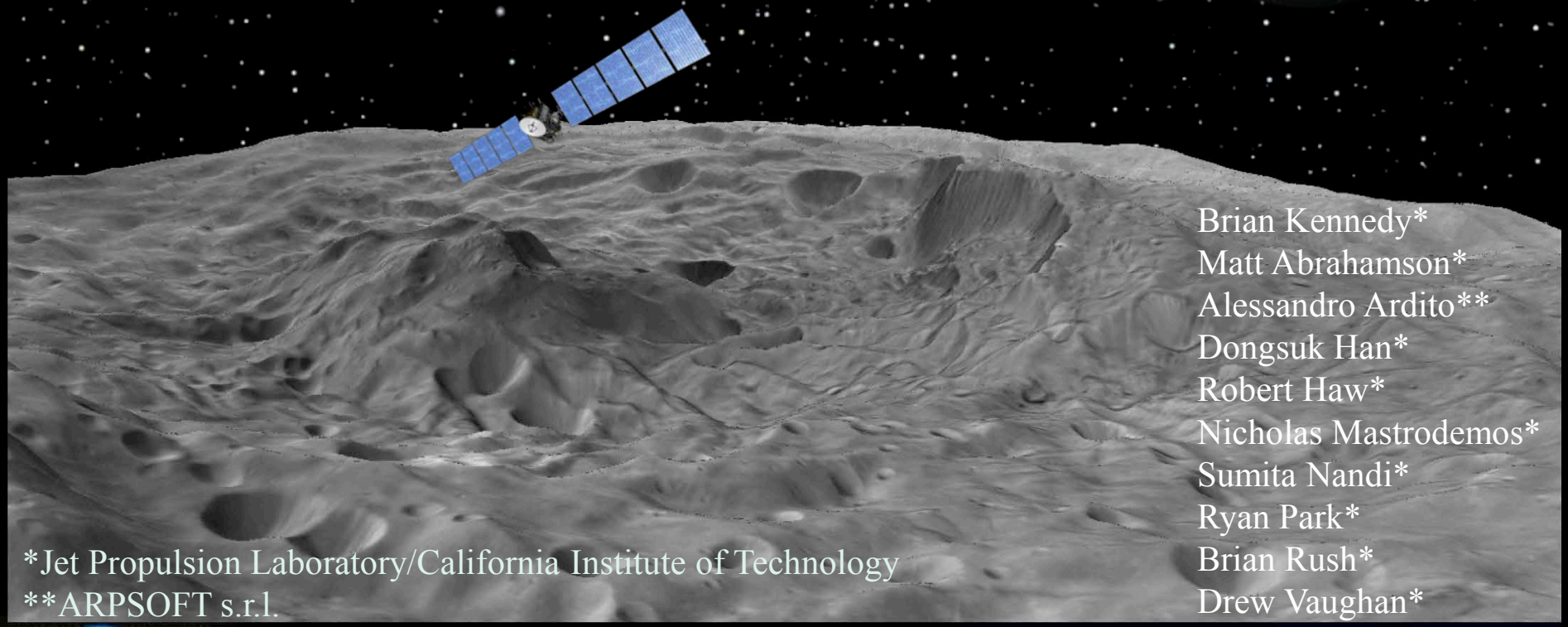
23rd AAS/AIAA Spaceflight Mechanics Meeting

Dawn Orbit Determination Team: Trajectory and Gravity Prediction Performance During Vesta Science Phases.



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Agenda

- Overview
- Trajectory Prediction
  - Approach to Vesta
  - Survey and the High-altitude Mapping orbits
  - Low-altitude Mapping orbit
- Gravity Prediction
  - Designing Survey
  - Designing the High-altitude orbit
  - Designing the Low-altitude orbit
  - How the predictions stack up
- Concluding remarks and the Ceres mission

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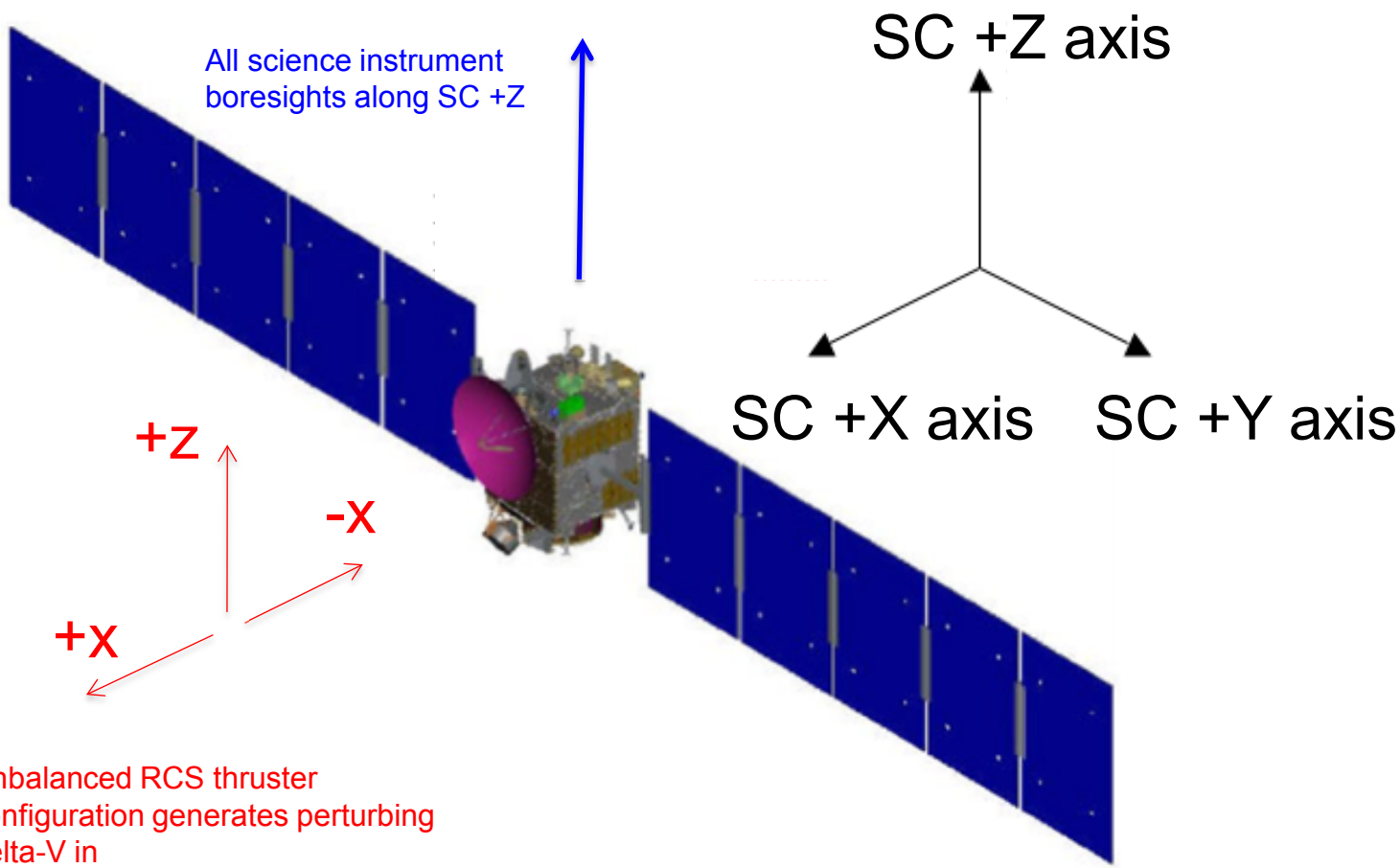
Spacecraft



Unbalanced RCS thruster configuration generates perturbing delta-V in
SC +X, -X and +Z directions only
(no delta-V along SC Y-axis)

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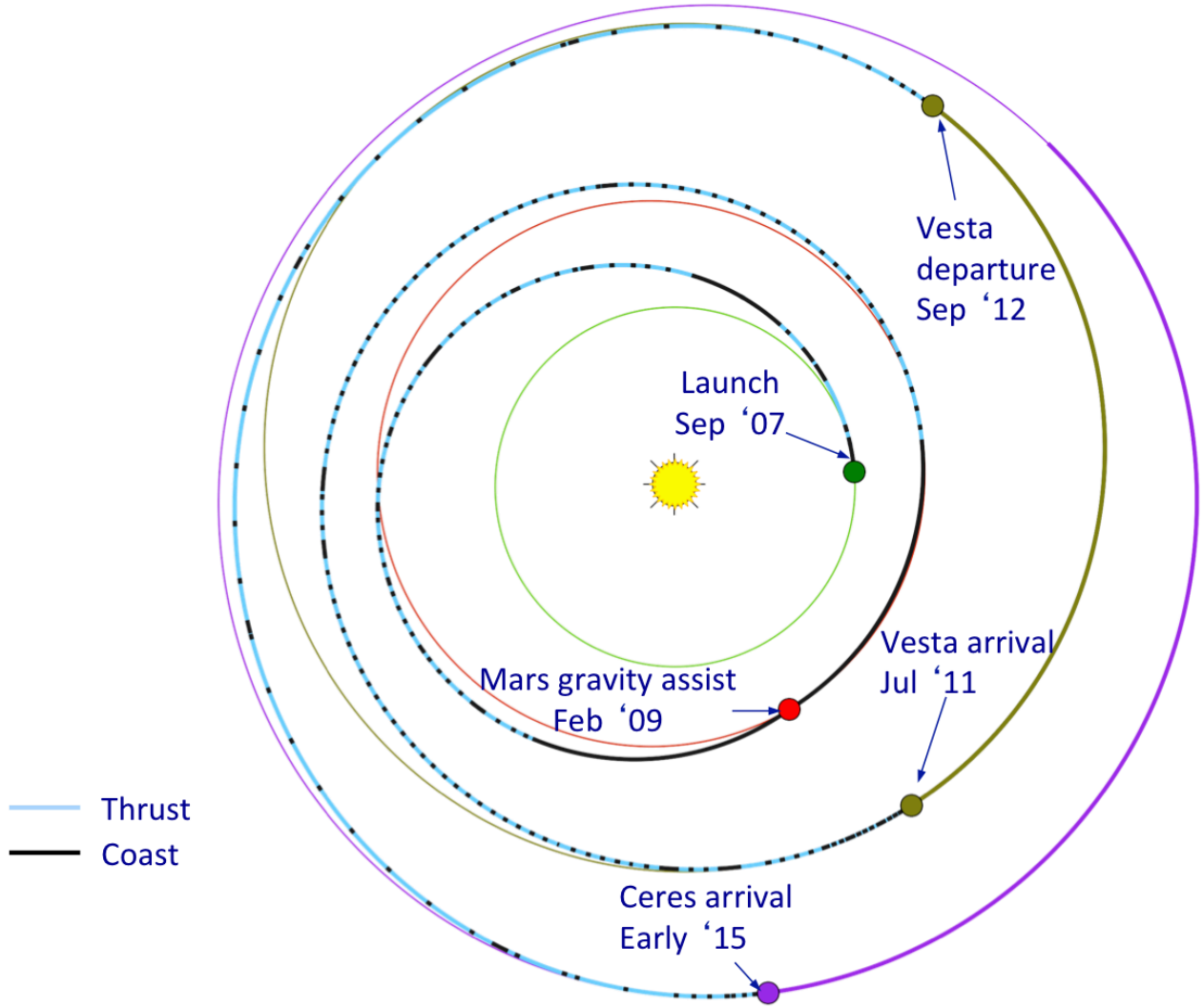
Dawn's first target: Vesta

- The asteroid Vesta is a massive, asymmetrical, highly oblate asteroid, located in the main asteroid belt.
  - Orbital period: 3.63 years
  - Rotational rate: 5.342 hours
  - GM: 17.28838 km^3/sec^2

Image credit: dawn.jpl.nasa.gov

Mission Trajectory



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Science phases

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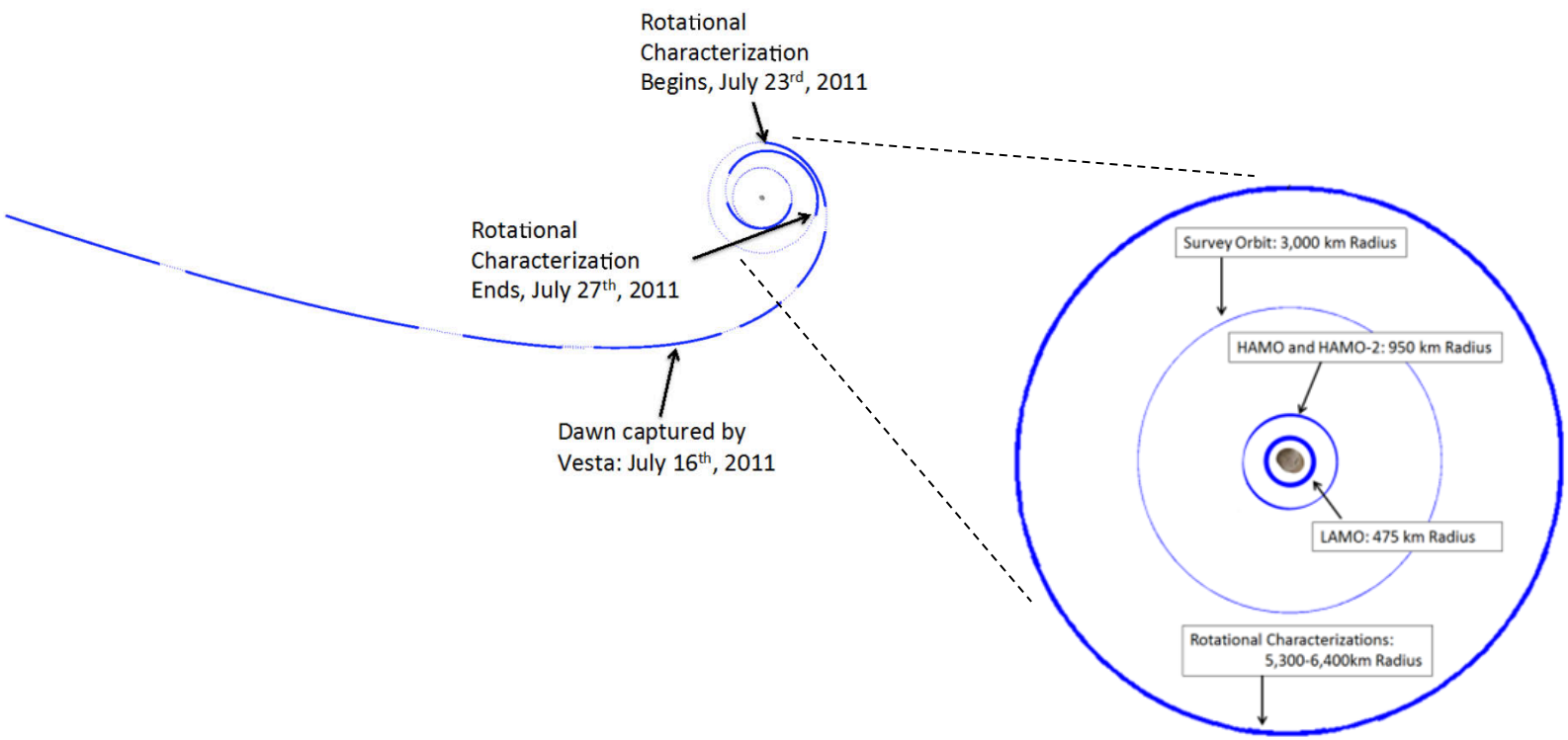
Phase	Distance from Vesta	Orbit period	Dates of phase
Approach	1,800,000 km – 3000 km	N/A	April, 2011 – August 2nd, 2011
Rotational Characterizations (RC1-3)	6000 km down to 4000 km	N/A	Late July, 2011
Survey	3000 km	2.5 days	August, 2011
High Altitude Mapping Orbit (HAMO)	950 km	12 hours	October, 2011
Low Altitude Mapping Orbit (LAMO)	47 5km	4 hours	December 2011 –May, 2012
High Altitude Mapping Orbit-2 (HAMO-2)	950 km	12 hours	June, 2012 – July, 2012

Approach to Science polar orbits



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Trajectory Predictions

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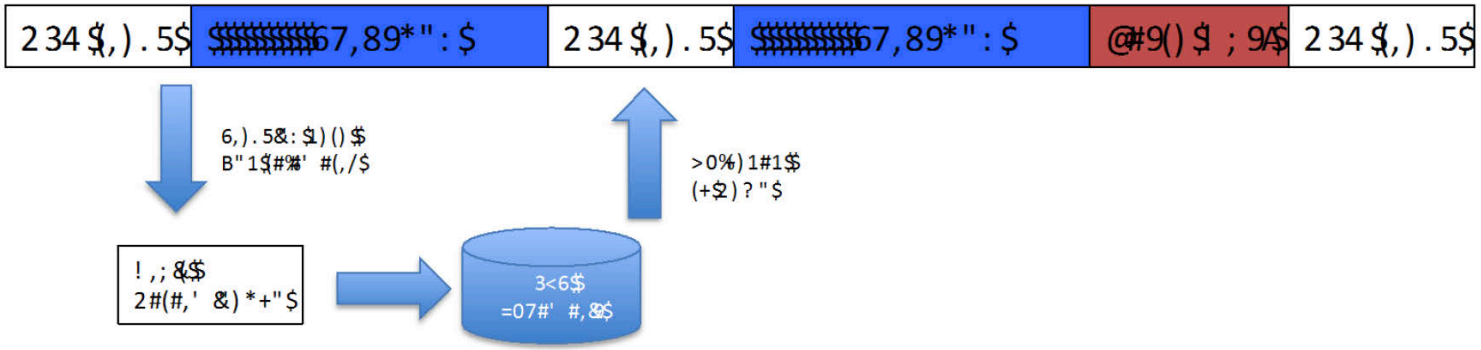
- During Vesta operations, the OD team provided trajectory predictions to the spacecraft team to direct pointing of science instruments at Vesta.
- Key forces:
  - Low thrust from IPS
  - Delta-V from RCS during RWA momentum desaturation
  - Gravitational pull from Vesta (GM and harmonics)
- During the Approach phase, the driver for pointing performance was the VIR instrument.
  - VIR had narrow IR slit scans that were tied to the OD team's predictive capability.
- During Survey, HAMO and HAMO-2, the pointing updates were needed to meet 2º, 1º, and 0.5º FC pointing requirements, respectively.
- During LAMO, the driver for pointing was the ACS.
  - ACS team was concerned with gravity gradient torque.

Approach pointing

- There were 8 VIR observations performed in Approach.
- Pointing performance was complicated by delivery errors due to IPS low thrust arcs, and relatively sparse communication passes used for orbit determination and on-board ephemeris update.
- In some cases, the best ephemeris had two thrust-arcs of error built in before it was first used in controlling the pointing to Vesta. This error could be quite large for thrust arcs that lasted a week.

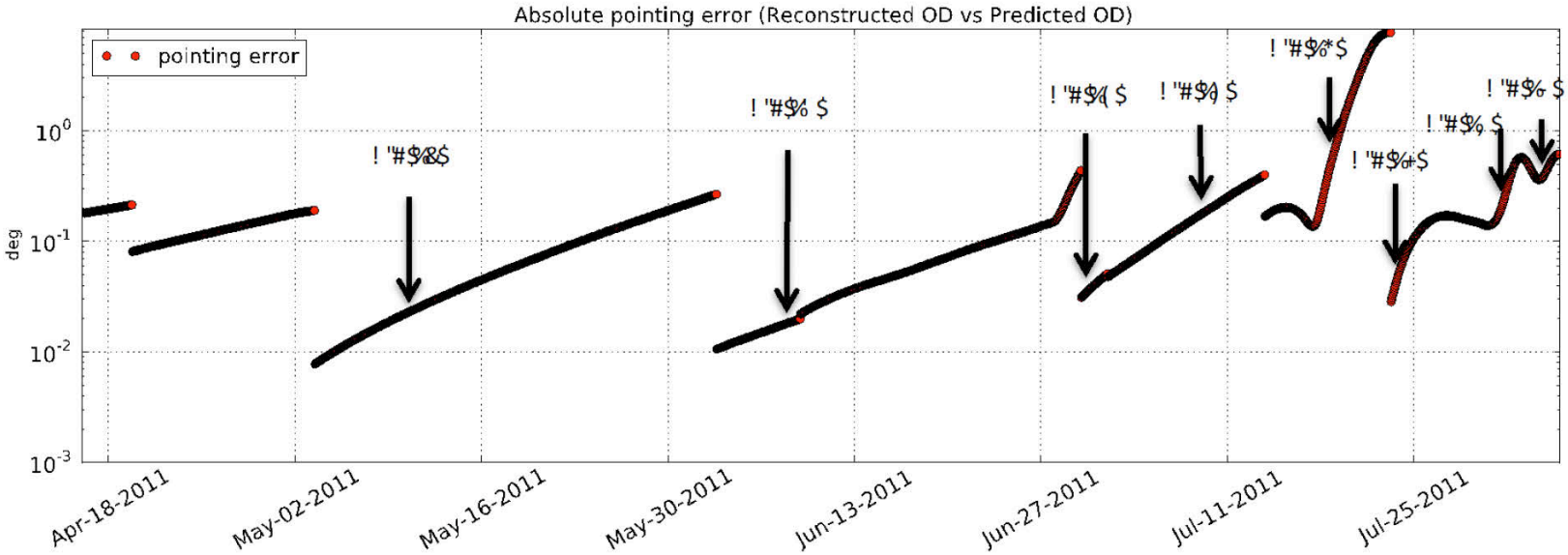


Approach Pointing

- VIR scan widths were based on 2-sigma pointing capabilities assuming latest available ephemeris was onboard.
- 1-sigma pointing errors only occurred twice, and 2-sigma pointing errors never occurred.

Date of VIR observation	Distance to Vesta (km)	Predicted pointing using ephemeris from thrust sequence design (mrad, 1-□)	Predicted pointing using ephemeris from late-as-possible update (mrad, 1-□)	Date of DCO for late update	Actual pointing error (mrad)
5/10/2011	1,018,000	1.46	0.29	4/27/2011	***0.39***
6/8/2011	363,000	2.38	0.84	6/1/2011	0.33
6/30/2011	102,000	2.59	2.59	6/24/2011	0.56
7/9/2011	42,000	14.22	4.61	6/30/2011	3.44
7/18/2011	12,400	8.34	8.34	7/13/2011	***9.35***
7/23/2011	5,600	77.03	18.70	7/19/2011	1.02
7/31/2011	4,400	187.70	6.34	7/24/2011	2.58
8/4/2011	3,000	335.59	39.8	7/28/2011	7.89

Approach Pointing



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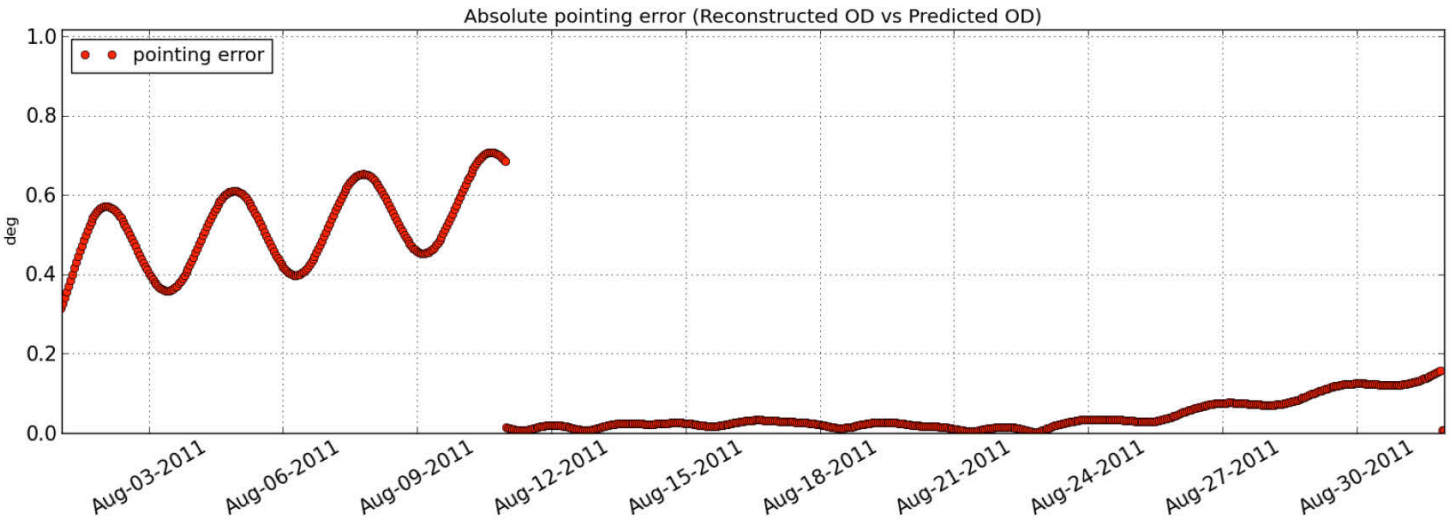
Survey Pointing

- Survey pointing performance was unremarkable, and the 2º pointing requirement was easily met with one update over one month.



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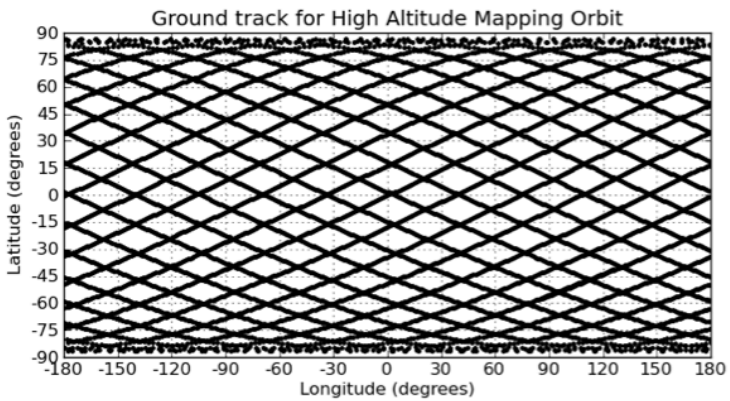
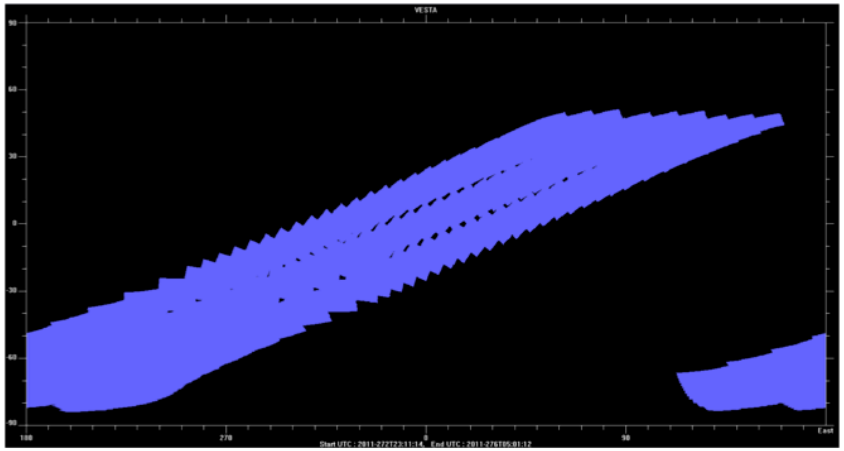
HAMO and HAMO-2 Pointing

- HAMO pointing performance was required to be 1º.
- For HAMO-2, this was tightened to 0.5º to reduce risk of opening up large gaps in the interlocking image coverage provided by the 10-orbit, 5-day repeat groundtrack.





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HAMO and HAMO-2 pointing

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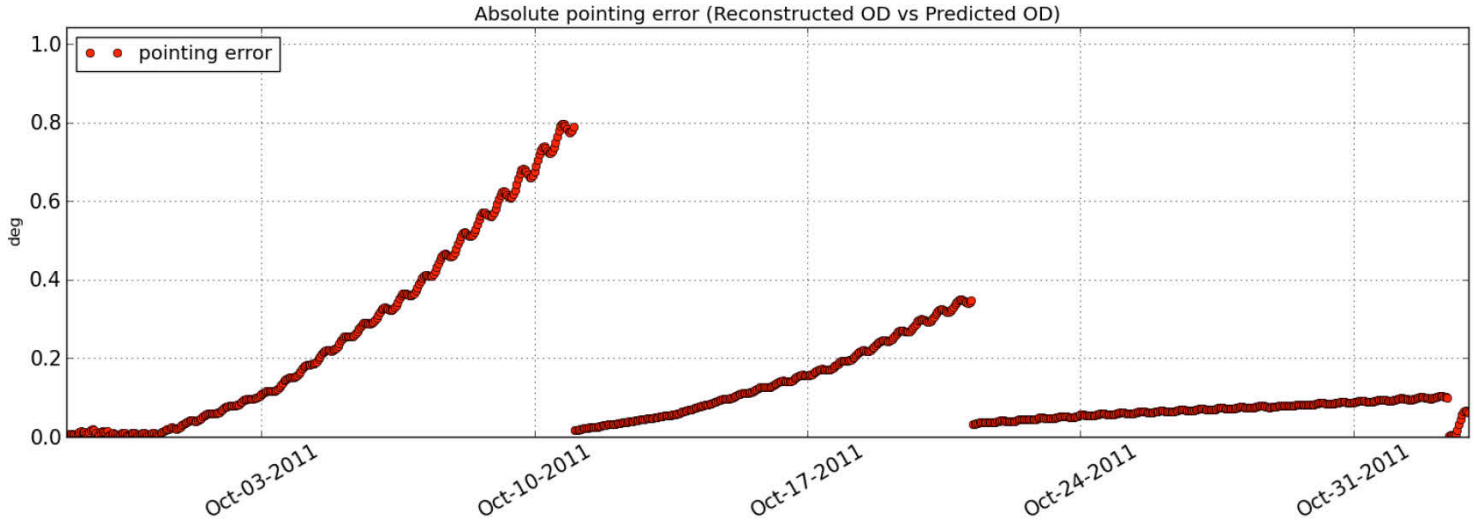
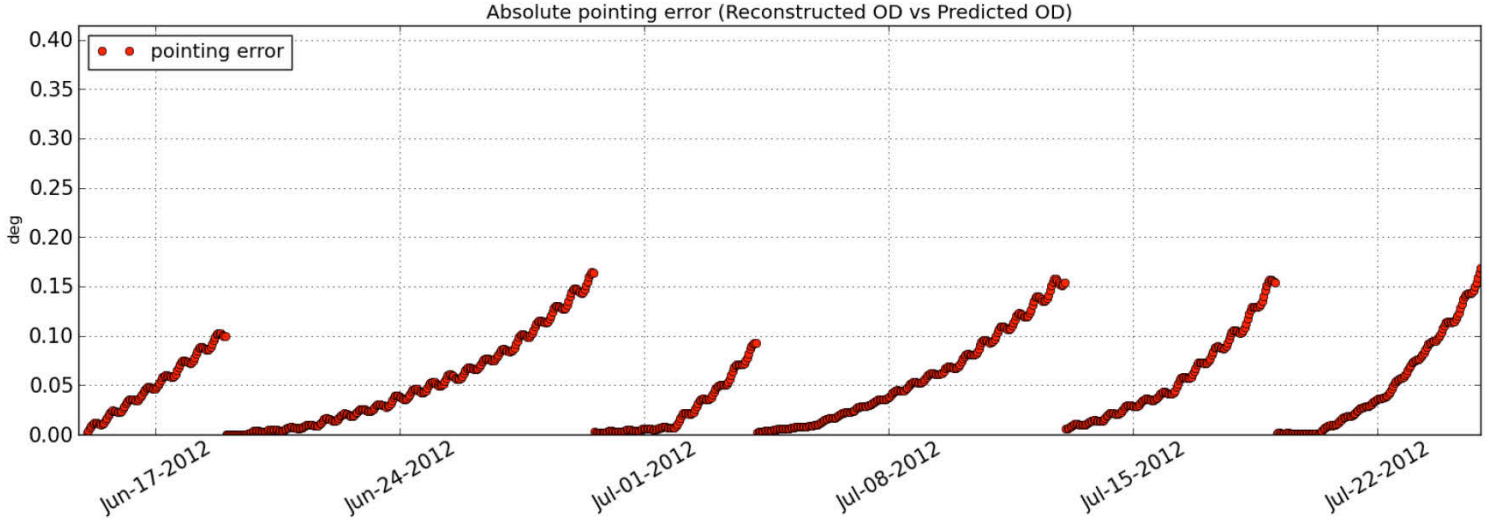
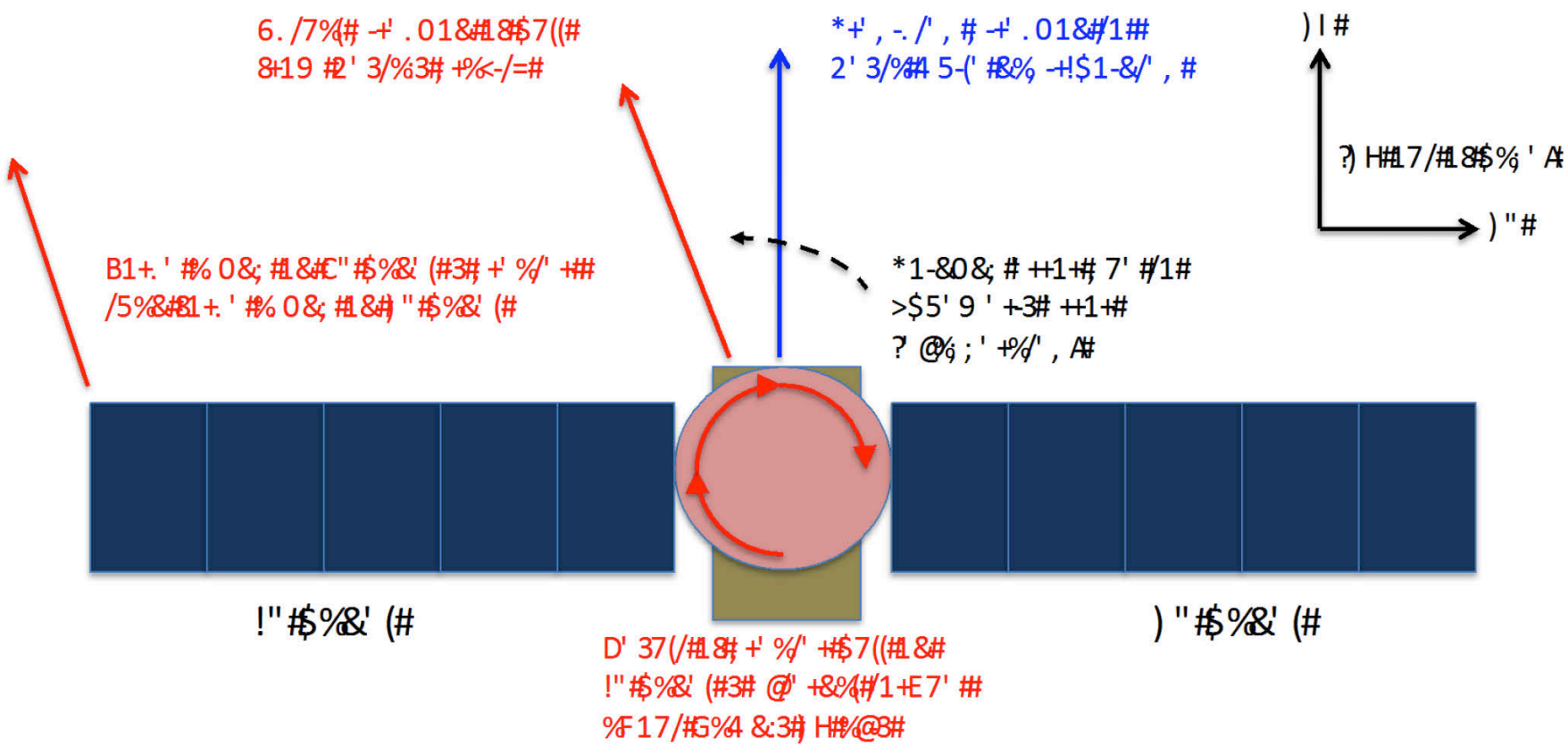




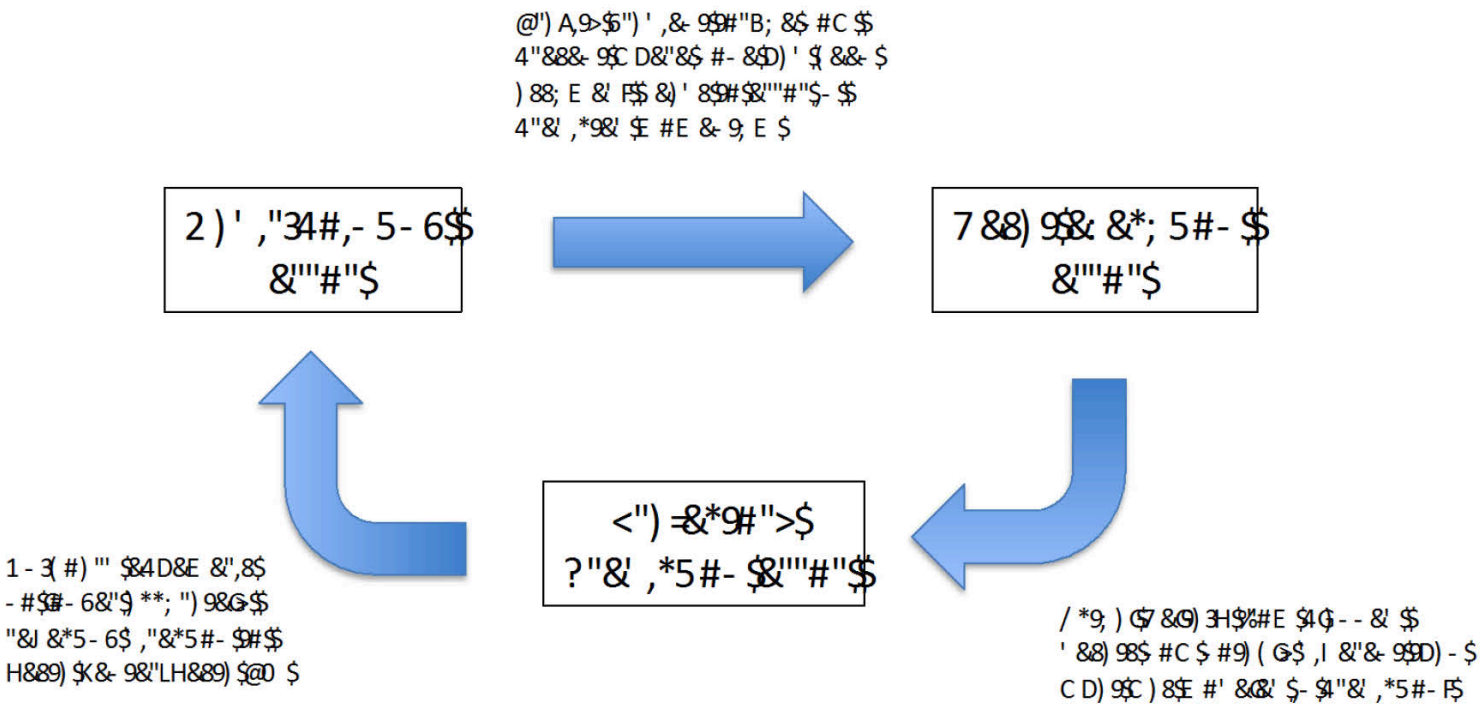
Gravity Gradients at LAMO

- The key concern at the LAMO altitude was the effect of gravity gradient torque.



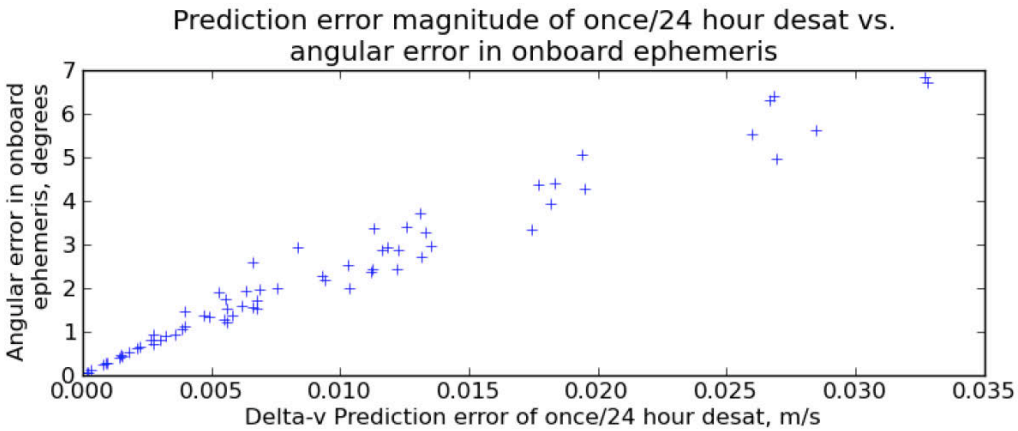
Error feedbacks in LAMO

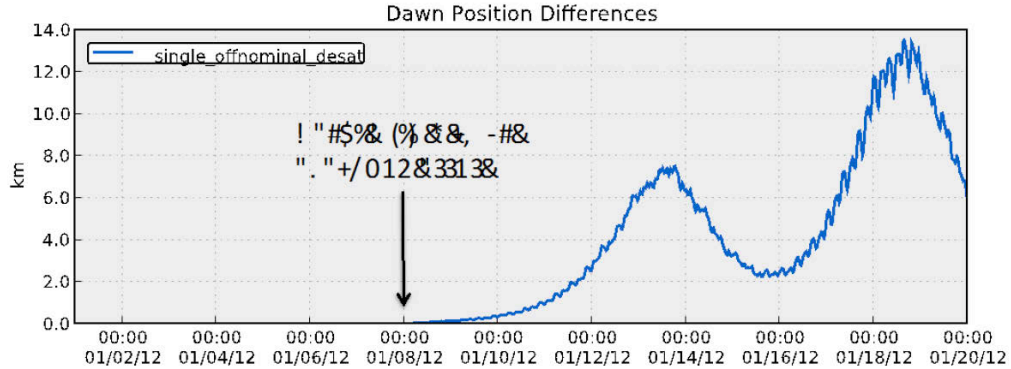
- Feedback caused by trajectory errors could lead to a build up of further error due to torque build up and desat execution error.



LAMO Pointing

- Effects of ephemeris error on gravity gradient torque were studied assuming 1 desat/24 hours.
- 1 cm/s desat errors were to be avoided, since these can possibly contribute 0.85º of additional pointing error in five days.
- An update criteria of 0.4º was used to support the operational desat frequency of 1 desat/3 days.





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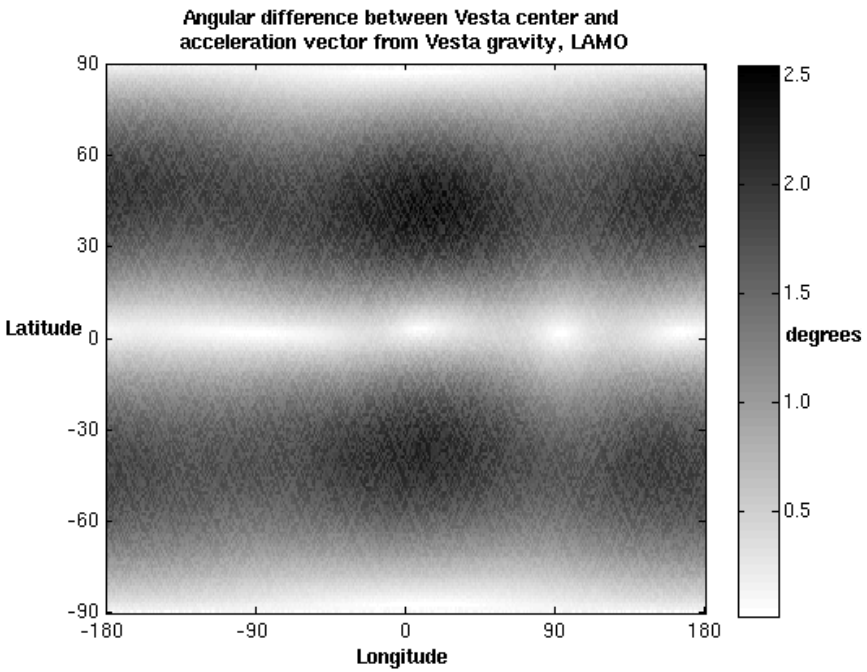
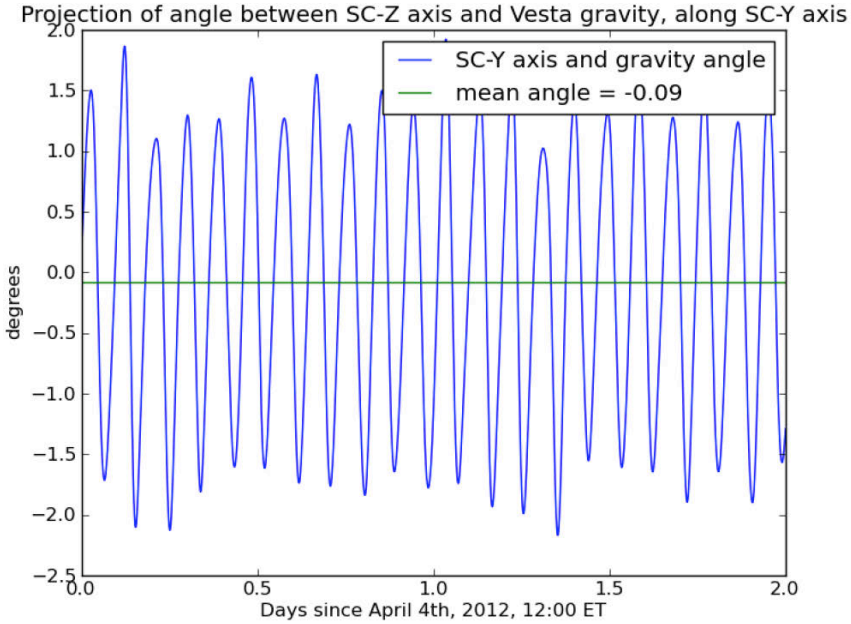
Oblateness at LAMO altitude

- Interestingly, the Vesta oblateness can also be a source of gradient torque, because the direction of the net pull of Vesta gravity is often > 2º from the direction to the assumed Vesta Center/GM.
- Fortunately, while this presents an obvious time varying angular bias, this does not present a persistant torque bias.





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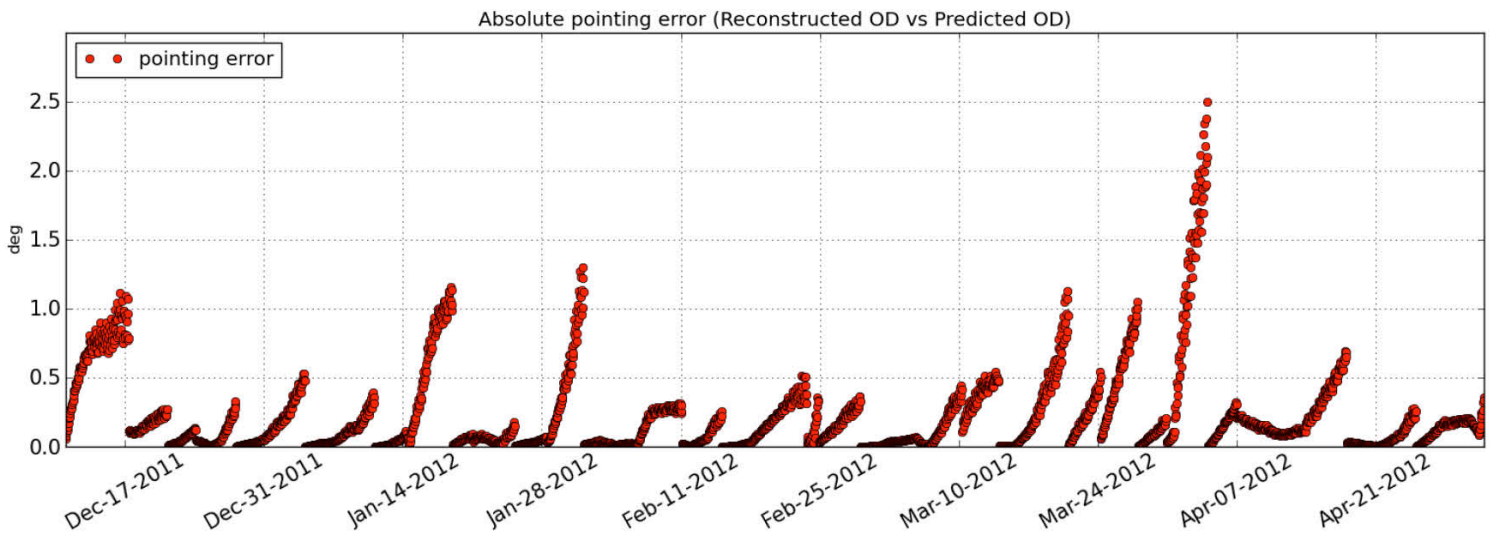
LAMO pointing

Date	Reason that pointing error exceeded 0.4º
12/17/2011	Team still finishing transition from HAMO-to-LAMO transfer and had not yet settled into LAMO operations schedule
1/19/2012	Safing event on January 14th
1/31/2012	Large desat occurred on January 28th, along with execution error from IPS OMM
3/21/2012	Large desat on March 17th
3/29/2012	Large desat on March 24th
4/5/2012	On-board ephemeris lacked appropriate attitude model during OMM due to OD team procedural error (identified and corrected)
4/19/2012	Large desat on April 14th



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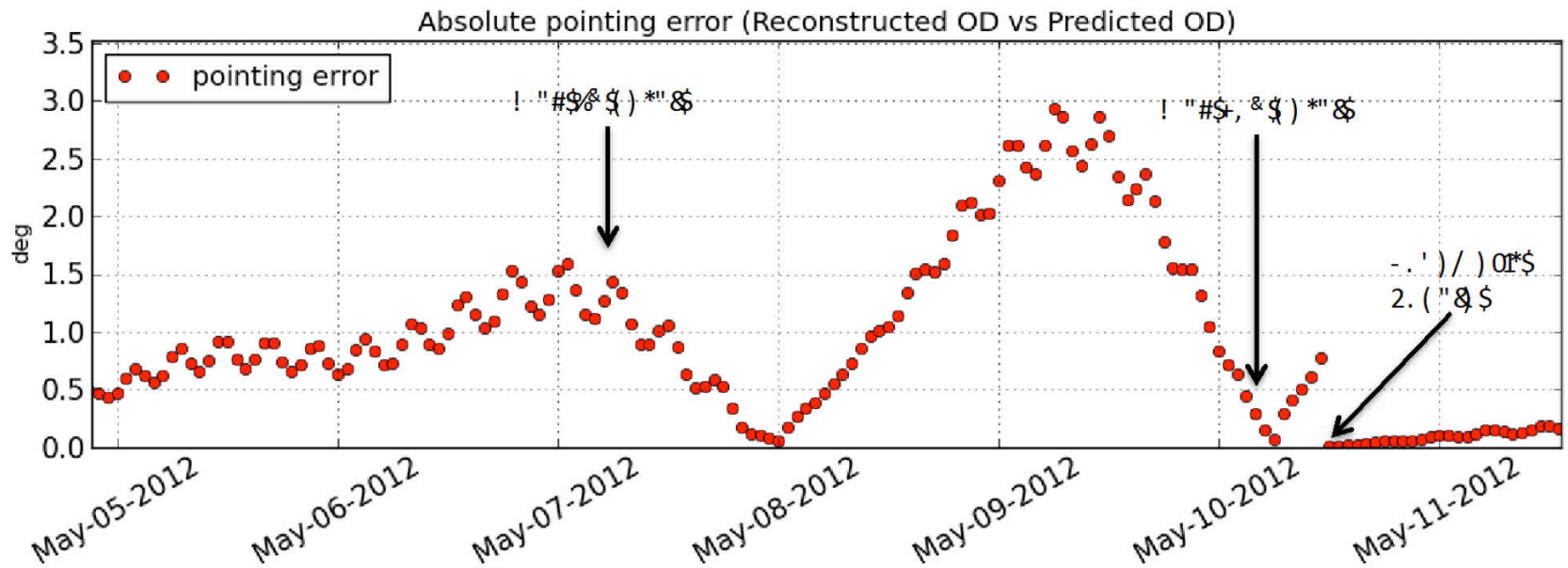
Gradient torque

- Following LAMO, during the transfer to HAMO-2, there was one instance where gradient torque was an issue.
- An average 1.5º pointing error during a quiet three-day coast in the Vesta resonance resulted in a large torque build up.
  - The wheel speeds during the turn to Earth were noteworthy.
- This was understood as being an error in the desat placement requirements.



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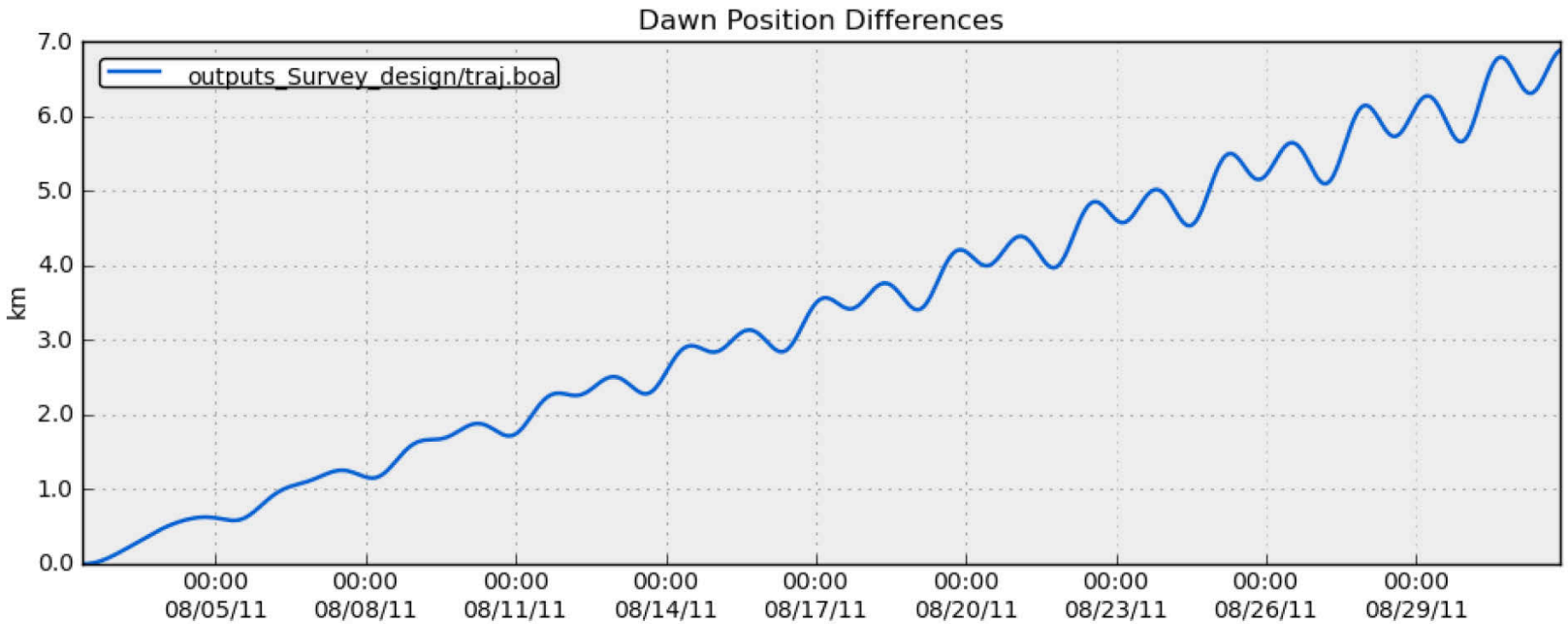
Gravity Predictions

- During Vesta operations, the OD team provided three estimates of the Vesta gravity to the Mission Design team.
- For the Survey orbit design work that began on 7/21, the OD team delivered an estimated GM, but an assumed an 8x8 field based on homogenous shape models established by Hubble imagery.
- For the HAMO orbit design work that began on 8/7, the OD team delivered an estimated GM and an estimated field.
- For the LAMO orbit design work that began on 10/17, the OD team delivered an estimated GM and an estimated field.

Gravity for Survey Design

- Performance of the Survey field is assessed by simply comparing Survey-altitude propagations of the design field and the OD team's best estimate of the field from LAMO.
- Even using a pre-Vesta gravity field, the estimate for GM from a higher altitude was enough to provide a Survey design that would only be in error by 7 km over one month.



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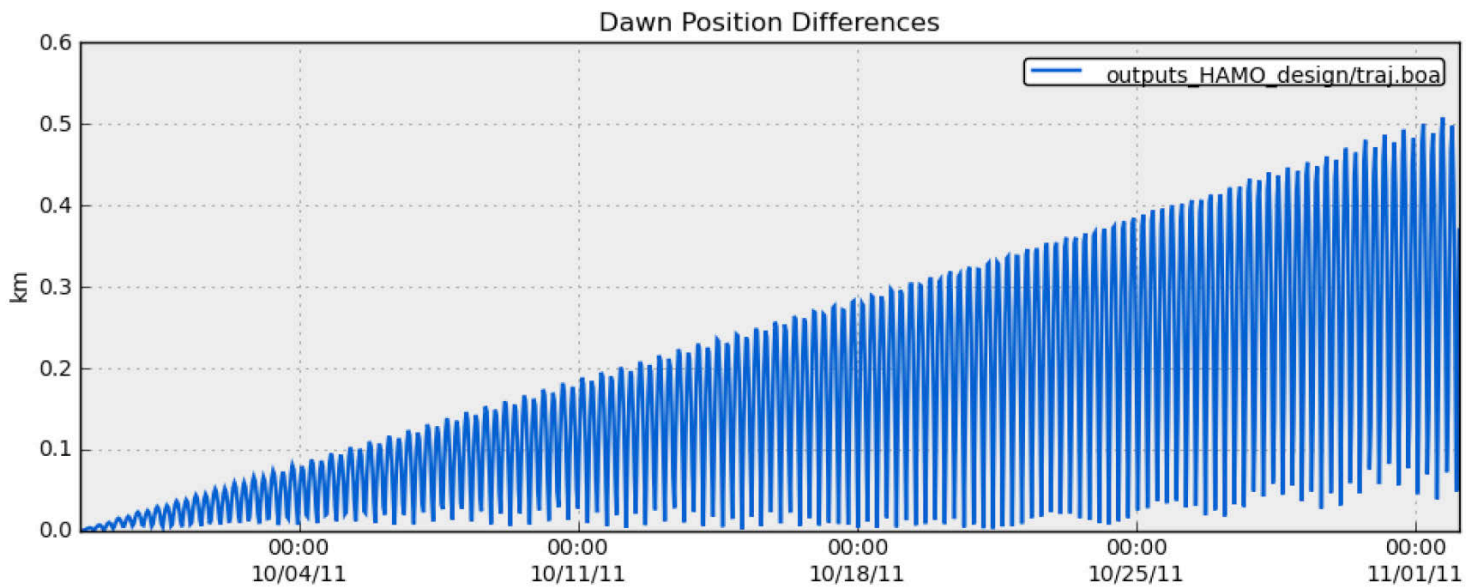
Gravity for HAMO Design

- Performance of the HAMO design field is assessed by simply comparing HAMO-altitude propagations of the design field and the OD team's best estimate of the field from LAMO.
- The estimate of GM and the gravity field from Survey altitude provided a good estimate for gravity at the HAMO altitude, with only a 0.6 km error over one month.



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Gravity for LAMO Design

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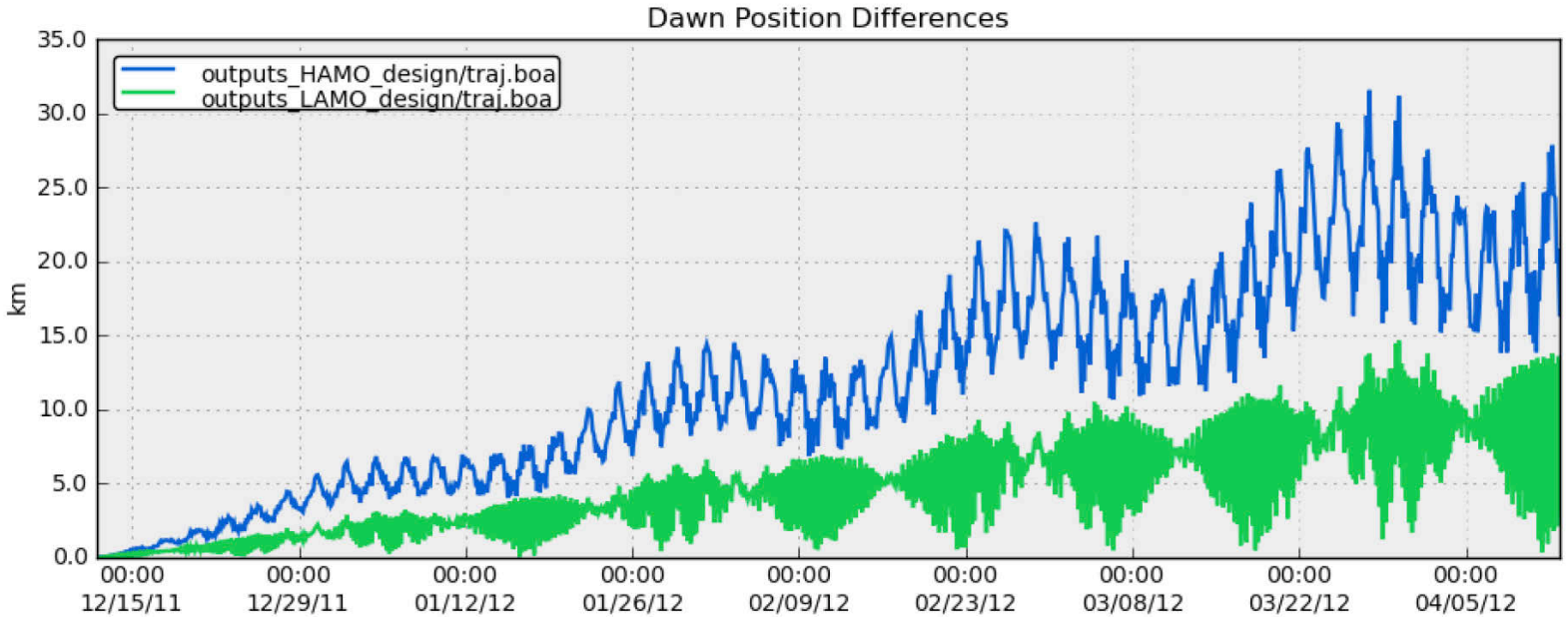
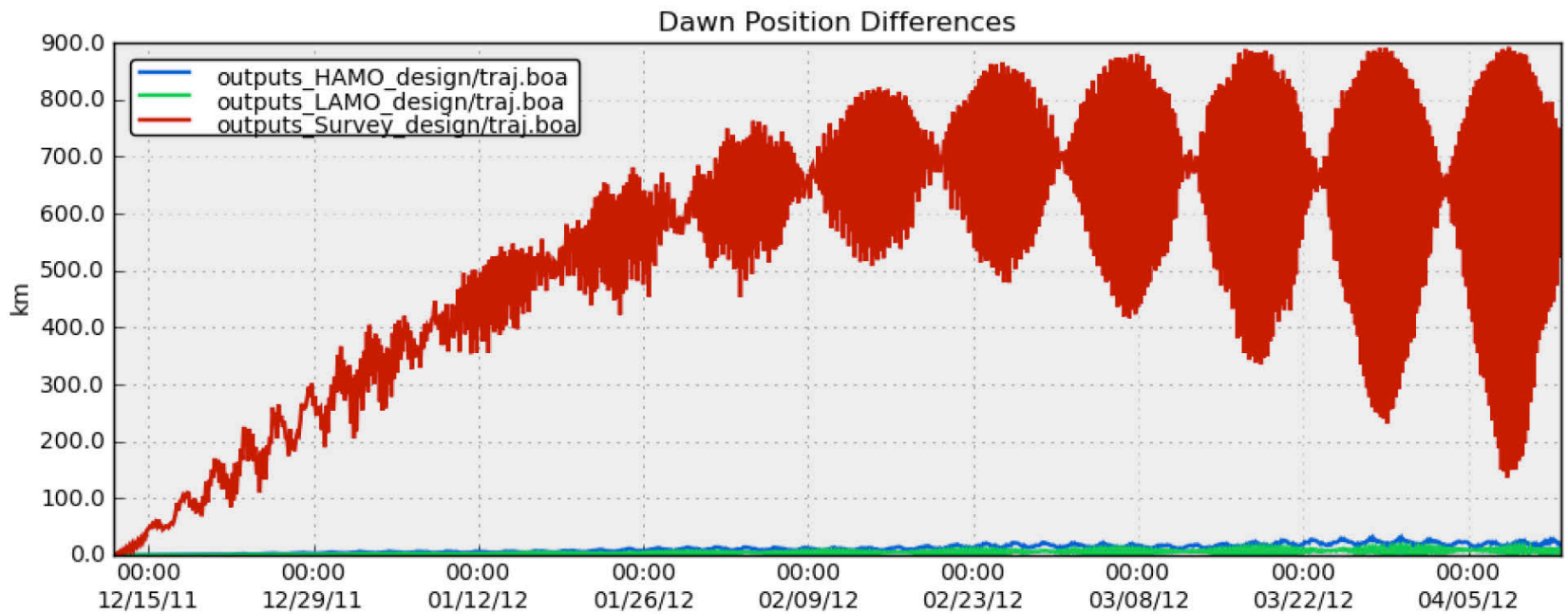
- Performance of the LAMO design field is first assessed by simply comparing LAMO-altitude propagations of the design field and the OD team's best estimate of the field from LAMO.
- The estimate of GM and the gravity field from the HAMO altitude provided a good field estimate for gravity at the LAMO altitude, with only ~10 km error over four months.
- Also shown here is the notable performance of the field estimated from the Survey altitude when propagated at LAMO altitudes.



Pre-Vesta gravity field at LAMO

- If the Survey design field were applied at LAMO, the predictions would be out of phase quite soon, with drifts of up to 90º inclination and 180º in node.



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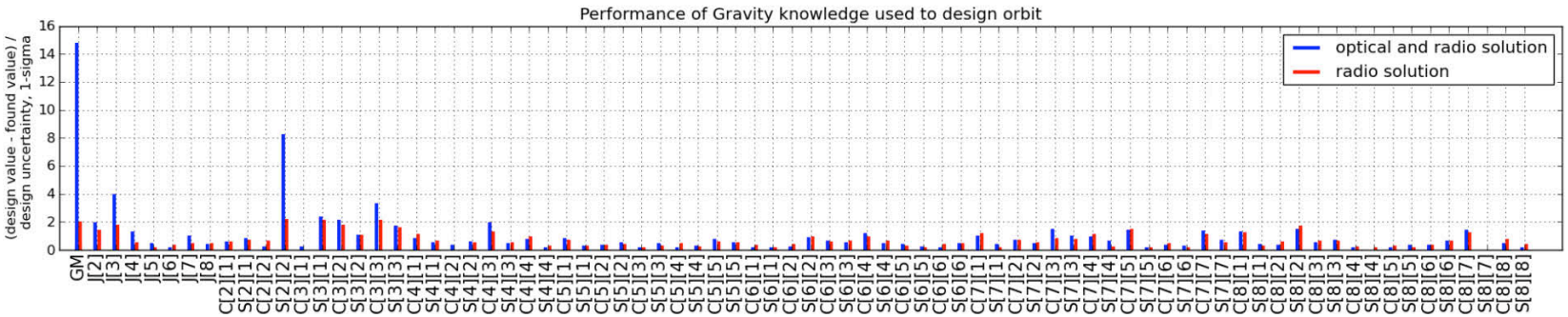
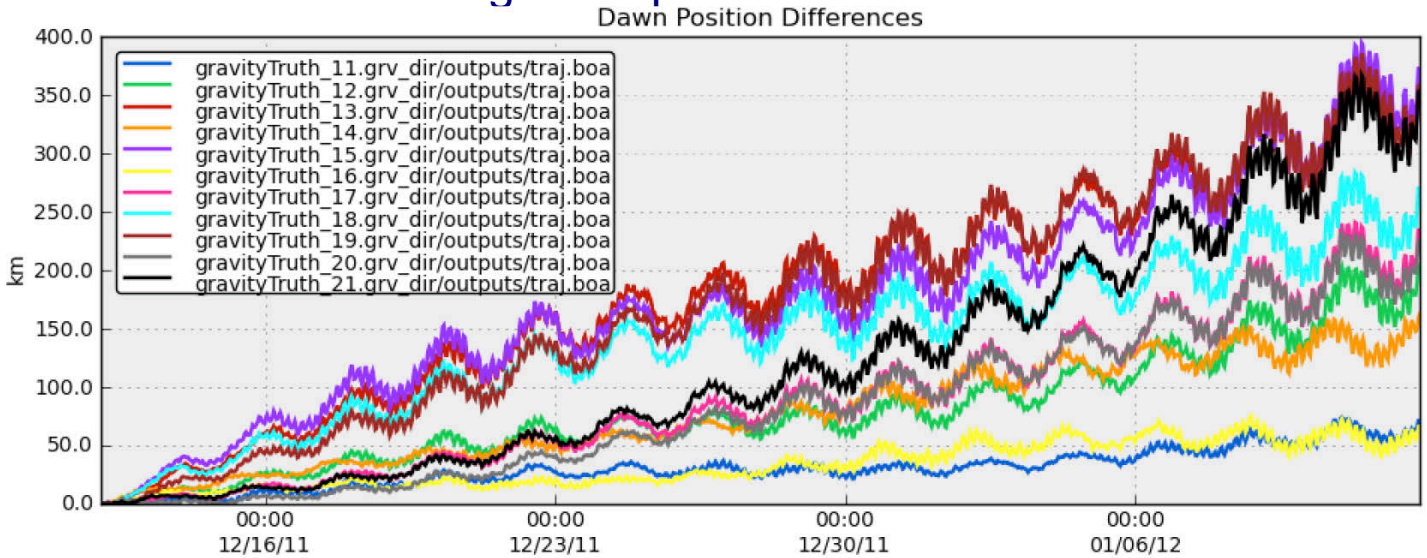
Statistical agreement of the fields

- In addition to examining propagation consistency, the performance of the filter error models is also investigated.
- Differences between the LAMO design field parameters and OD's best field estimate were mostly consistent, but were multi-sigma in GM, J[3], S[2][2] and C[3][3].
- Primarily due to optical data in the solution used to provide the LAMO design field When only radio data is used, the field differences are statistically consistent.



Assumed uncertainty of field

- Before starting the transfer from HAMO into a LAMO, the Dawn Navigation Team performs Monte Carlo studies to verify the feasibility of both the LAMO and the transfer to it.
- Below are propagations based on a random 1% of the sampled fields from a Monte Carlo run that assumed HAMO-altitude knowledge for the true field injection.
- Based on how poorly they compare with the previously shown performance of the as-estimated LAMO design field, the OD covariances going into the Monte Carlo studies might be quite conservative.



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Concluding Remarks

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- At Vesta, the pointing performance based on trajectory prediction was successful in all mission phases.
- At Ceres, OD will still recommend 2-sigma performance of the trajectory predictions for VIR scan sizing.
- Gradient torque will be less of a factor with the higher orbit radii at Ceres, but will still be studied.
- Due to recent failure of a second RWA, lessons learned from Vesta might be applied differently at Ceres.
- Gravity fields estimated from high altitudes predict low-altitude trajectories much better than expected.
- Gravity field covariances used for Vesta studies seem overly conservative, and we seek to better understand this in order to take advantage of it for Ceres studies.