ISS-RapidScat Mission, Instrument and Expected Performance


Jet Propulsion Laboratory, California Institute of Technology
IOVWST meeting Hawaii, May 5-8 2013
The ISS Rapidscat instrument consists of legacy SeaWinds Engineering Model hardware plus new power and digital interface and new antenna (0.75 m diameter).
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 $A + B \cos(\theta + \text{phase})$
  - 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.

**Nadir return**

**QuikSCAT timing**

**RapidScat timing**

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RapidScat</th>
<th>QuikSCAT</th>
<th>Unit</th>
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<tr>
<td>Orbital attitude</td>
<td>435</td>
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<td>Antenna size</td>
<td>0.75</td>
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<td>3dB beamwidth – 1 way - elevation</td>
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<td>1.6, 1.4</td>
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<td>3 dB beamwidth – 1 way - azimuth</td>
<td>2.1</td>
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<td>Antenna rotation rate</td>
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<td>Peak radiated power</td>
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<td>46, 54</td>
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<td>Azimuth resolution (inner, outer)</td>
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<td>Ground swath (inner, outer)</td>
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<td>1410,1800</td>
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<td>Data window length</td>
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<td>ms</td>
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<td>NE sigma0 (inner, outer)</td>
<td>-31.8, -30.5</td>
<td>-31.2, -32.2</td>
<td>dB</td>
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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°)
  - 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**
- **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**
- 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**
- Routine science ops

**DECOM/DEORB**
- 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

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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

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Frequency</td>
<td>13.4 GHz</td>
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<tr>
<td>Bandwidth</td>
<td>250 kHz</td>
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<tr>
<td>Pulse Width</td>
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<tr>
<td>Pulse Repetition Interval</td>
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<td>Tx Peak Power</td>
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<td>Polarization</td>
<td>HH and VV</td>
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<td>Spin Rate</td>
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<td>NEσ₀</td>
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<td>Backscatter Resolution</td>
<td>&lt;16 x 2 km</td>
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<td>Swath Width</td>
<td>800-1000 km</td>
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### ISS Accommodation

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Altitude</td>
<td>380 – 430 km</td>
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<tr>
<td>Orbit Inclination</td>
<td>51.6 deg</td>
</tr>
<tr>
<td>Location</td>
<td>Columbus SDX Site</td>
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<tr>
<td>Pointing Control*</td>
<td>+/- 2° (3 sigma)</td>
</tr>
<tr>
<td>Pointing Knowledge</td>
<td>+/- 1° (3 sigma)</td>
</tr>
<tr>
<td>Pointing Stability</td>
<td>Capability of ISS</td>
</tr>
<tr>
<td>Coverage</td>
<td>&gt; 90% global in 48 hours</td>
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</tbody>
</table>

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

ISS pitch angle data HICO RAIDS

- Shuttle Undocking (STS-129)
- MRM2 PAO Undocking
- Dedicated Thruster Firing
- Soyuz TMA-1721S Docking
- Progress M-04M(36P) Docking
- Shuttle Docking (STS-130)
- Transfer Node 3 On SSRMS
- Relocation of Soyuz TMA-1620S

This document has been reviewed and determined not to contain export controlled technical data.
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.
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°); error grows to about 10 km for 6° off nadir, timing error of .066 ms still OK.
- Doppler errors for 3° < 1 kHz, very small; error grows to 3 kHz for 6°.

**Range and Doppler errors using cosine table for 6° off nadir**
• Nominal timing design

Timing solution for 410km altitude 45deg inner, 50.5deg outer and elevation beamwidths
2.4deg 2.2deg respectively
red-Tx inner, cyan-nadir return, blue-Rx inner, black-Tx outer, green-Rx outer
PRI 6ms and 0.4ms extra width
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

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

<table>
<thead>
<tr>
<th>5 m/s</th>
<th>Altitude (km)</th>
<th>Pitch bias (deg)</th>
<th>Speed Error (near swath)</th>
<th>Speed Error (mid swath)</th>
<th>Direction error (near swath)</th>
<th>Direction error (mid swath)</th>
<th>Slice resolution (m)</th>
<th>Swath width (km)</th>
<th>QuikSCAT</th>
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### 7 m/s

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<th>Altitude (km)</th>
<th>Pitch bias (deg)</th>
<th>Speed Error (near swath)</th>
<th>Speed Error (mid swath)</th>
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</tbody>
</table>

### 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

ISS-RapidScat Launch Profile

ISS-RapidScat Integrated Payload (10356200-1)

Columbus Module

Nadir Adapter (10356300-1)
- Mounts to Columbus via FRAM interface

Instrument (10356210-1)
- Mounts to Nadir Adapter via FRAM interface

Nadir Adapter and Instrument mount individually to Dragon Trunk via FRAM interface. Placement into 1, 2 or 2, 3 or 1, 3 is TBD.
Antenna RF Design

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

<table>
<thead>
<tr>
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<th>H-pol (Inner Beam)</th>
<th>V-pol (Outer Beam)</th>
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<tbody>
<tr>
<td>Do</td>
<td>37.4dB</td>
<td>37.8dB</td>
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<tr>
<td>BW, AZ</td>
<td>2.09°</td>
<td>2.07°</td>
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<td>BW, EL</td>
<td>2.41°</td>
<td>2.19°</td>
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<td>Beam EL Angles</td>
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<td>+2.76°</td>
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<tr>
<td>Spillover</td>
<td>0.18dB</td>
<td>0.36dB</td>
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</table>

Field data in cuts

- Cuts centered on +2.75deg
- Cuts centered on -2.75deg

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