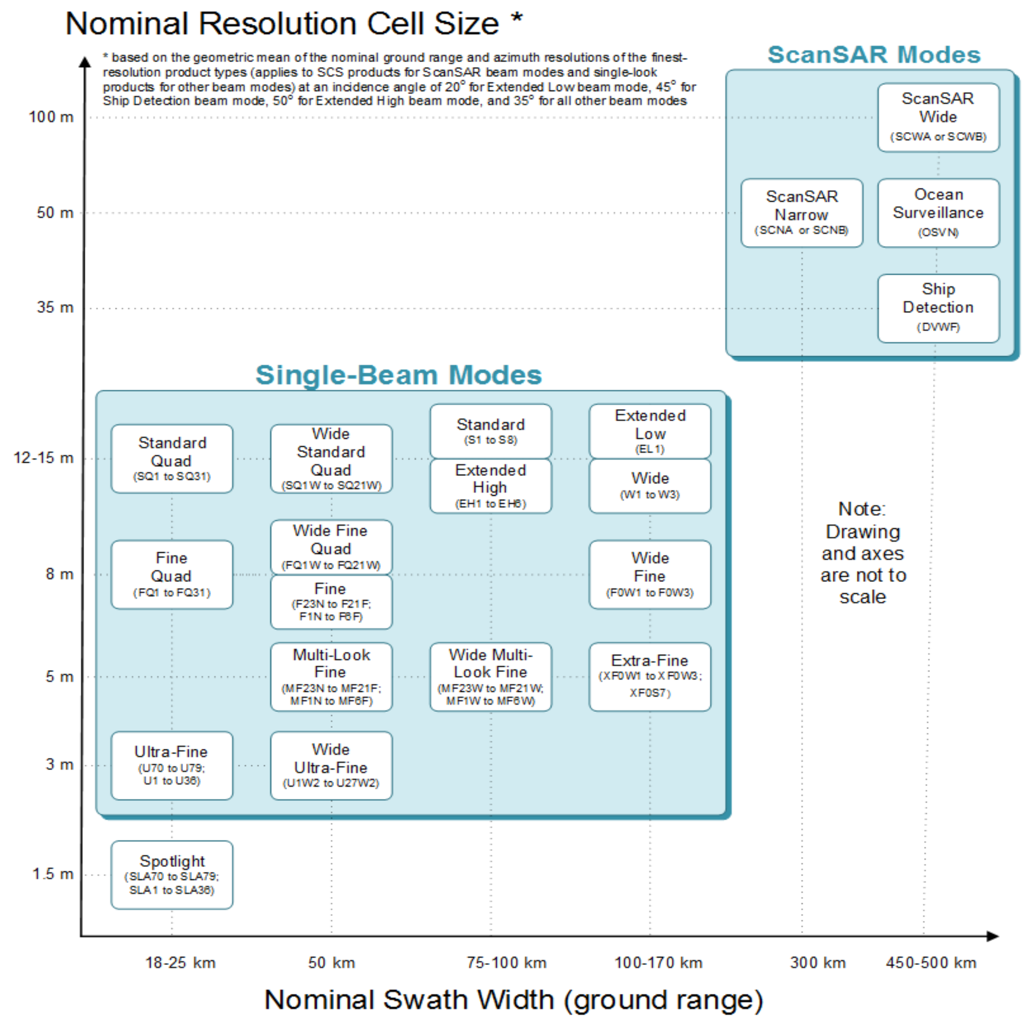


New dual-polarization capability in Extended Low Incidence mode for improved ship detection

Ref: http://mdacorporation.com/docs/default-source/technical-documents/geospatial-services/52-1238_rs2_product_description.pdf

RADARSAT-2 Commercial SAR Modes

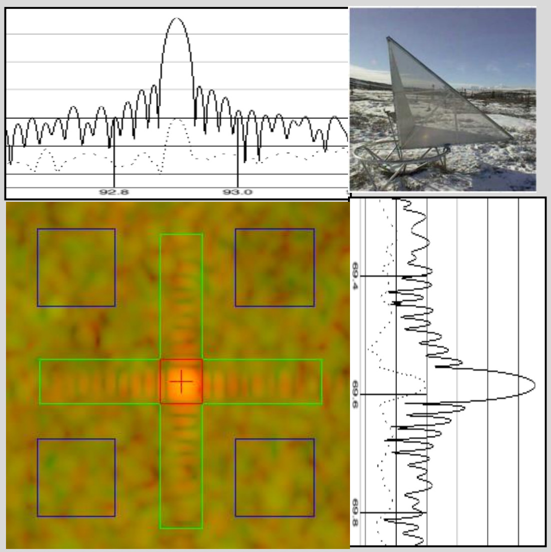
- 20 Beam Modes
  - 4 ScanSAR (2 to 8 Beams)
  - 15 Stripmap (Single Beam)
  - 1 Spotlight (Steered Beam)
- Swath Widths
  - 20-500 km
- Nominal resolutions
  - Range: ~3 - 100 m
  - Azimuth: ~0.8 – 100 m
- Commercial operations began April 24, 2008
  - Launched December 2007



Ref: http://mdacorporation.com/docs/default-source/technical-documents/geospatial-services/52-1238_rs2_product_description.pdf

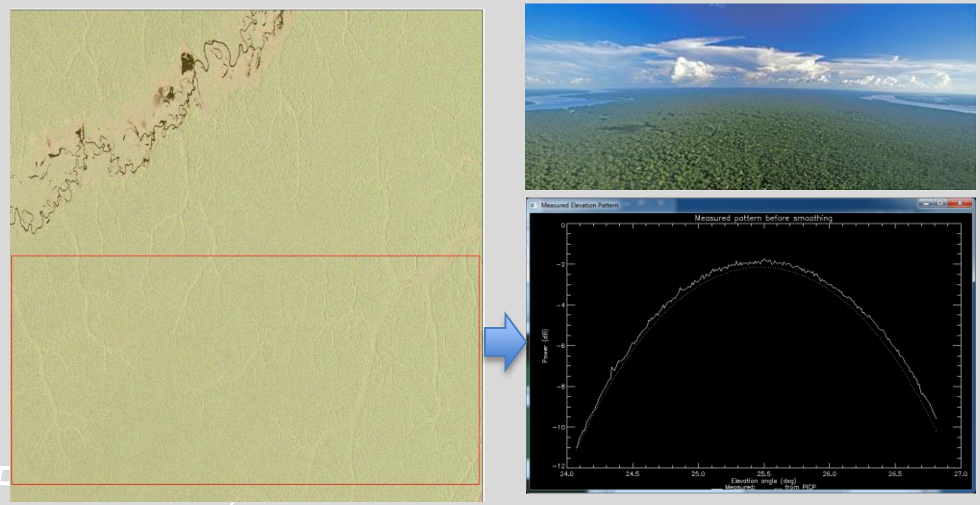
Overview of Image Quality and Calibration

- Ongoing monitoring & calibration program
  - Acquisitions over calibration sites
  - Analysis and trending of quality measures
  - Calibration adjustments as warranted
- Ongoing work to enhance accuracy and minimize artifacts
- Creation of new modes
  - (e.g. Dual-Pol Extended Low, Maritime Surveillance ScanSAR, Extra-Fine, Wide Quad Pol Modes)



Corner Reflector and Antenna Dish Point Target Measurements

(Resolution, sidelobe ratios, geolocation)



Amazon Rainforest Distributed Target Measurements

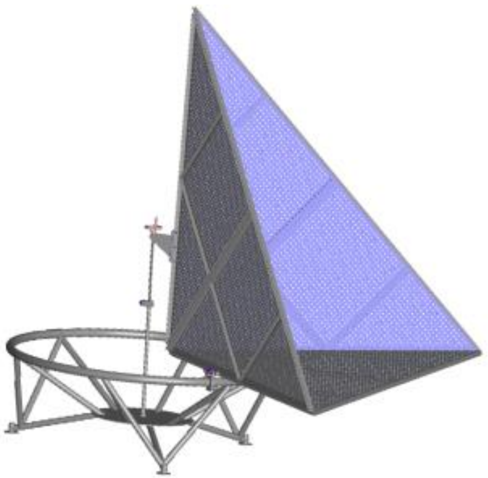
(Radiometric accuracy, beam patterns, beam pointing, polarimetric correction matrices, inter-wing phase balance)

Other

(Noise levels, antenna diagnostics, local oscillator frequency, new mode evaluation, issue investigations)

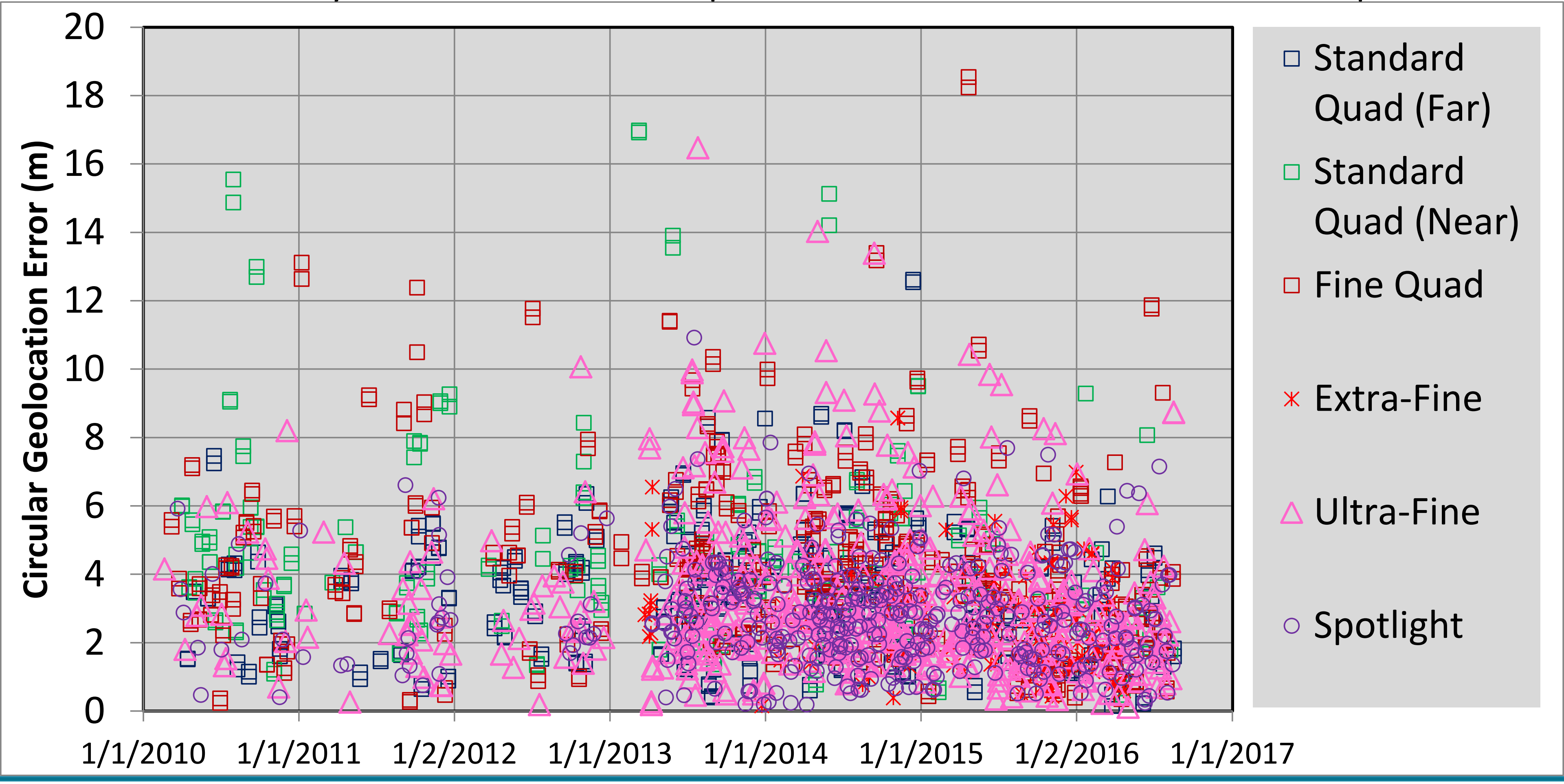
Point Target Monitoring

- MDA owned, precision surveyed corner reflectors in Canada
  - 2 in Vancouver, 2 in Quebec City
- Corner reflectors in other countries
  - JAXA (Tomakomai, Japan)
  - JPL (California)
  - Geoscience Australia (testing in progress)
  - Simon Fraser University (Bolivia)
  - CONAE (Argentina)*
  - DTSO (Adelaide Australia)*
  - U of Zurich (Dubendorf, Switzerland)*
  - * past deployments
- Antenna dishes in Canada
  - Gatineau, Prince Albert, Saskatoon, St-Hubert, Aldergrove, Masstown, Inuvik
  - Higher radar cross-section than corner reflectors, but less accurate
- For geolocation, resolution and sidelobe measurement
- Results are filtered to eliminate non-representative measurements
  - Dish not tracking sensor
  - Contamination from surrounding clutter
  - Snow on reflectors in winter
  - Ground truth accuracy limitations



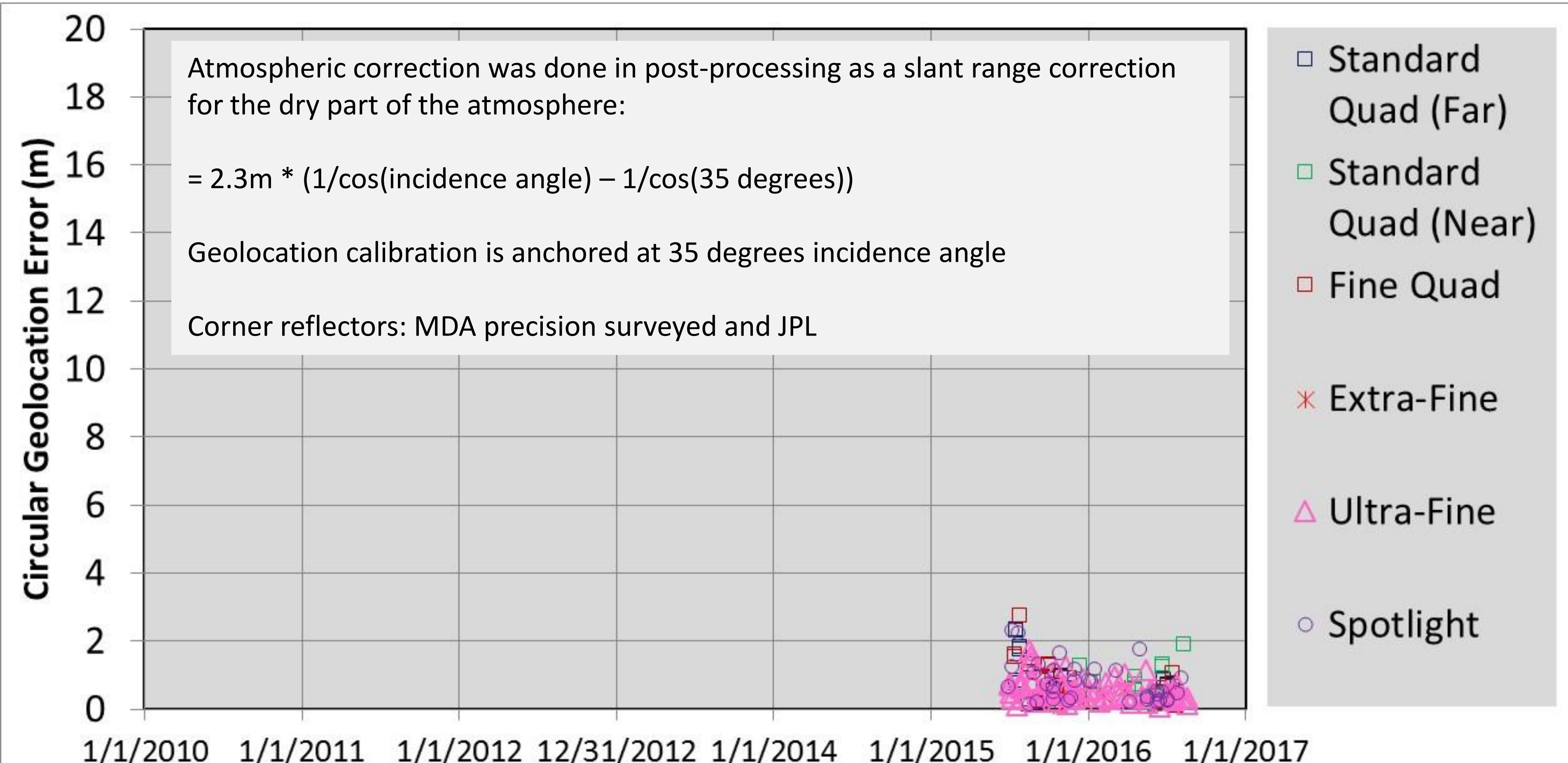
Geolocation Measurement Results

(with Downlinked Orbit data, over Corner Reflectors)
Excellent accuracy at downlink thanks to precision orbit determination on-board spacecraft



Geolocation Measurement Results

(with Definitive Orbit data, over Precision Corner Reflectors, with Atmospheric Correction, since release of enhanced accuracy Definitive Orbit on 30-June-2015)

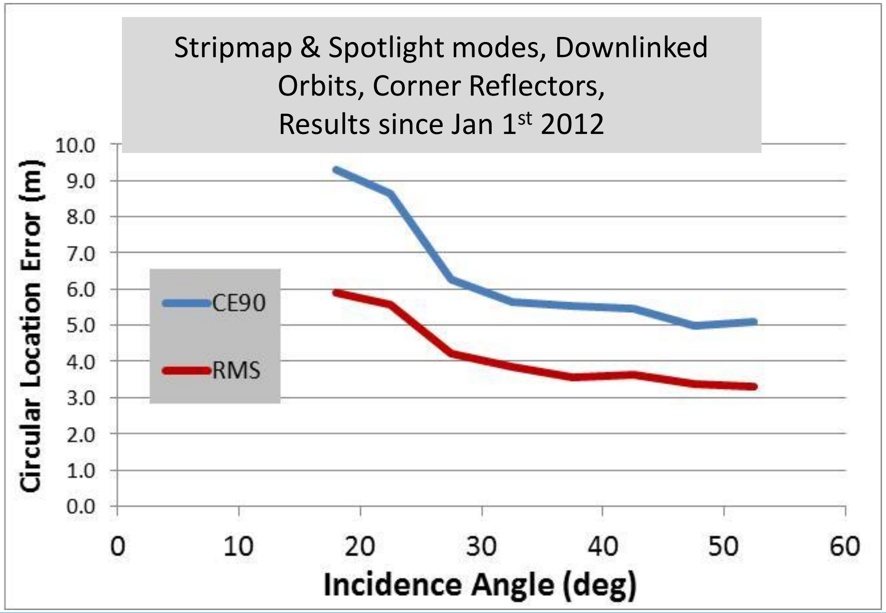


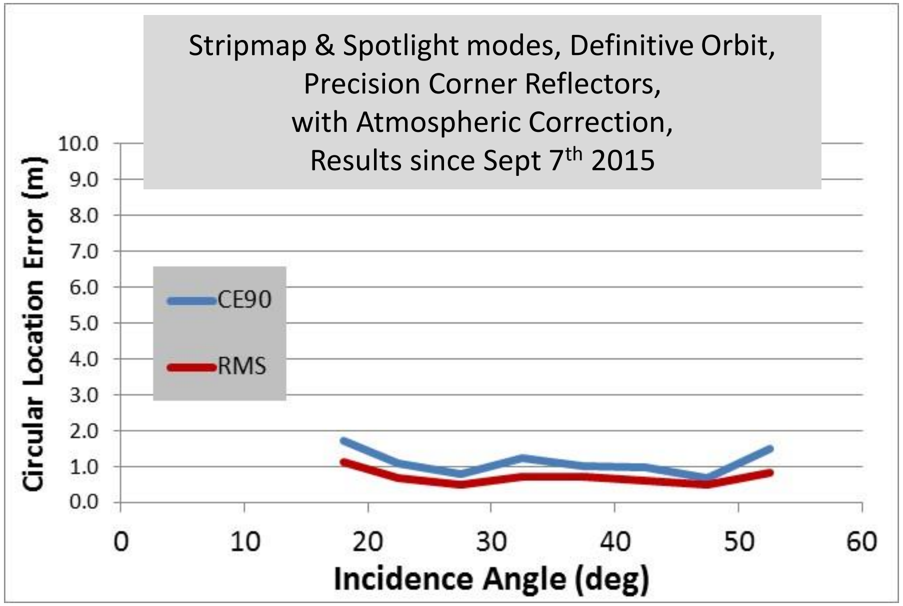
MDA

Geolocation Measurement Statistics

- Measured location errors with Downlinked orbit data
  - < 6 m RMS in most Single-Beam and Spotlight modes
  - <10 m RMS in Extended Low Incidence mode
  - <20 m RMS in ScanSAR modes
- Measured location errors with Definitive orbit data (available with ~1-2 days latency)
  - <2 m RMS in most Single-Beam and Spotlight modes after atmospheric correction in post-processing
- Generally better than the conservative accuracy values given in RADARSAT-2 Product Description documentation
  - Much better than original mission performance goals
  - Continues to improve through orbit accuracy, calibration and SAR processing refinements

Note: Accurate geolocation requires accurate terrain height knowledge. These geolocation measurements are for calibrated corner reflectors of known elevation.



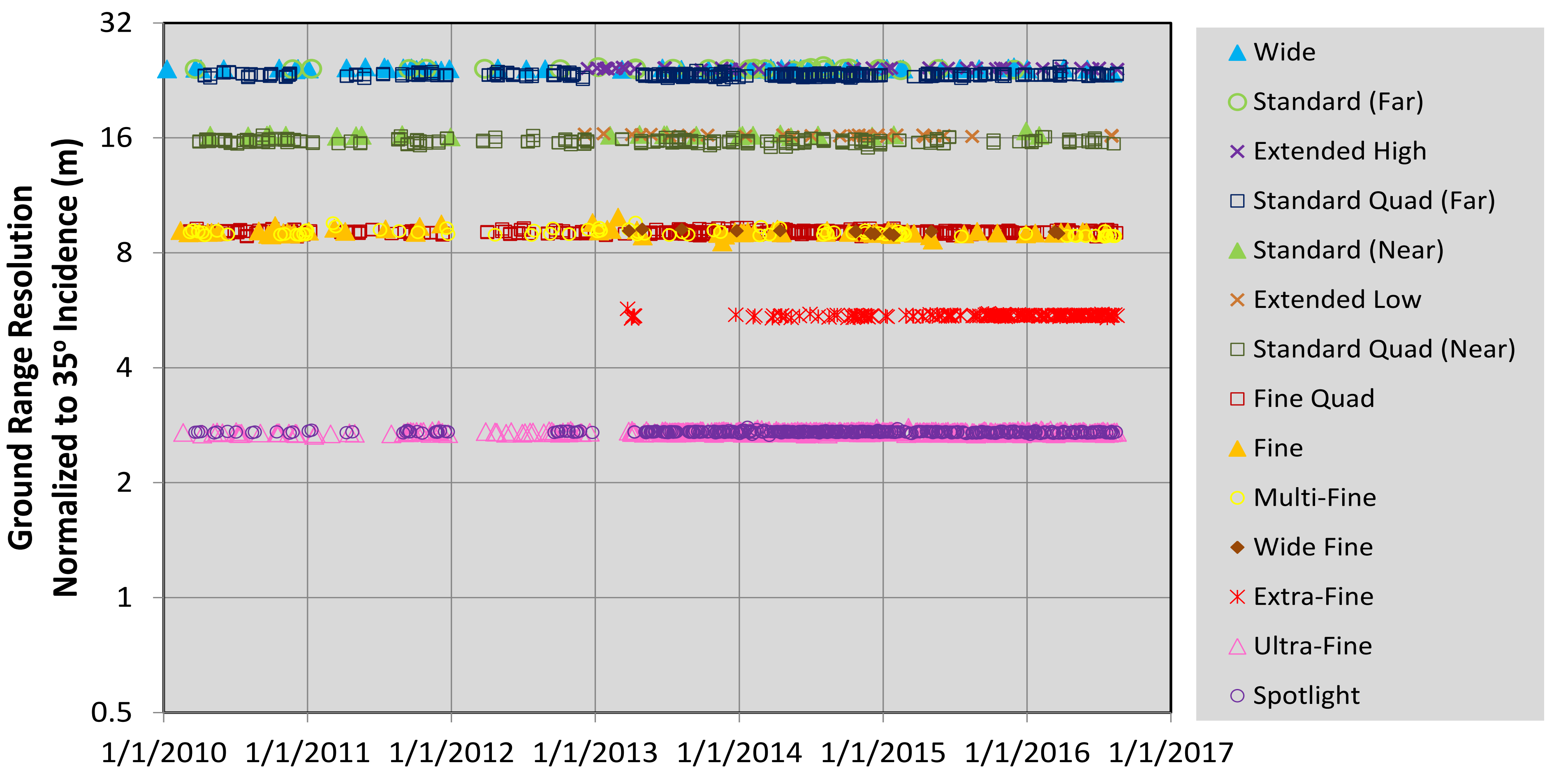


RMS = root mean square; CE90 = circular error, 90th percentile

Ground Range Resolution (SGX Products)

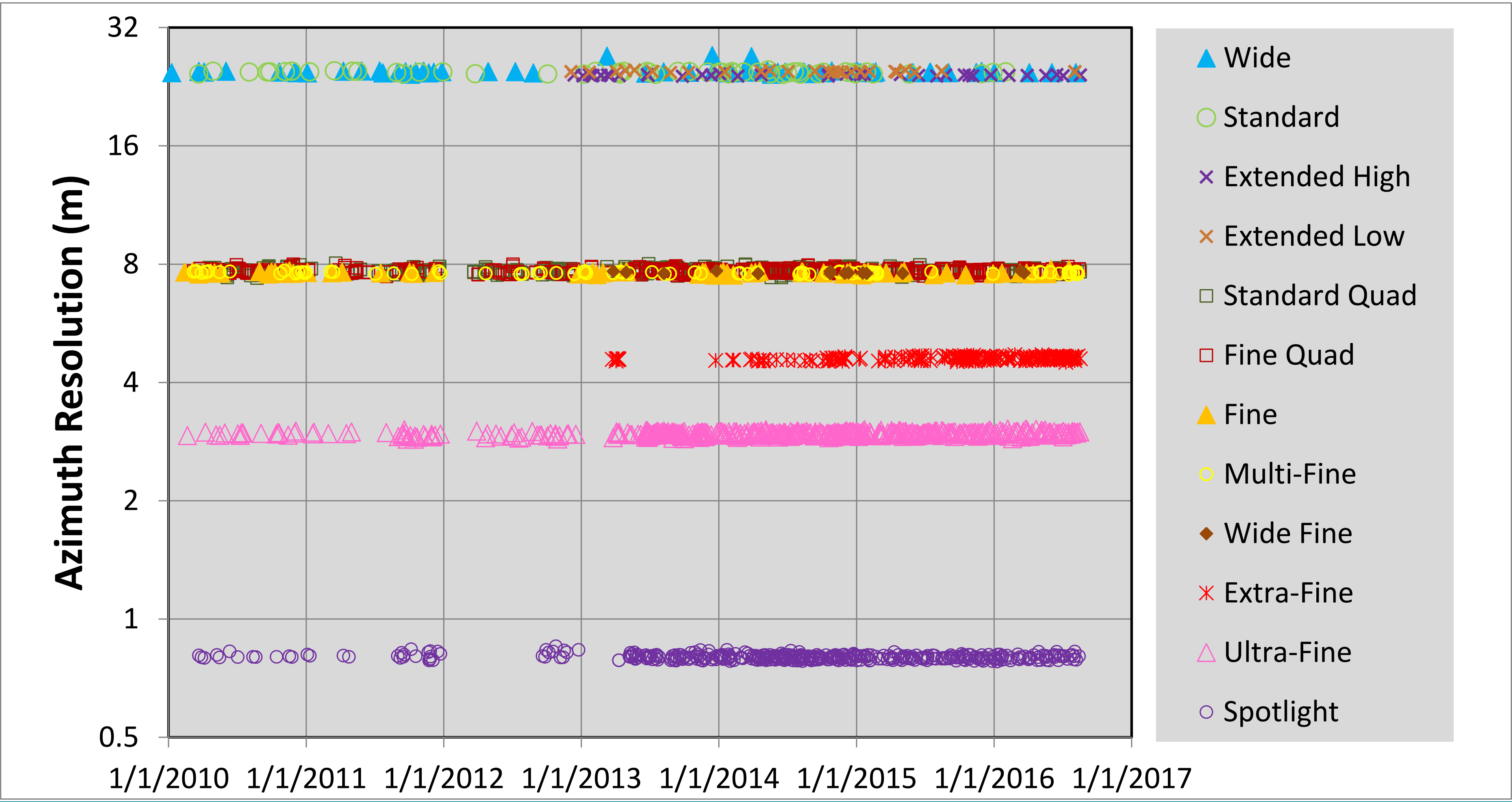
Very stable (when normalized by incidence angle)

Normalized resolution = resolution * sin(incidence angle) / sin(35o)

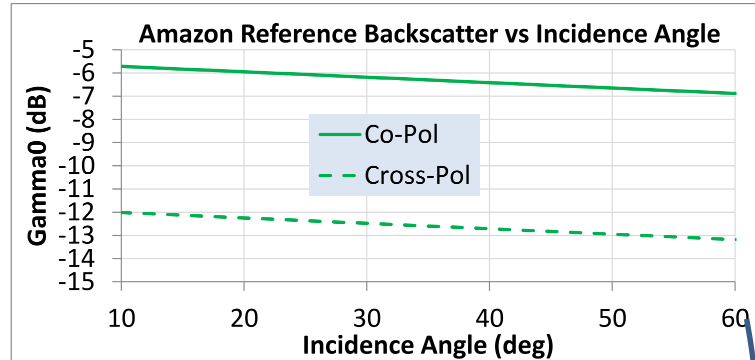


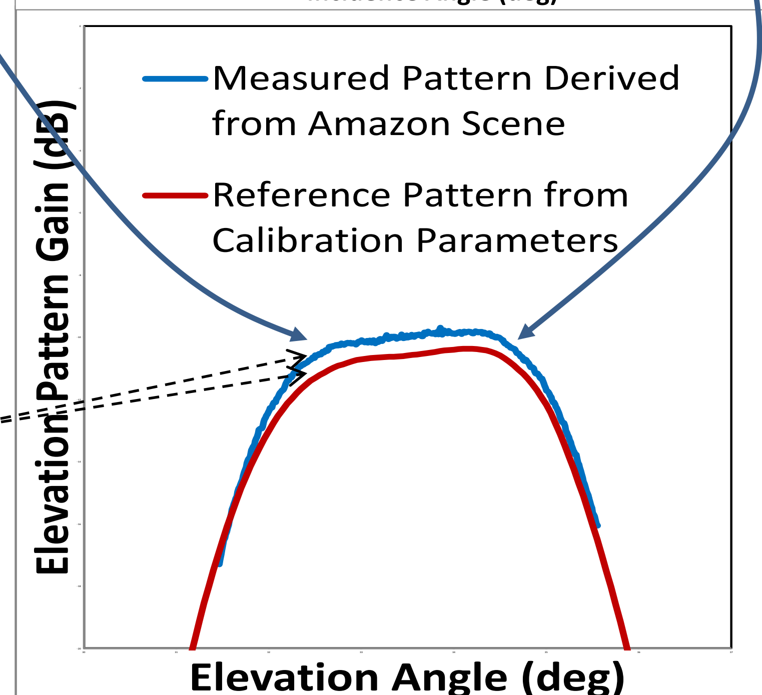
Azimuth Resolution (SGX Products)

Very stable



Radiometric Accuracy Monitoring (1)



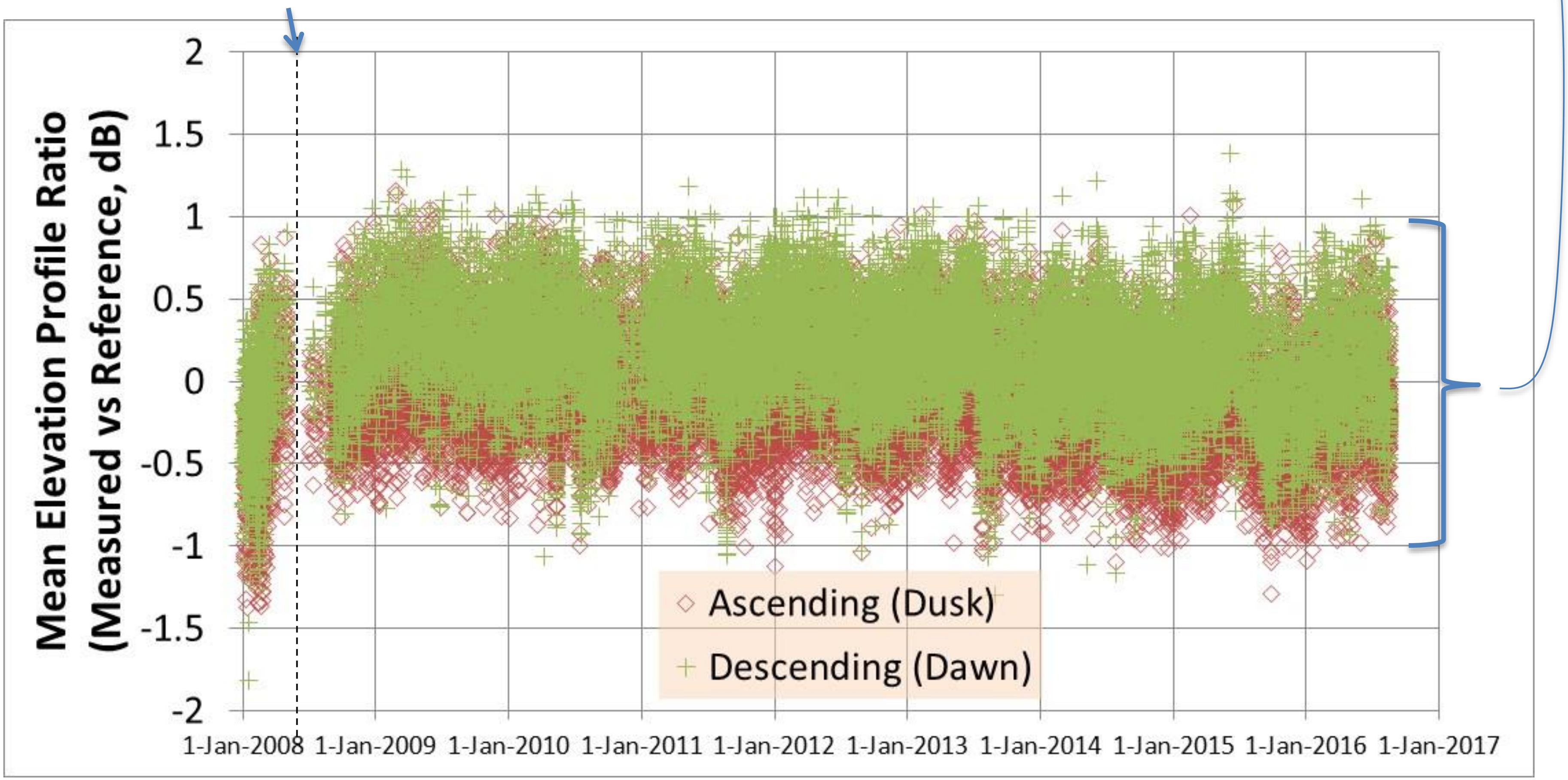


- The main method for monitoring absolute radiometry is through antenna elevation pattern analysis in Single Beam modes:
  - Measure backscatter profile as a function of range over a homogeneous area of the Amazon rainforest
  - Convert into a measured elevation pattern by subtracting noise, scaling by the assumed mean backscatter function of the Amazon, and backing out the elevation pattern correction applied during processing
  - Align the measured pattern with the reference pattern from the calibration parameters, take the power ratio between the 2 patterns, and track it over time

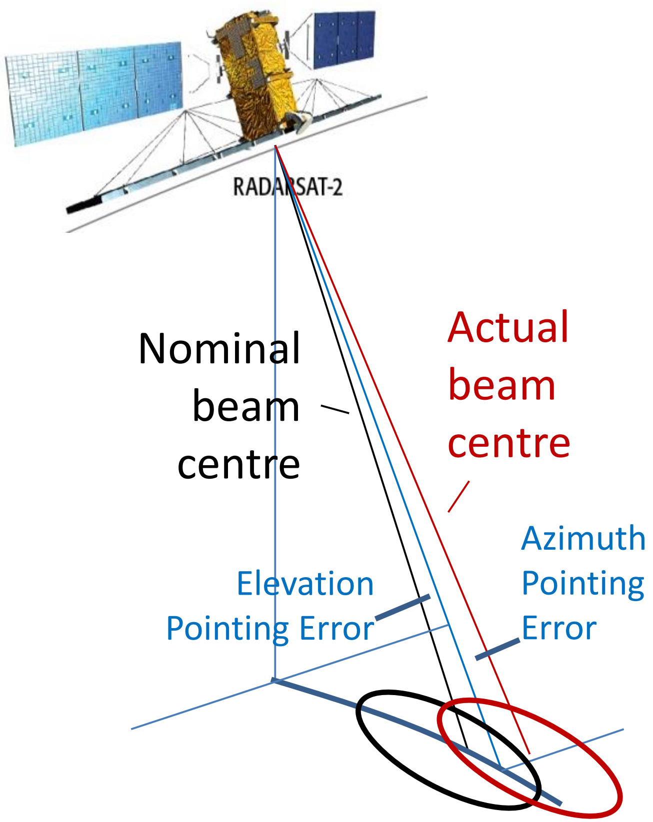
Mean Radiometric Offset

Overall results (for all beams) are gradually improving (ongoing beam-specific calibration refinements since initial operations in April 2008)

Mean difference from Amazon reference is nearly zero
(~ -0.15 dB on Ascending passes, +0.1 dB on Descending passes)
Mean per-scene differences typically within +/- 1 dB (std. dev. = 0.3 dB)

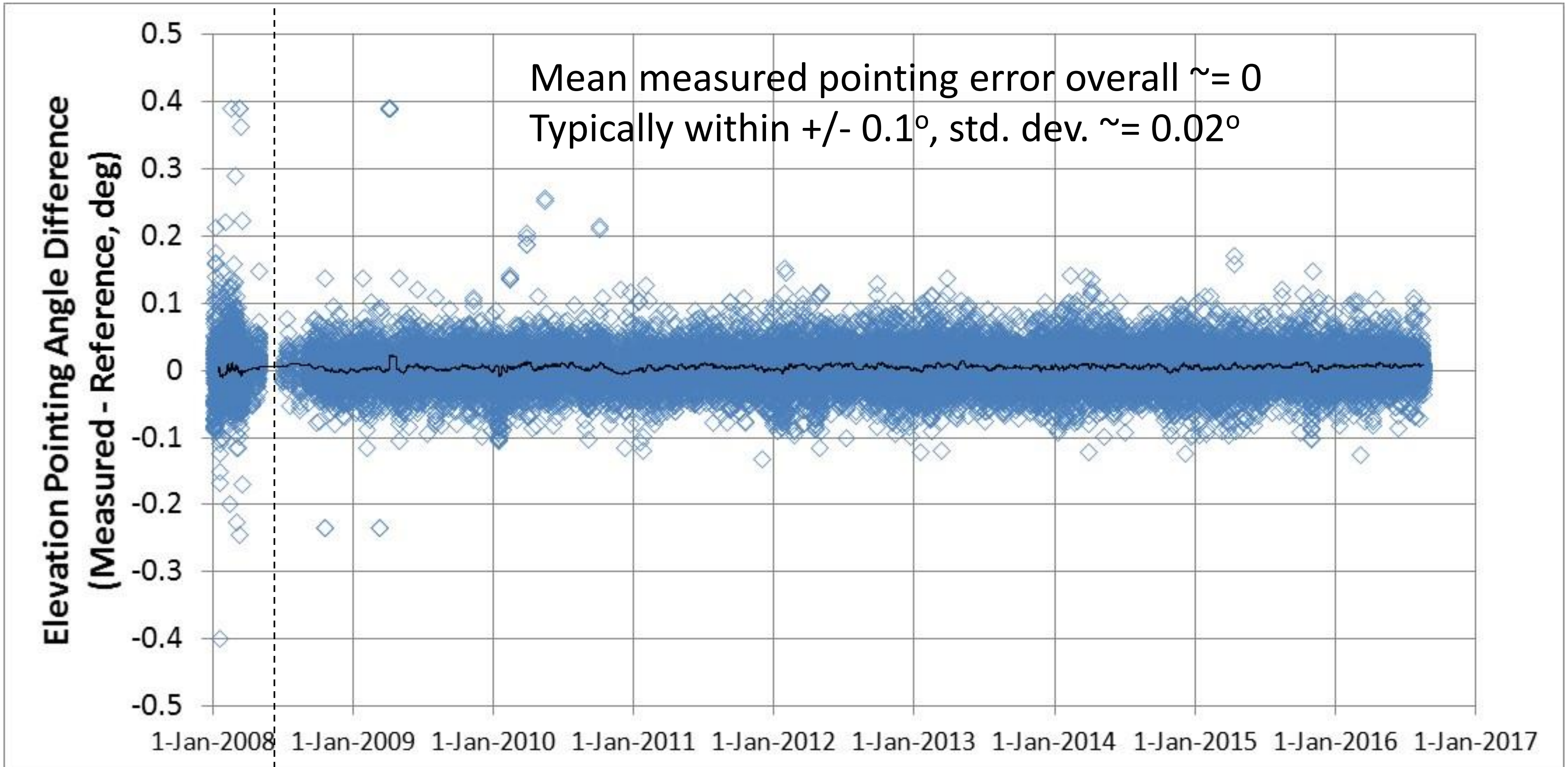


Beam Pointing Monitoring



- Elevation beam pointing is monitored using elevation pattern analysis over the Amazon
  - The shifts needed to align the measured and reference elevation patterns are recorded and trended over time
- Azimuth beam pointing is monitored by comparing pitch and yaw measured on-board with Doppler centroid frequency estimated adaptively during SAR processing
  - For image quality monitoring products over the Amazon
- This shows trends in how the beam pointing varies with respect to nominal

Elevation Beam Pointing Results

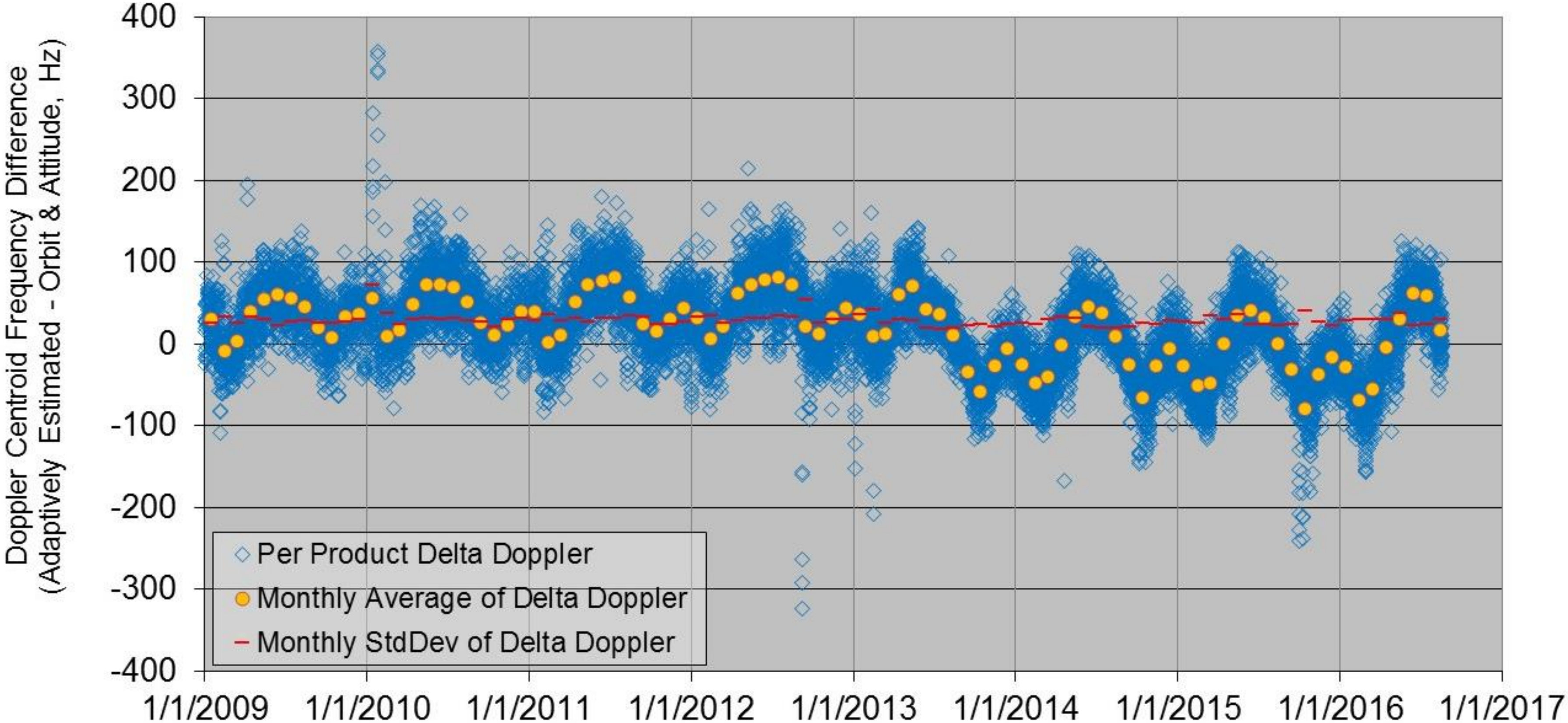


Overall results are stable since initial operations in April 2008

The measurements contain a few outliers, mainly due to variations in scene content (Amazon scenes not perfectly uniform)

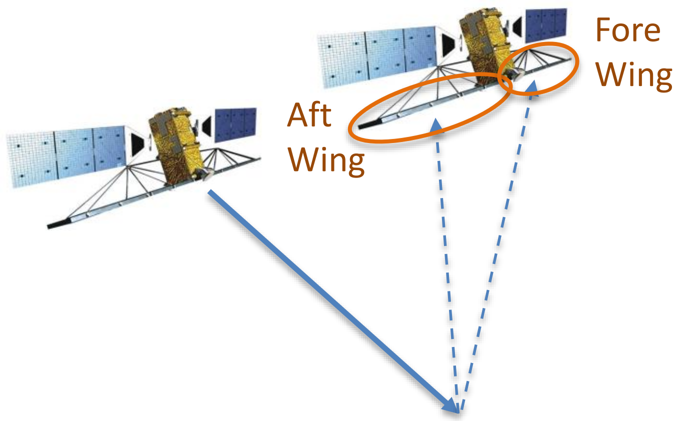
Azimuth Beam Pointing Results

- Mean azimuth beam pointing from antenna boresight is nearly zero
- Follows seasonal trends, likely due to thermal effects
  - Within +/- 100 Hz ~= 0.02°, regular trend since solar arrays began tracking the sun year-round (August 2013)
  - Compensated by adaptive Doppler centroid estimation in SAR processing and inter-wing phase calibration adjustments
- Minor problems with a small number of Left-looking slews in fall 2015 were corrected by adjusting star tracker operations



Inter-Wing Phase Balance Monitoring

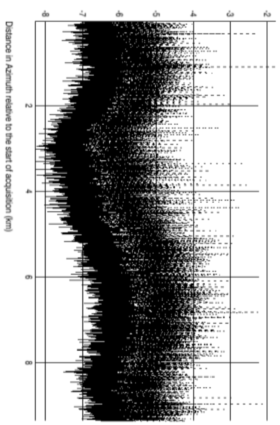
- RADARSAT-2 can operate with dual receive apertures (wings)
  - Doubles the effective pulse repetition frequency
  - Used in Multi-Fine, Extra-Fine, Ultra-Fine, Spotlight, and DVWF modes

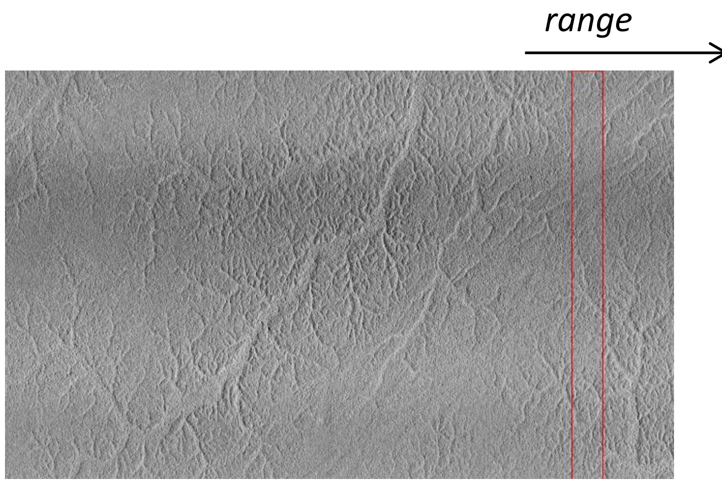


- A phase difference between fore and aft wings causes an azimuth beam pointing shift (Doppler shift) from boresight

- The main impacts of uncompensated phase differences are subtle radiometric residual ripples in Spotlight images
  - Not typically visible except in scenes of uniform ground cover
  - Not a significant issue in other commercial operations

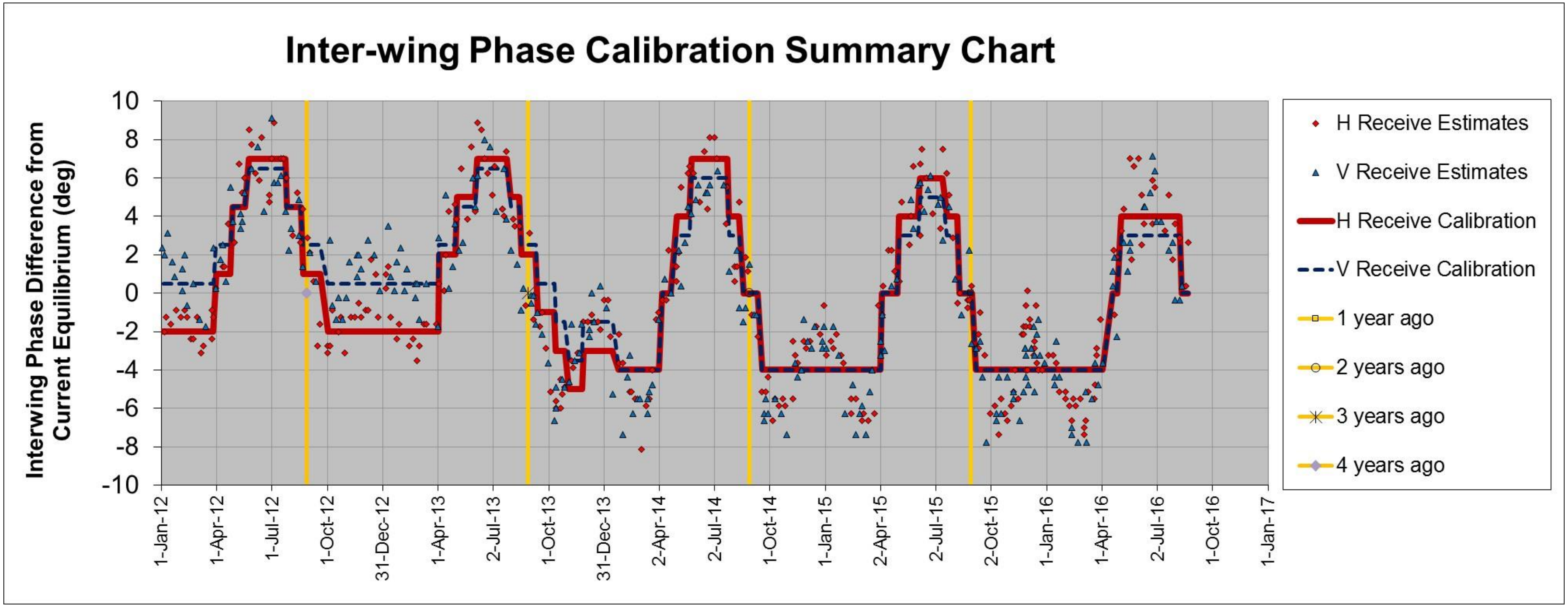
- We use Spotlight images over the Amazon to monitor and correct for this:
  - Observed radiometric errors are used to estimate inter-wing phase imbalances, which drive regular seasonal calibration adjustments





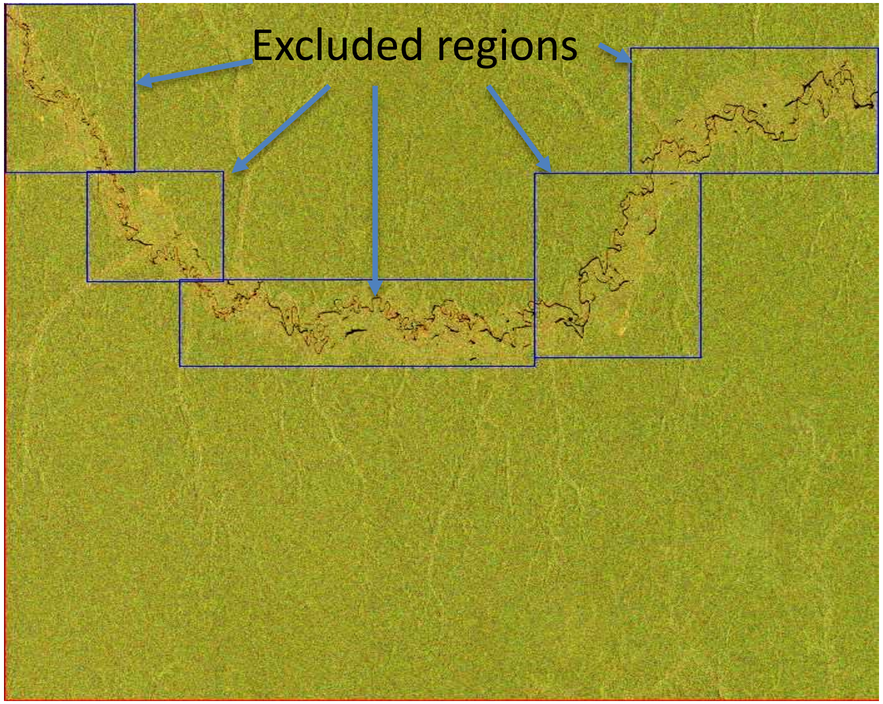
Inter-Wing Phase Balance Results and Seasonal Calibration Adjustments

- Seasonal trends resemble those of the mean Doppler Centroid frequency delta from boresight
- Changes are compensated through adaptive processing and calibration adjustments to maintain optimal image quality
  - Calibration adjustments are made at discrete intervals in both H and V receive polarizations



Polarimetric Calibration Monitoring

- For RADARSAT-2, polarization distortion is characterized over homogeneous regions of the Amazon rain forest:
  - Supports calibration over the entire swath
  - Known, stable, polarimetric signature:
    - Reciprocity
    - Azimuth symmetry
  - High signal to noise ratio
  - No ground infrastructure cost
- Input:
  - SLC products with HH absolute radiometric calibration applied
- Procedures:
  - The homogoneous area of each product is identified (regions to exclude are selected manually if necessary)
  - This area is partitioned into range sections, each spanning a fixed elevation angle (~0.2°)
  - An average 4 x 4 covariance matrix is calculated over each section, representing the observed polarimetric signature
  - Imbalance and cross-talk on TX and RX are estimated from each covariance matrix
  - These are tracked and trended over time



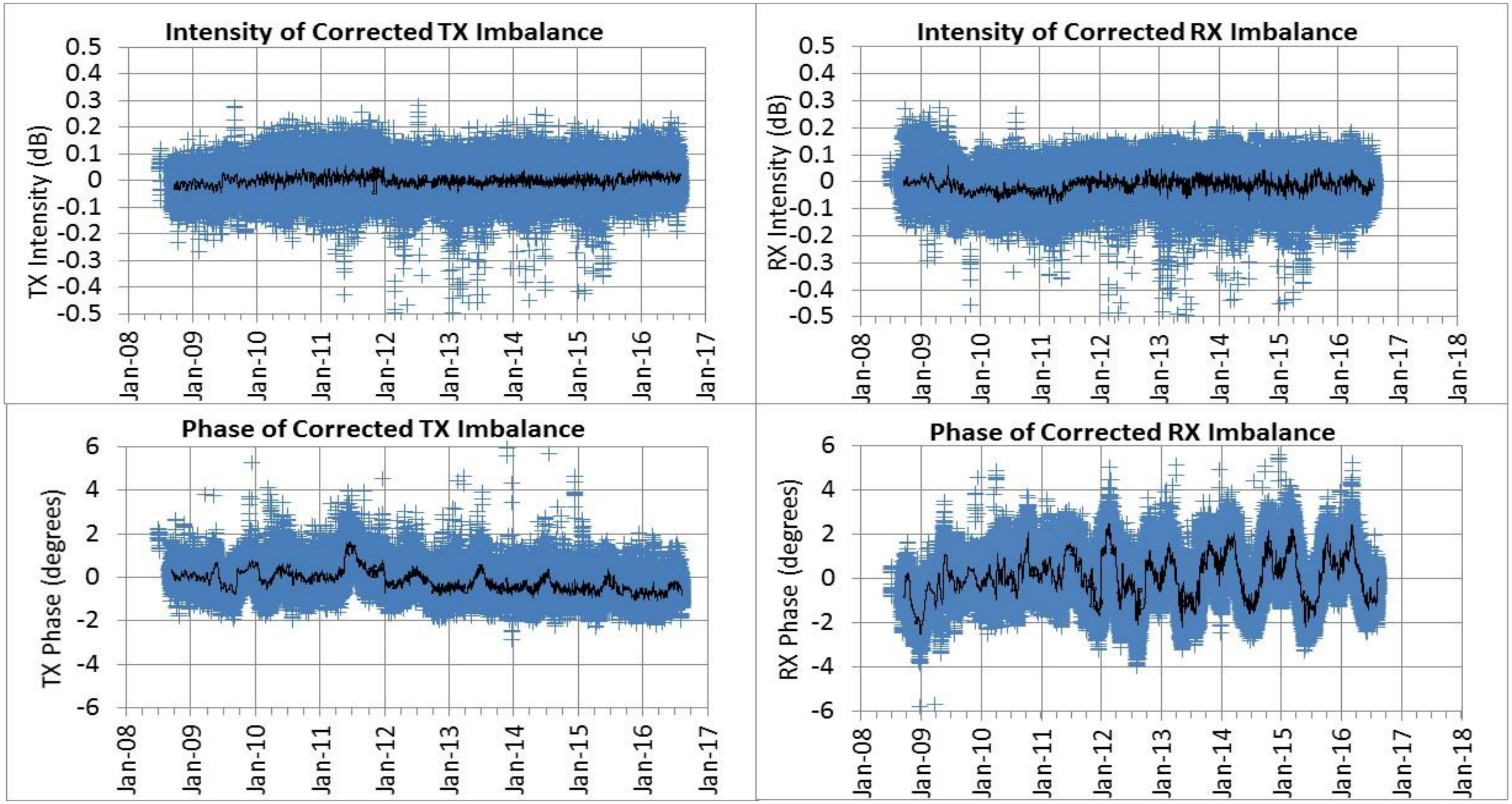
Expected covariance matrix for Amazon rain forest

$$\mathbf{C}=\begin{pmatrix} a & 0 & 0 & d \\ 0 & b & b & 0 \\ 0 & b & b & 0 \\ d & 0 & 0 & a \end{pmatrix}$$

Co-pol γ^0 backscatter: $a \sim -6.5$ dB
X-pol γ^0 backscatter: $b \sim -12.5$ dB
Co-pol γ^0 product: $d \sim -9.5$ dB

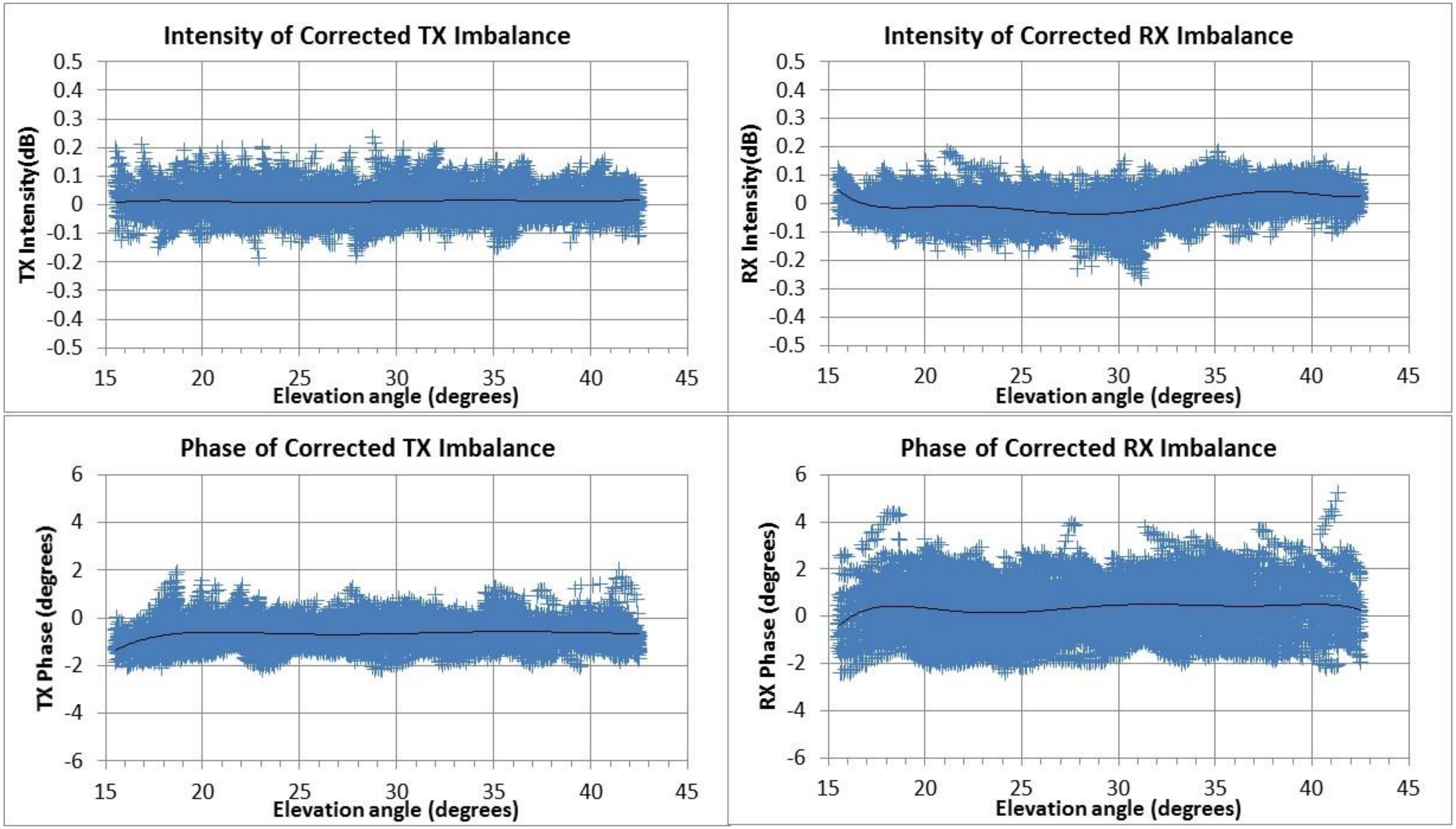
Polarimetric Balance Results

- Following calibration, overall accuracy is well within performance goals:
  - TX imbalance: mean ~= 0, std. dev. = 0.1 dB intensity, 1° phase
  - RX imbalance: mean ~= 0, std. dev. = 0.1 dB intensity, 2° phase



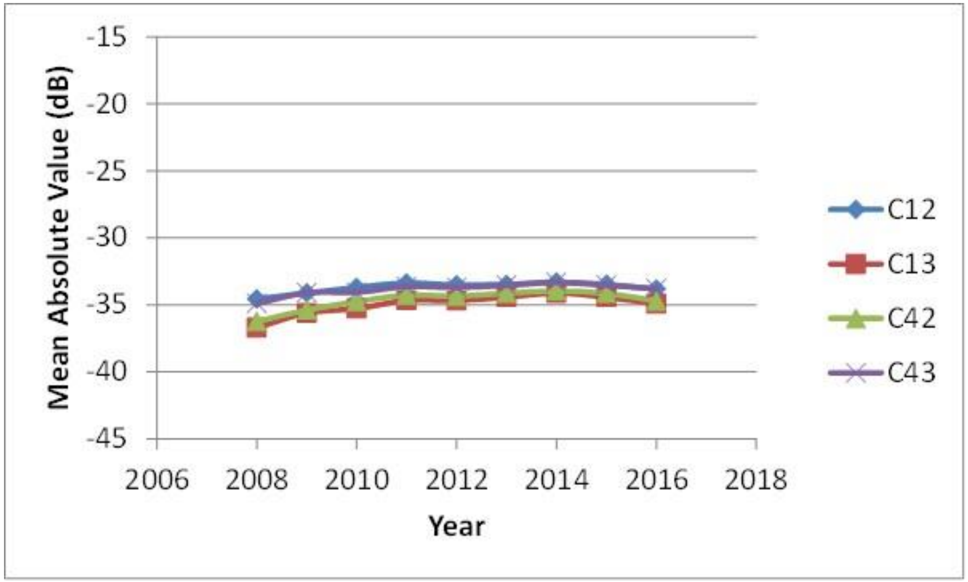
Polarimetric Balance Results vs Angle

- Trends shown as a function of elevation (off-nadir) angle over the past year, for right-looking beams
  - Performance remains well within operating goals for all beams (0.5 dB intensity, 5 deg phase)
  - Beam-specific calibration adjustments to Tx phase balance are being planned
    - Gradual changes since last polarimetric calibration update in 2013



Polarimetric Cross-Talk Results

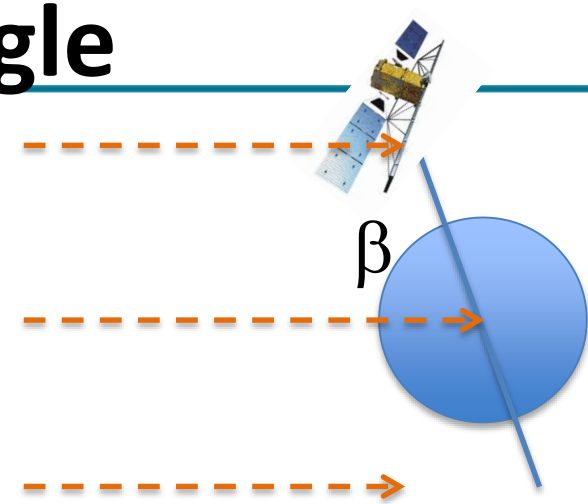
- Following calibration, cross-talk levels remain excellent

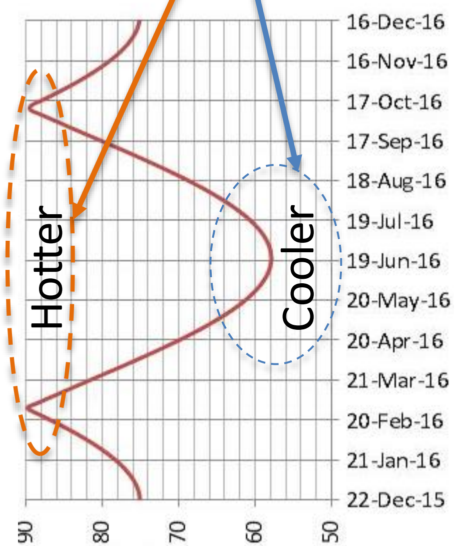


C12 = spatial averaged Hermitian product of the HH and HV complex scattering amplitudes
C13 = spatial averaged Hermitian product of the HH and VH complex scattering amplitudes
C42 = spatial averaged Hermitian product of the VV and HV complex scattering amplitudes
C43 = spatial averaged Hermitian product of the VV and VH complex scattering amplitudes
All less than -30 dB, well within performance goals

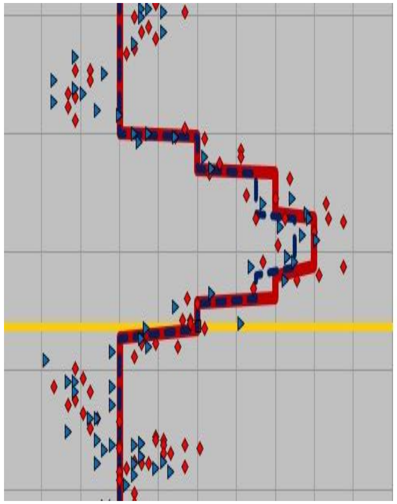
Influence of Solar Beta Angle

- Solar beta is the angle between solar illumination and the orbital plane
- Its variation throughout the year is closely mirrored by some of the quality measures we track
  - Inter-wing phase balance (addressed by calibration updates)
  - Azimuth beam pointing (compensated by adaptive Doppler centroid estimation)
  - Polarimetric receive phase balance (impact on quality is very small)
- Spacecraft component temperatures show similar trends and are the likely mechanism

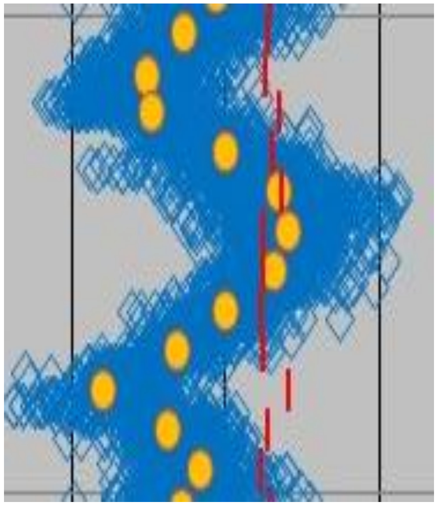




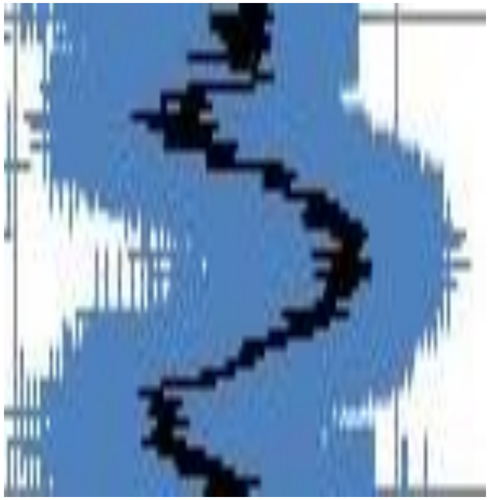
Solar Beta Angle (deg)



Inter-Wing Phase Balance



Azimuth Pointing Variation from Boresight



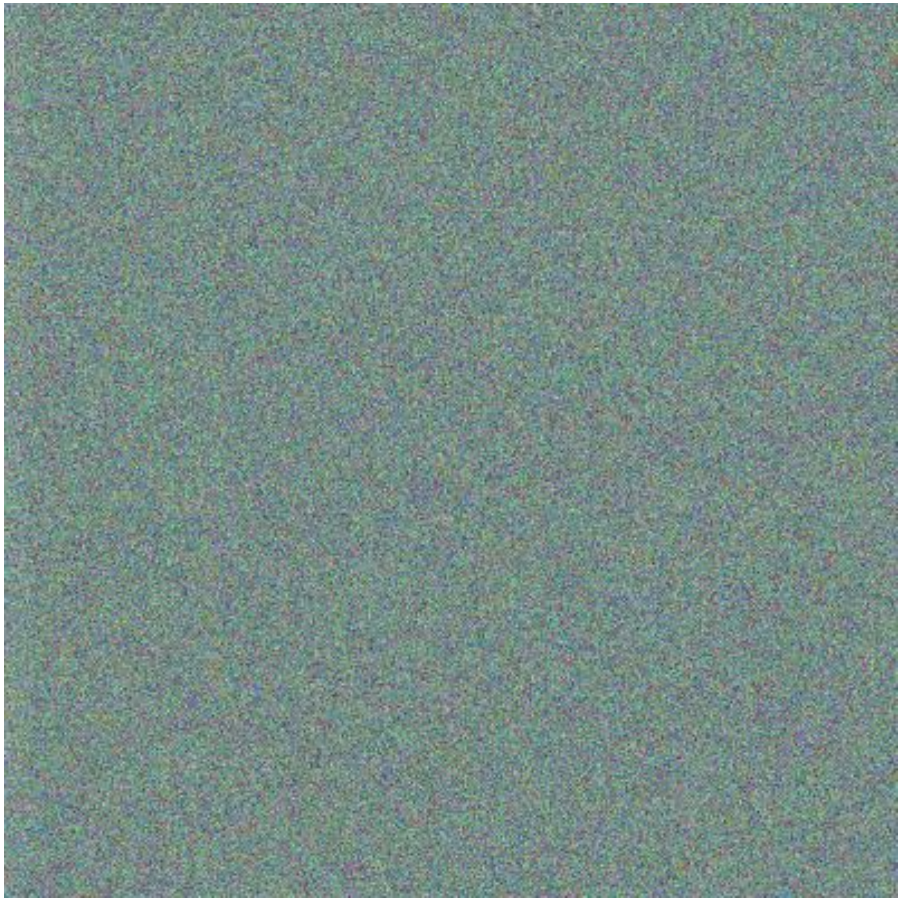
Polarimetric Receive Phase Balance

Noise Level Monitoring

- Data collected in “receive-only” modes
  - Antenna receives but does not transmit
  - Processed image contains only noise
  - Acquisitions cover all pulse types used in commercial modes

- Processed image levels are analyzed and converted to estimates of noise levels in the raw data

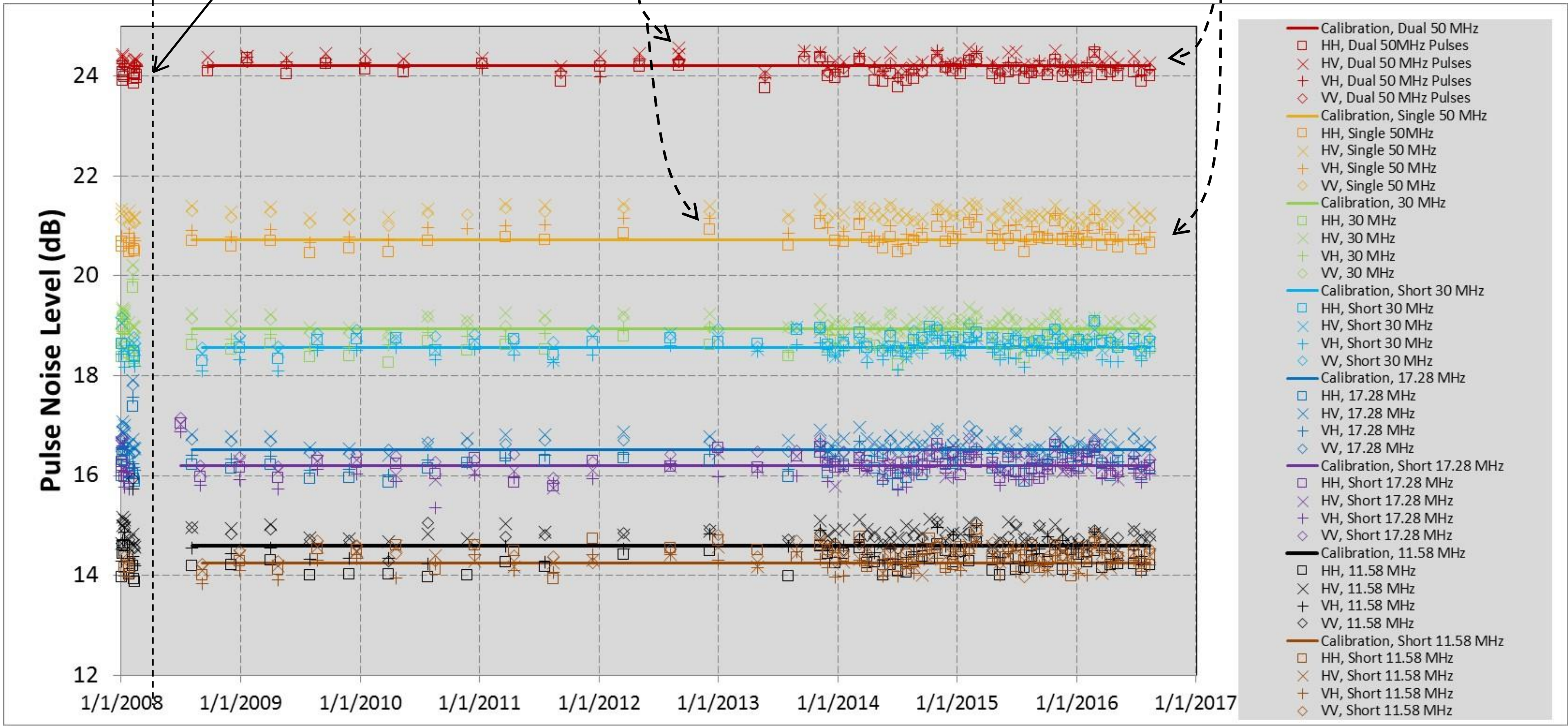
- These estimates are compared to the calibrated noise level associated with each pulse



Noise Level Measurement Results

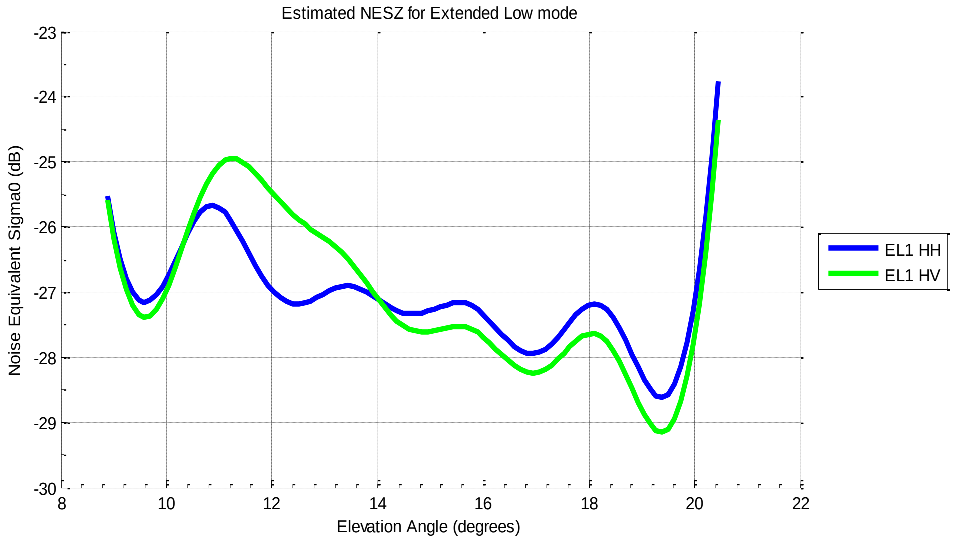
Results are stable since initial operations in April 2008

Measurements in all polarizations remain within ~1 dB of calibrated levels



Noise Equivalent Sigma0 (NESZ)

- The NESZ depends on the pulse noise levels shown in the previous slide, plus beam-related noise factors and processing gains
- Using the Extended Low Incidence Mode as an example:
  - The pulse noise level is ~16.5 dB (as shown in the previous slide for the 17.28 MHz pulse)
  - This is equivalent to ~10^(16.5/20)/sqrt(2) ~= 4.7 digital amplitude counts for both I and Q channels, before front-end attenuations
  - Processing gains include radiometric corrections, which depend on antenna array and sub-array patterns, which are slightly different for the V polarization than for the H polarization
  - Overall the NESZ of the new HV channel is slightly higher than for the HH channel but both are <= -24 dB

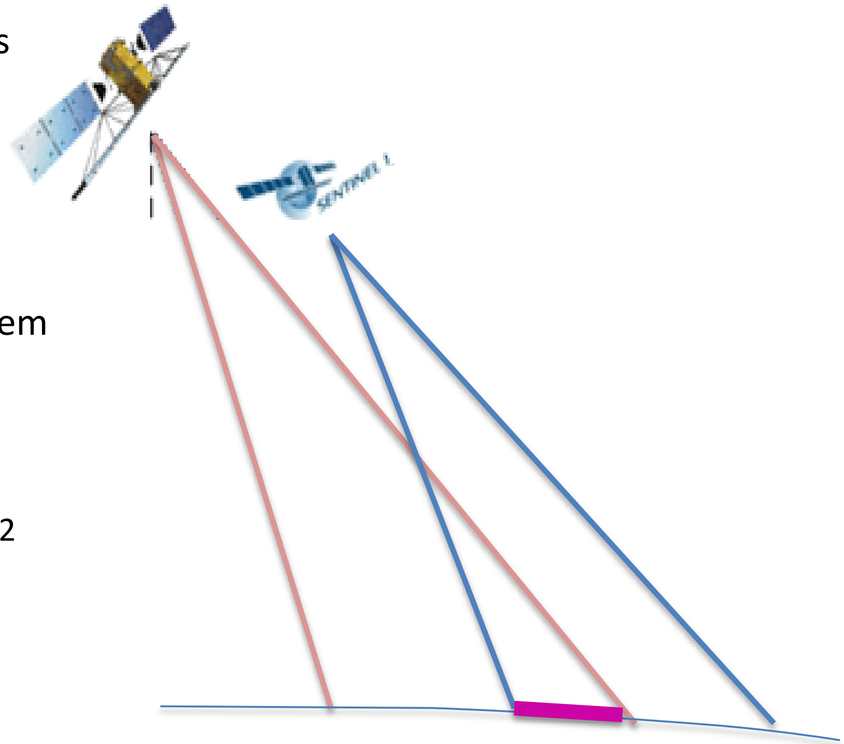


Other Aspects of RADARSAT-2 Image Quality Monitoring

Type of Monitoring	Description
Point target sidelobe ratios	Stable (within specifications where clean measurements are possible), <= -18 dB peak SLR, <= -14.9 dB integrated SLR
Azimuth pattern shape	Stable since initial operations (correlations of measured patterns with reference patterns > 98%)
Ambiguity levels	Stable (results of occasional spot checks in selected modes are consistent with models)
Chirp replica coefficients	Stable
BAQ table usage	Stable (good use of available dynamic range)
Payload local oscillator	Stable (based on timing analysis of raw echo data)
Antenna Diagnostics	Nominal (all T/R modules are operating well; results show minor seasonal magnitude and phase variations within design expectations)
Product Quality Control at Gatineau HQ	Each product is checked for artifacts, geolocation discrepancies, and coverage errors – any problems are reported and tracked

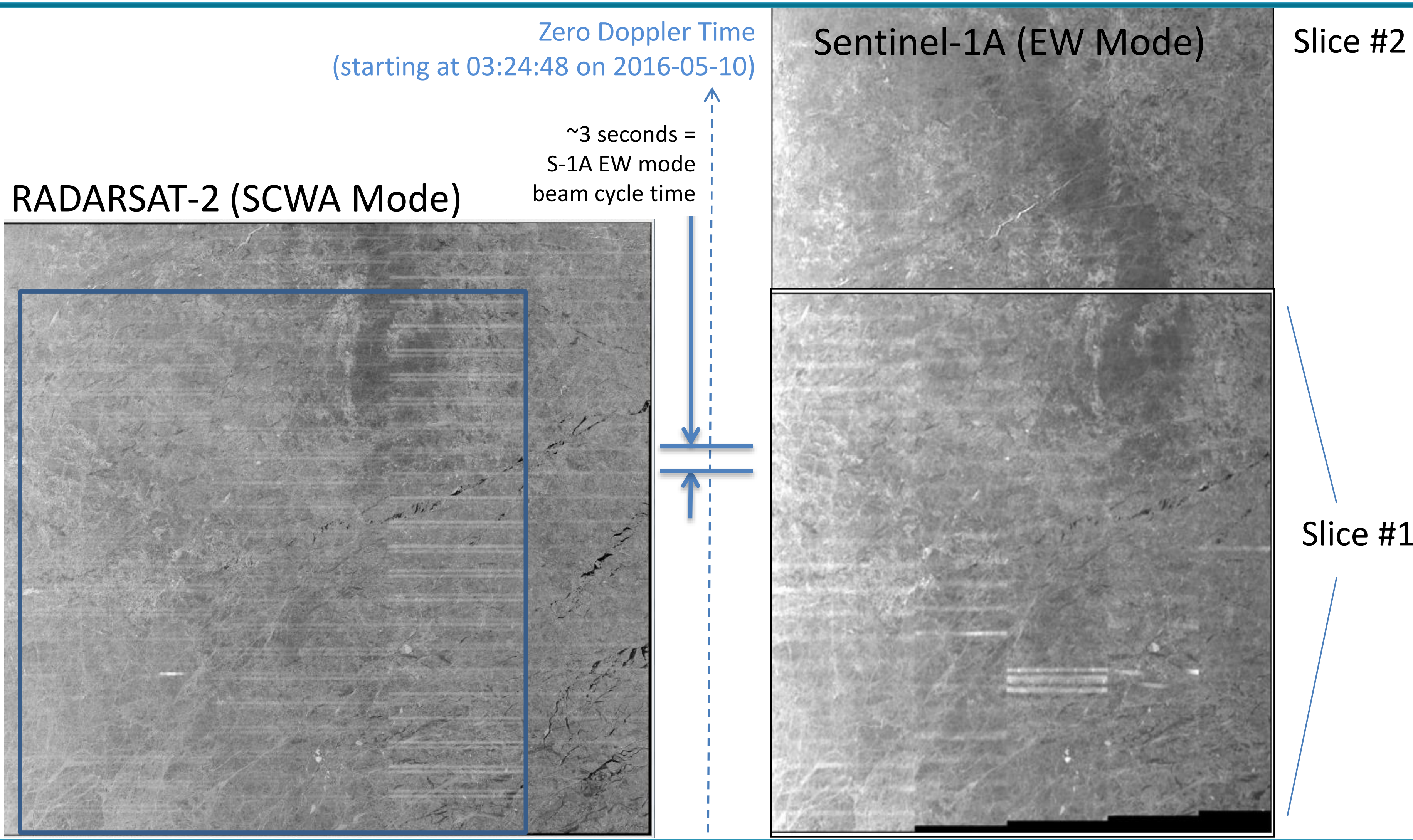
Sentinel-1 Mutual Interference

- Mutual interference occurs when pulses transmitted by antenna on one spacecraft are received by antenna on the other spacecraft
  - Sentinel-1 operates at similar C-Band frequencies as RADARSAT-2
  - Main concern is the bistatic case where both missions illuminate the same area on the ground at the same time
    - Temporary rise in noise level



- MDA is taking a pro-active approach
  - Discussing with ESA approaches to mitigate the problem through orbit control adjustments
  - Monitoring the known orbit crossing points where interference may occur and issuing quality notices to users when necessary
    - 11 events affecting image quality observed in the last 12 months (< 0.1% of acquisitions)
  - Developing a software tool to predict future interference events with S-1 and other missions
  - Considering future missions in collaboration with Canadian Space Agency
  - Raising awareness

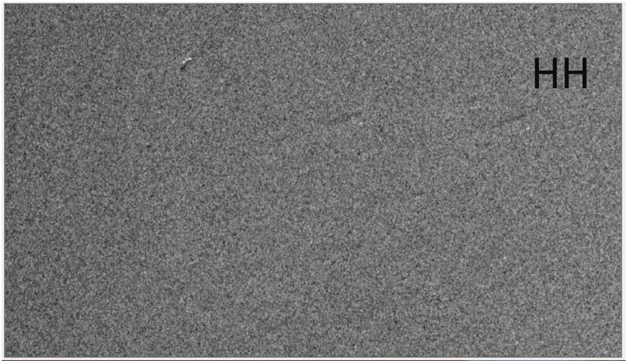
Sentinel-1 Interference Example

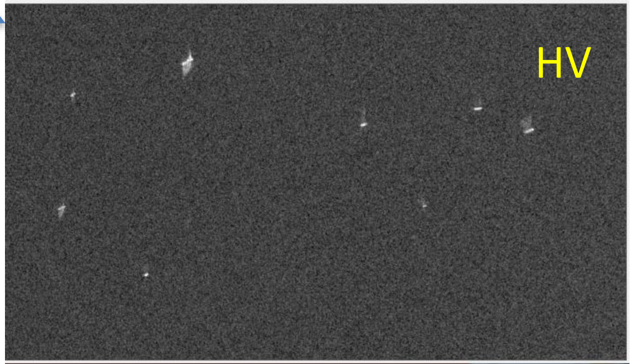


Sentinel-1A imagery is from ESA Copernicus Sentinels Scientific Data Hub

New Dual-Polarized Extended Low Mode

- Currently the Extended Low Incidence mode operates in HH polarization only
- However, HV polarization is useful for ship detection at low incidence angles
  - Ships stand out well thanks to lower sea clutter
- New Dual-Polarized HH+HV mode is prepared and calibrated
  - Products expected to be available commercially soon

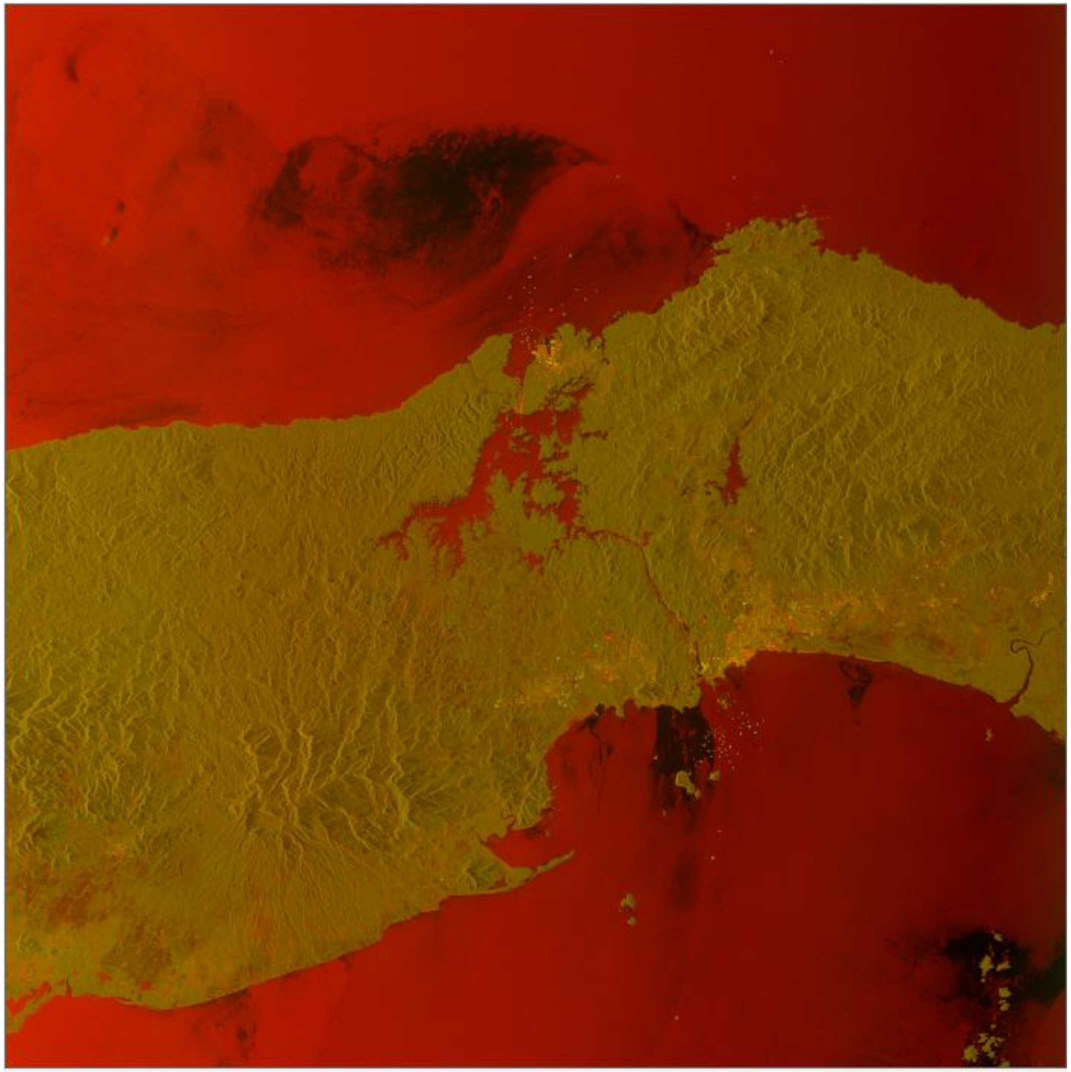




BEAM MODE	PRODUCT	Nominal Pixel Spacing Range x Azimuth (metres)	Nominal Resolution Range x Azimuth (metres)	Nominal Scene Size Range x Azimuth (kilometres)	Range of Angle of Incidence (degrees)	No. of Looks Range x Azimuth	Polarizations Options
Extended Low	SLC	8.0 x 5.1	9.0 x 7.7	170 x 170	10 - 23	1 x 1	Single Pol (HH only) or Dual Pol (HH + HV)
	SGX	10.0 x 10.0	52.7 - 23.3 x 24.7			1 x 4	
	SGF	12.5 x 12.5					
	SSG, SPG						

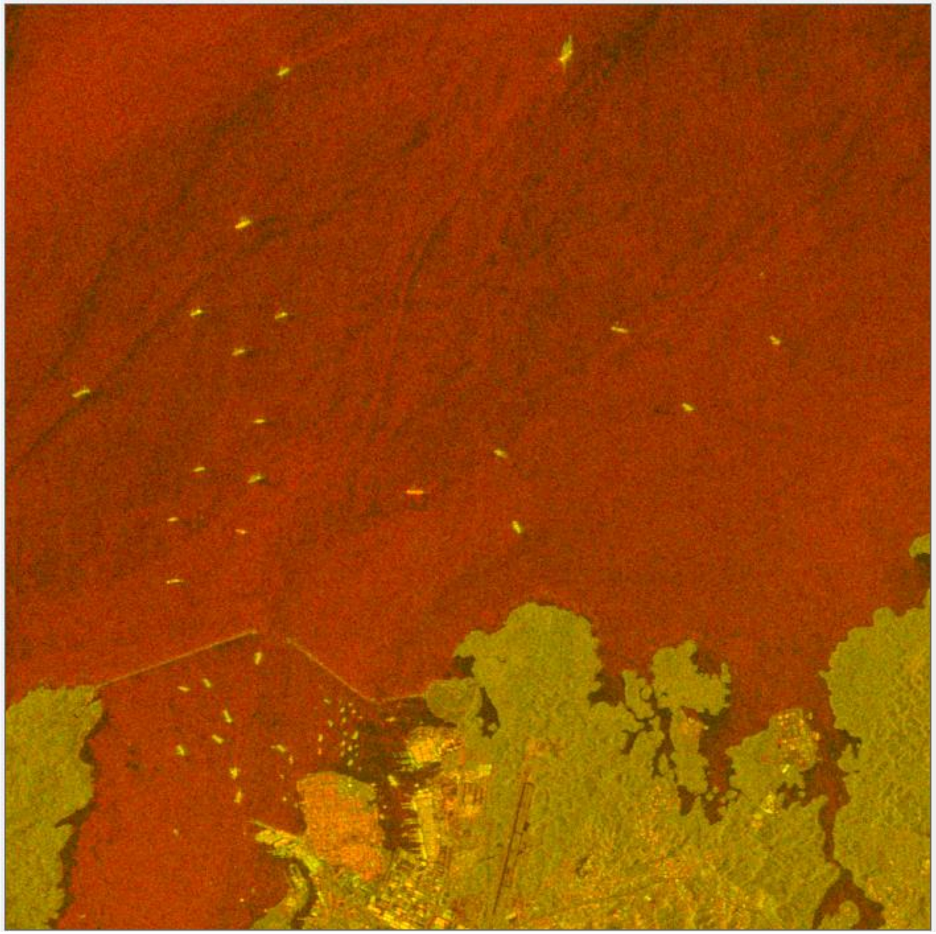
Extended Low Mode Dual-Pol Example

- Panama Canal Zone

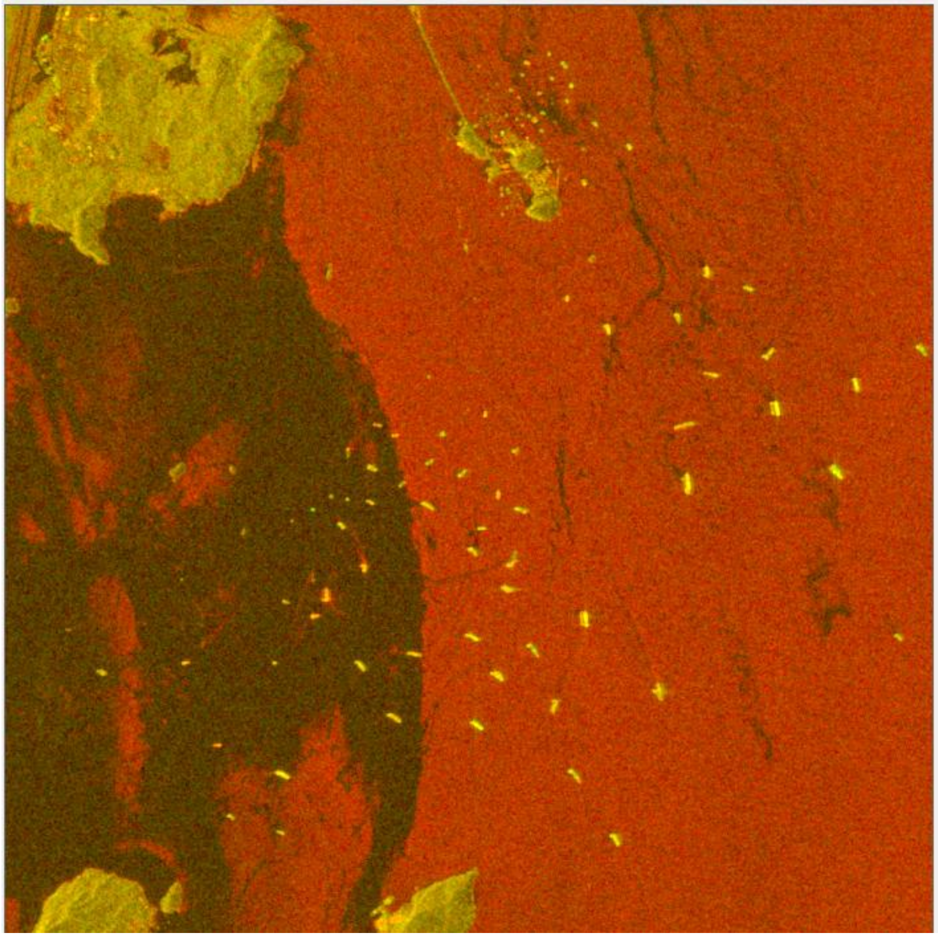


Zoom on Ships – Dual Pol

North end of Canal



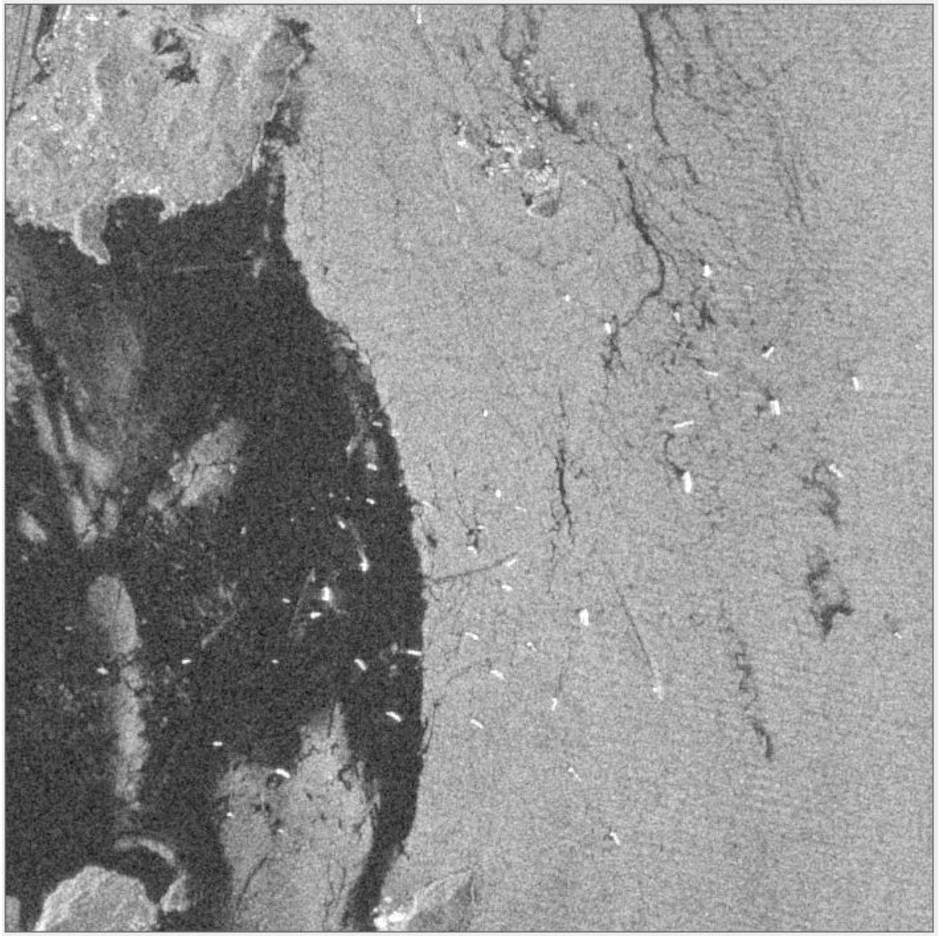
South end of Canal



Zoom on Ships – HH Pol

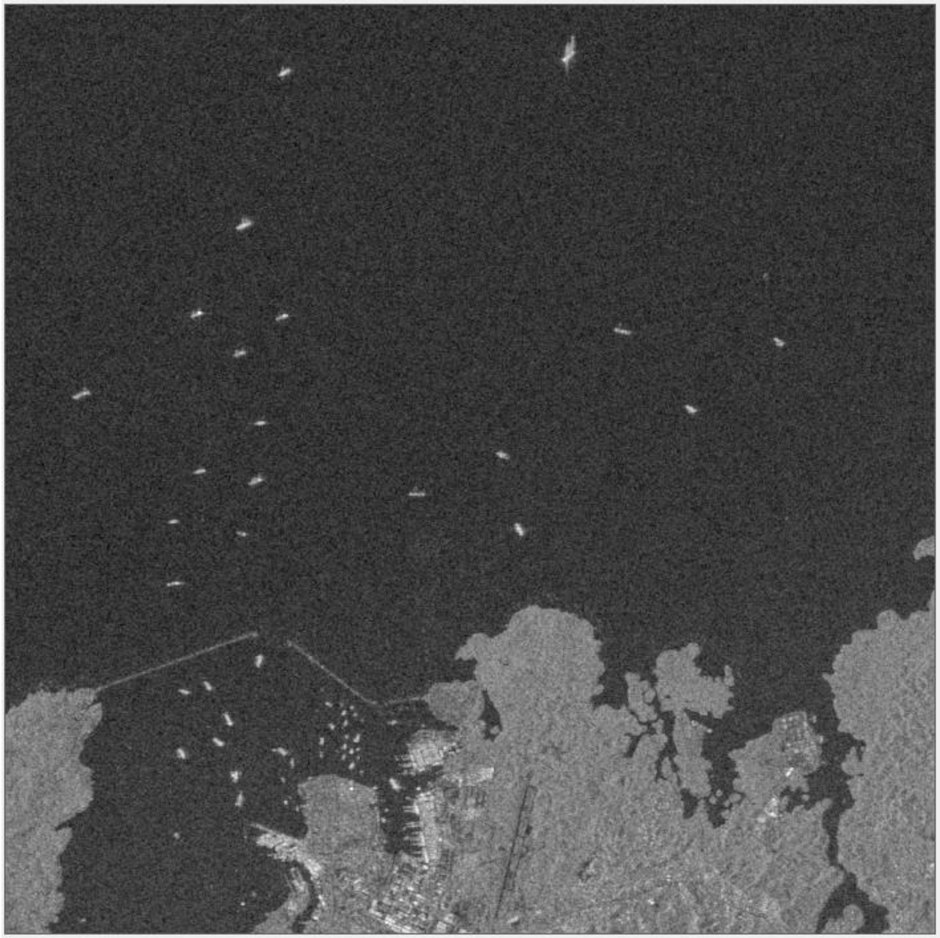
North end of Canal

South end of Canal

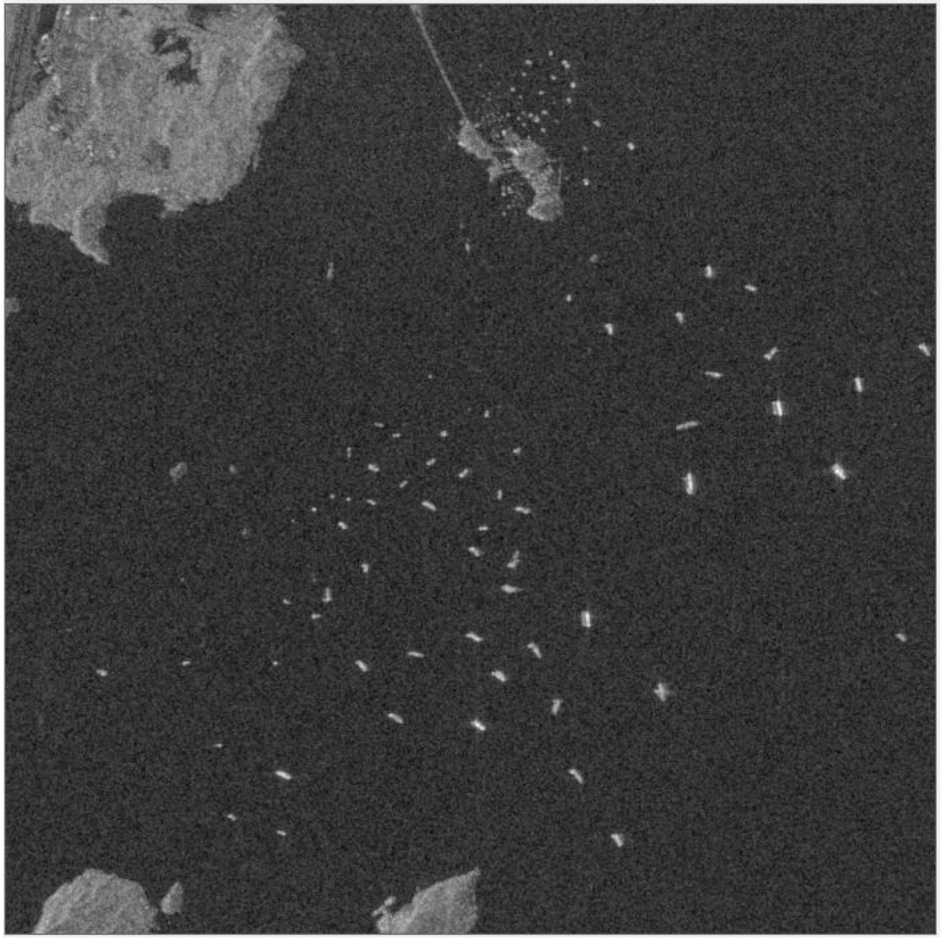


Zoom on Ships – HV Pol

North end of Canal



South end of Canal



Conclusion

- RADARSAT-2 image quality remains excellent
  - Ongoing improvements continue through software updates and calibration refinement
  - Occasionally affected by mutual radar interference with Sentinel-1
- Calibration adjustments applied as needed to maintain quality within operating objectives
  - As per seasonal fluctuations in inter-wing phase
  - As per long-term gradual changes in other quality monitoring measures (e.g. radiometric levels, polarimetric balance)
- New Extended Low Incidence Dual-Polarization mode
  - Calibration completed, commercial release forthcoming

THANK YOU!