International Earth Science Constellation
Mission Operations Working Group
June 2-4, 2015
Aqua/Aura No-Slew Maneuver Results
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Mission Operations Working Group
June 2-4, 2015
Agenda

• **Background**

• **Aqua no-slew results December 19, 2012 to Current**
  - Inclination change
  - RAAN change

• **Aura no-slew results July 12, 2012 to Current**
  - Inclination change
  - RAAN change

• **Aqua comparison of definitive to predicted data**

• **Aura comparison of definitive to predicted data**

• **Conclusions**
Background

- **Performing drag makeup maneuvers (DMU) and risk mitigation maneuvers (RMM) without slewing the spacecraft is operationally desirable**
  - However, a small out-of-plane component is introduced during maneuvers

- **Analysis has shown that performing no-slew DMU maneuvers at the poles minimizes the change in inclination**
  - Change in RAAN can be nominally canceled out by executing maneuvers in pairs at opposing poles
  - Referred to as “mirror pole maneuvers”
  - Introduces small negative effect on frozen orbit (eccentricity and Argument of Perigee)

- **Expect minimal impact to the MLT (hence no impact to the MLT separation between Aqua and the constellation members)**
• **In 2012, Aqua and Aura began demonstrating no-slew maneuver capability**
  
  – Aura has been performing exclusively no-slew maneuvers since December 2012
  
  – Prior to October 2014, Aqua performed slewed maneuvers for DMUs and no-slew maneuvers for RMMs
  
  – Since October 2014, Aqua has performed exclusively no-slew maneuvers

• **Both spacecraft now operate with a hybrid maneuver scheme**
  
  – Maneuvers are nominally performed at alternating “mirror pole” locations
  
  – 1-2 frozen orbit maneuvers per year are added to maintain frozen orbit requirements
  
  – RMM locations are dictated by conjunction timing and geometry
Aqua No-Slew Demonstration Results

- **Aqua has executed 14 no-slew maneuvers since Dec 19, 2012**

- **The standard deviation of the maneuver SMA error for no-slew maneuvers is ± 6.9% difference in the predicted to definitive data**
  - Excludes the first no-slew maneuver
  - Includes both DMU and RMM maneuvers
  - Historical slewed maneuvers had an accuracy of ± 6.5%
  - Prediction accuracy will increase as more data is collected for various burn durations and orbit locations
  - No-slew maneuvers have been sized from 3.0 – 60.0 seconds
Aqua No-Slew ΔInclination Results

Annual Δinclination induced by no-slew maneuvers has been minimal
Aqua No-Slew ΔRAAN Results

Annual ΔRAAN induced by no-slew maneuvers has been minimal
Aura No-Slew Demonstration Results

• **Aura has executed 32 no-slew DMU maneuvers since July 19, 2012**

• **The standard deviation of the maneuver SMA error for no-slew maneuvers is ± 2.1% difference in the predicted to definitive data**
  
  – Excludes the first no-slew maneuver

  – Historical slewed maneuvers had an accuracy of ± 3.1%

  – Current prediction accuracy is now comparable to historical slewed accuracies

  – No-slew maneuvers have been sized from 8.0 – 44.0 seconds
Annual Δinclination induced by no-slew maneuvers has been minimal.
Annual ΔRAAN induced by no-slew maneuvers has been minimal
DEFINITIVE TO PREDICTED DATA COMPARISON
Aqua and Aura utilize similar lifetime simulations for yearly IAM planning and lifetime predictions.

In 2014, three lifetime analysis were performed utilizing the Spring 2014 Schatten solar flux values:
- All Slew – All 2014 DMU’s modeled as slewed maneuvers
- No-Slew – All 2014 DMU’s modeled as no-slew maneuvers
- Mixed Slew – Included in the Summer 2014 lifetime update, DMU’s up to October 2014 model as slewed maneuvers. All maneuvers after which are modeled as slewed

The next slides show a comparison of definitive data, “mixed” prediction, slewed prediction, and no-slew prediction for various orbit parameters.
Aqua Maneuver Predictions

- **Between the Spring 2014 and the Spring 2015 IAM campaigns** Aqua performed substantially more DMUs than predicted in all three lifetime analysis performed in summer 2014

- **Operationally, Aqua maneuvers more frequently due to a desired WRS “buffer” not yet accounted for in the lifetime predictions**

<table>
<thead>
<tr>
<th>Maneuver Type</th>
<th>Definitive Maneuver Count</th>
<th>No-Slew Lifetime Count</th>
<th>All Slew Lifetime Count</th>
<th>Mixed Slew Lifetime Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMM – No-Slew</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DMU - Slewed Frozen Orbit</td>
<td>8</td>
<td>0</td>
<td>6</td>
<td>6(TBR)</td>
</tr>
<tr>
<td>DMU – No-Slew Mirror Pole</td>
<td>5</td>
<td>6(TBR)</td>
<td>0</td>
<td>2(TBR)</td>
</tr>
<tr>
<td>DMU – No-Slew Frozen Orbit</td>
<td>1</td>
<td>(TBR)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15</strong></td>
<td><strong>6</strong></td>
<td><strong>6</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>
Aqua maintains MLT between 13:15 Z and 13:45 Z (13.25 – 13.75 hr)
Further constellation flight constraints reduce the MLT range to 13:35:00 Z – 13:36:30 Z (13.583-13.608 hr)
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Aqua MLT - Zoomed

Note: Lines overlay
Aqua MLT Difference: Definitive - Predicted

All cases closely follow Definitive
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Aqua Inclination

Note: Lines overlay
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Aqua Inclination Difference: Definitive - Predicted

- Large no-slew Frozen Orbit maneuvers in Definitive
- All cases closely follow Definitive
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Aqua RAAN Difference: Definitive - Predicted

All cases closely follow Definitive
Aqua Comparison of Frozen Orbit Parameters

Note: Red box indicates frozen orbit requirements

Argument of Perigee: 90 ± 20 degrees
Eccentricity: .0012 ± .0004

Frozen Orbit Requirements Maintained
- Definitive
- No Slew
- All Slew
- Mixed Slew
• **Aqua and Aura utilize similar lifetime simulations for yearly IAM planning and lifetime predictions**
  – The Summer 2014 prediction used the Spring 2014 Schatten solar flux values

• **The next slides show a comparison of definitive data and no-slew predictions from Summer 2014 for various orbit parameters**
Aura Maneuver Predictions

- **Between the Spring 2014 and the Spring 2015 IAM campaigns** Aqua performed more maneuvers than predicted by the lifetime predictions.

- **Operationally, Aura maneuvers more frequently due to a desired WRS “buffer” not yet accounted for in the lifetime predictions.**

<table>
<thead>
<tr>
<th>Maneuver Type</th>
<th>Definitive Maneuver Count</th>
<th>Summer 2014 Lifetime Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMM – No Slew</td>
<td>(1) *</td>
<td>-</td>
</tr>
<tr>
<td>DMU - Slewed</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DMU – Mirror Pole</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>DMU – Frozen Orbit</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
</table>

*Occurred at Mirror Pole location
Aura maintains a tight bound within its mission requirement of 13:45 Z +/- 15 minutes (13.75 +/- 0.25 hr) and is phased with Aqua at 8.5 minutes +/- .25 minutes.
Aura MLT Zoom

- Definitive
- No Slew Predicted

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Aura MLT Difference: Definitive - Predicted
Monday, June 2 - Thursday, June 4, 2015

Aura Inclination

**Note:** Lines overlay

**Reference Frame:** Mean of J2000 Earth-Equator
Aura Inclination Difference: Definitive - Predicted

-0.00000
-0.00005
-0.00010
-0.00015
-0.00020
-0.00025
-0.00030
-0.00035
-0.00040
-0.00045
-0.00050

Definitive
No Slew Predicted

Note: Lines overlay
Aura RAAN Difference: Definitive - Predicted

The graph shows the Aura RAAN Difference from August 10, 2014, to February 6, 2015. The difference decreases over time, with the predicted values consistently higher than the definitive values, indicating a consistent trend of convergence between the two.
Aura Comparison of Frozen Orbit Parameters

Note: Red box indicates frozen orbit requirements

Argument of Perigee: $90 \pm 20$ degrees
Eccentricity: $0.0012 \pm 0.0004$

Frozen Orbit Requirements Maintained
Definitive
No Slew Predicted
Conclusions

• **Analysis has shown that minimal (2-3) frozen orbit maneuvers per year should be sufficient to maintain long-term frozen orbit requirements**
  – Frozen orbit adequately maintained in 2014

• **±2 seconds/year error goal for MLT prediction was achieved for 2014 using post-INc predictions**
  – Each IAM series will “reset” Aqua and Aura’s MLT

• **The under prediction of the drag environment during 2014 has had some impact on MLT and frozen orbit prediction accuracy due to the substantial increase in number of maneuvers executed**
Questions?

- **Future no-slew DMU performance will continue to become more accurate as data is collected**

- **Aqua’s long-term prediction can be found on CCS**
  - Long-term plan based on hybrid maneuver scheme

- **Please contact us with any comments or questions at:**
  esmo-eos-fds@lists.nasa.gov
BACKUP
Future Work

• **Re-evaluate the hybrid maneuver scheme with an updated Schatten solar flux prediction**
  – Include studies utilizing the plus/minus mean nominal and early/late Schatten predictions for a fuller understanding of the drag effects on the hybrid maneuver scheme

• **Consider using INC and RAAN change to aid in long-term MLT maintenance**
  – Could potentially execute DMUs at nodes to get MLT change to eliminate some future IAMs
  – Could have minor fuel saving potential
Future Work

- **Look at other maneuver schemes for no-slew e.g. Split each maneuver into a pair performed at each pole**
  - This would allow time between maneuvers to be more tightly controlled, keep mirror pole maneuver sizes consistent, reduce concern of a large amount of time between maneuvers during low drag

- **Further improvements to lifetime simulation**
  - Lifetime simulation currently uses a static coefficient of drag \((C_d)\). Accuracy could be improved by incorporating dynamic modeling
  - Update script to target maneuvers earlier to match reality of more conservative maneuvers during high drag
### Aura Demonstration Results

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Date</th>
<th>Maneuver Duration (seconds)</th>
<th>Delta-INC (deg)</th>
<th>Delta-RAAN (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aura DMU 43*</td>
<td>Jul 19, 2012</td>
<td>8.00</td>
<td>8.82E-05</td>
<td>-3.11E-05</td>
</tr>
<tr>
<td>Aura DMU 46</td>
<td>Oct 04, 2012</td>
<td>8.00</td>
<td>1.06E-04</td>
<td>-2.91E-05</td>
</tr>
<tr>
<td>Aura DMU 50</td>
<td>Dec 20, 2012</td>
<td>14.50</td>
<td>2.10E-05</td>
<td>-8.42E-05</td>
</tr>
<tr>
<td>Aura DMU 51</td>
<td>Jan 16, 2013</td>
<td>33.00</td>
<td>-2.42E-04</td>
<td>3.37E-05</td>
</tr>
<tr>
<td>Aura DMU 52</td>
<td>Apr 03, 2013</td>
<td>38.50</td>
<td>-1.91E-05</td>
<td>-3.57E-04</td>
</tr>
<tr>
<td>Aura DMU 53</td>
<td>May 22, 2013</td>
<td>25.00</td>
<td>5.60E-05</td>
<td>1.86E-04</td>
</tr>
<tr>
<td>Aura DMU 54</td>
<td>Jun 26, 2013</td>
<td>17.50</td>
<td>-2.53E-05</td>
<td>-2.75E-05</td>
</tr>
<tr>
<td>Aura DMU 55</td>
<td>Aug 01, 2013</td>
<td>21.50</td>
<td>-1.62E-06</td>
<td>-7.74E-05</td>
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<tr>
<td>Aura DMU 56</td>
<td>Sep 02, 2013</td>
<td>17.75</td>
<td>1.87E-05</td>
<td>9.07E-05</td>
</tr>
</tbody>
</table>

*This maneuver was planned based on slewed data. Subsequent maneuvers used only no-slew data.
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<th>Delta-INC</th>
<th>Delta-RAAN</th>
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<tbody>
<tr>
<td>Aura DMU 57</td>
<td>Oct 09, 2013</td>
<td>27.50</td>
<td>9.83E-07</td>
<td>-1.75E-04</td>
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<tr>
<td>Aura DMU 58</td>
<td>Oct 31, 2013</td>
<td>25.50</td>
<td>5.00E-05</td>
<td>1.11E-04</td>
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<tr>
<td>Aura DMU 59</td>
<td>Nov 15, 2013</td>
<td>19.50</td>
<td>-1.55E-05</td>
<td>-1.61E-04</td>
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<tr>
<td>Aura DMU 60</td>
<td>Dec 05, 2013</td>
<td>15.00</td>
<td>3.52E-05</td>
<td>4.05E-05</td>
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<tr>
<td>Aura DMU 61</td>
<td>Dec 19, 2013</td>
<td>34.50</td>
<td>1.98E-04</td>
<td>-1.18E-04</td>
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<tr>
<td>Aura DMU 62</td>
<td>Jan 16, 2014</td>
<td>26.25</td>
<td>1.54E-04</td>
<td>-5.47E-05</td>
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<td>Aura DMU 63</td>
<td>Feb 06, 2014</td>
<td>23.75</td>
<td>-1.50E-04</td>
<td>-2.26E-05</td>
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<tr>
<td>Aura DMU 64</td>
<td>Feb 26, 2014</td>
<td>34.00</td>
<td>1.02E-04</td>
<td>-2.03E-04</td>
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<tr>
<td>Aura DMU 65</td>
<td>Apr 17, 2014</td>
<td>25.00</td>
<td>1.67E-05</td>
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<tr>
<td>Aura DMU 66</td>
<td>May 07, 2014</td>
<td>23.50</td>
<td>-4.68E-06</td>
<td>-9.75E-05</td>
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<tr>
<td>Aura DMU 67*</td>
<td>May 15, 2014</td>
<td>8.00</td>
<td>-8.38E-05</td>
<td>-2.66E-05</td>
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### Aura Demonstration Results

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Date</th>
<th>Manuever Duration (seconds)</th>
<th>Delta-INC (deg)</th>
<th>Delta-RAAN (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aura DMU 68</td>
<td>Jun 19, 2014</td>
<td>23.25</td>
<td>-1.56E-04</td>
<td>-1.67E-05</td>
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<tr>
<td>Aura DMU 69</td>
<td>Jul 24, 2014</td>
<td>21.00</td>
<td>1.28E-05</td>
<td>1.18E-04</td>
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<tr>
<td>Aura RMM 70</td>
<td>Aug 29, 2014</td>
<td>21.00</td>
<td>1.37E-05</td>
<td>-1.18E-04</td>
</tr>
<tr>
<td>Aura DMU 71</td>
<td>Sep 24, 2014</td>
<td>31.50</td>
<td>1.39E-05</td>
<td>1.66E-04</td>
</tr>
<tr>
<td>Aura DMU 72</td>
<td>Oct 10, 2014</td>
<td>19.25</td>
<td>2.20E-05</td>
<td>-4.01E-05</td>
</tr>
<tr>
<td>Aura DMU 73</td>
<td>Oct 30, 2014</td>
<td>44.00</td>
<td>-2.26E-05</td>
<td>2.81E-04</td>
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<tr>
<td>Aura DMU 74</td>
<td>Nov 25, 2014</td>
<td>36.50</td>
<td>5.89E-05</td>
<td>-4.32E-04</td>
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<tr>
<td>Aura DMU 75</td>
<td>Dec 11, 2014</td>
<td>35.00</td>
<td>-1.46E-04</td>
<td>1.61E-04</td>
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<tr>
<td>Aura DMU 76</td>
<td>Jan 06, 2015</td>
<td>39.00</td>
<td>3.72E-06</td>
<td>1.72E-04</td>
</tr>
</tbody>
</table>

**Total Inclination change since Spring 2014 IAM Series: TBR degrees**

*DMU 67 was a demonstration burn for FOT RMM (QDAM) capabilities*
# Aura Demonstration Results

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Date</th>
<th>Maneuver Duration (seconds)</th>
<th>Delta-INC</th>
<th>Delta-RAAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aura DMU 77</td>
<td>Jan 28, 2015</td>
<td>22.000</td>
<td>-1.11E-05</td>
<td>-2.32E-04</td>
</tr>
<tr>
<td>Aura DMU 78</td>
<td>Feb 20, 2015</td>
<td>33.750</td>
<td>-2.93E-04</td>
<td>-1.56E-04</td>
</tr>
</tbody>
</table>
### Aqua Demonstration Results

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Date</th>
<th>Maneuver Duration (seconds)</th>
<th>Delta-INC (deg)</th>
<th>Delta-RAAN (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqua DMU 66*</td>
<td>Dec 19, 2012</td>
<td>3.00</td>
<td>-3.72E-05</td>
<td>2.15E-05</td>
</tr>
<tr>
<td>Aqua DMU 67</td>
<td>Jan 25, 2013</td>
<td>22.50</td>
<td>6.73E-05</td>
<td>1.15E-04</td>
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<tr>
<td>Aqua DMU 68</td>
<td>Feb 14, 2013</td>
<td>30.75</td>
<td>-2.26E-05</td>
<td>-3.10E-05</td>
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<tr>
<td>Aqua DMU 69 - RMM</td>
<td>Mar 10, 2013</td>
<td>15.75</td>
<td>3.05E-05</td>
<td>1.84E-04</td>
</tr>
<tr>
<td>Aqua DMU 70 - RMM</td>
<td>Mar 23, 2013</td>
<td>21.50</td>
<td>1.38E-04</td>
<td>2.74E-05</td>
</tr>
<tr>
<td>Aqua DMU 76- RMM</td>
<td>Oct 25, 2013</td>
<td>27.50</td>
<td>2.67E-04</td>
<td>2.11E-04</td>
</tr>
<tr>
<td>Aqua DMU 77 - RMM</td>
<td>Nov 28, 2013</td>
<td>19.50</td>
<td>-1.15E-05</td>
<td>4.12E-05</td>
</tr>
<tr>
<td>Aqua DMU 90 - RMM</td>
<td>Oct 21, 2014</td>
<td>31.00</td>
<td>1.23E-04</td>
<td>1.28E-04</td>
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<tr>
<td>Aqua DMU 91</td>
<td>Nov 12, 2014</td>
<td>48.50</td>
<td>-1.07E-04</td>
<td>-1.41E-04</td>
</tr>
<tr>
<td>Aqua DMU 92</td>
<td>Dec 03, 2014</td>
<td>60.00</td>
<td>3.70E-05</td>
<td>2.61E-04</td>
</tr>
</tbody>
</table>

*This maneuver was planned based on slewed data. Subsequent maneuvers used only no-slew data.*
## Aqua Demonstration Results

<table>
<thead>
<tr>
<th>Maneuver</th>
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<th>Delta-RAAN (deg)</th>
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</thead>
<tbody>
<tr>
<td>Aqua DMU 93</td>
<td>Dec 17, 2014</td>
<td>31.75</td>
<td>-2.03E-04</td>
<td>-5.30E-05</td>
</tr>
<tr>
<td>Aqua DMU 94</td>
<td>Jan 07, 2015</td>
<td>53.00</td>
<td>-6.09E-05</td>
<td>3.54E-04</td>
</tr>
<tr>
<td>Aqua DMU 95</td>
<td>Feb 04, 2015</td>
<td>24.25</td>
<td>-4.25E-05</td>
<td>7.26E-05</td>
</tr>
<tr>
<td>Aqua DMU 96</td>
<td>Feb 26, 2015</td>
<td>46.25</td>
<td>-1.83E-04</td>
<td>1.74E-04</td>
</tr>
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</table>