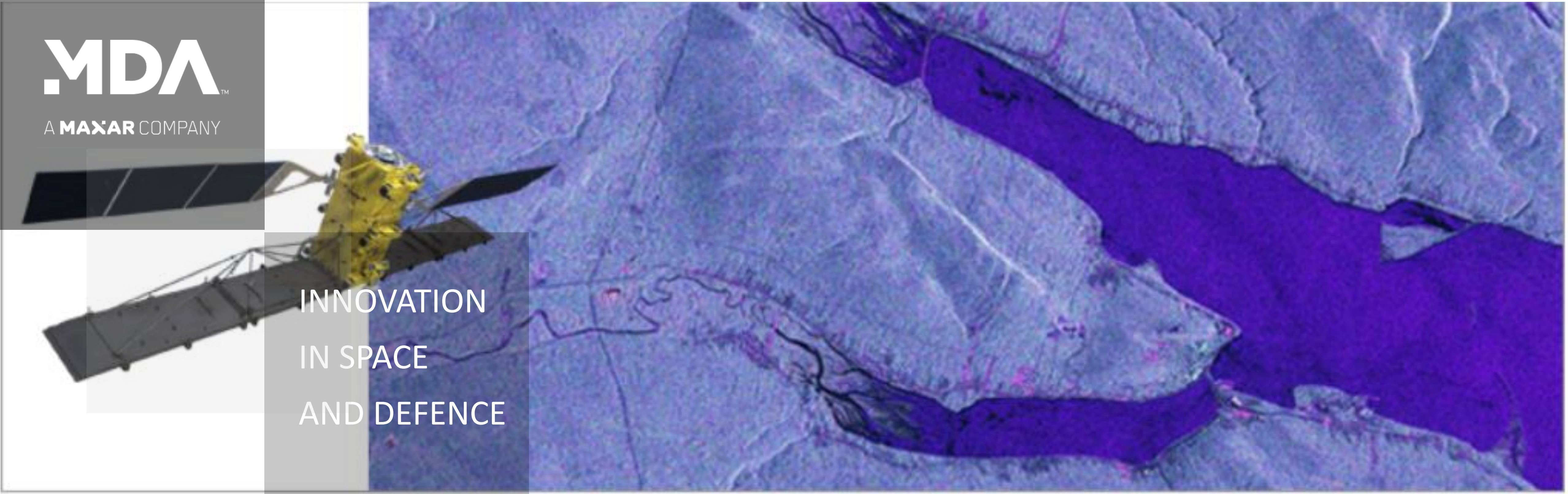


RADARSAT-2
IMAGE QUALITY AND CALIBRATION OVERVIEW

by Dan Williams, Yiman Wang, Gordon Fitzgerald, Neil Gibb , Ron Caves,
Peter Allan, Yan Wu, Janette Hiew, and Alan Thompson

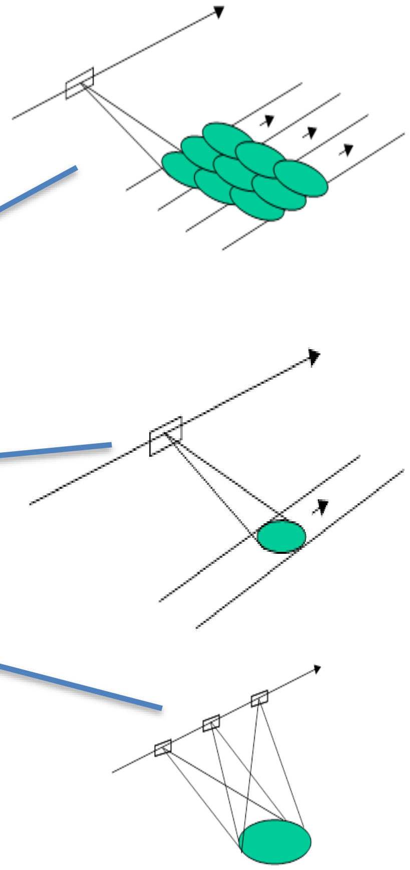
November 19, 2019

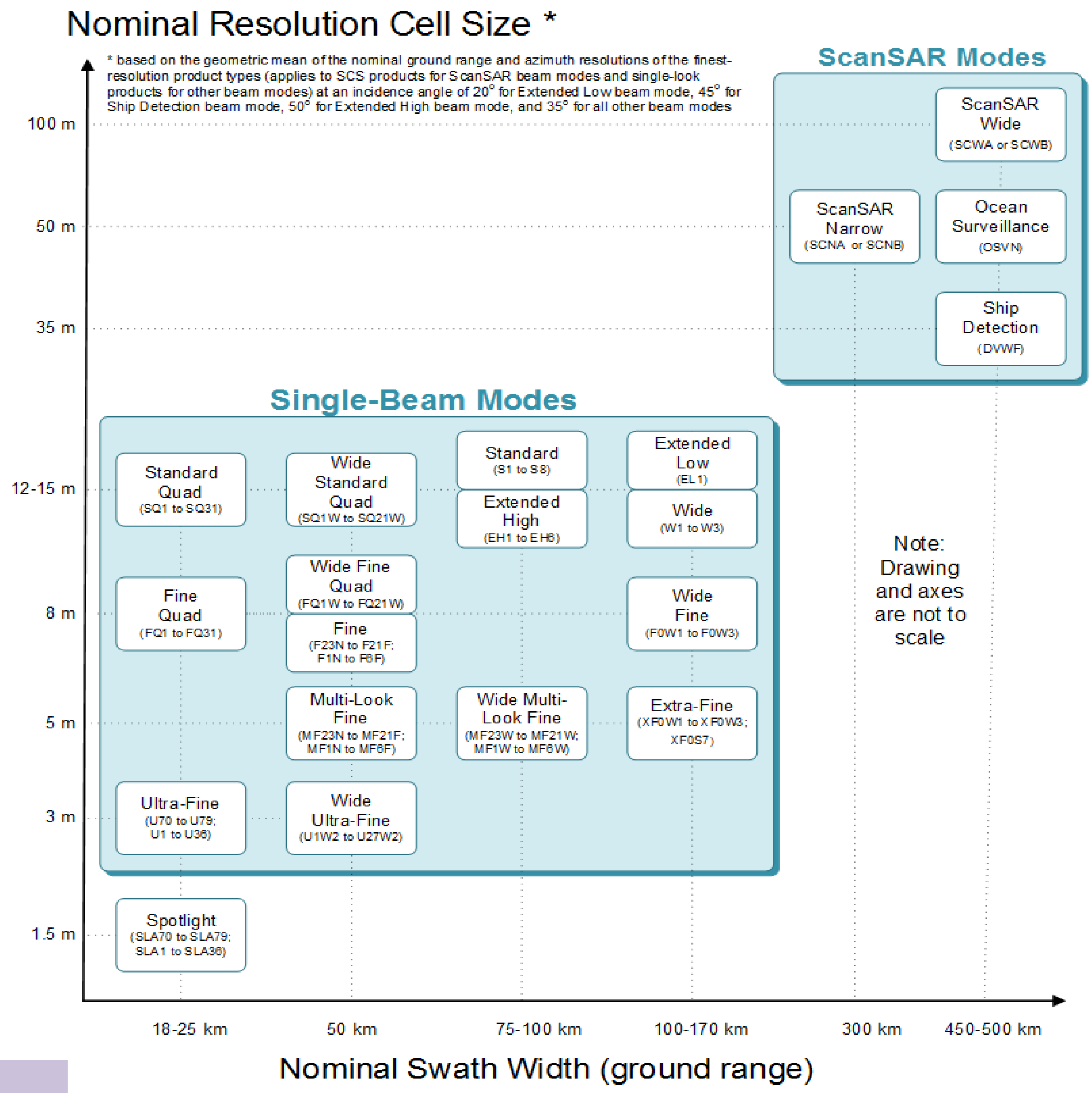
Image Credits and Disclaimer Language

GENERAL ACKNOWLEDGEMENTS:
Base world map on Page 30 by www.satsig.net

RADARSAT-2 Commercial SAR Modes

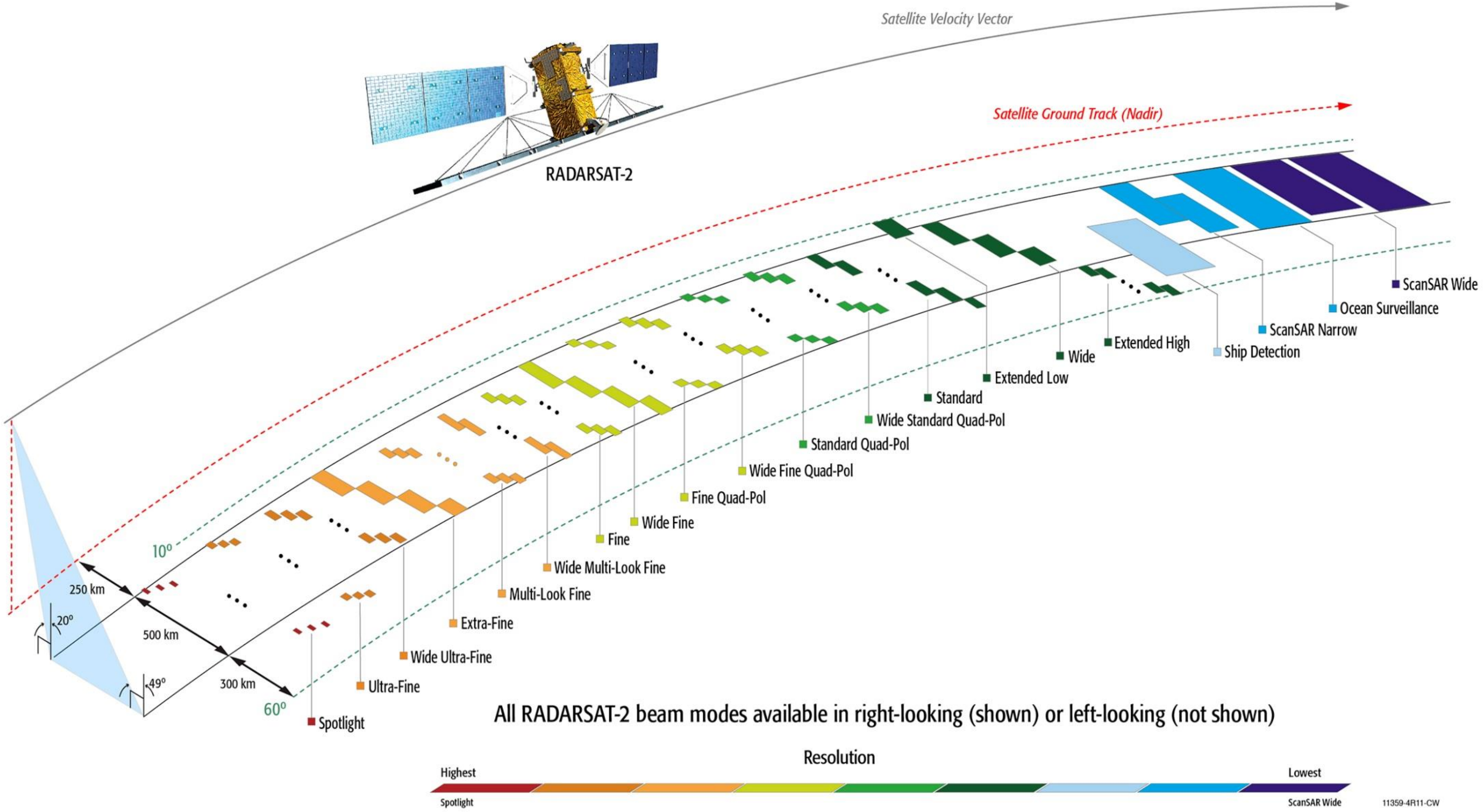
- C-Band SAR system launched Dec 2007
  - Commercial operations since April 24, 2008
- Right or Left-looking
- 20 Beam Modes
  - 4 ScanSAR (2 to 8 Beams)
  - 15 Stripmap (Single Beam)
  - 1 Spotlight (Steered Beam)
- Swath Widths
  - 20-500 km
- Nominal resolutions
  - Range: ~3 - 100 m
  - Azimuth: ~0.8 – 100 m





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

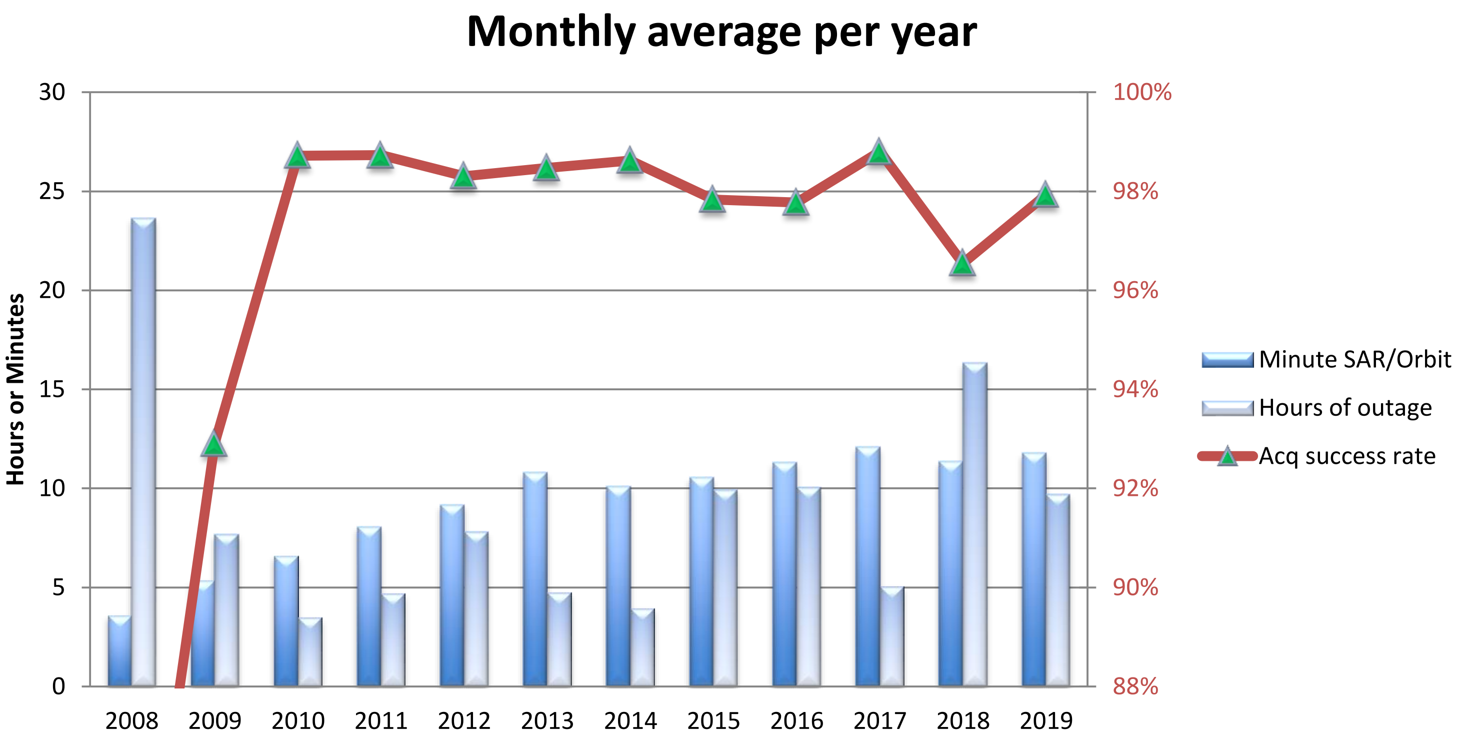
RADARSAT-2 Commercial SAR Modes



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

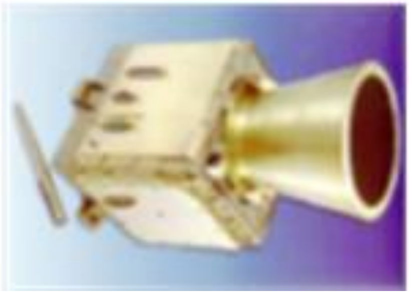
RADARSAT-2 System Performance

- Over 750,000 successful acquisitions (~98% success rate)
- No significant degradation in image quality
- Ongoing activities to improve the system and extend the mission life
  - Ground System upgrades
  - Spacecraft risk mitigation strategies
  - Image quality monitoring and calibration



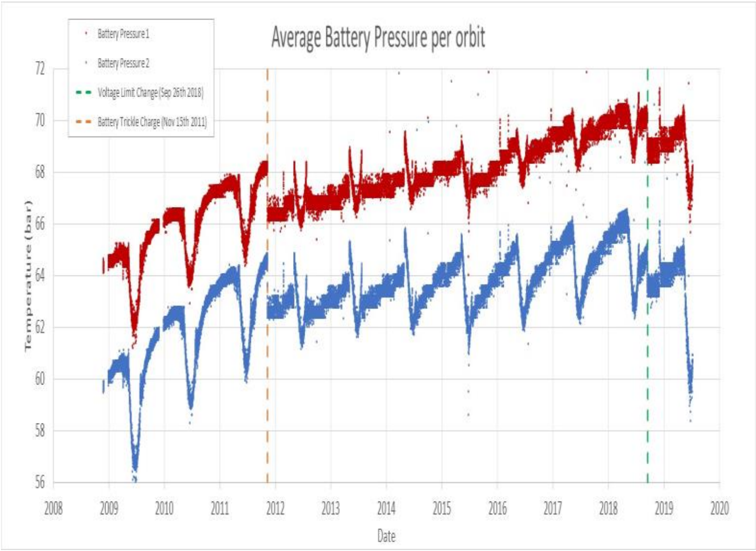
Spacecraft Risk Mitigation (1/2)

Throughout the mission, an active risk mitigation strategy has been in place and active system monitoring has helped identify potential issues early on. Key recent activities:

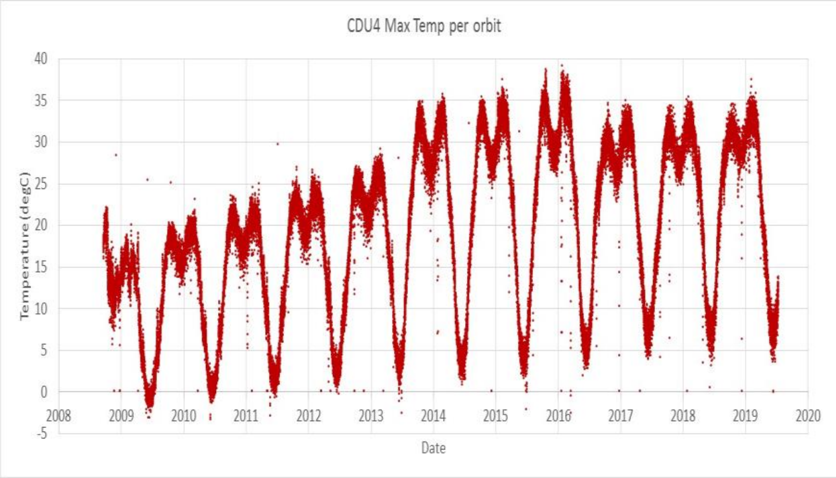


- **Star Tracker (STT) performance:** in 2018, sub-contract with manufacturer allowed a re-calibration of both STTs with the result that the concern in number of stars decline over the years has been discarded.

- **Battery health:** Various strategies have been implemented over the years (e.g. reduction in trickle charge, solar panel orientation outside of eclipse season) and the last one implemented in 2018 (reduced battery voltage limits) is proving effective for containing the risk of increased battery pressure.



Spacecraft Risk Mitigation (2/2)

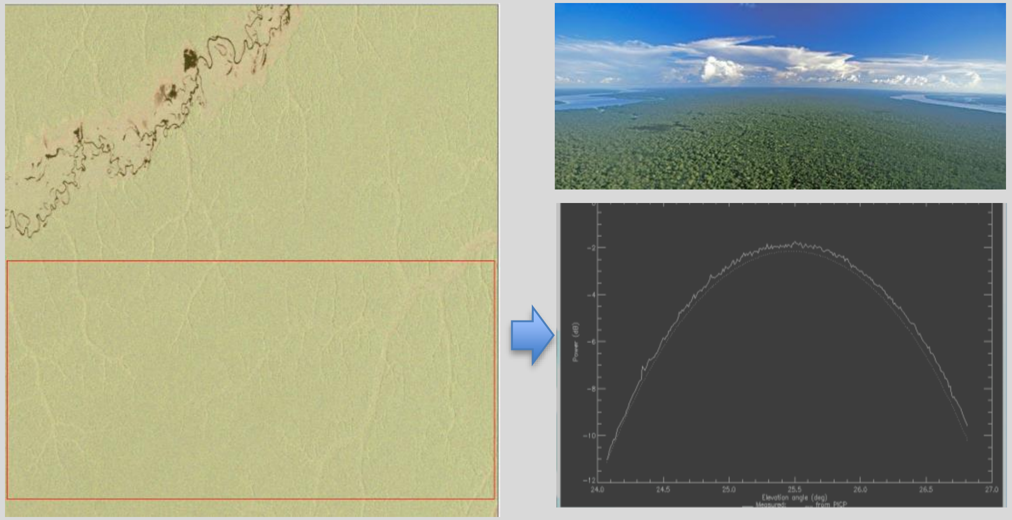


- **SAR Antenna temperatures:** Continue to be monitored. Solar array tracking operations modified to increase heat dissipation. Payload capacity over the peak of the hot season (20 days duration) has been reduced as a preventive measure.

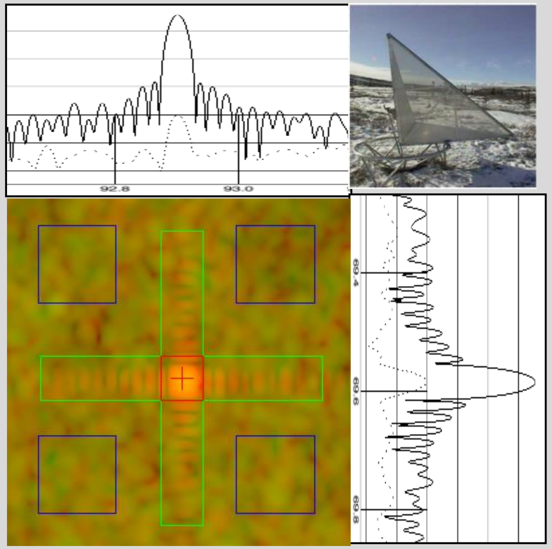
- **Attitude Determination and Control System**: Modified in 2018 with the capability to replace attitude rate measurements from any attitude knowledge gyro with Star Tracker measurements. This software is currently using 2 gyros + 1 gyro channel using STT measurement, but can handle 1 or 0 gyro as well, ensuring good performance even if all gyros failed.

Image Quality and Calibration Activities

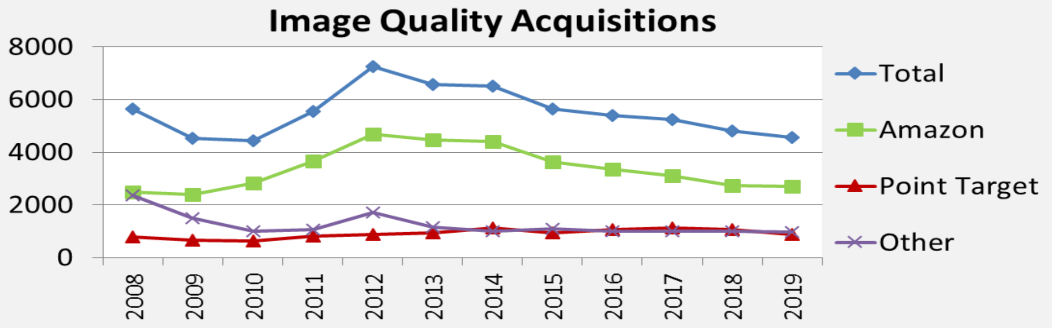
- Product quality control
  - Check coverage, report unexpected artifacts
- Ongoing monitoring and calibration program
  - Acquisitions over calibration sites
  - Product analysis
  - Trending of quality measures
  - Calibration adjustments as warranted
- Ground system robustness and accuracy enhancements



Amazon Rainforest
Distributed Target Measurements
(Radiometric accuracy, beam patterns, beam pointing, polarimetric correction matrices, inter-wing phase balance)



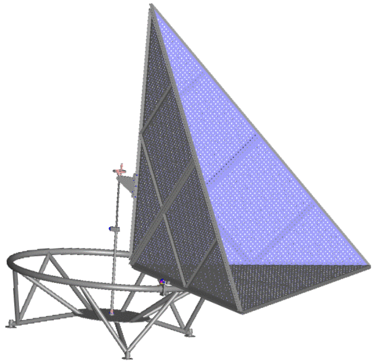
Corner Reflector and Antenna Dish
Point Target Measurements
(Resolution, sidelobe ratios, geolocation)



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

Point Target Monitoring

- Point targets are used to monitor geolocation and impulse response (resolution and sidelobe ratio)
  - Results are filtered to eliminate non-representative measurements (e.g. dish not tracking sensor, surrounding clutter, snow on reflectors in winter, ground truth accuracy limitations)

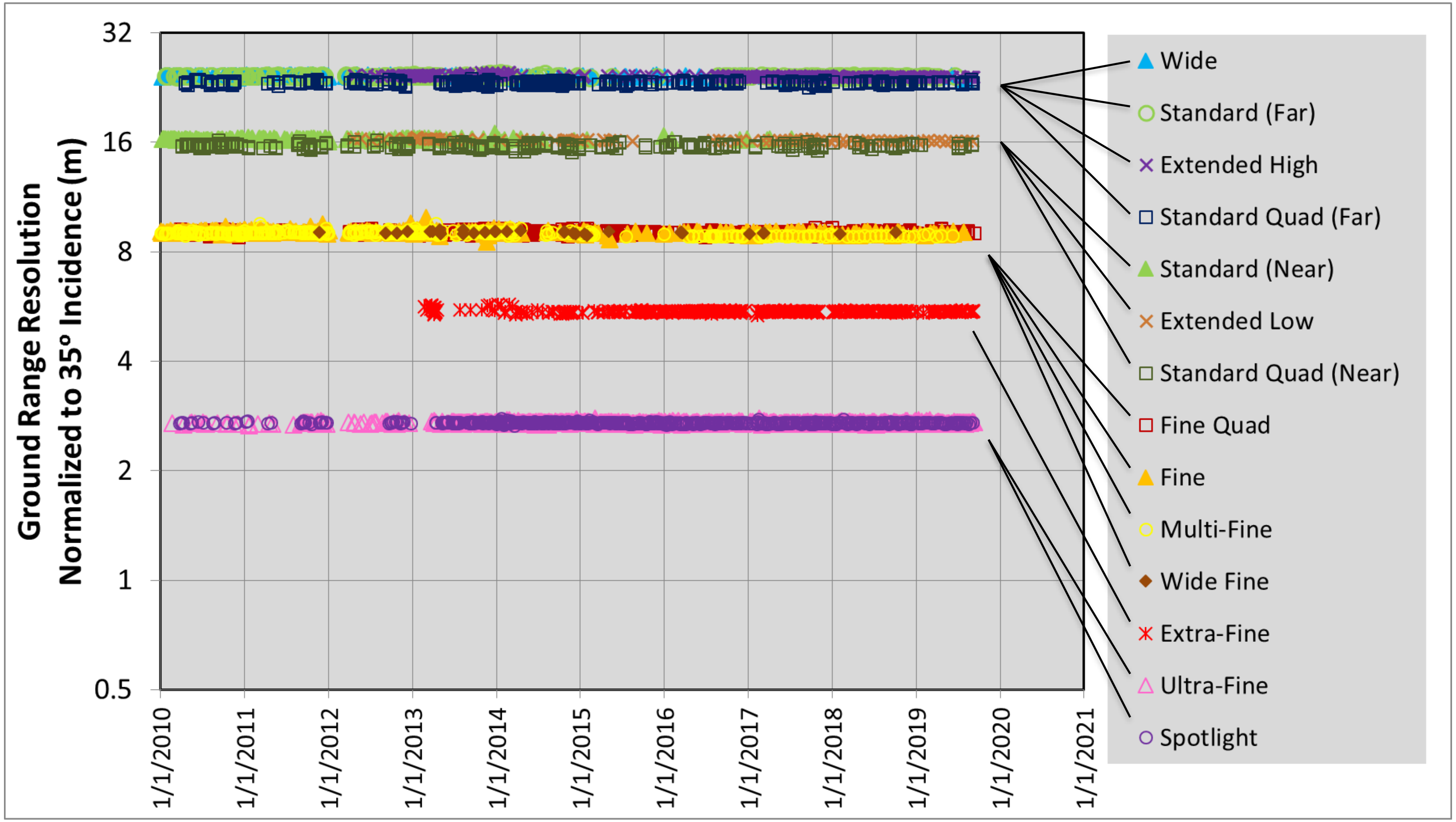


Target Type	For Geolocation Accuracy	For Impulse Response	In Canada	Elsewhere
Trihedral Corner Reflectors	Yes	High and moderate resolution modes	Vancouver and Quebec City (MDA) **	Rosamund, California (JPL) ** Tomakomai, Japan (JAXA) Bolivia (Simon Fraser University) Argentina (CONAE)* Adelaide Australia (DTSO)* Dubendorf, Switzerland (U of Zurich)*
Antenna Dishes	No	Low resolution modes	Gatineau Prince Albert Saskatoon St-Hubert Aldergrove Masstown Inuvik	

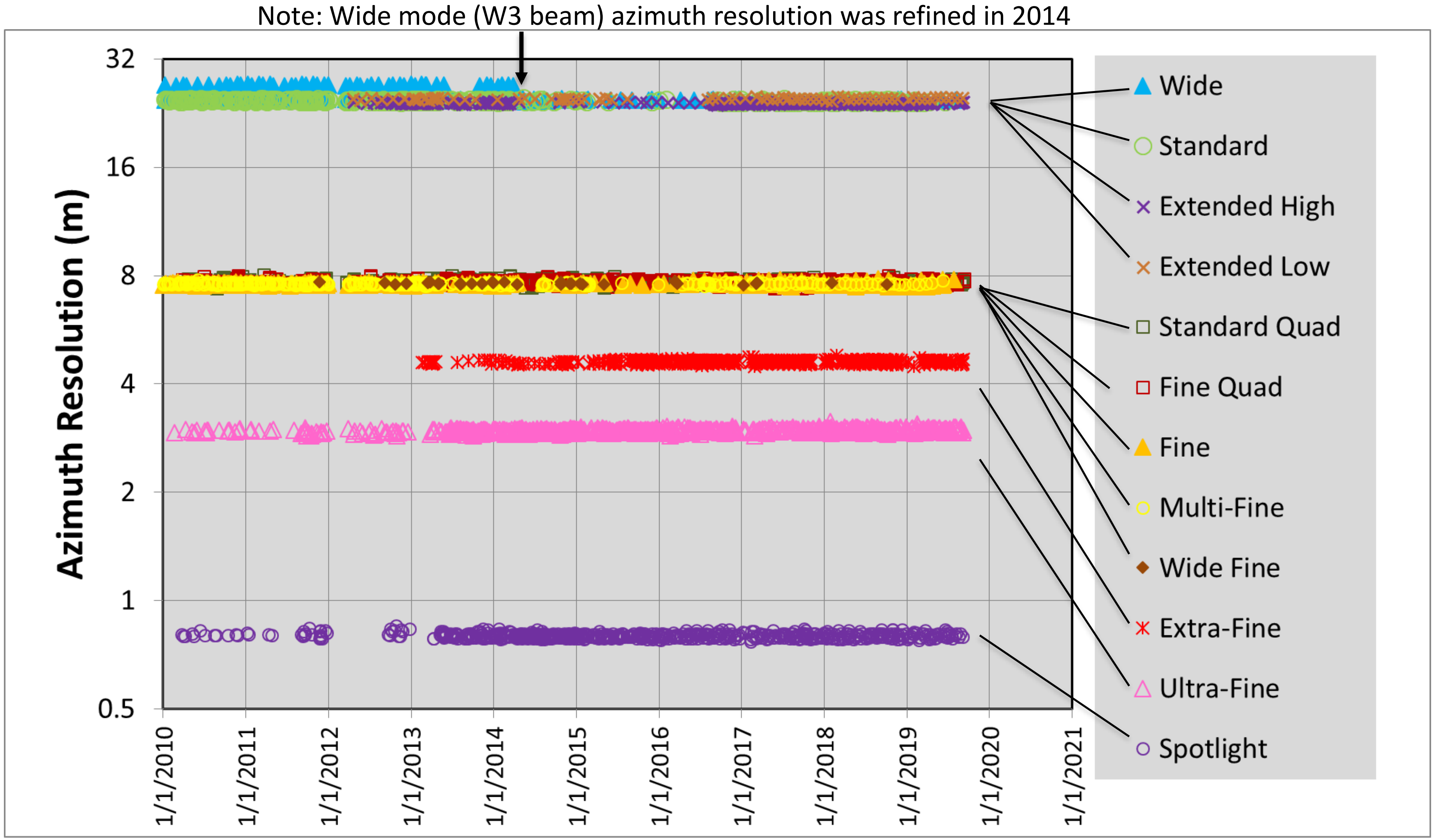
* past deployments ** currently deployed with precision surveyed ground truth knowledge

Ground Range Resolution (SGX Products)

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

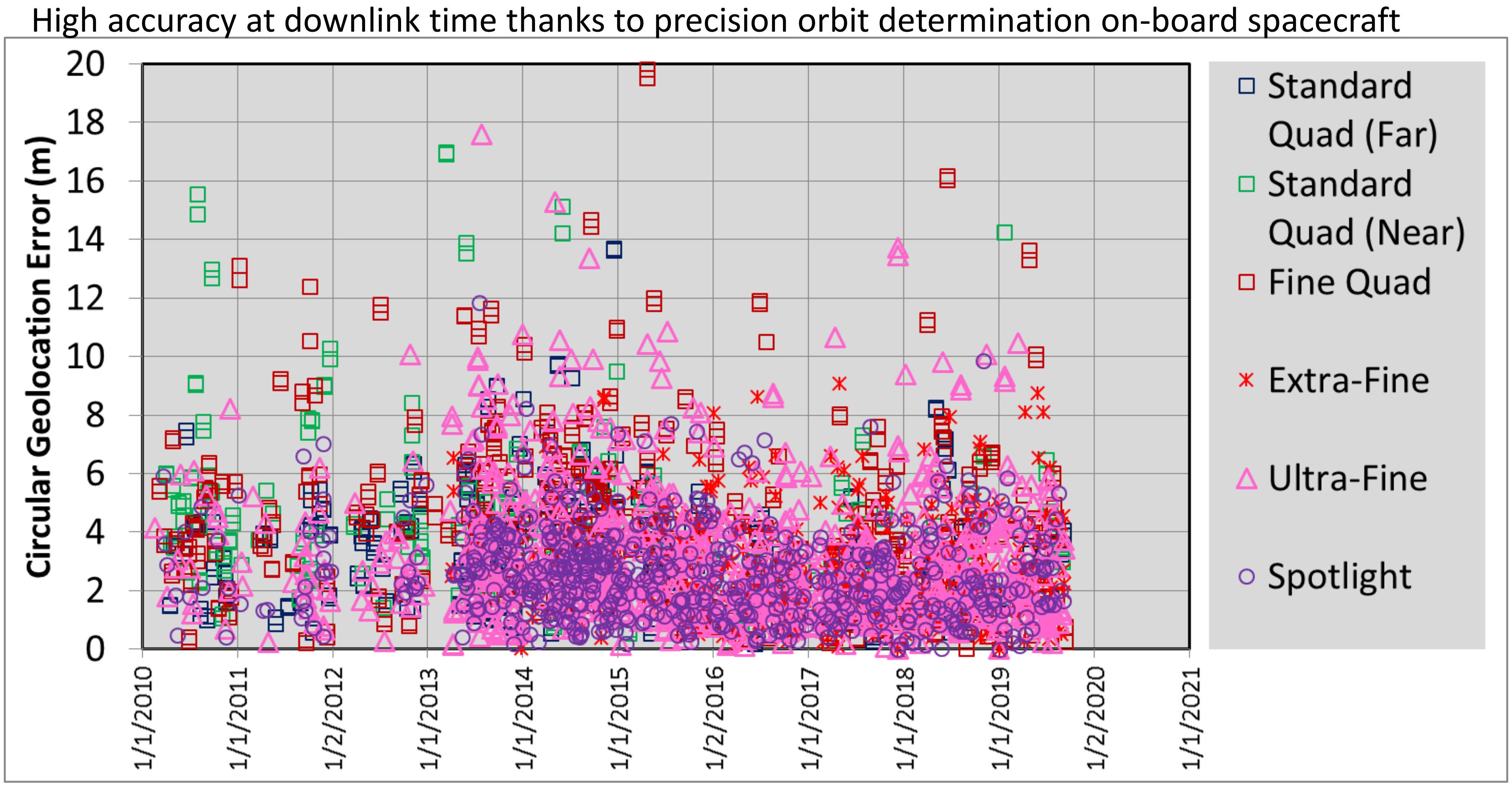


Azimuth Resolution (SGX Products)



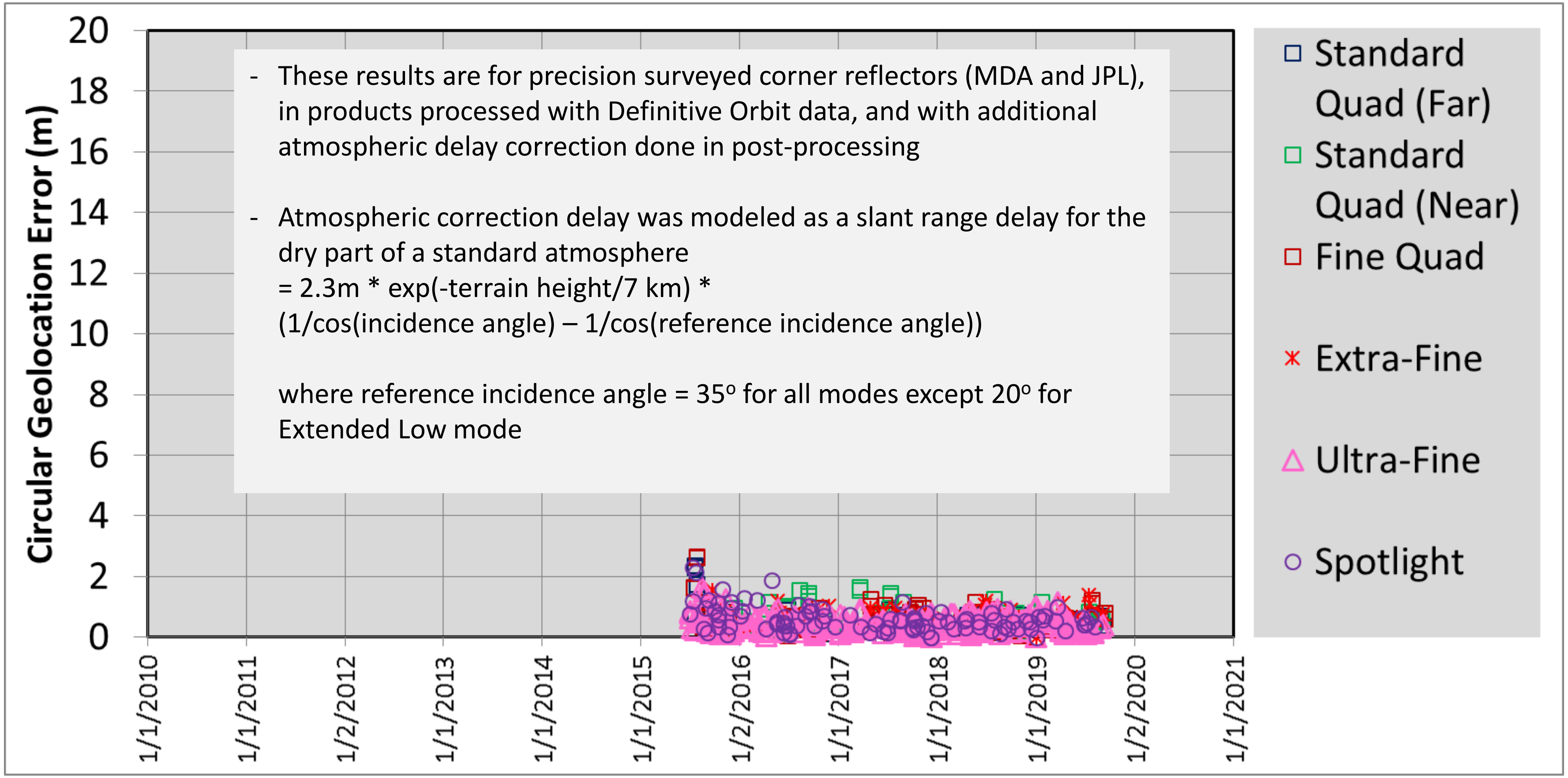
- Stable

Geolocation Measurement Results (Downlinked Orbit Data, All Corner Reflectors)



Geolocation Measurement Results (Definitive Orbit, Precision Surveyed Reflectors)

Processing with Definitive Orbit data (available with ~1-2 days latency) provides enhanced accuracy, since 30-June-2015

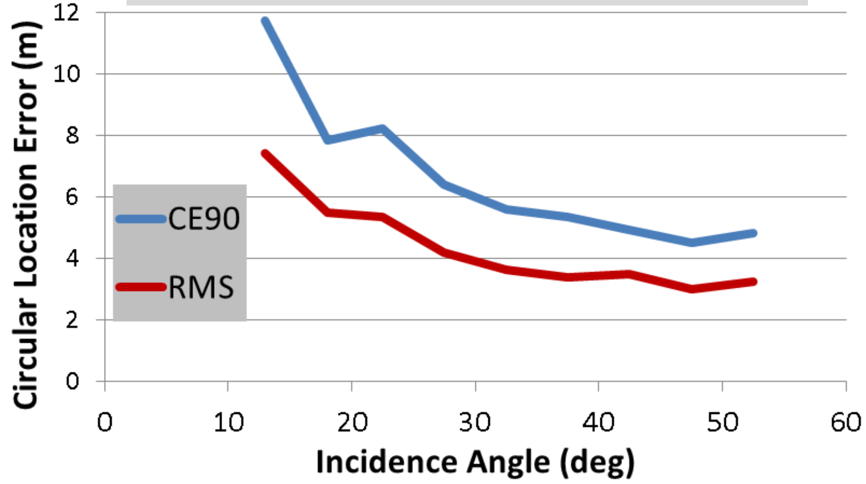


Geolocation Measurement Statistics

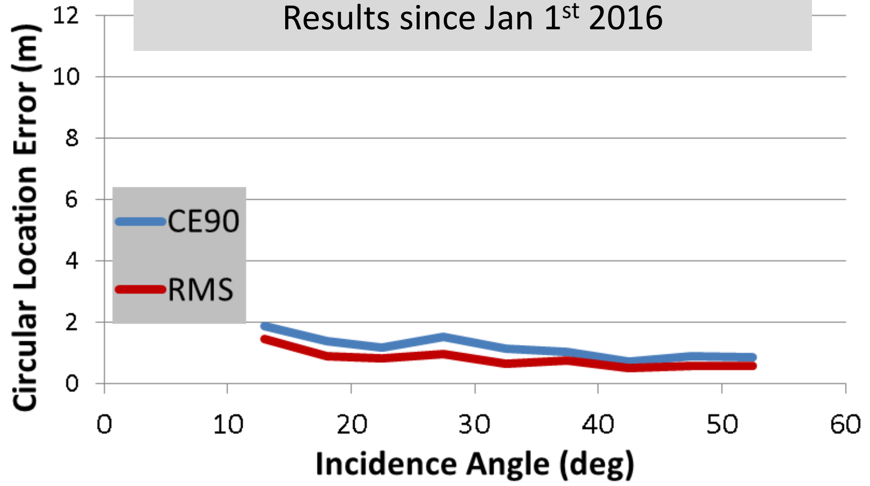
- Measured location errors with Downlinked orbit data:
  - < 6 m RMS in most Single-Beam and Spotlight modes
  - <10 m RMS in Extended Low Incidence mode
  - <20 m RMS in ScanSAR modes

- Measured location errors with Definitive orbit data
  - <2 m RMS in Single-Beam and Spotlight modes after atmospheric correction in post-processing

Stripmap & Spotlight modes,
Downlinked Orbits,
Corner Reflectors,
Results since Jan 1st 2012



Stripmap & Spotlight modes,
Definitive Orbit,
Precision Surveyed Corner Reflectors,
with Atmospheric Correction,
Results since Jan 1st 2016

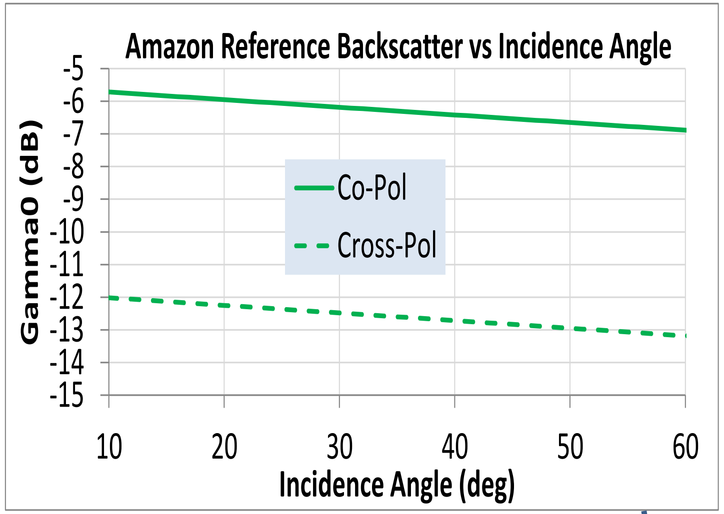


- These results are better than the more conservative location accuracy values given in the RADARSAT-2 Product Description
- Much better than original mission performance goals
- Improved during mission thanks to improved orbit accuracy, calibration and ongoing SAR processing refinements

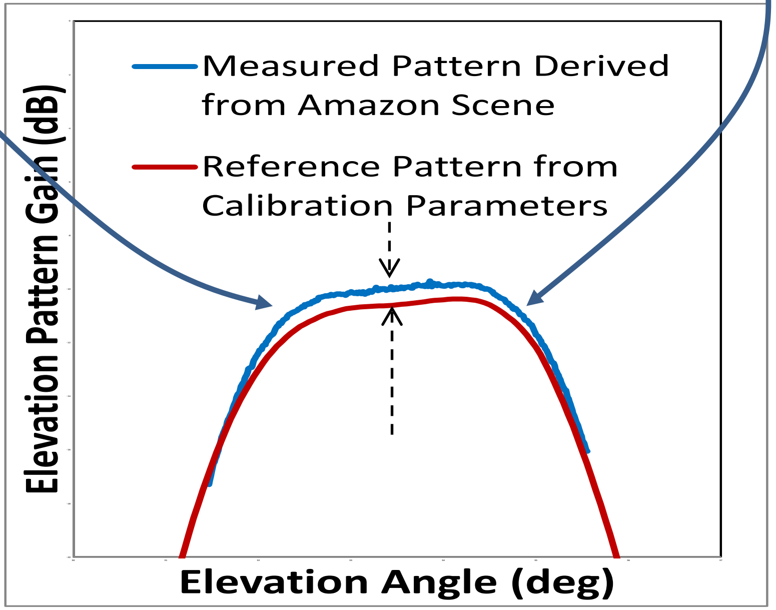
Note: Accurate geolocation requires terrain height knowledge. These geolocation measurements are for calibrated corner reflectors of known elevation.

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

Radiometric Accuracy Monitoring

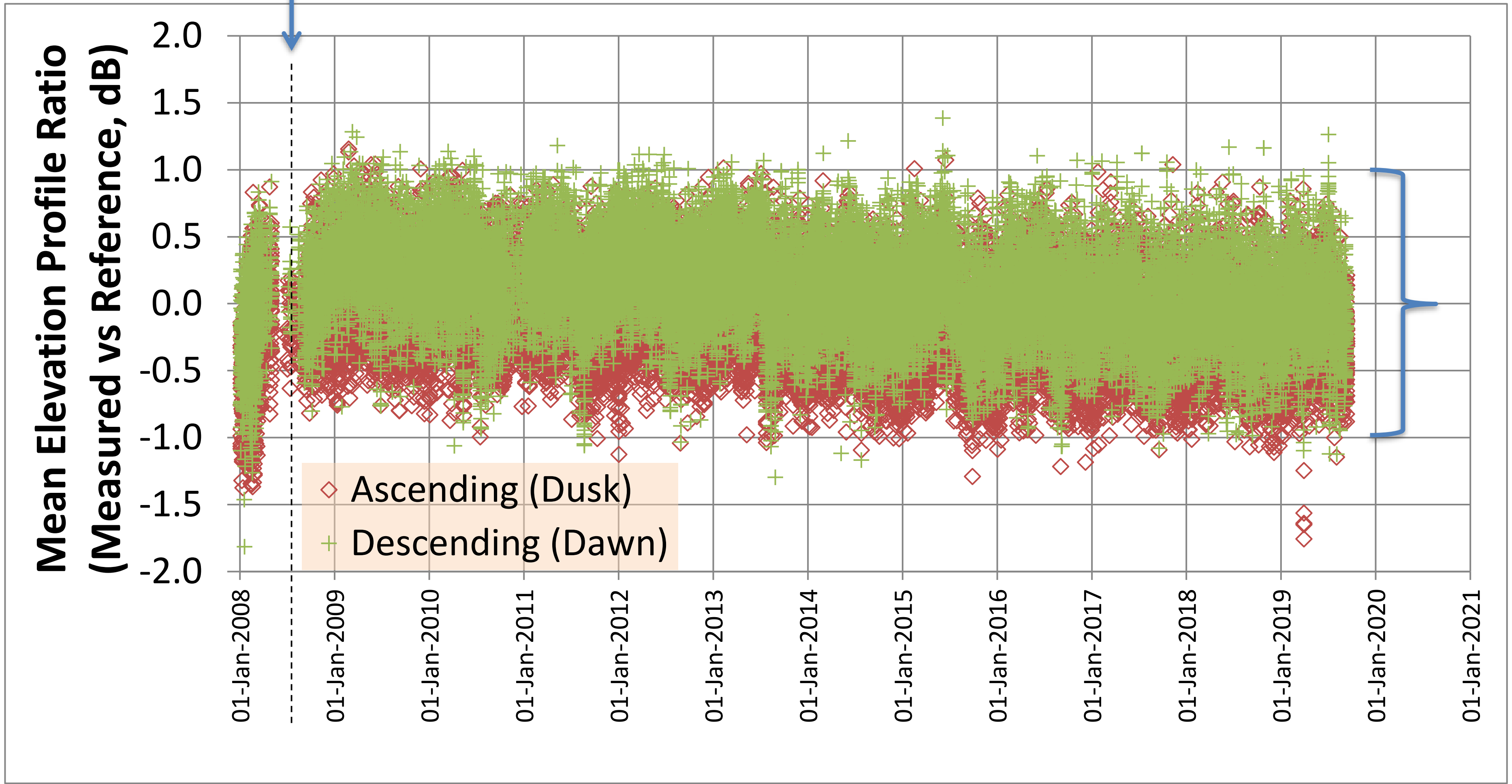


- Backscatter profiles as a function of range are measured over homogeneous areas of the Amazon rainforest in Single Beam modes
- Each profile is converted into a measured elevation pattern by backing out the elevation pattern correction applied during processing, subtracting noise, and scaling by the assumed mean backscatter function of the Amazon
- The measured pattern is aligned with the reference pattern from the calibration parameters, and the mean power ratio between the 2 patterns is taken (=mean radiometric offset)



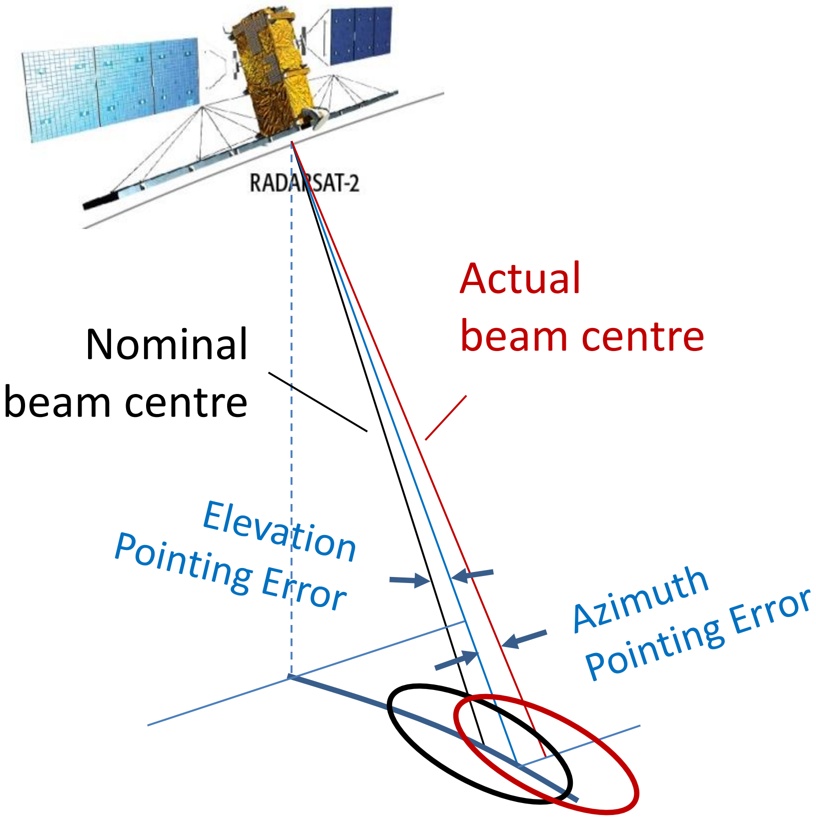
Mean Radiometric Offset

Overall results generally stable since routine operations began in April 2008, with slight changes due to release of new beam modes, a subtle seasonal pattern, and a slight gradual decline that has now stabilized



- Overall mean difference is near zero
  - Currently ~ -0.2 dB on Ascending passes, 0.0 dB on Descending passes
- Mean per-scene differences from Amazon reference are typically within +/- 1 dB
  - Std. dev. ~= 0.3 dB
- Occasional outliers, generally due to scene non-uniformities
  - 3 results < -1.5 dB, all from a single pass on 2019-03-30, are under investigation

Beam Pointing Monitoring

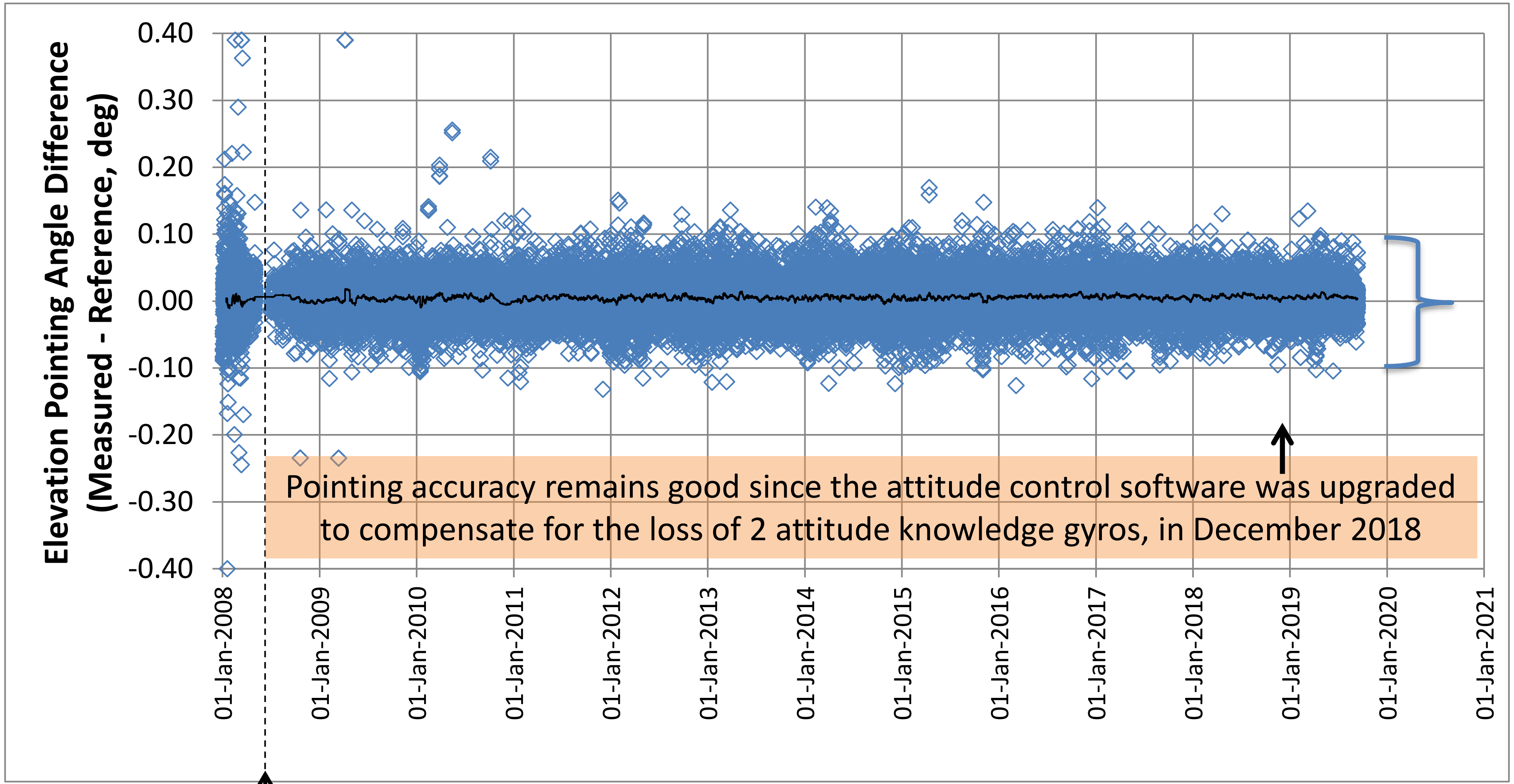


- Objective is to monitor how the actual beam pointing varies with respect to nominal

- Elevation beam pointing is monitored using elevation pattern analysis over the Amazon in Single Beam modes
  - The elevation angle 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 vs Doppler centroid frequency estimated adaptively during SAR processing, for the same data takes over the Amazon
  - The difference expressed as a Doppler frequency is trended over time

Elevation Beam Pointing Results



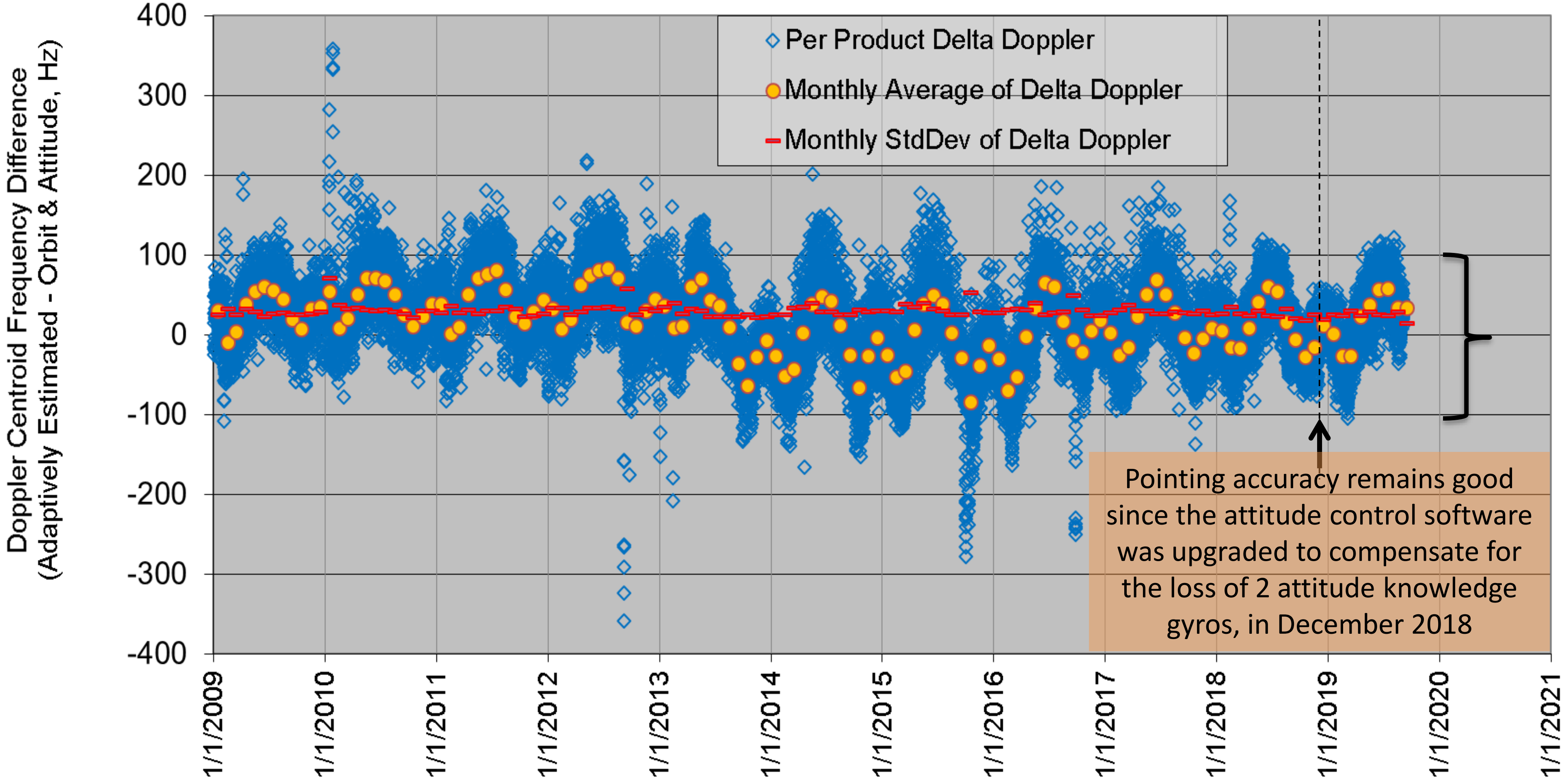
Mean measured pointing error overall ~= 0

Typically within +/- 0.1°, std. dev. ~= 0.02°

Overall results are stable since initial operations in April 2008

Occasional outliers are mainly due to variations in scene content (Amazon scenes not perfectly uniform)

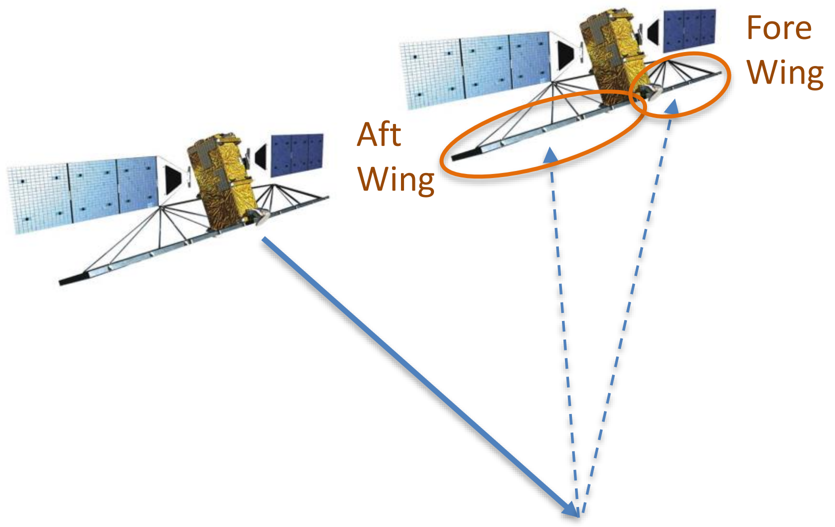
Azimuth Beam Pointing Results

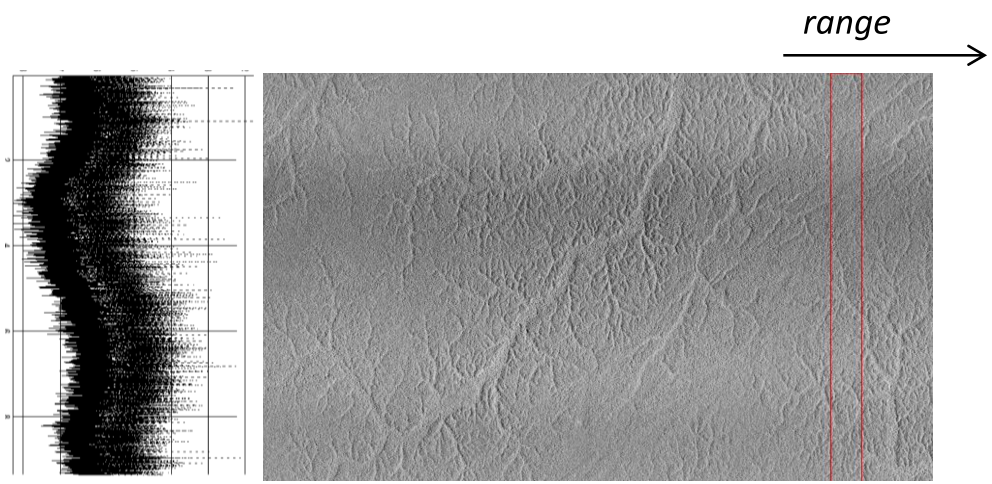


- Measured azimuth beam pointing accuracy with respect to antenna boresight has generally improved since launch
  - Thanks to refinements in solar array tracking, star tracker operations, SAR processing, and Amazon scene uniformity
- It follows a seasonal oscillation, due to thermal effects in the payload
  - Average is well centered close to zero
  - Generally within +/- 100 Hz ~= 0.02°
- Pointing errors are compensated by adaptive Doppler centroid estimation in SAR processing and inter-wing phase calibration adjustments

Inter-Wing Phase Balance Monitoring

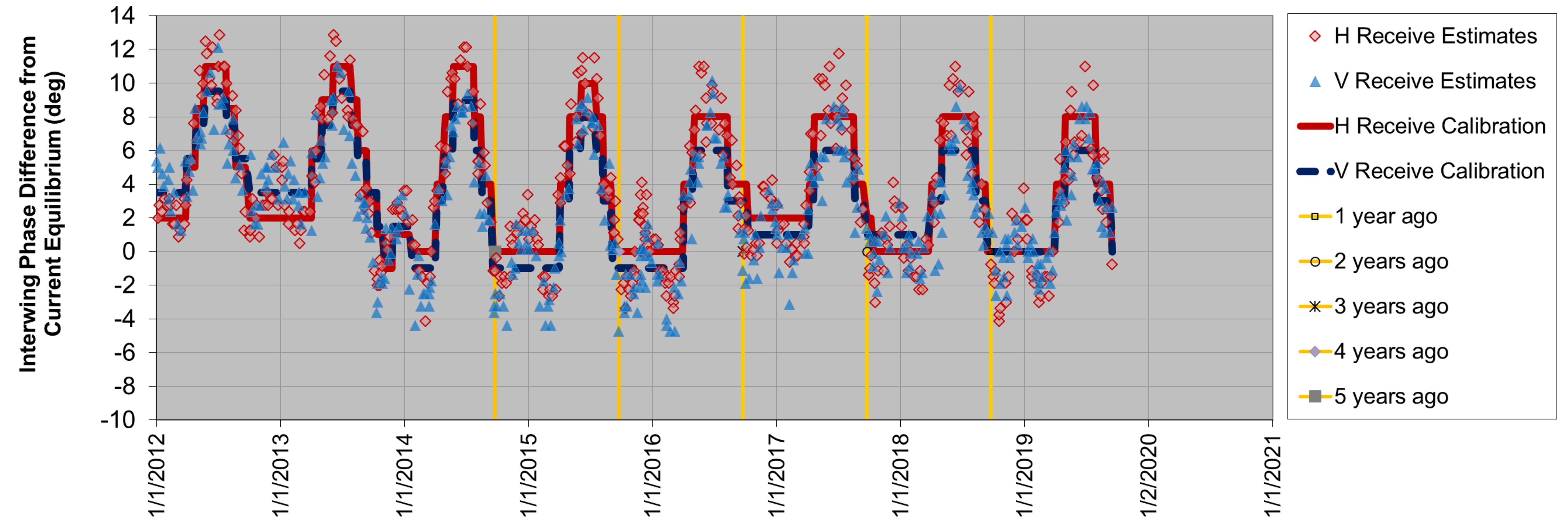
- RADARSAT-2 can operate with dual receive apertures (wings)
  - Doubles the effective pulse repetition frequency
  - Used in Multi-Fine, Extra-Fine, Ultra-Fine, Spotlight, and DVWF modes
- A phase difference between fore and aft wings causes an azimuth beam pointing shift (Doppler shift) from boresight
- 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 modes
- 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 (Right-Looking)

- Seasonal trends 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
  - Currently being expanded to allow separate left-looking vs right-looking adjustments



Polarimetric Calibration Monitoring

- Polarization distortion is characterized over homogeneous regions of the Amazon rain forest:
  - Supports calibration over the entire swath
  - Stable polarimetric signature with known characteristics:
    - Reciprocity
    - Azimuth symmetry
  - High signal to noise ratio
  - No ground infrastructure cost

- Input:
  - Quad-Pol (HH+HV+VH+VV) SLC products

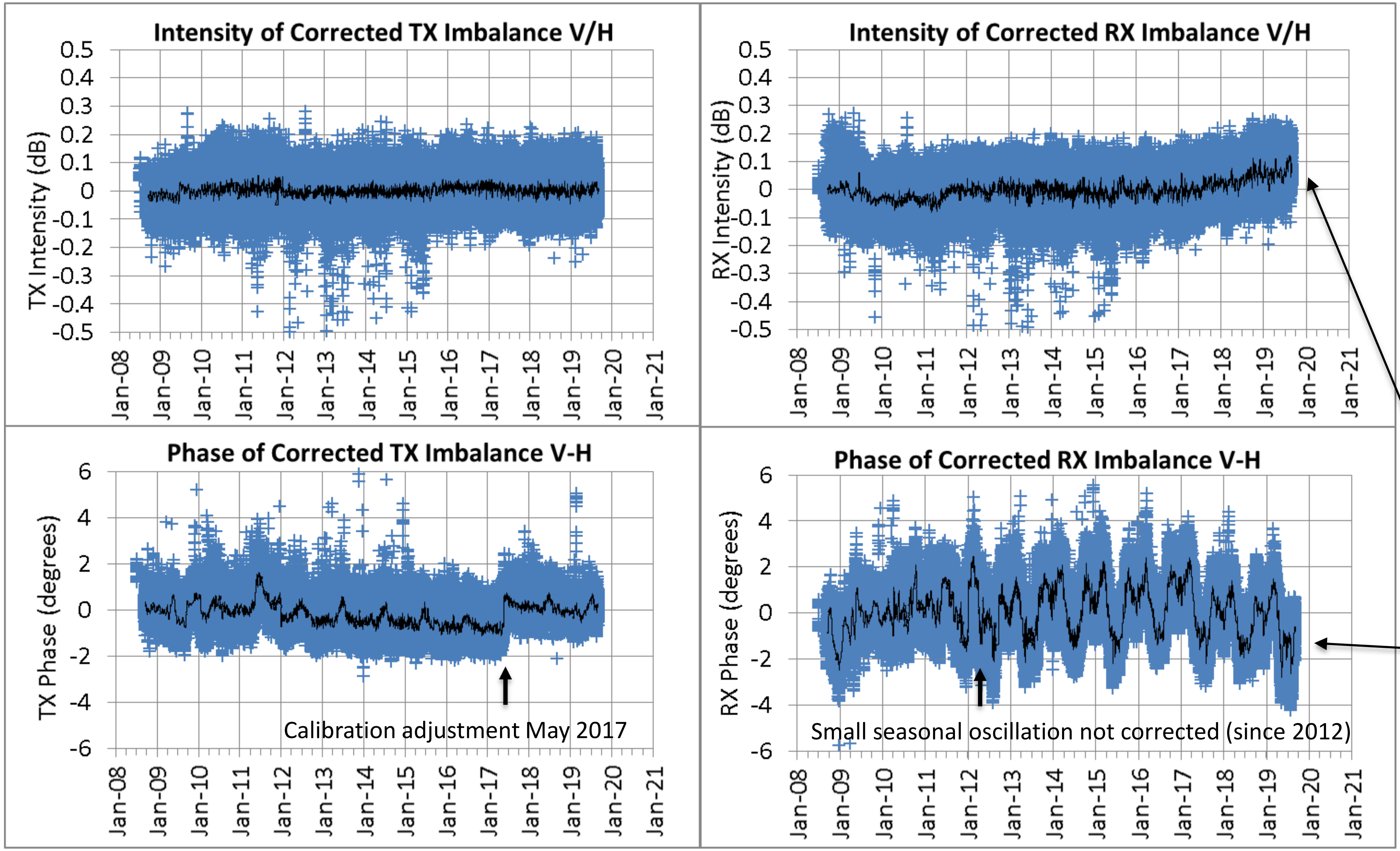
- Procedures:
  - The homogeneous area of each product is identified (regions to exclude are selected manually if necessary)
  - This area is partitioned into range sections, each spanning a fixed elevation angle (~0.2°)
  - An average 4 x 4 covariance matrix is calculated over each section, representing the observed polarimetric signature
  - Imbalances on TX and RX and cross-talk 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



Summary of current trends

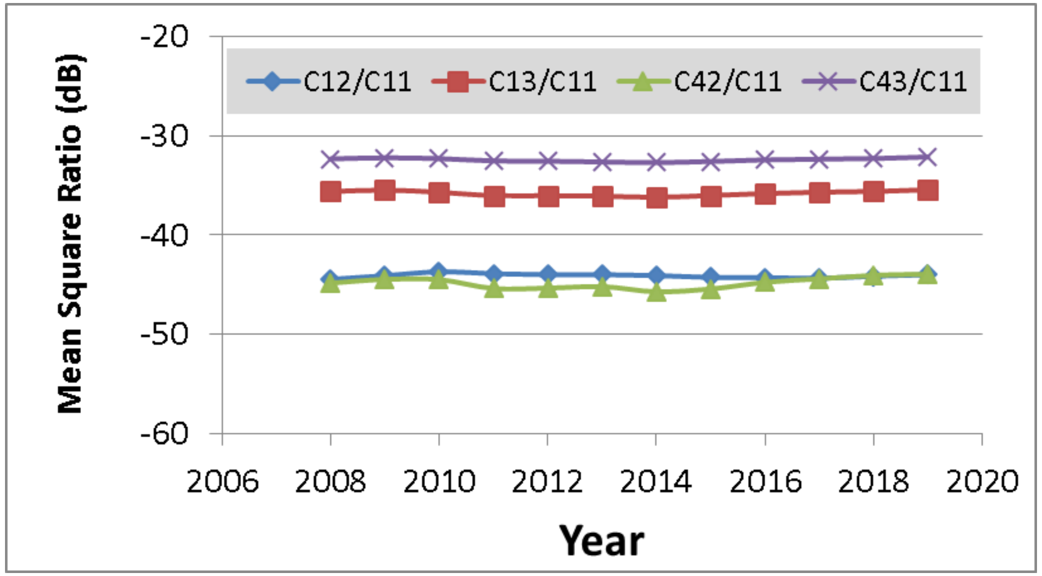
Balance Measure	Mean	Std Dev	Span
TX Intensity	~ 0	< 0.1 dB	± ~0.25 dB
RX Intensity	+0.05 dB	< 0.1 dB	± ~0.25 dB
TX Phase	~ 0	< 1°	± ~2°
RX Phase	-0.3°	1.1°	± ~4°

- Following corrections, polarimetric balance accuracy for all Quad-Pol beams remains well within mission performance goals of:
  - +/- 0.5 dB intensity
  - +/- 10° phase
- Small calibration adjustments may be warranted soon in:
  - Receive intensity balance (~0.1 deg)
  - Receive phase balance (~1 deg)
- Outliers (due to Amazon scene inhomogeneity) are few in recent years thanks to improved analysis methods

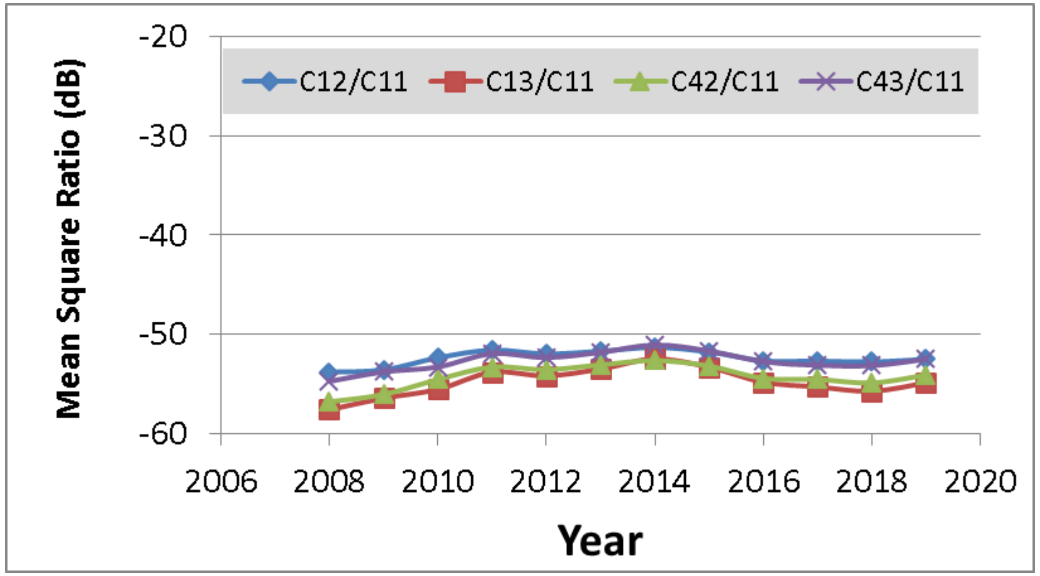
Polarimetric Cross-Talk Results

- Measured cross-talk levels remain excellent and well within performance goals
  - < -30 dB before and < -50 dB after polarimetric corrections on SLC products
  - Based on yearly averages of Amazon rainforest results over all beams

Before Correction

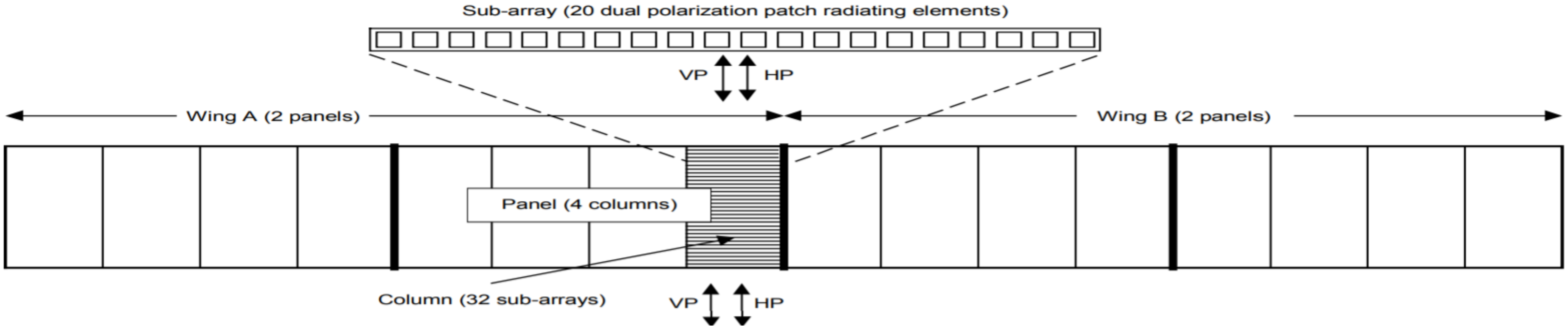


After Correction



C11 = spatial averaged product of the HH complex scattering amplitude by its complex conjugate
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

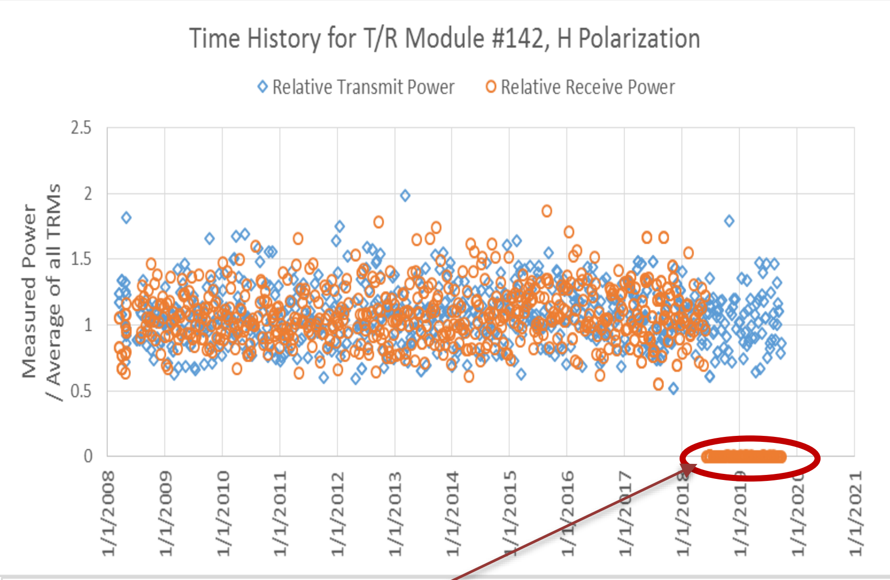
Antenna Characterization Testing

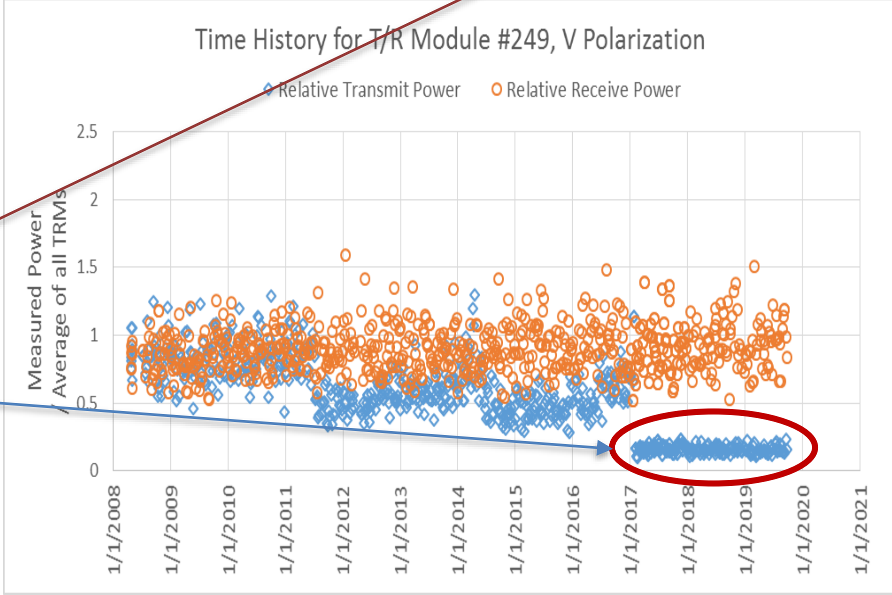


- The RADARSAT-2 SAR antenna is composed of 512 sub-arrays:
  - Each comprised of 20 dual polarization patch radiating elements
  - Each controlled by a Transmit/Receive Module (TRM)
  - Arranged in 16 columns with 32 rows per column (approx. size 15 m x 1.4 m)
- It is designed to operate in a series of special characterization modes to verify:
  - The signal amplitude generated by each antenna row and column
  - The phase of each antenna row and column relative to its neighbors
  - The signal magnitude generated by, and health status of, each TRM individually
  - On transmit and receive separately, for H and V polarization separately
- These tests are run on a regular basis and the results are trended over time

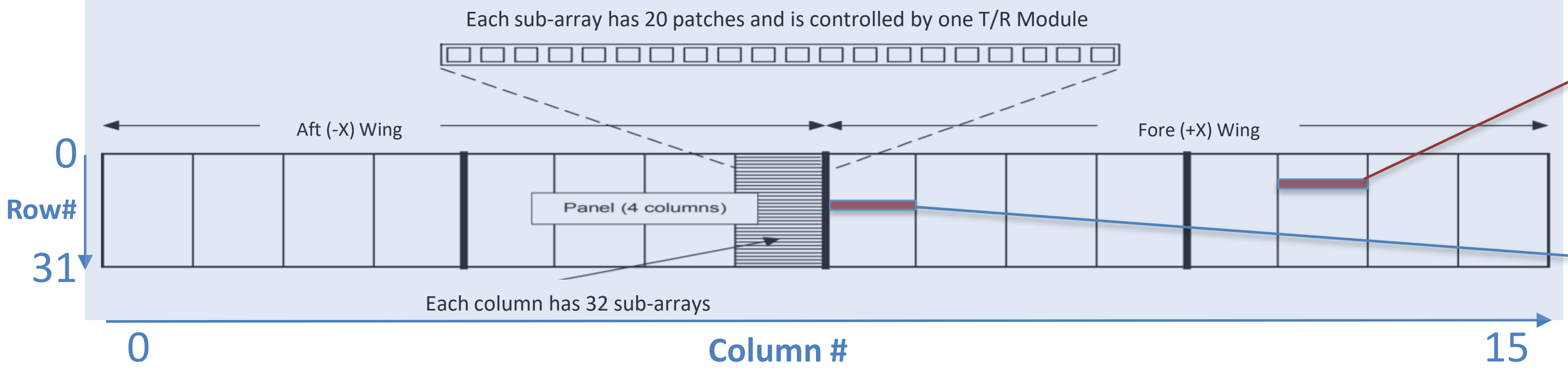
Antenna Characterization Testing (TRM Go/NoGo)

- Each T/R module test is run in both H and V polarization, with a nadir-looking beam over the Pacific ocean:
  - Transmit on full antenna, receive on each TRM sequentially
  - Receive on full antenna, transmit on each TRM sequentially
  - Range compress all received pulses
  - Measure average energy for each TRM on Tx and Rx
  - Compare with configurable threshold
- Results show that all 2048 channels (4 channels on each of the 512 T/R modules) are still operating within expectations, except:
  - The H receive channel of T/R module #142 (Column #13, Row #8), since sometime between May 31st and June 5th 2018
  - The V transmit channel of T/R module #249 (Column #8, Row #15), beginning in 2011 and more significantly since sometime between Feb 3rd and Feb 6th 2017
- There has not been any measurable degradation in image quality
  - Affected T/R module channels represent only 0.1% of the 2048 channels on the antenna



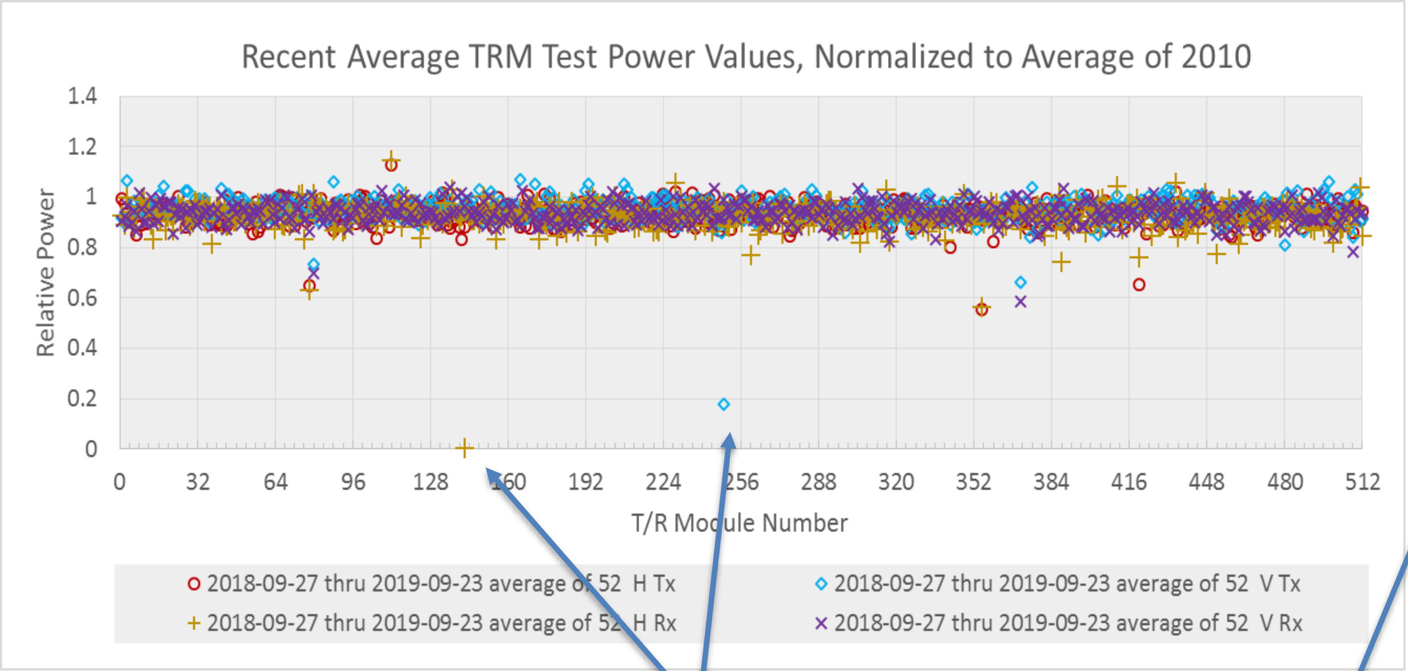


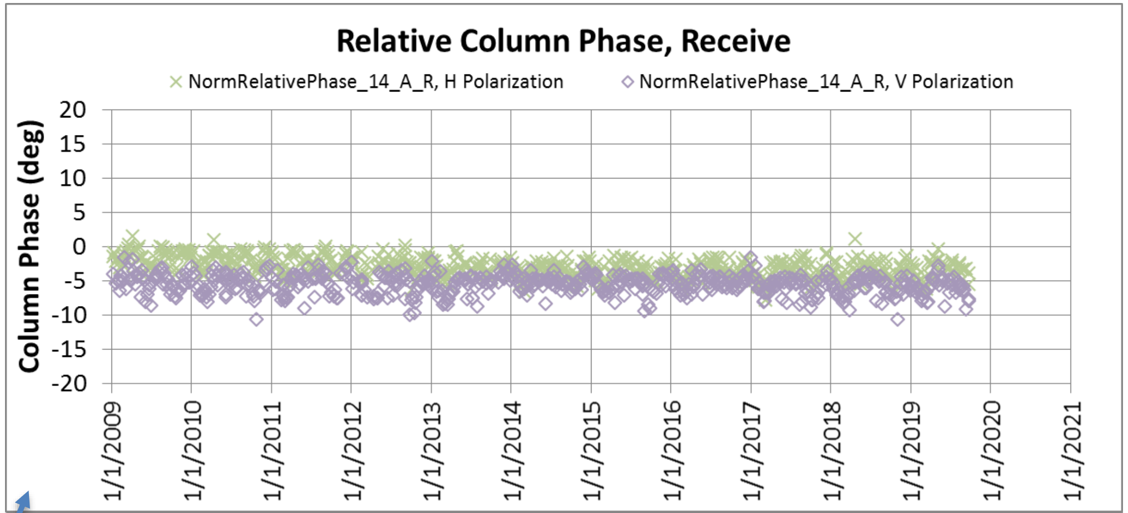
Front face of SAR Antenna during Right-Looking Operations

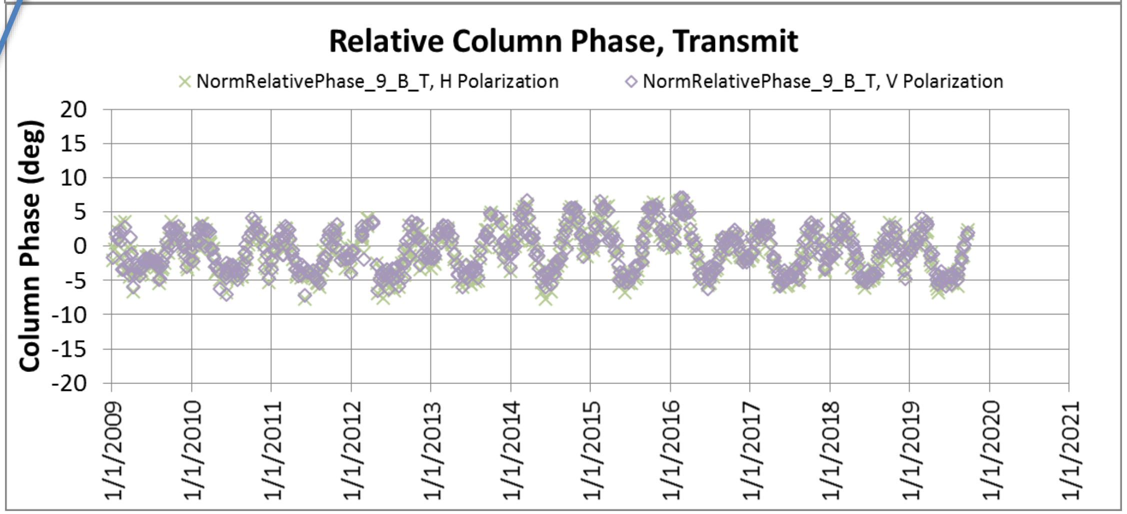


TRM # = 1 + (Column #) + (Row #) * 16

Antenna Characterization Results Summary







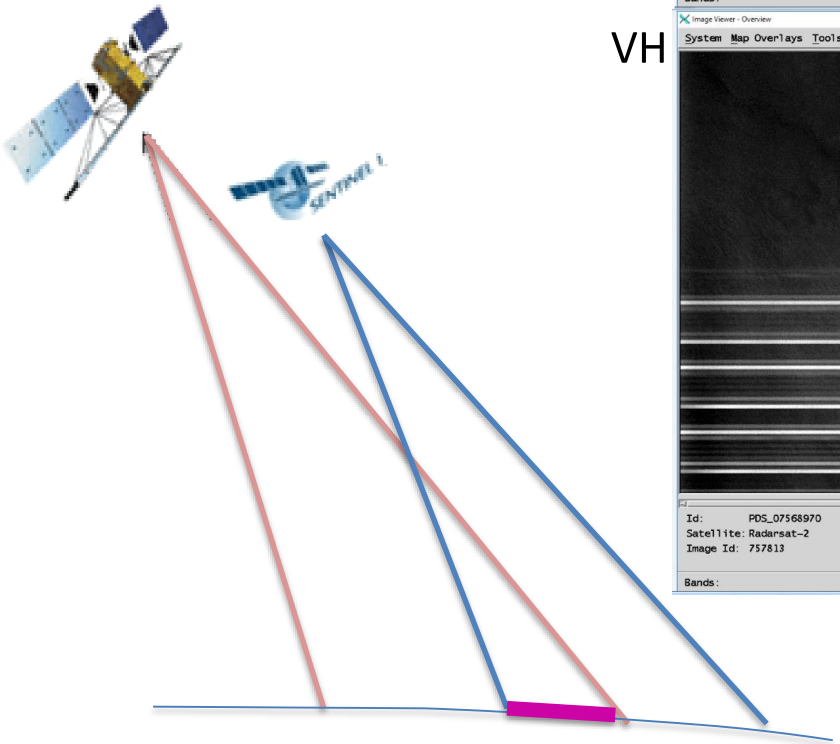
- Aside from the 2 malfunctioning channels, the other TRM channels collectively do not show significant changes since the start of the mission
- On a per column and row basis the phase remains stable with regular seasonal patterns
- No degradation in image quality

Mutual Interference with Other C-Band SAR Satellites

- Mutual interference occurs when radar pulses transmitted by one spacecraft at similar frequencies are received by another spacecraft
  - Main concern is the bistatic case where both satellites illuminate the same area on the ground at the same time
  - Temporary rise in noise level

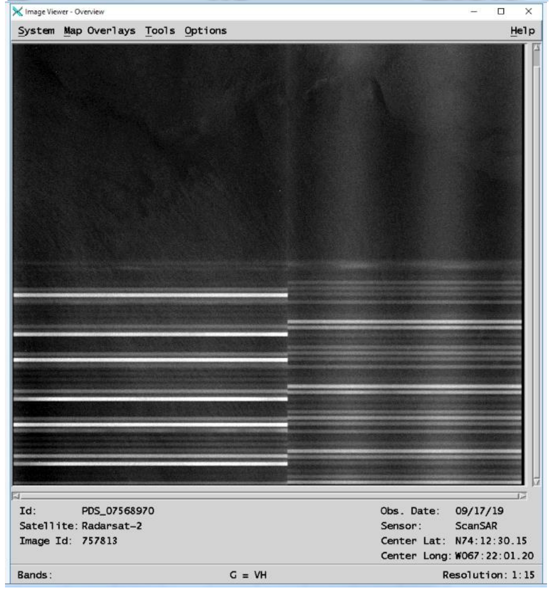
- Mitigation activities
  - Developed a software tool for Canadian Space Agency to predict future interference events
  - Using the tool on a weekly basis to predict and confirm the cause of artifacts noted during quality assurance
  - Issuing notices to users when image quality is affected by interference

- << 0.1 % of acquisitions affected



VV

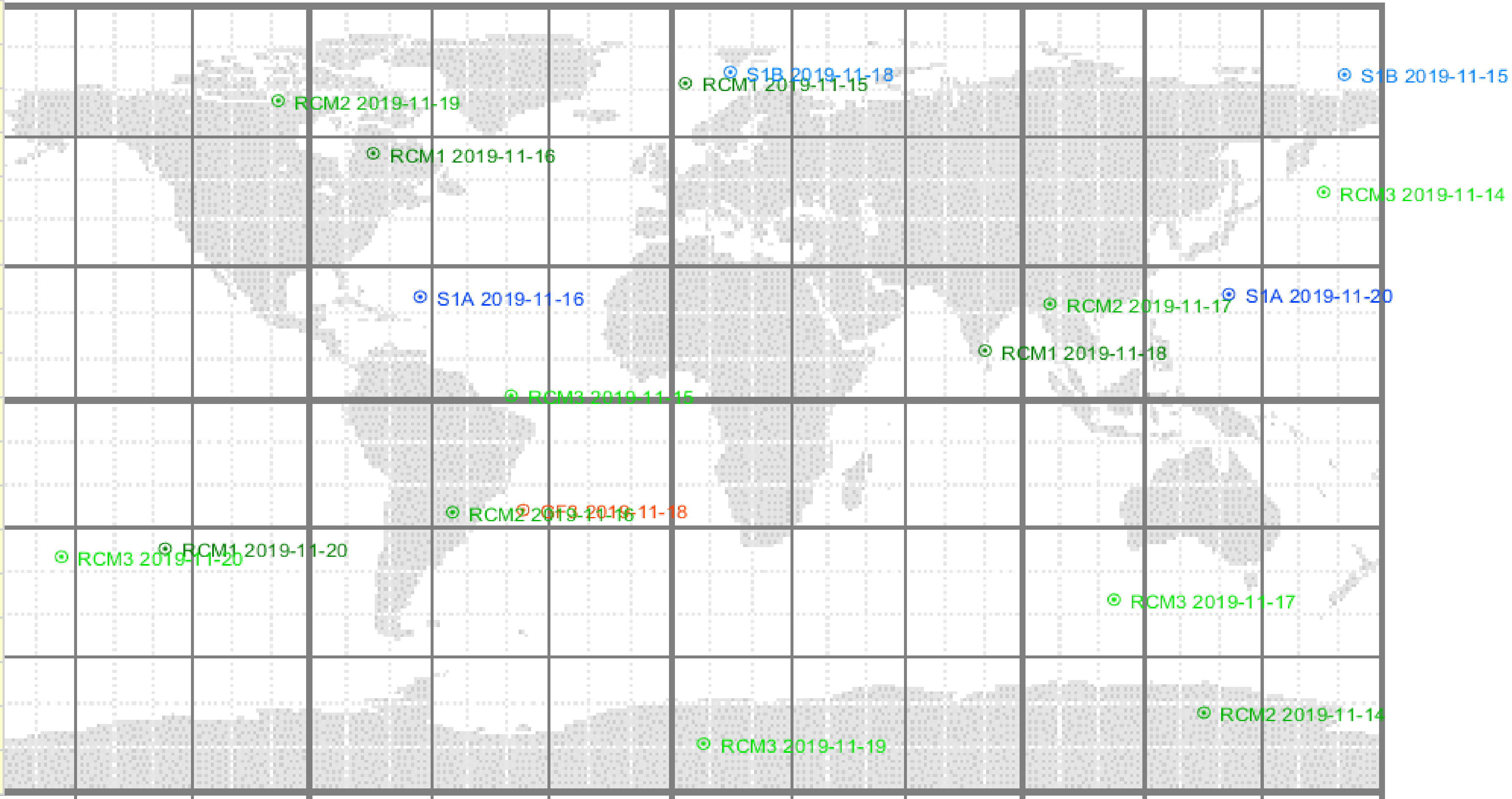
VH



Orbit Crossings with Other C-Band SAR Satellites

- Weekly prediction of potential C-Band SAR interference events
- Assists in checking for and diagnosing interference artifacts

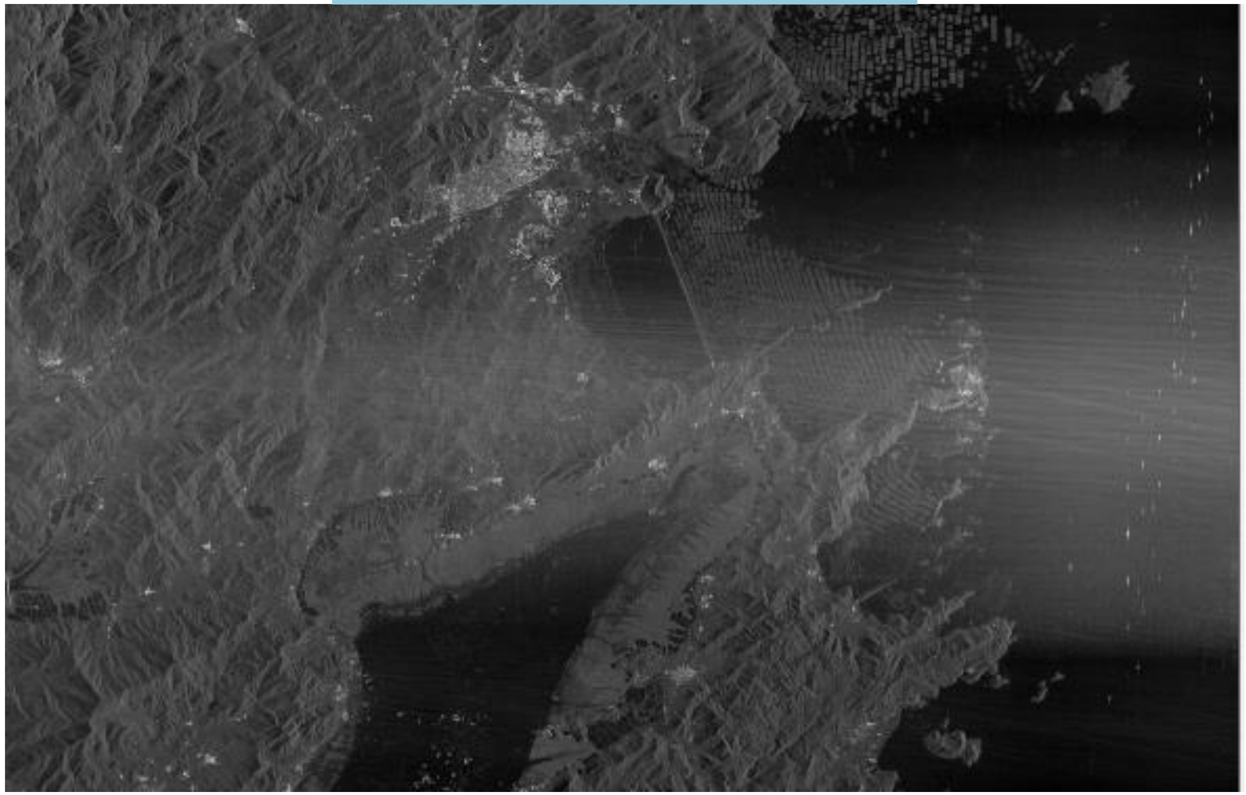
2019-11-14T06:15:34	RCM-3
2019-11-14T18:58:39	RCM-2
2019-11-15T04:13:37	Sentinel-1B
2019-11-15T07:42:35	RCM-1
2019-11-15T20:39:38	RCM-3
2019-11-16T09:22:29	RCM-2
2019-11-16T21:57:28	Sentinel-1A
2019-11-16T22:06:58	RCM-1
2019-11-17T11:03:39	RCM-3
2019-11-17T23:46:17	RCM-2
2019-11-18T12:31:23	RCM-1
2019-11-18T14:30:58	Sentinel-1B
2019-11-18T20:44:44	Gaofen-3
2019-11-19T01:27:39	RCM-3
2019-11-19T14:10:06	RCM-2
2019-11-20T02:55:50	RCM-1
2019-11-20T08:14:46	Sentinel-1A
2019-11-20T15:51:39	RCM-3



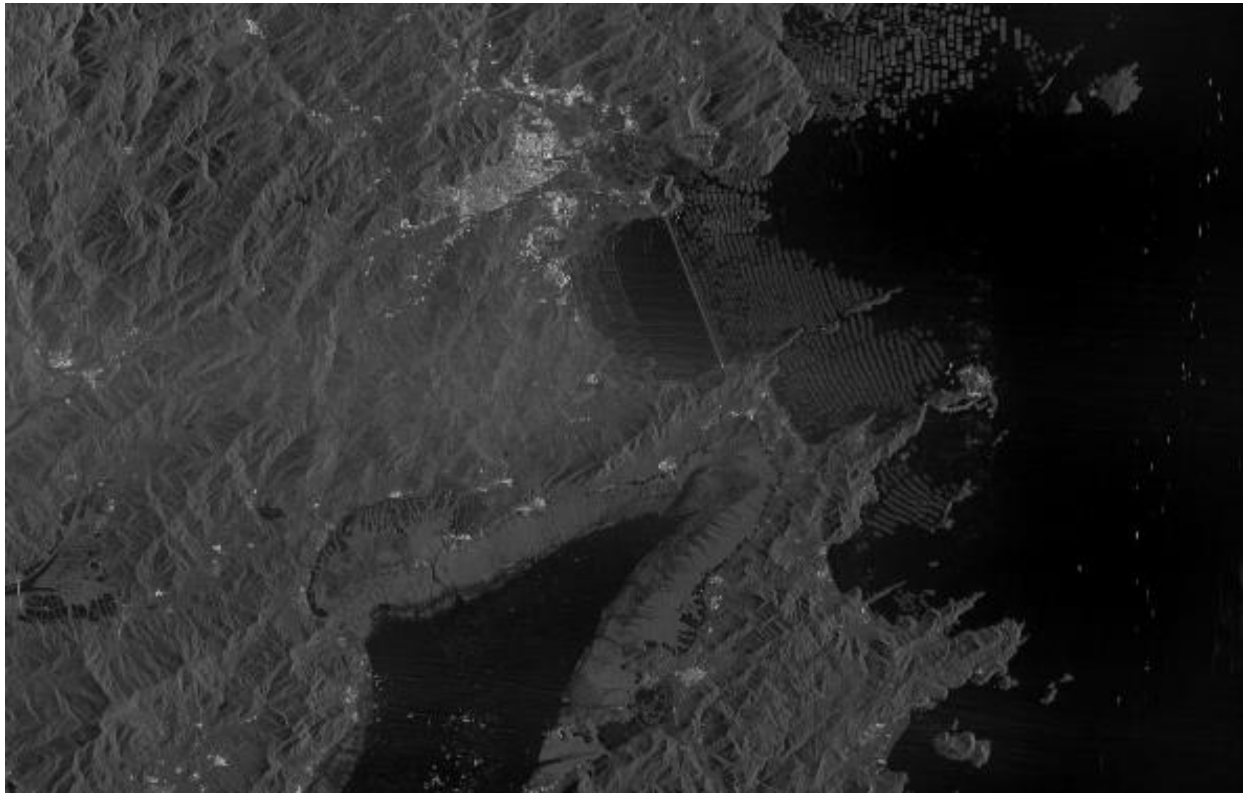
Surface Radar Interference Filtering Improvement

- Surface radar interference filter in SAR processor is upgraded to be more effective
  - For narrow band and/or short-pulse radar sources (wide band or continuous sources such as WAN/LAN cannot be filtered effectively)

Before Upgrade



After Upgrade



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)
Noise levels	Stable (pulse noise levels derived from receive-only data collections remain consistent over mission; spot-checks show cross-polarized image levels over calm ocean are consistent with reported Noise Equivalent Sigma Zero)
Chirp replica coefficients	Stable
Dynamic range	Stable (good use of available BAQ tables)
Payload local oscillator	Stable (based on occasional timing analysis of raw echo data)

Conclusion

- RADARSAT-2 passed its eleventh year of operations and it continues to function extremely well
  – Active system monitoring and spacecraft risk mitigation

- RADARSAT-2 image quality remains excellent
  – Monitored extensively and maintained through calibration updates as needed
  – Occasionally affected by radar interference (mitigated through orbit prediction and quality assurance checking)
  – Ongoing improvements to ground systems