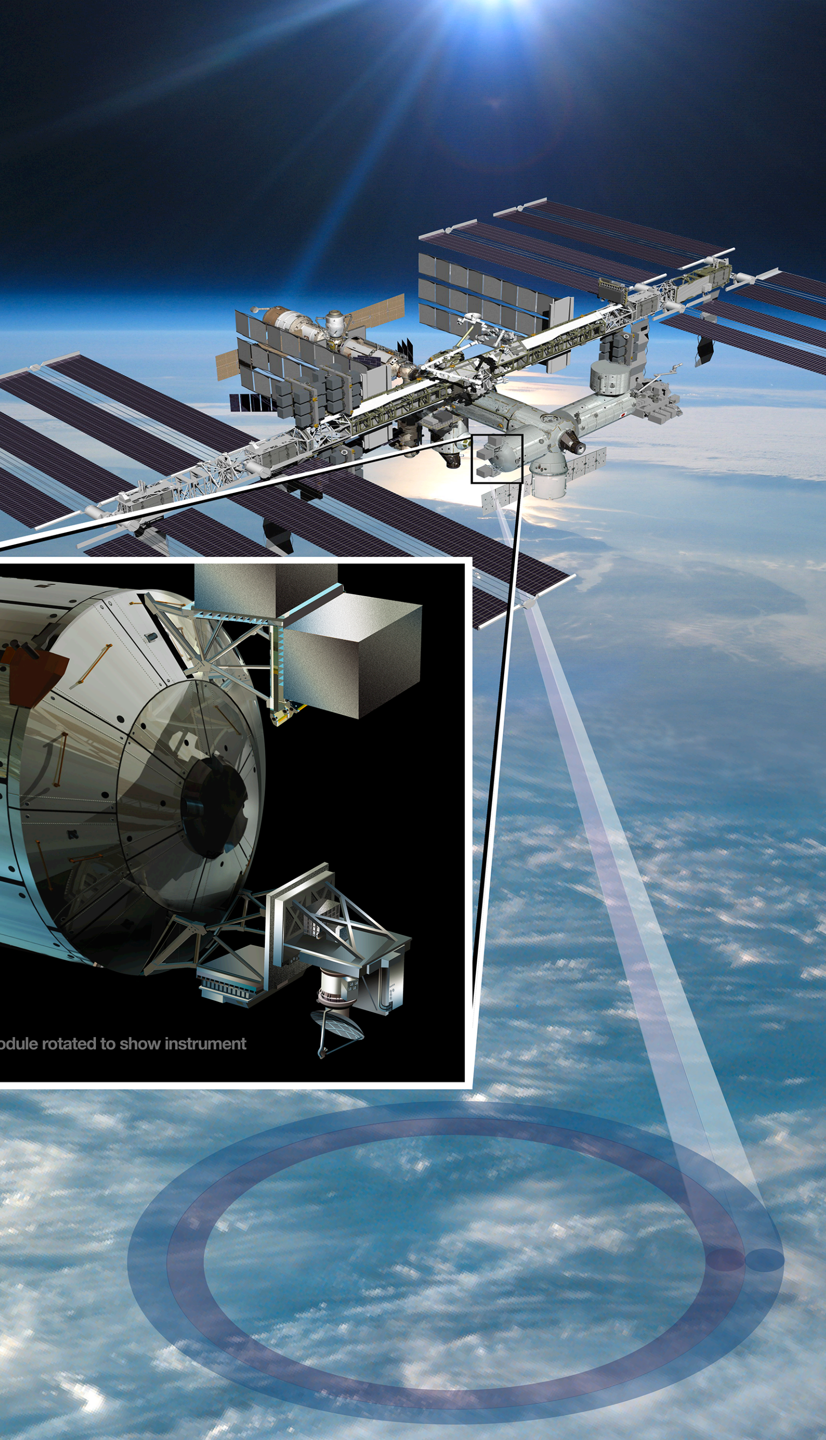

ISS-RapidScat Mission, Instrument and Expected Performance

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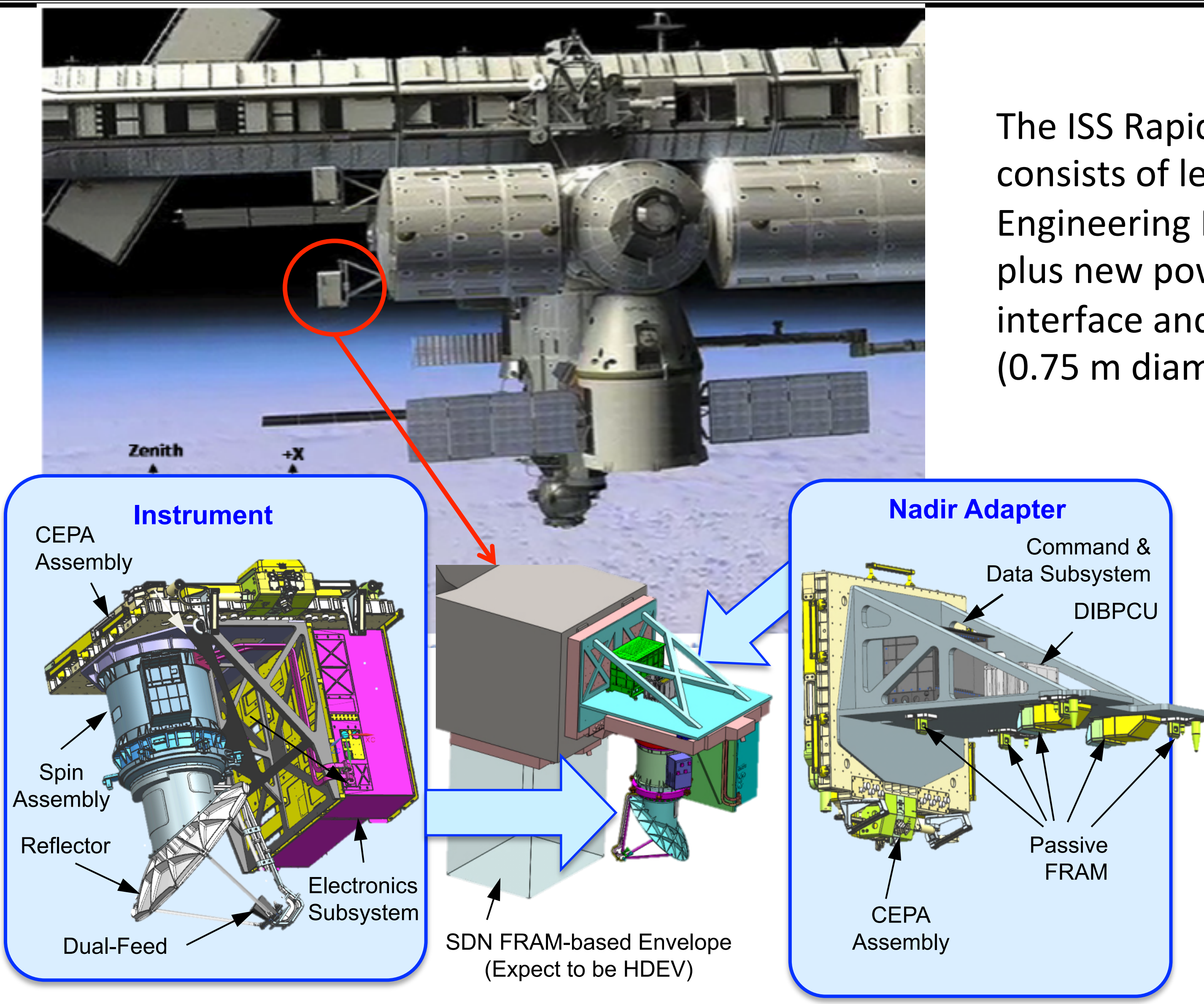
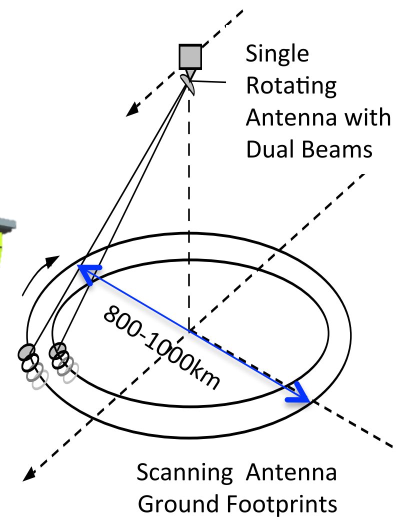
Jet Propulsion Laboratory, California Institute of Technology

IOVWST meeting Hawaii, May 5-8 2013

Flight System Overview



The ISS Rapidscat instrument consists of legacy SeaWinds Engineering Model hardware plus new power and digital interface and new antenna (0.75 m diameter)



This document has been reviewed and determined not to contain export controlled technical data.

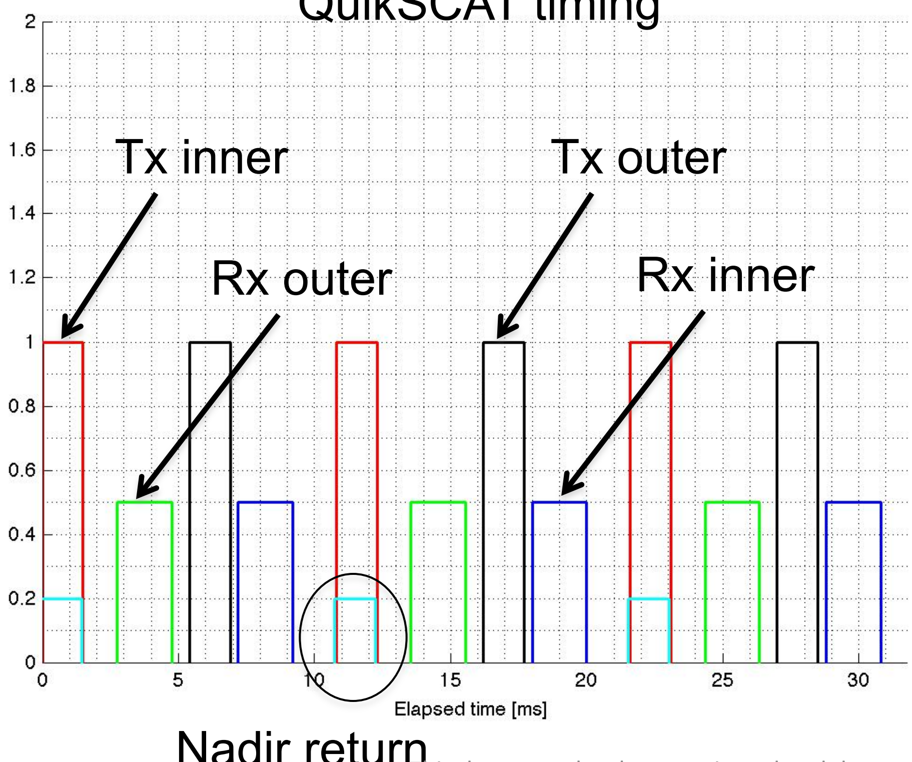
Inherited Hardware Constraints

- Pulse Repetition Interval (PRI) commandable between 5 and 6 ms
- Fit within the dynamic range of the receiver
  - Roughly 45 dB instantaneous
  - Attenuator can be set over 20 dB range
- Pulse width commandable between 0.5 and 1.5 ms
  - Bandwidth is tied to pulse width via constant chirp rate of 250 kHz/ms. Reducing the pulse width from the 1.5 ms used with QuikSCAT reduces the bandwidth and range resolution
  - Frequency resolution of processed slices is tied to length of the data collection, increasing range gate width decreases resolution
- Antenna spin rate 18 rpm or 19.8 rpm
- Range delay and Doppler frequency offset are commanded via tables
  - The variation of these parameters over a 360-degree scan has to be represented as A + B cos(θ+phase)
  - Maximum Doppler 600 kHz, max range delay 12.75 ms
- SeaWinds EM is being used as is with the exception of the antenna system, thus the design space consists of:
  - Selection of operating parameters within existing constraints (ISS and existing hardware)
  - Design of antenna characteristics for desired performance
- Timing is a central concern in our analyses due to ISS altitude and attitude constraints

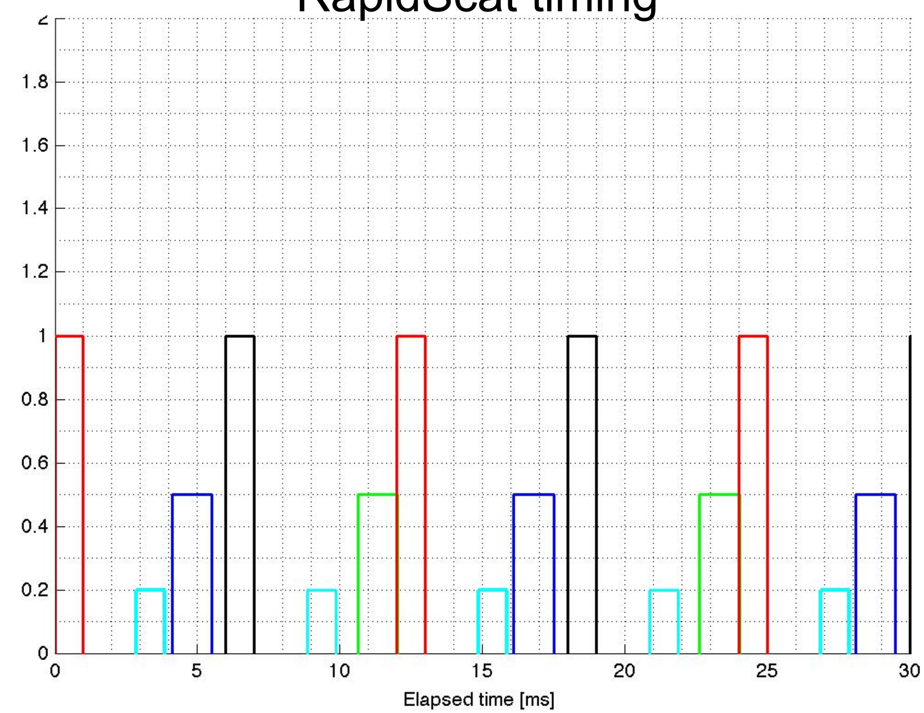
System Timing

- SeaWinds was designed to transmit on one beam and then receive on the other (interleaved), operating at 800 km altitude
- At 400 km altitude the roundtrip time to match the inner OceanSat2 angle is 4.0 ms; to match outer is 4.7 ms
- These are within the commandable PRI range of 5-6 ms
- To match Seawinds interleaved operational design, the PRI would need to be reduced to less than 3 ms – not feasible.
- Hence, timing must be modified to transmit and receive on the same beam

QuikSCAT timing



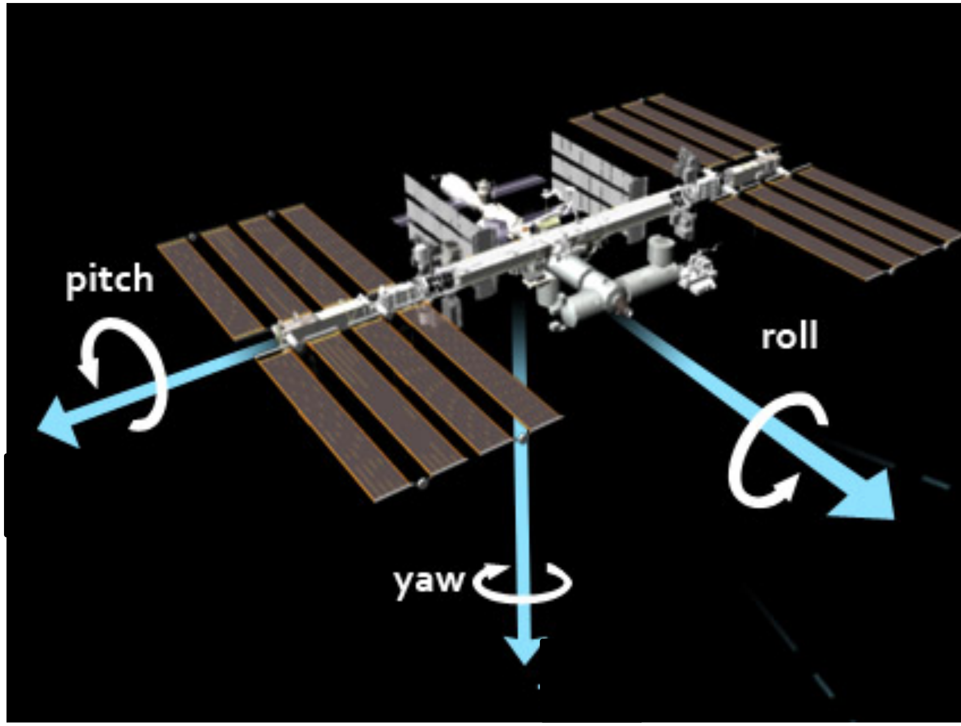
RapidScat timing



ISS Constraints on Instrument Design and Performance

- EMC requirements
  - Fields from RapidScat must on all ISS equipment and on ISS solar panels must be below required limits

- ISS altitude and attitude variations
  - *Expected altitude range: near 410 km mean altitude, plan for 375 km to 435 km (variation over an orbit ~ 20 km)*
  - *Pitch can be roughly 0° to -10°, depending on visiting vehicles and presence of MLM module*
  - *Roll should generally be less than 1°*
  - *Yaw around -6°*
  - *Control is to LVLH system; adds max of about 0.2° error to our desired geodetic nadir (based on our calculations)*



Excessive Field Intensity on ISS

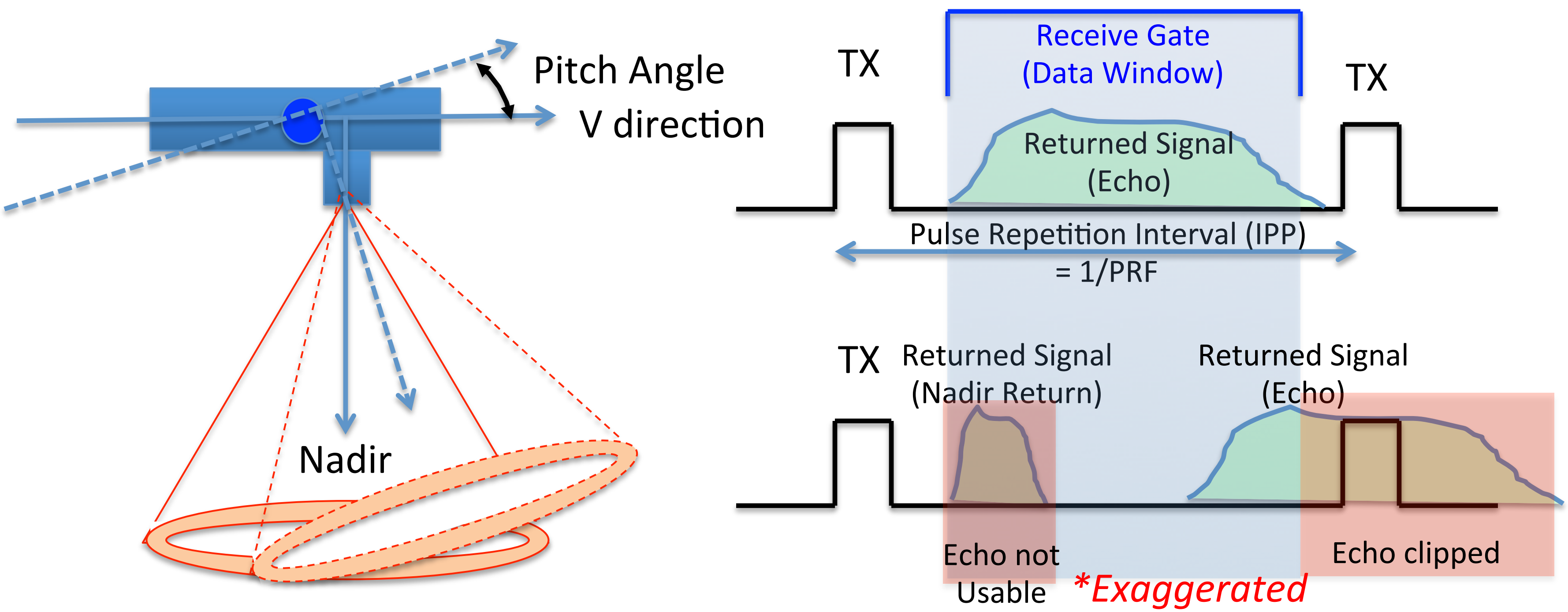
- Problem
  - Visiting vehicles and solar arrays are within the RapidScat main beam (E-field limits exceed specs by up to 9.5 dB)
- Impact (if not mitigated)
  - While ISS solar arrays can handle the radiation level, they do create a blockage in RapidScat's FOV (worst case = 8%)
  - Reducing tx level by 9.5 dB for visiting vehicle safety not feasible; would need to turn off instrument during all visits
  - Estimate about 300 days of visiting vehicles at Node 2 during RapidScat's 2-year on-orbit period; about half time not operating
- Mitigation
  - Implementation of a sector blanker; the RF energy will be blanked over a sector of up to 60° on every rotation of the antenna
  - The sector blanker will affect performance of the radar by reducing the swath up to approximately 50 km

ISS Attitude and Altitude Variability

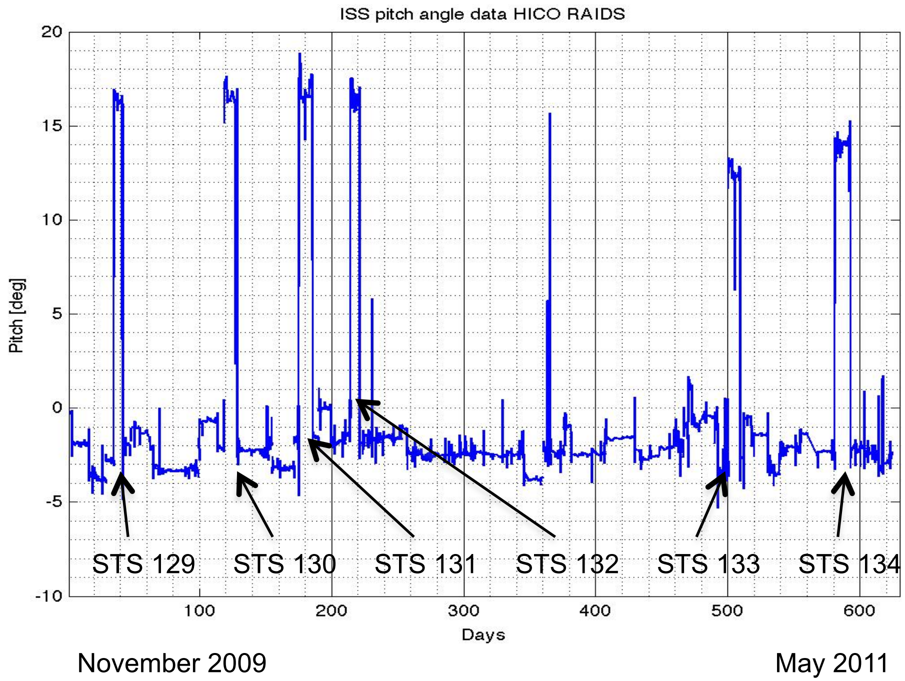
- The ISS can have significant changes in attitude (primarily pitch) due to docking of vehicles
- Additionally, MLM module is scheduled for launch and install on ISS in Dec 14: will shift station's pitch bias by -4°
- The future Russian module will shift station's pitch bias by another -2°; however it is not likely to be installed till the middle or end of RapidScat mission
- Previous history of attitude variation has been evaluated from ISS data and from HICO RAIDS data
  - Study found good agreement between the two sources
  - Attitude mean difference is typically less than 0.1 degrees
- Future attitude variation are predicted by JSC

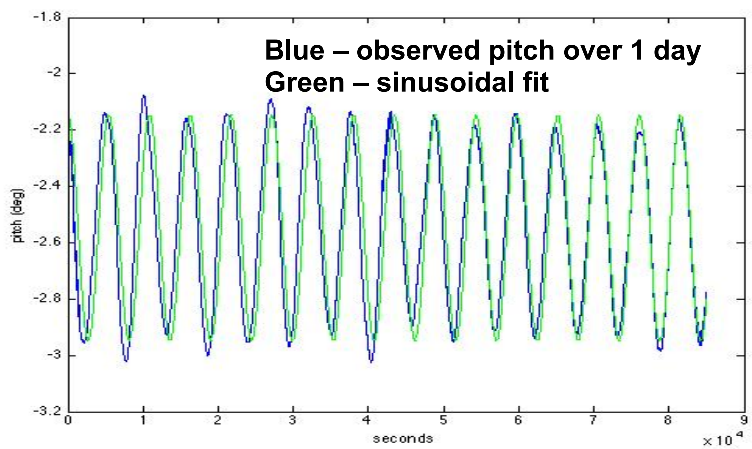
ISS Attitude (Pitch) Change Effects

- Excessive ISS attitude changes throughout the RapidScat ops period can lead to RapidScat performance loss (echo overlap with nadir return or next transmitted event)
  - The radar can compensate for small changes by adjusting the pulse width and data range window
  - Excessive change is beyond radar's capability to compensate and will lead to loss of signal

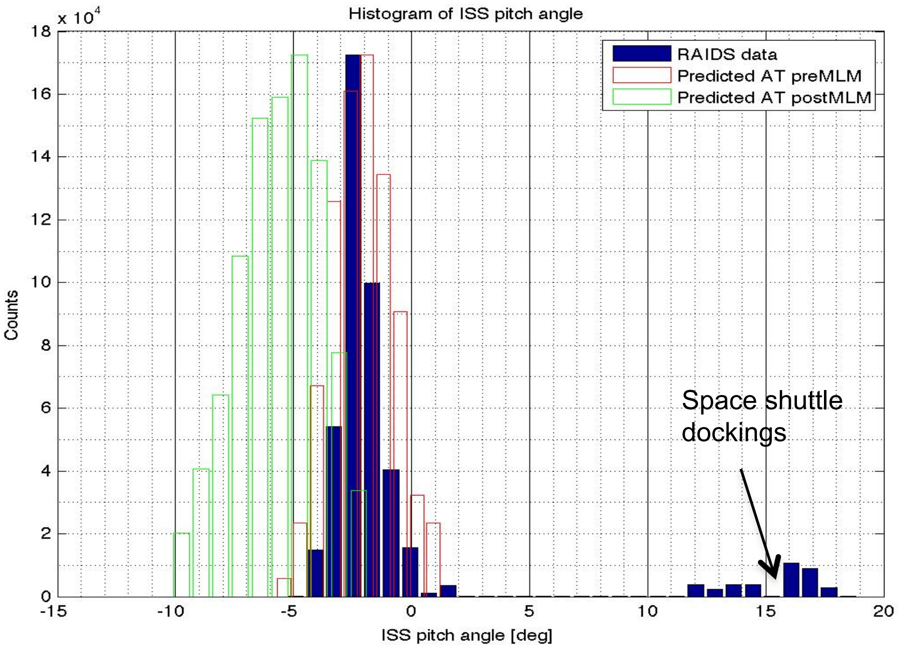


Pitch Variation of the ISS (Historical Data from HICO RAIDS)





- Predicted and measured mean pitch over 18 months period match within 0.5 deg



- Pitch variation over 1 day is shown on the plot to the left, along with sinusoidal fit; maximum error is near 0.2°
- Errors of 0.2° result in timing errors of about 0.02 ms, which can easily be accommodated
- Doppler errors also small in this case
- Attitude errors of several degrees become more problematic

ISS Attitude Variability: Mitigation

- PRI will be set to 6 ms; this gives maximum timing margin between end of received pulse and start of new transmit event
- Pulse width is reduced to 1 ms (or less) for timing margin
- Rx gate width to 1.4 ms for 10 km slice width (based on Seawinds processor operation); maximized to allow for pitch variations
- Frequently update (daily-weekly) range delay and Doppler tables (which tell the radar when to start recording data and what frequency offset to use for compensating Doppler shift)
  - Tables are designed to hold parameters for an orbit
  - The largest short term variation in attitude is due to orbital motion, so this must be predicted with sufficient accuracy
  - Due to on-board implementation of Doppler shift update a maximum of +/-12.5 kHz error can be expected in the return echo in addition to errors from attitude variation
- Mount radar with forward pitch offset (+2.5 or +5.5 degrees) to reduce pitch bias over mission
- Roll bias is expected to be small; yaw bias of 6 degrees will not have significant impact on conically scanning instrument
- Simulations indicate that for expected altitude and attitude range, data loss should be small (less than a few %)

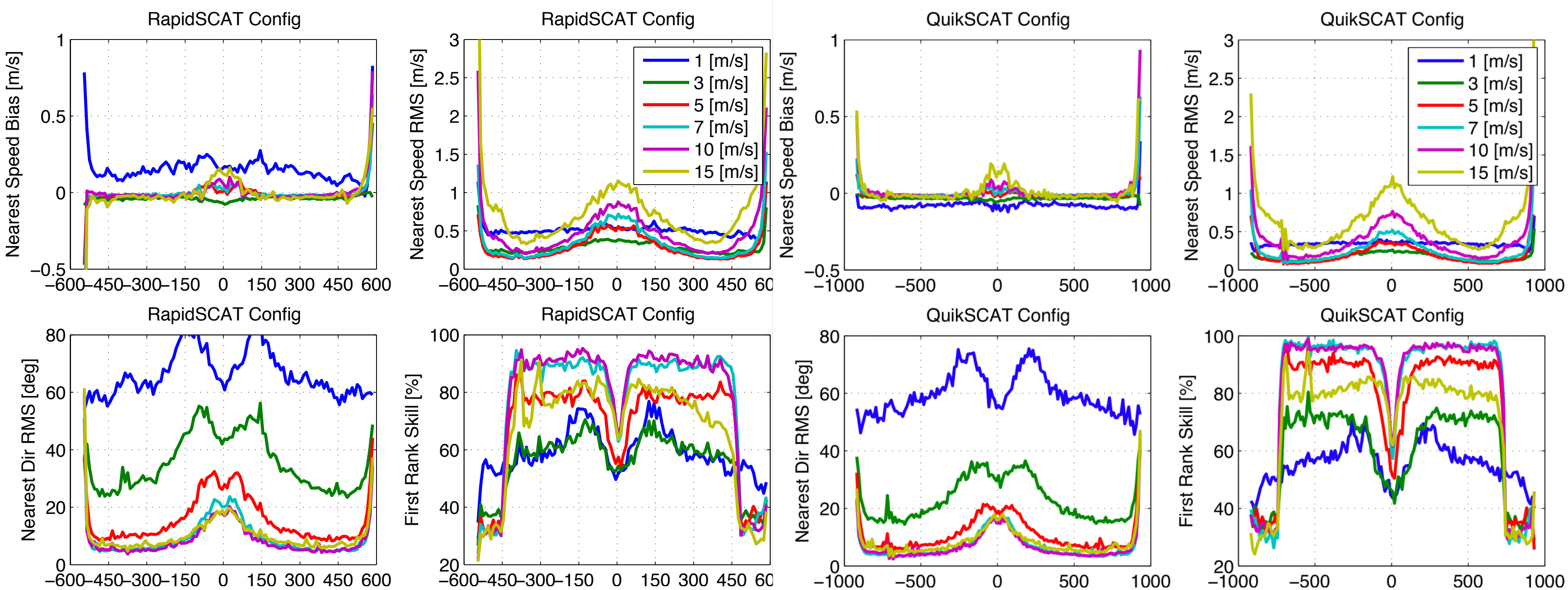
System Performance

- Initial assessment of system performance is based on simple spreadsheet calculations of the the noise equivalent sigma0
- For parameters shown here it was assumed that station's orbit and attitude were perfectly known and stable i.e. no variability in pitch or altitude.
  - Direct assessment of the scatterometer's wind retrieval ability relies on a simulation that uses a wind field as input

Parameter	RapidScat	QuikSCAT	Unit
Orbital attitude	435	800	km
Antenna size	0.75	1	m
3dB beamwidth – 1 way - elevation	2.4, 2.2	1.6, 1.4	degree
3 dB beamwidth – 1 way - azimuth	2.1	1.8, 1.7	degree
Antenna rotation rate	18	18	rpm
Operating frequency	13.4	13.4	GHz
Chirp rate	250	250	kHz/ms
Pulse width	1.0	1.5	ms
PRI	6.0	5.4	ms
Peak radiated power	80	80	W
Incidence angle (inner, outer)	49, 56	46, 54	degree
Look angle (inner, outer)	45, 50.5	40, 46	degree
Ground-range resolution (inner, outer)	0.79, 0.73	0.55, 0.49	km
Azimuth resolution (inner, outer)	15.5, 17.3	24.5, 26.0	km
Slant range (inner, outer)	600, 678	1095, 1242	km
Ground swath (inner, outer)	900, 1100	1410,1800	km
Data window length	1.4	1.8	ms
NE sigma0 (inner, outer)	-31.8, -30.5	-31.2, -32.2	dB

Simulation results: baseline RapidScat performance vs QSCAT

- Used QuikWinds simulation tool to simulate wind retrieval performance
  - Uses simulated wind field
  - Assumptions RapidScat: Peak power 110W (TWTA o/p), 1 ms pulse width, no pitch bias, constant altitude of 435 km, blanked sector 270°-290°
  - Assumptions QSCAT: Peak power 110W (TWTA o/p), 1.5 ms pulse width, constant altitude of 800 km



This document has been reviewed and determined not to contain export controlled technical data.

Calibration Strategy

- Pre-launch:
  - Measure antenna gain, antenna pointing relative to alignment feature (e.g., cube or tooling balls)
  - Calibrate antenna encoder (measure actual antenna position versus digital readout)
  - Measure spin axis orientation relative to CEPA/ISS
  - Measure receiver gain and noise over expected temperature range
  - Measure transmit power over expected temperature range
  - Update tables used by ground processor with these measurements
- Post-launch
  - Absolute calibration, slice balance, sigma0 from all slices match the sigma0 from the whole footprint, sigma0 vary appropriately along the scan (Amazon rain forest to determine scan bias)
  - Use data to estimate pointing and update Doppler and range tables
  - Use data to update gain and update calibration tables
  - Solar array positions used to discard affected data (<8%)

Summary

- RapidScat can be accommodated at the ISS SDX site
  - Requires two FRAM-based units
  - Becomes an oversized payload once installed on orbit
- Partial FOV blockage leads to some degradation in performance
  - In worst case, when solar arrays are in FOV, up to 8% of the scan is blocked
- Radiation level exceeding ISS subsystem safe level requires sector blanking (up to 60^o)
  - Radiation on ISS solar arrays not a concern
  - Mitigation to allow ops when visiting vehicles are present will reduce swath and may impact calibration
- RapidScat measurements will provide vector winds retrieval to the accuracies comparable to those from QuikSCAT
  - Requires pitch pointing offset to counter ISS attitude bias variations
  - Design provision to set pitching pointing offset as late as feasible during the integration period
  - If ISS pitch bias is incorrectly predicted performance is degraded
    - Meet stated performance 99% of the time if pitch bias predicted correctly
    - If assumed presence of MLM is incorrect, performance met 32% of the time

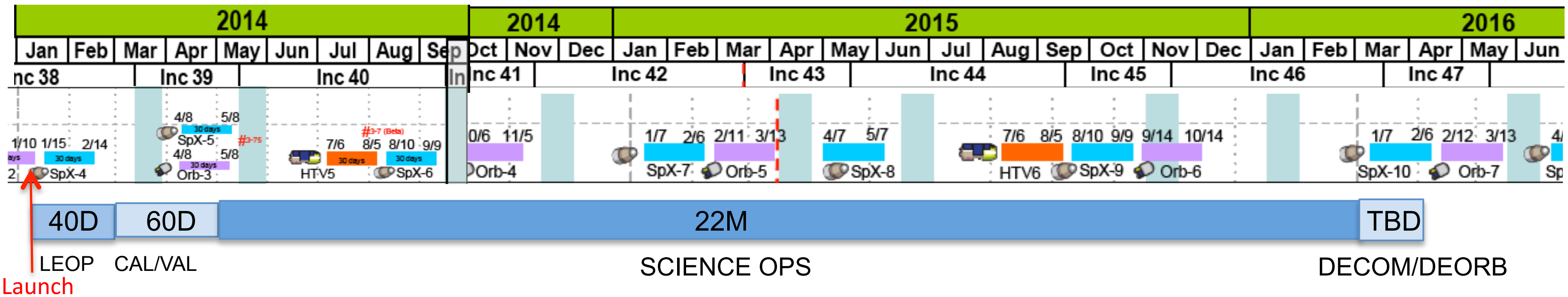
Backup

What is the ISS-RapidScat project?

- An experiment at JPL in a new form of faster, ~~better~~, cheaper, utilizing inherited and commercial hardware.
- A pathfinder at JPL in tailoring processes and rules for “lower than Class D” missions
- An attempt to gain useful science data at a fraction of the typical cost
- A zero-fault tolerant activity (one major problem and we may have to stop)

Mission Timeline

ISS Flight Plan, Nov 13, 2012 (Assumed SpaceX-4 Launch 1/13/2014)

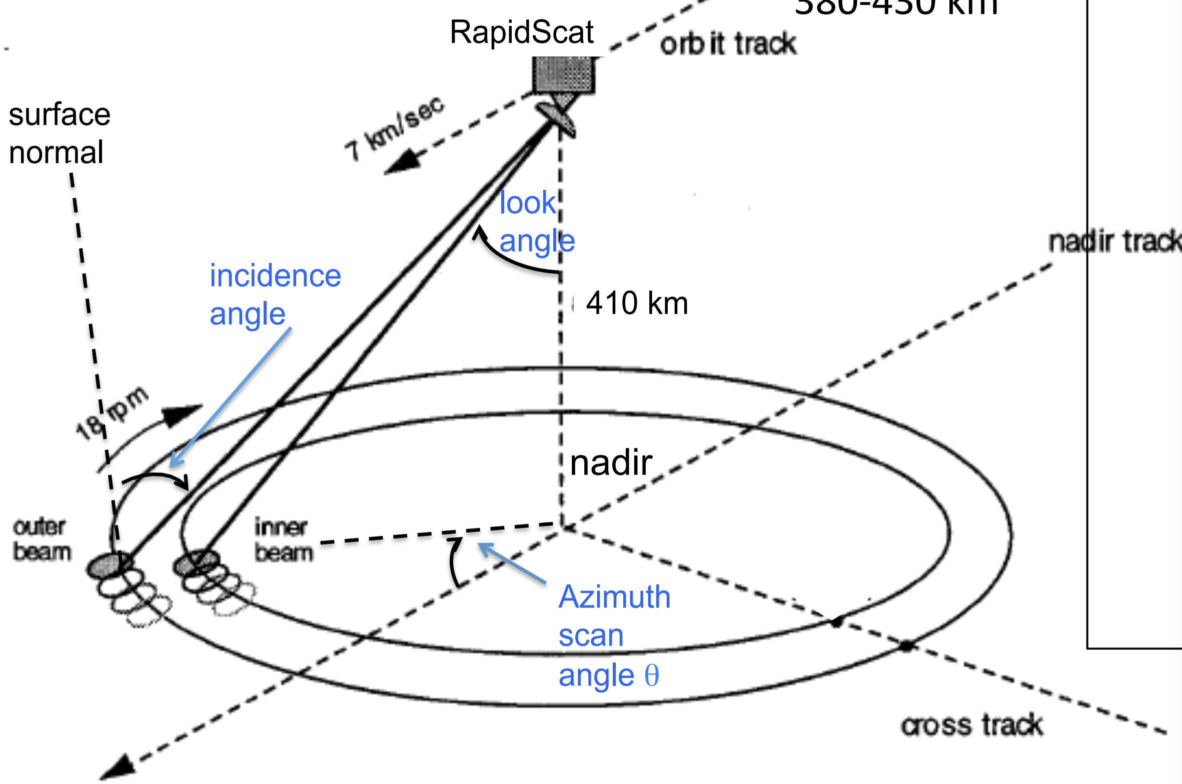


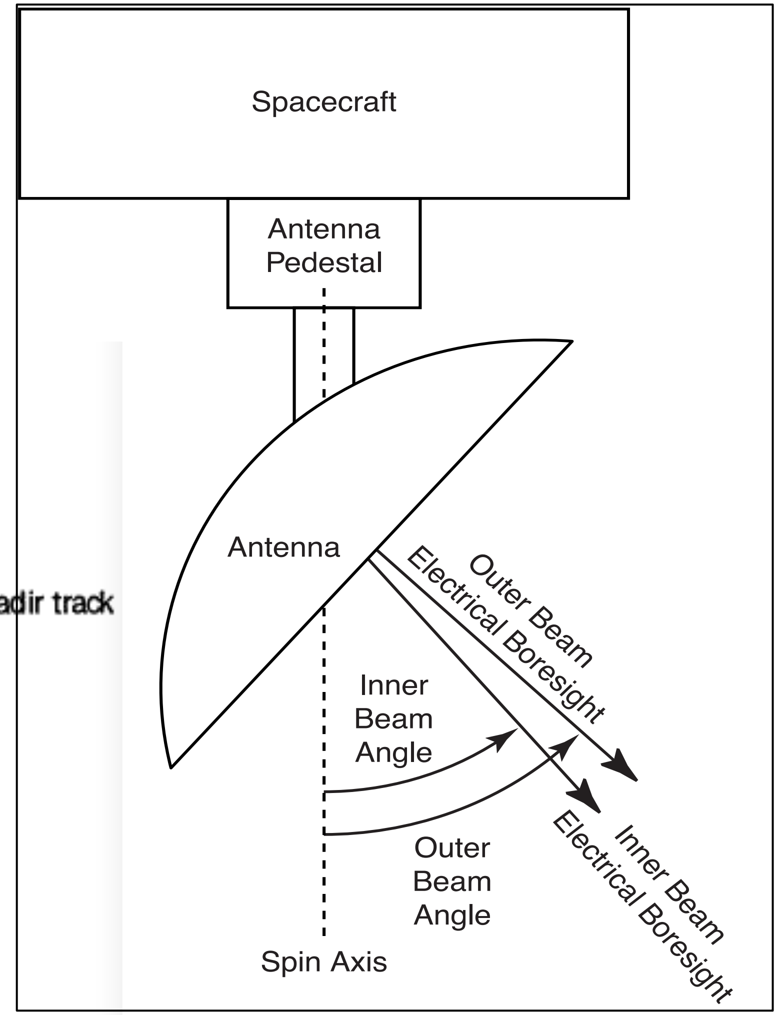
- LEOP (Launch & Early Orbit Ops) [40D]
  - 3D: Launch to Dock/Berth
  - 3D: P/L EVR Installation (applied heaters)
  - 24D: No ops until Dragon departs due to RF hazard; unpowered (heaters on)
  - 3D: P/L activation and checkout
  - 3D: System stabilization and characterization
  - 4D: Preliminary calibration and validation
- CAL/VAL (Science Calibration and Validation) [>60D]
  - Was planned for 60D but no-ops during visiting vehicle presence might extend duration
  - [See Section 15 for more detail about activities during this period]
- SCIENCE OPS [22M]
  - Routine science ops
- DECOM/DEORB (Decommission/De-Orbit)
  - Power off; Remove from COL and install in trunk of return vehicle; destructive deorbit on return

Measurement Geometry

- Constrained to pencil-beam scatterometer geometry
- New antenna allows choice of look angles and instrument pitch offset

Altitude
380-430 km





Mission Objectives

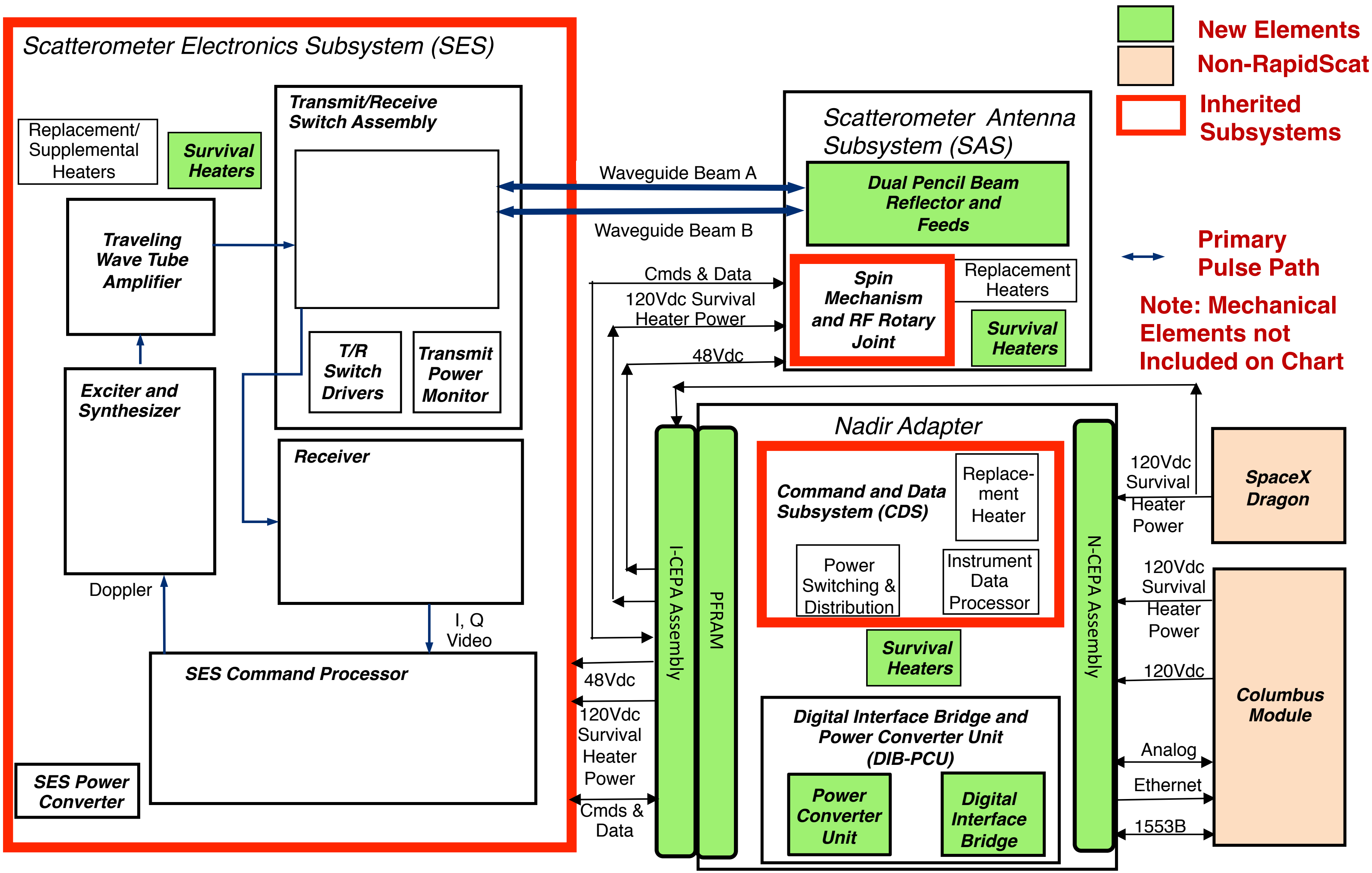
- To implement a scatterometer payload, utilizing as much SeaWinds residual hardware as possible, to fly on the ISS and acquire measurements from which the derived vector winds accuracies are comparable to those from QuikSCAT with coverage that can be afforded by ISS

RapidScat Parameters	
Frequency	13.4 GHz
Bandwidth	250 kHz
Pulse Width	1 ms
Pulse Repetition Interval	6 ms
Tx Peak Power	80 W
Polarization	HH and VV
Spin Rate	18 rpm
$NE\sigma_0$	– 30 dB
Backscatter Resolution	<16 x 2 km
Swath Width	800-1000 km

ISS Accommodation	
Altitude	380 – 430 km
Orbit Inclination	51.6 deg
Location	Columbus SDX Site
Pointing Control*	+/– 2° (3 sigma)
Pointing Knowledge	+/– 1° (3 sigma)
Pointing Stability	Capability of ISS
Coverage	> 90% global in 48 hours

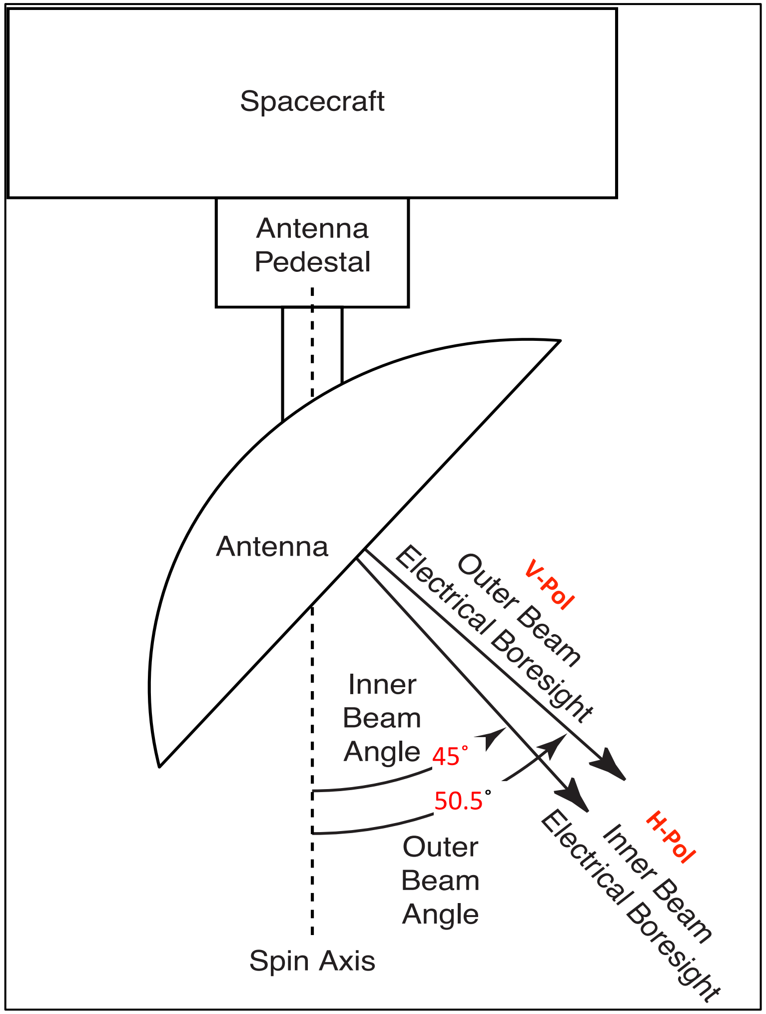
*Original 2° attitude control requirement assumed for ISS can be relaxed to 3°

Flight System Configuration Block Diagram – Instrument Constraints

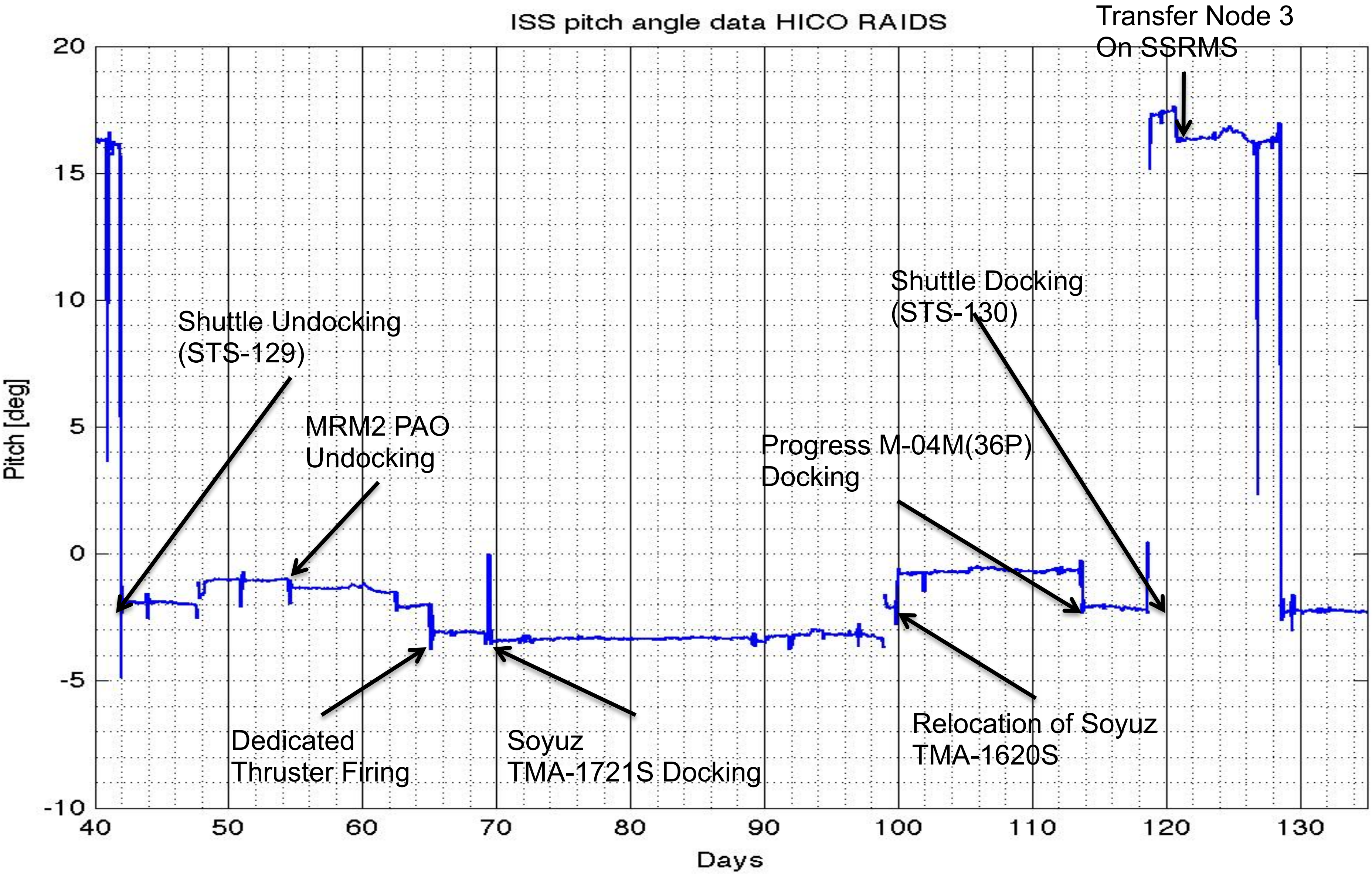


Timing and Antenna

- Timing constraints also impact selection of antenna beam angles
  - Set inner beam to avoid overlap with nadir return (45° off nadir results in 49° incidence angle to match OceanSat, 45° prevents overlap between the end of the nadir return and the start of the main beam return)
  - Set outer beam to avoid overlap with following transmit pulse, causing received pulse to be clipped (50.5° off nadir chosen as smallest feasible outer beam angle; smaller angles not feasible due to feed spacing)
  - Allow margin for changes in ISS attitude (52° off nadir would match the OceanSat 2 outer beam incidence but would provide little timing margin when ISS is at maximum altitude)
- Antenna beam footprint sizes should be chosen to give contiguous coverage (azimuth beamwidths are matched at 2.1° to provide resolution better than that of QuikSCAT; elevation 2.4° and 2.2° for contiguous coverage – verified by simulation)
- Antenna reflector size constrained by launch envelope to a maximum of 0.75 m and by need for gain and beamwidth to meet SNR and resolution specifications



Zoom-in Around Day 100 (Historical Data HICO RAIDS)



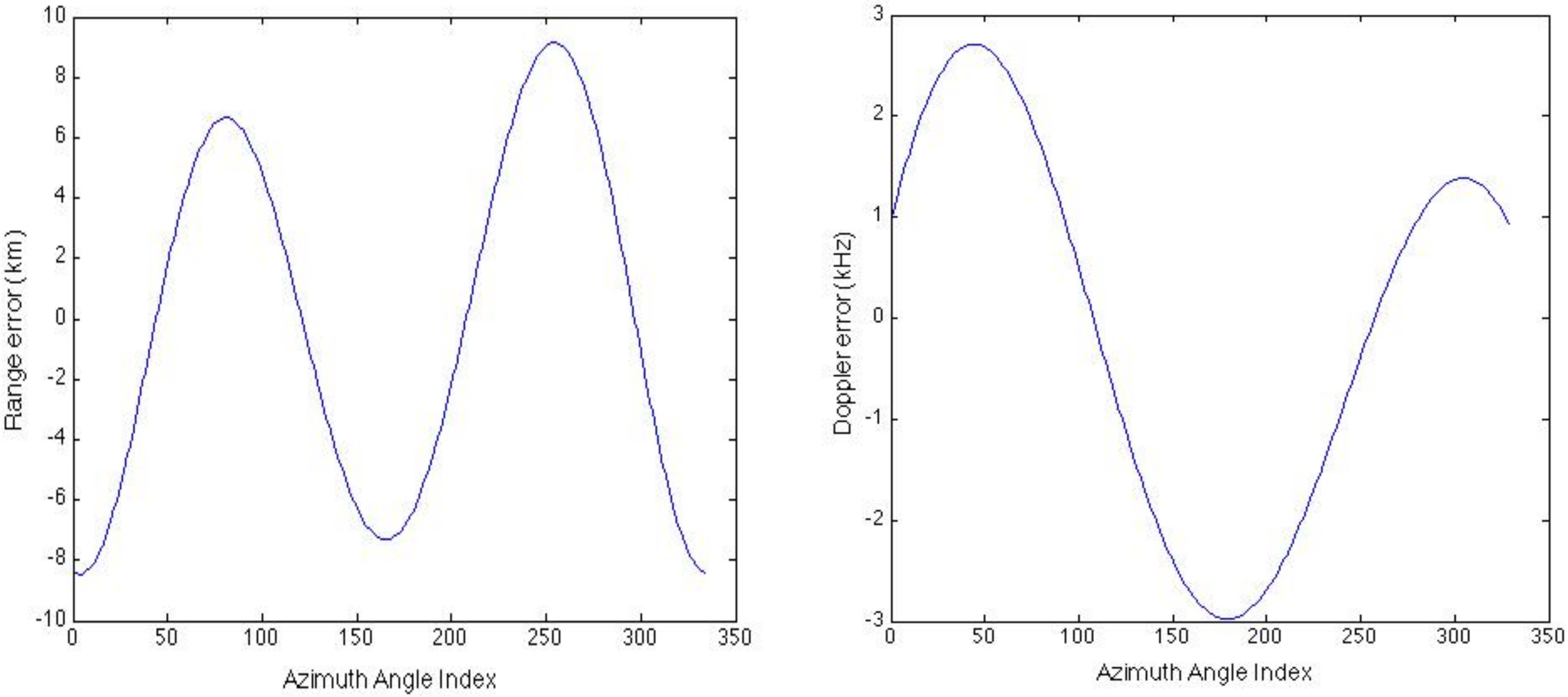
Nadir return impact

- SeaWinds was designed so that the unwanted signal from nadir would return during transmit event
- At 410 km nadir return starts at 2.9 ms and ends at 3.9 ms for 1 ms pulse => nadir return and inner beam return can overlap
- We derived an analytical formula for nadir return versus main beam return
  - Sigma0 drops from 15 dB linearly (in dB) with incidence angle
  - Antenna pattern is Bessel function, -35 dB at nadir
  - Resulting nadir clutter corresponds to sigma0 of roughly -32 dB
- Pulse compression will reduce its impact on the signal channel; more likely to impact noise channel
- Assessment: calculations with predicted antenna sidelobe level indicate that nadir return may be comparable to thermal noise level
  - Possible problem at low wind speeds
  - If impact more severe than expected, transmitted pulse length can be reduced, with the impact of degraded resolution

Spin Axis Pitched Off Nadir

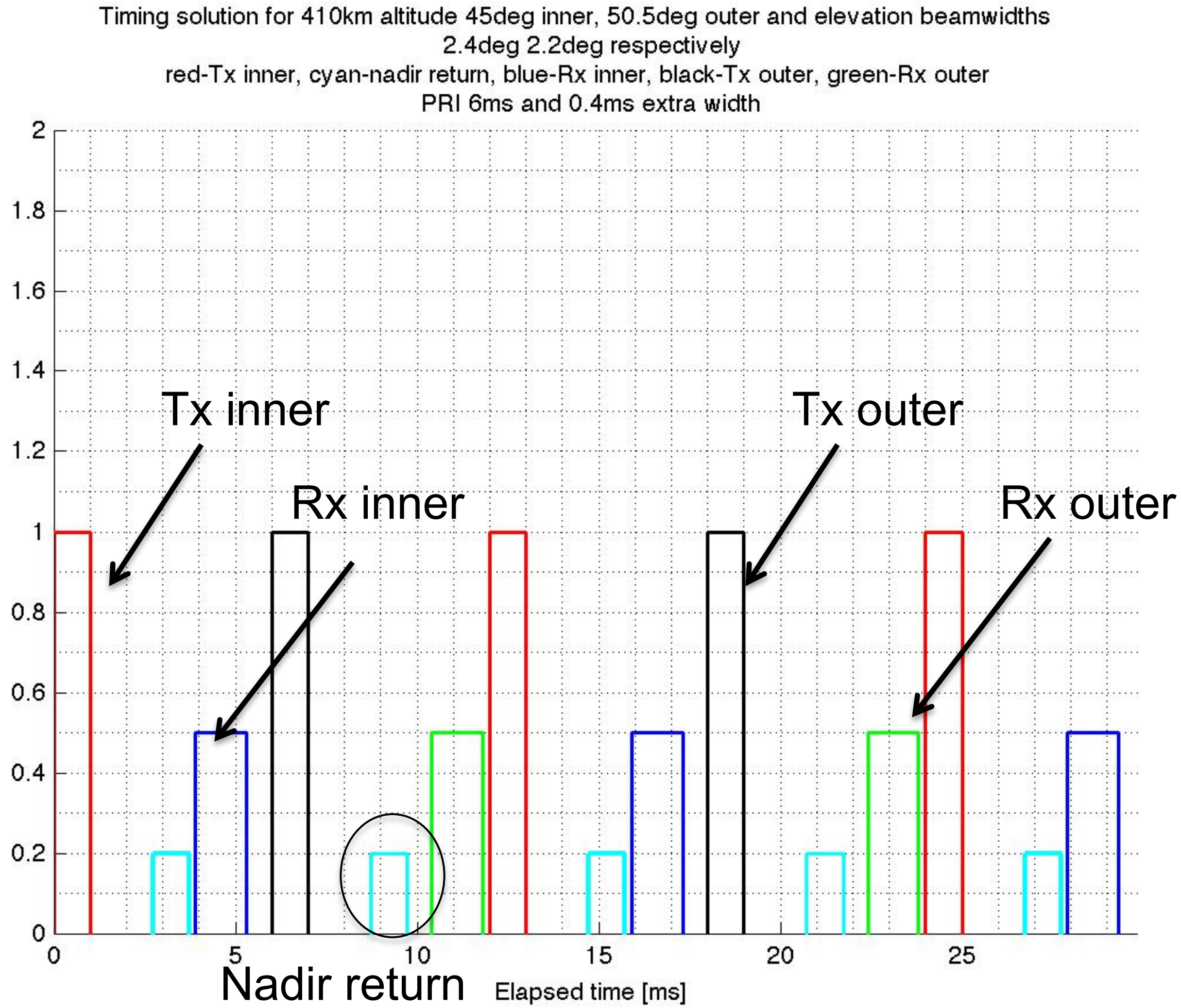
- RapidScat will not have an active compensation accounting for pitch angle offsets and thus an error in spin axis pointing is likely over the mission lifetime
- Range window easily accommodates the 1-2 km error (3^o); error grows to about 10 km for 6^o off nadir, timing error of .066 ms still OK
- Doppler errors for 3^o < 1 kHz, very small; error grows to 3 kHz for 6^o

Range and Doppler errors using cosine table for 6^o off nadir



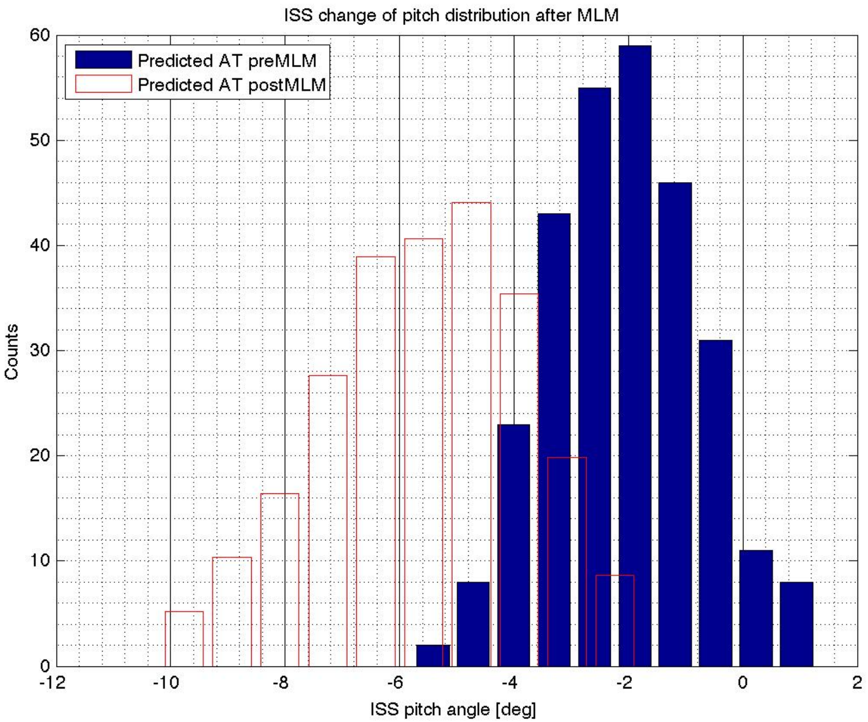
Timing Diagrams and Pitch Margins

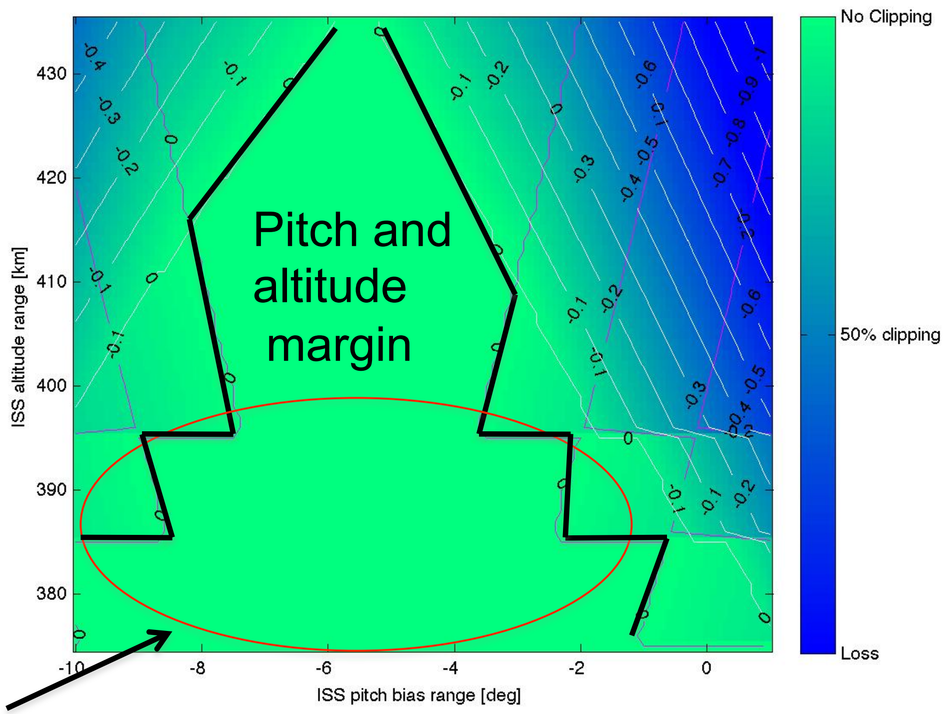
- Nominal timing design



Timing Diagrams and Pitch Margins

- RapidScat margin simulation on forward and aft look with pitch offset +5.5°, pulse width 1 ms or less for low altitudes (right)
- Histogram of predicted ISS pitch pre and post MLM (left)
- If the mean bias is correctly compensated by the instrument pitch the exceedance of 3° pitch has a low probability of occurrence ~ 1% of time





Use pulse
Width < 1ms

Simulation results: impact of off-nadir spin axis on performance

- Results shown here assume perfectly calibrated data was used to retrieve winds in both QuikSCAT and RapidScat case.

5 m/s	RapidScat												QuikSCAT
Altitude (km)	**435**				**410**				**375**				**800**
Pitch bias (deg)	**0**	**2**	**4**	**6**	**0**	**2**	**4**	**6**	**0**	**2**	**4**	**6**	**0**
Speed Error (near swath)	0.4 m/s	0.6 m/s	0.6 m/s	0.6 m/s	0.4 m/s	0.6 m/s	0.6m/s	0.6 m/s	0.5 m/s	0.5 m/s	0.5 m/s	0.6 m/s	0.4 m/s
Speed Error (mid swath)	0.2 m/s	0.2 m/s	0.5 m/s	0.5 m/s	0.2 m/s	0.2 m/s	0.3 m/s	0.3 m/s	0.2 m/s	0.2 m/s	0.2 m/s	0.2 m/s	0.3 m/s
Direction error (near swath)	22°	27°	32°	32°	22°	30°	30°	30°	22°	22°	24°	32°	20°
Direction error (mid swath)	7°	9°	12°	12°	7°	10°	10°	10°	7°	7°	7°	7°	7°
Slice resolution (m)	600	600	600	600	600	600	600	600	857	857	857	857	400
Swath width (km)	1100	1100	1100	1100	1050	1050	1050	1050	950	950	950	950	1800

7 m/s	RapidScat												QuikSCAT
Altitude (km)	**435**				**410**				**375**				**800**
Pitch bias (deg)	**0**	**2**	**4**	**6**	**0**	**2**	**4**	**6**	**0**	**2**	**4**	**6**	**0**
Speed Error (near swath)	0.6 m/s	1 m/s	1 m/s	1 m/s	0.6 m/s	1 m/s	1 m/s	1 m/s	0.7 m/s	0.7 m/s	0.7 m/s	1.2 m/s	0.6 m/s
Speed Error (mid swath)	0.2 m/s	0.2 m/s	0.5 m/s	0.5 m/s	0.2 m/s	0.3 m/s	0.3 m/s	0.3 m/s	0.2 m/s	0.2 m/s	0.2 m/s	0.2 m/s	0.3 m/s
Direction error (near swath)	20°	25°	30°	30°	20°	23°	23°	24°	20°	20°	22°	30°	18°
Direction error (mid swath)	5°	7°	10°	10°	5°	8°	8°	8°	5°	5°	5°	5°	5°
Slice resolution (m)	600	600	600	600	600	600	600	600	857	857	857	857	400
Swath width (km)	1100	1100	1100	1100	1050	1050	1050	1050	950	950	950	950	1800

Color legend	**Better or equal QSCAT**	**Marginally worse than QSCAT**	**Significantly worse than QSCAT**

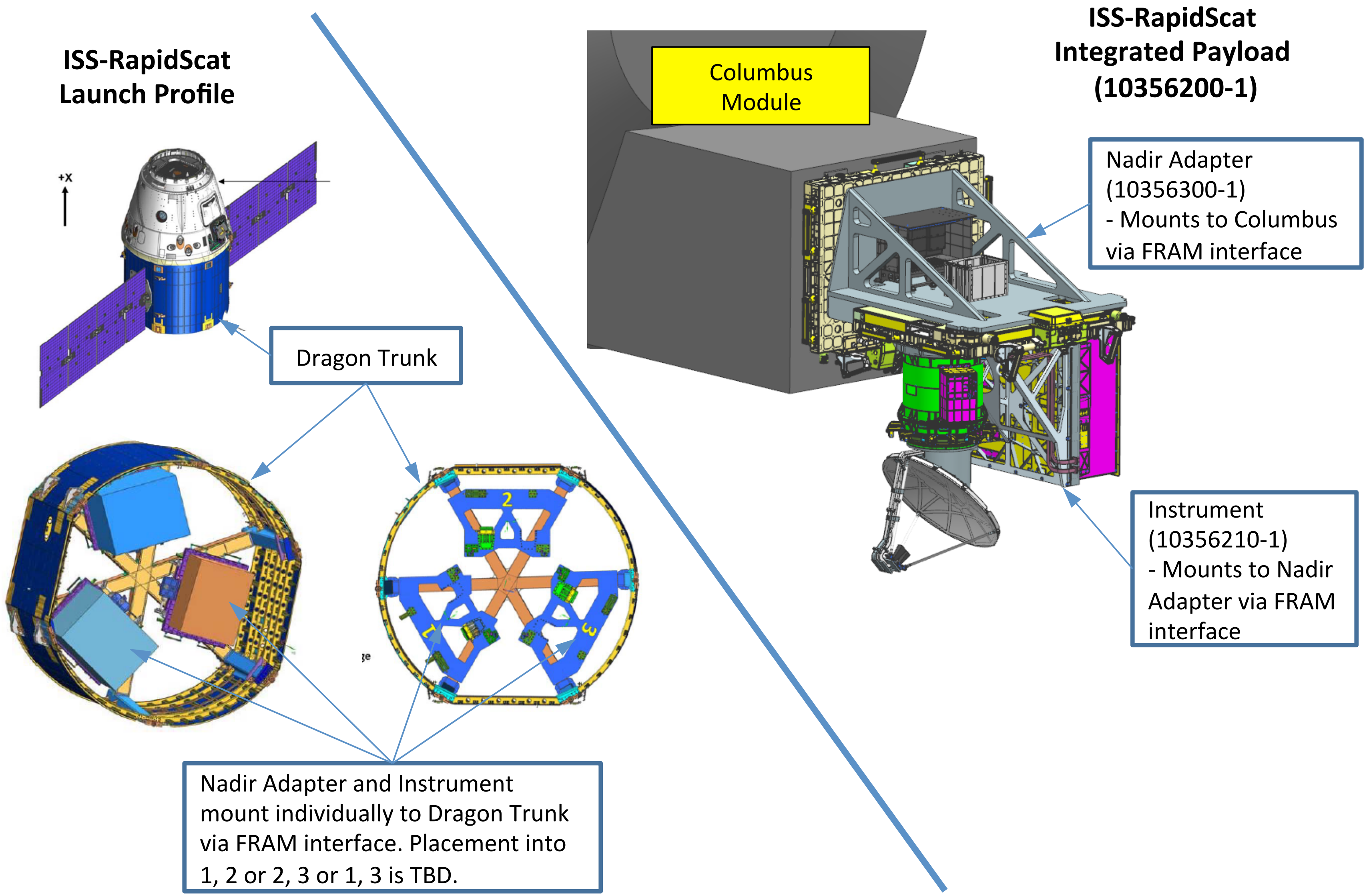
Simulation Results: Impact of Blockage by Solar Arrays

- It is possible for ISS solar arrays to intersect radar beam(s). Worst case is when array panel is rotated so that it is broadside relative to the radar beam
- This results in approx blockage of 8% of scan, the analysis neglected multi-path effects due to solar panels.
- Generally, presence of the solar panel in the beam will cause contamination of data; corresponding data will be discarded. To flag the contaminated data we will pre-process it on ground using solar array position found in broadcast ancillary data (BAD)
- Impact: left side of the swath will be reduced by tens of km occasionally.
- Beam is also blocked by visiting vehicles
  - Due to EMI/EMC requirements this situation requires RapidScat to turn off, results in large outages (~ 40%) of science data

Comparison with QuikSCAT

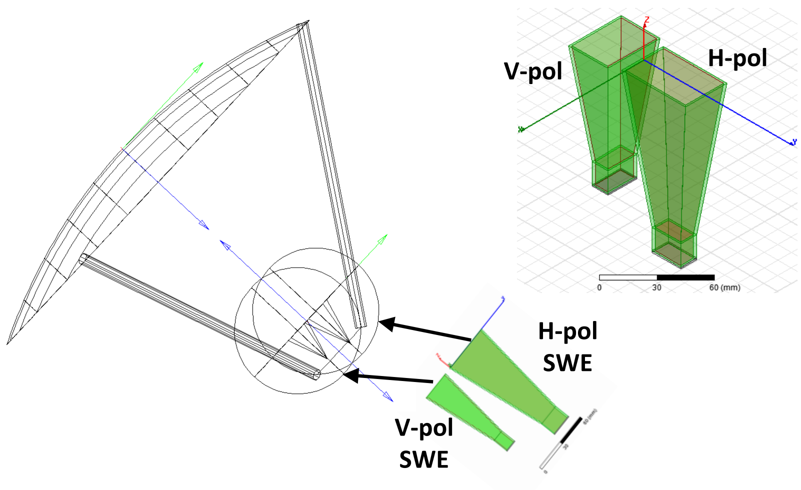
- RapidScat's 400 km altitude is roughly half that of QuikSCAT
  - This would increase the return by a factor of 8 (9 dB)
  - Actually about 8 dB, since the incidence angles are different
- Rapidscat antenna is 0.75 m versus 1 m of QuikSCAT
  - This reduces the RapidScat gain by about 2.5 dB (5 dB 2-way)
  - This increases the resolution cell size and return by 0.5 dB
- QuikSCAT radiated about 0.5 dB more power
- RapidScat has more waveguide loss (0.5 dB)
- The result is that the signal returned to RapidScat is about 2.5 dB larger for inner beam; less than 0.5 dB for outer beam due to larger gain for QuikSCAT
  - RapidScat has only slightly better NE sigma0 than QuikSCAT
- QuikSCAT resolution cell is roughly 0.5 x 25 km; RapidScat resolution cell is roughly 0.75 x 16 km
  - In certain cases of extreme altitude or pitch, it may be necessary to shorten the RapidScat pulse below 1 ms thus worsening the resolution cell to approx 1.1 x 16 km
  - There will be no impact NE sigma0

Flight System

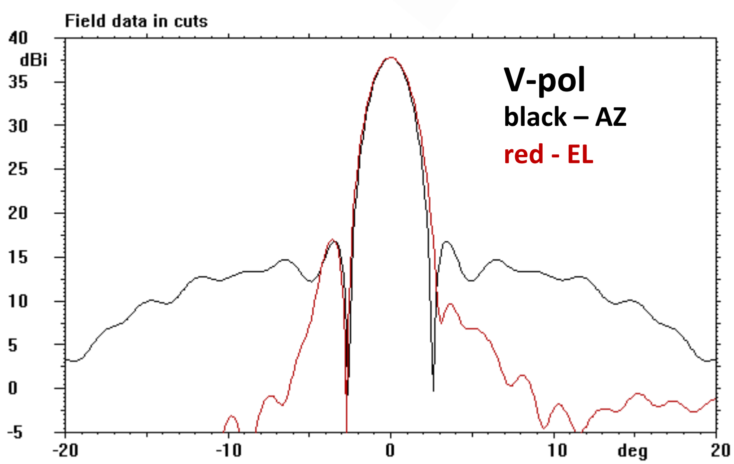


Antenna RF Design

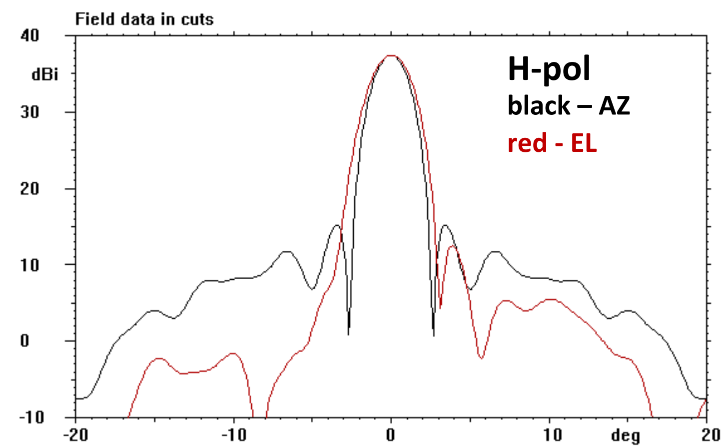
- The HFSS feed model is used to compute the antenna predicted performance
- Antenna patterns are shown below – slight feed interaction seen



	H-pol (Inner Beam)	V-pol (Outer Beam)
Do	37.4dB	37.8dB
BW, AZ	2.09°	2.07°
BW, EL	2.41°	2.19°
Beam EL Angles	-2.74°	+2.76°
Spillover	0.18dB	0.36dB



Cuts centered on +2.75deg



Cuts centered on -2.75deg