Dawn Orbit Determination Team: Trajectory Modeling and Reconstruction Processes at Vesta

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Agenda

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  - Mission
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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
  - Polar radius: ~220 km
  - Equatorial radius: ~290 km

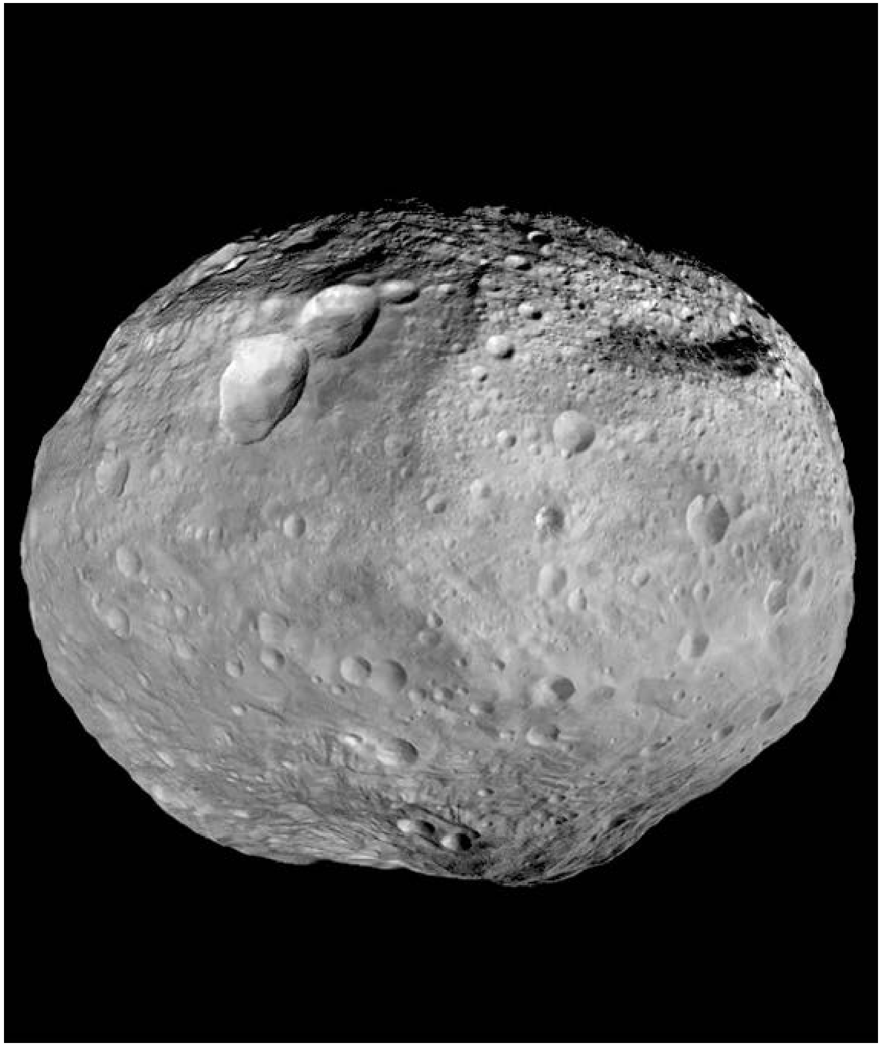
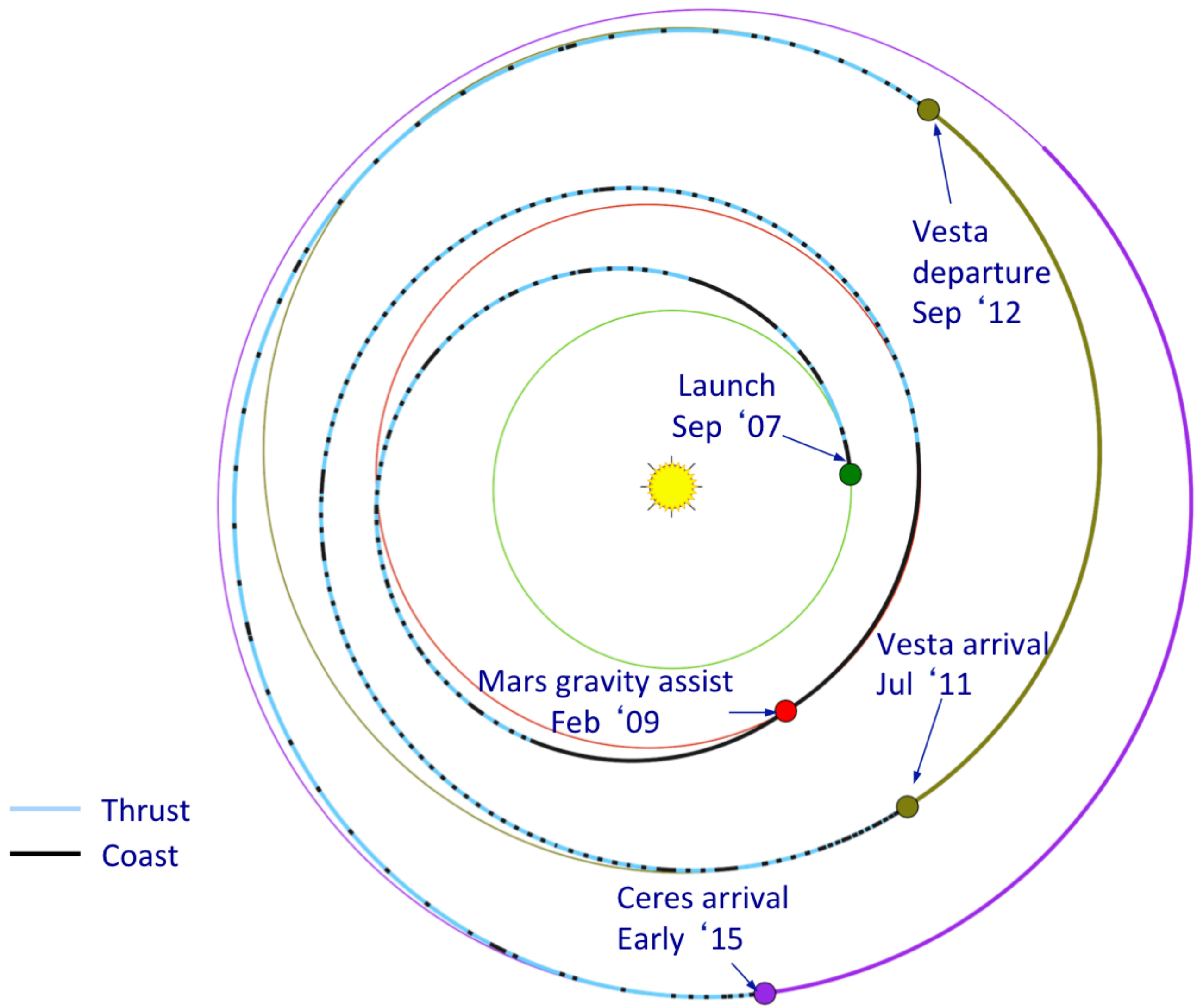
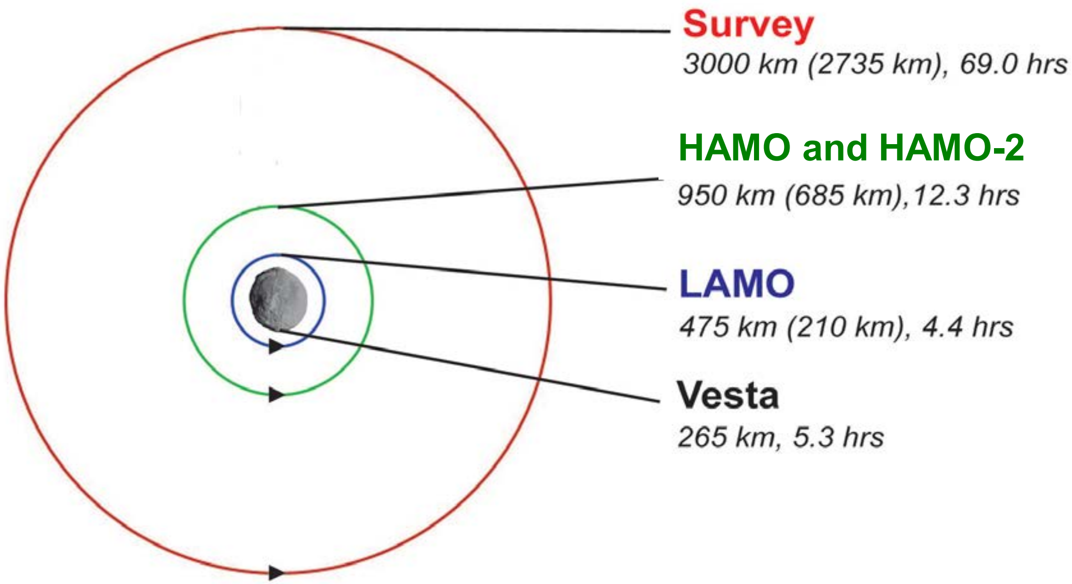


Image credit: dawn.jpl.nasa.gov

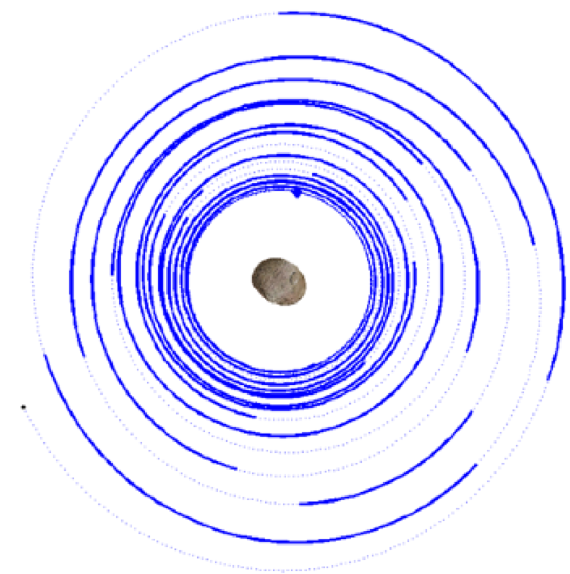
Mission Trajectory



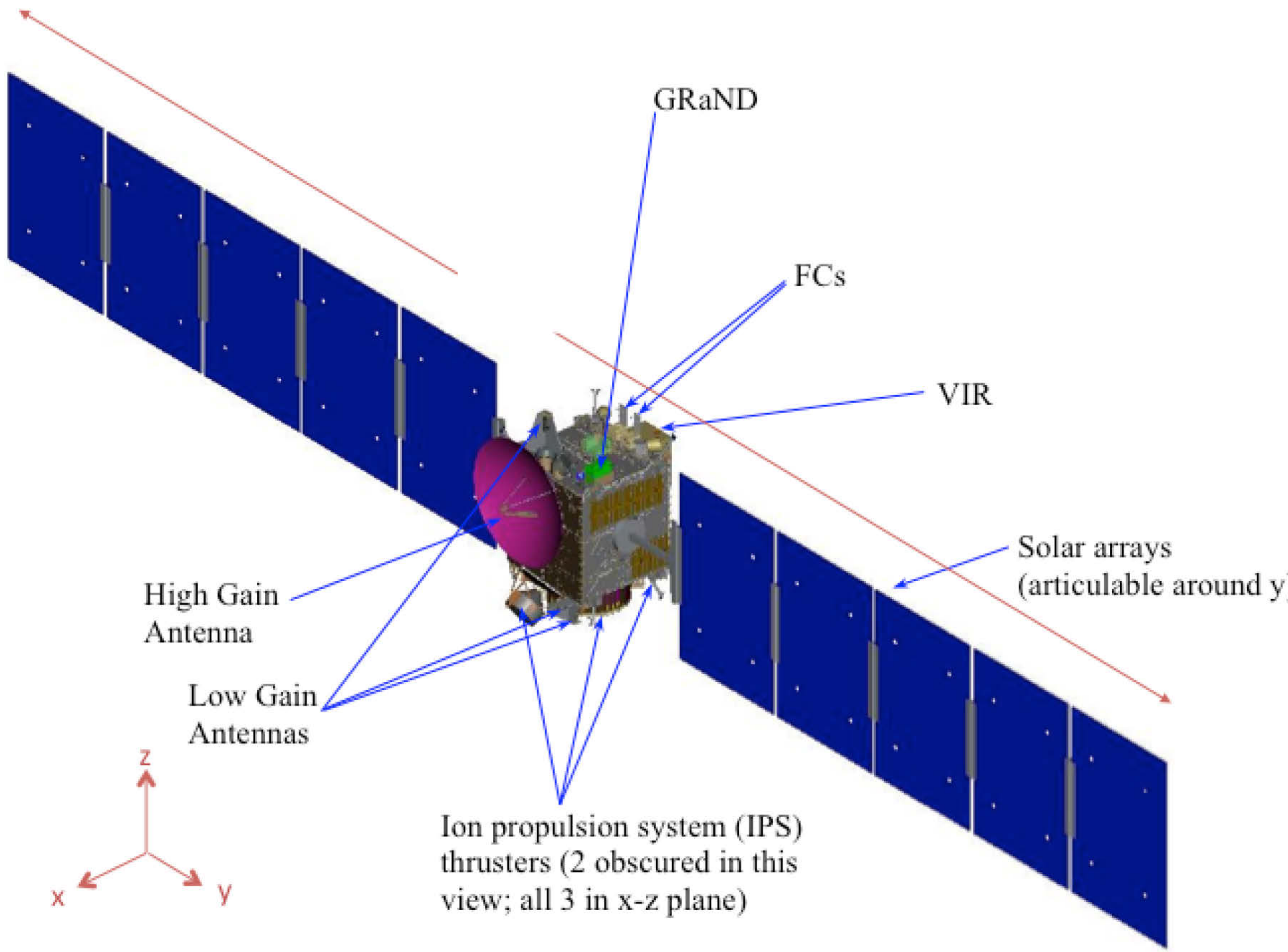
Science Phases at Vesta



Example of Survey to HAMO transfer



Dawn Spacecraft



Attitude Control

- Attitude Control System (ACS)
  - ACS provides three-axis stabilized control in any of four modes:
    - **RCS mode**:
      - uses the 6-thruster Reaction Control System to attitude control.
      - Y-axis control is unbalanced, with net delta-V along +X or –X axis
      - X-axis control is unbalanced, with net delta-V along +Z axis, and along +X or –X axis.
      - Z-axis control is balanced.
    - **RWA mode**: uses 3 of 4 Reaction Control Wheels. Requires desats using the RCS every 1-3 days, with DV of 1-3 cm/s
    - **Two Thrust Vector Control (TVC) Modes**:
      - While IPS is operational, it gimbals the thrust vector to control and/or change attitude along two axes that are orthogonal to the thrust direction.
      - RCS-TVC: Uses RCS to control the axis that cannot be controlled by TVC.
      - RWA-TVC: Uses RWA to control the axis that cannot be controlled by TVC.

Ion Propulsion System (IPS)

- The Dawn IPS has three IPS thrusters.
  - all direct thrust within the spacecraft XZ frame (within the plane of this slide)
- Each thrust is on 2-D controllable gimbal.
  - Allows the thrust to be directed through or around the spacecraft CG to minimize external torque or generate desired torque.
- Each thruster supports 111 mission levels of discrete thrust magnitude,
  - ranging from 91mN (ML111) down to 18 mN (ML0)
  - As Dawn and Vesta moved away from the Sun during the Vesta encounter, available power for thrusting dropped from 2.0kW to 1.2kW, allowing thrust magnitudes of 76mN to 46mN.

Dynamics Models

- For the Vesta OD, the following dynamic models were used:
  - Pointmass gravity
  - Vesta gravity harmonics
    - 4^{th} degree/order in Survey, 8^{th} degree/order in HAMO, 13^{th} degree/order in LAMO
  - High fidelity attitude models
    - Interpolated quaternions from ACS prediction and from ACS telemetry
  - Finite burns for the IPS thrusters
    - Modeled in the Dawn body-fixed frame as an applied force over a finite time interval
    - One Finite Burn per IPS arc, with thrust level / mass flow changes modeled as a time series and thrust pointing modeled as a fixed direction relative to the Dawn body-fixed frame
  - Small burns, to model RCS thrusting
    - Predicted as impulsive delta-V predictions from ACS team
    - 1-minute/record granularity in playback telemetry
  - Polynomial accelerations
    - High frequency batches to to clean up time varying system noise.
  - Solar pressure
    - 3-plate model

Filter Models

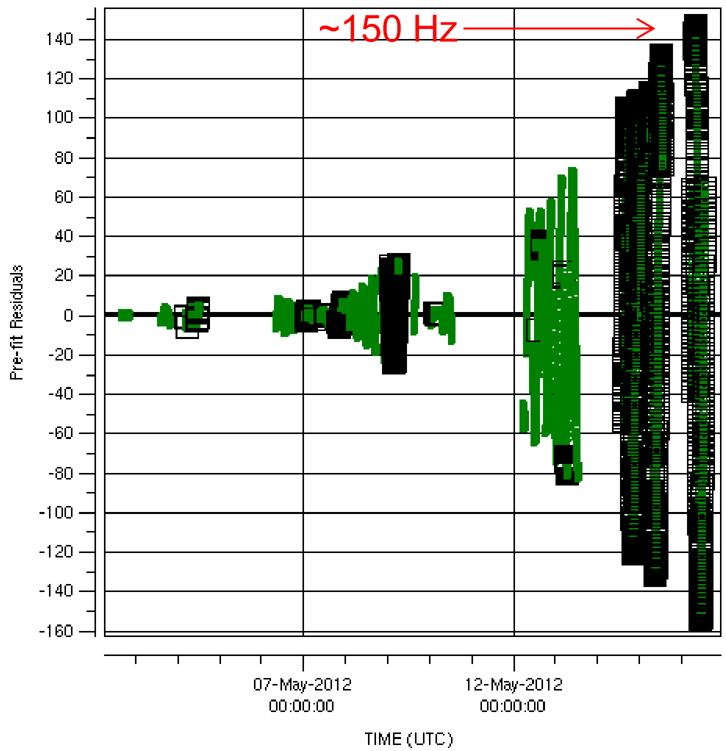
- A priori values for Vesta physical parameters based on a homogeneous Hubble model
  - Rescaled at each science phase based on statistics of independent 1-week OD solutions
- A priori IPS values based on thrust level calibrations performed prior to Approach
  - A scale factor table is used to bookkeep multiplicative scale factors for each IPS thrust level

Error Source	Est?	A priori 1σ error	Correlation Time	Update Time	Comments
2-way Doppler	-	5.6 mHz	-	-	0.1 mm/s
Range	-	14 Range Units	-	-	2 m
Optical Centers	-	0.25 to 1.0 pixels	-	-	
Optical Landmarks	-	0.25 to 1.0 pixels	-	-	
Spacecraft State	Y	20 km, 1 m/s	-	-	
Vesta GM	Y	0.4 km^3/sec^2	-	-	
Vesta harmonics	Y	500% of Kaula power law[9]	-	-	
Vesta Pole	Y	5°, RA and Dec			
Vesta Rotation	Y	2.5° phase, 15°/day rotation			
IPS thrust	Y	0.25% of thrust	-	-	
IPS direction	Y	0.25°, RA and Dec			
Range Biases	Y	2 m per pass	-	pass	
RWA Desats	Y	5 mm/s (3 axis)	-	Per desat	
Stochastic Noise (Poly Accel)	Y	1e-11 km/s/s ballistic 1e-10 km/s/s while thrusting	-	1 hour	
Solar Pressure Scale	Y	5%	-	-	Three Plate Model
Station locations	C	2-5 cm per axis	-	-	W. Folkner, Oct 2003
Troposphere	C	1 cm	-	-	Wet and Dry Components
Ionosphere	C	5 cm day and 1 cm night	-	-	X-band values
Earth Orientation	C	10 cm per axis	-	-	X, Y pole position, TAI-UT1

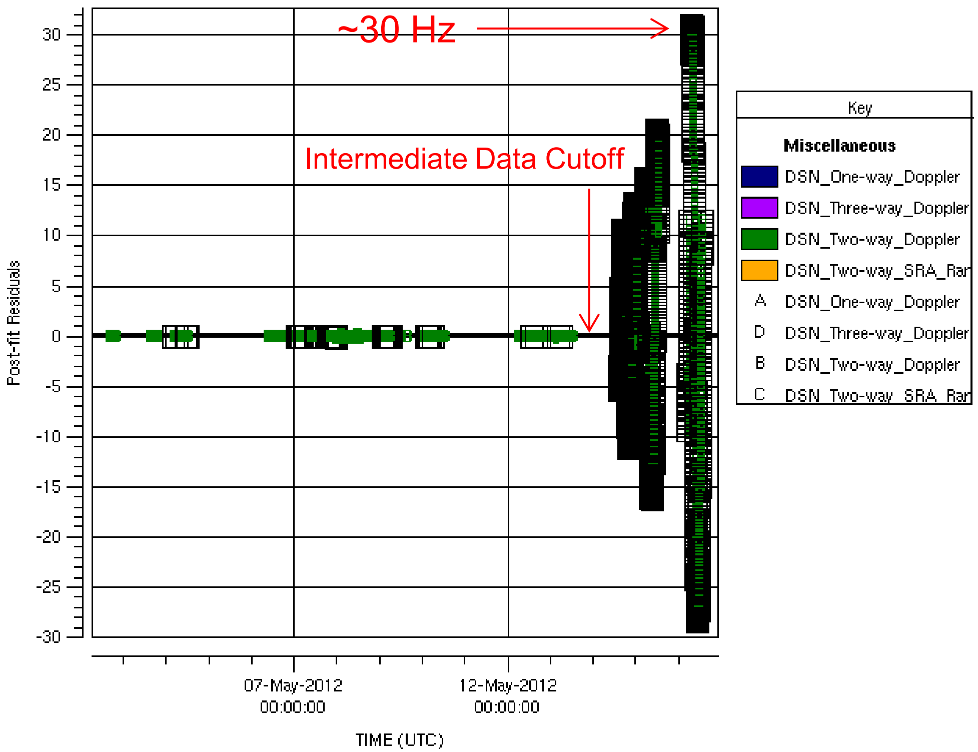
Measurement Fitting

- Strong nonlinear signatures in measurement residuals due to propagated IPS thrusting errors and orbital motion about Vesta
- Two methods used to minimize prefit amplitude:
  1. Feed forward latest IPS, gravity, and Vesta frame estimates as a priori values for the next OD
  2. Fit the data in smaller segments by incrementally advancing the data cutoff (see below)

Prefit Residuals

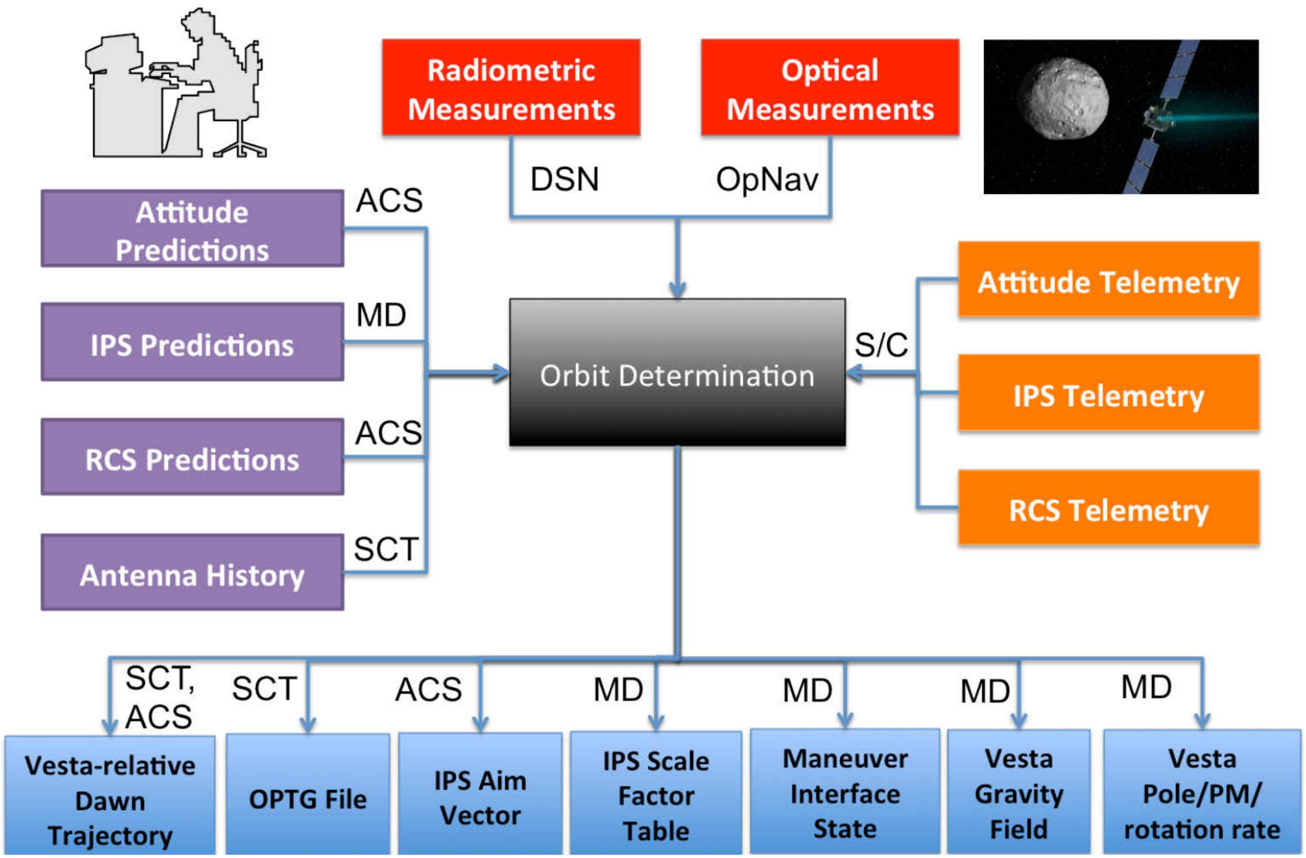


Postfit Residuals



OD Interfaces

- Predictions (left) delivered based on most recent sequence design
- Telemetry records (right) replace predictions as events are executed on the spacecraft and transmitted to the ground
  - Automated scripts process the telemetry records into OD model inputs
- OD deliverables include Vesta gravity and frame, IPS estimates, and trajectory products

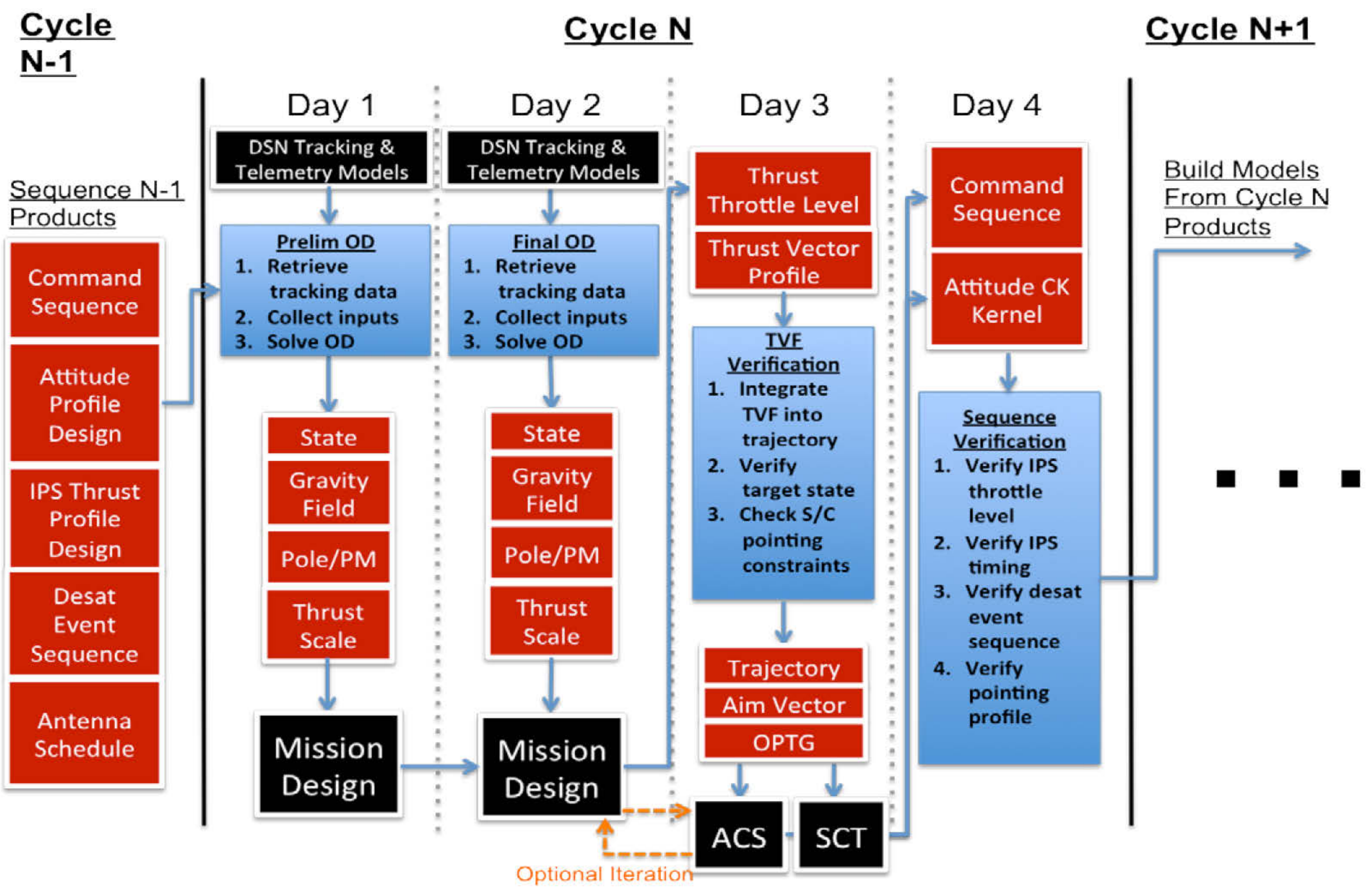


Thrust build Schedule

- As originally designed, there were 43 maneuver design cycles to be performed at Vesta, with design cycle lengths varying from 2 to 7 days.
  - Will later be referred to by sequence designations: DL002 through DL044
  - 5 on Approach (DL002 to DL006)
  - 4 during Survey to HAMO transfer (DL007 through DL010)
  - 10 during HAMO to LAMO transfer (DL011 through DL020)
  - 10 during LAMO to (DL021 through DL030)
  - 11 during LAMO to HAMO-2 (DL031 through DL041)
  - 3 on Departure (DL042 through DL044)

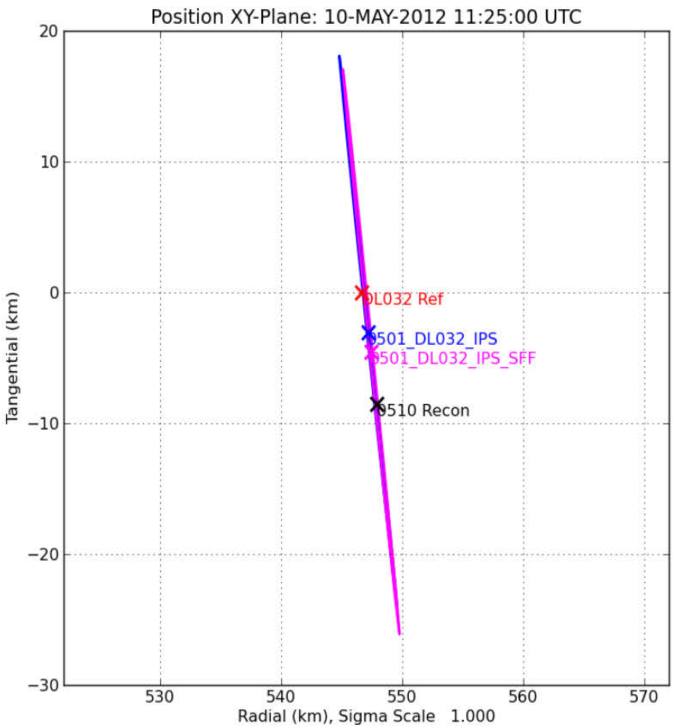
Maneuver Design Cycle

- Four OD Functions in Maneuver Design Cycle:
  1. Preliminary OD (to be used for preliminary thrust vector profile design)
  2. Final OD (to be used for final thrust vector profile design)
  3. Integration, verification, and delivery of a trajectory implementing the thrust vector profile design
  4. Verification of thrust command sequence and build of products for next OD cycle



IPS/RCS Execution Errors

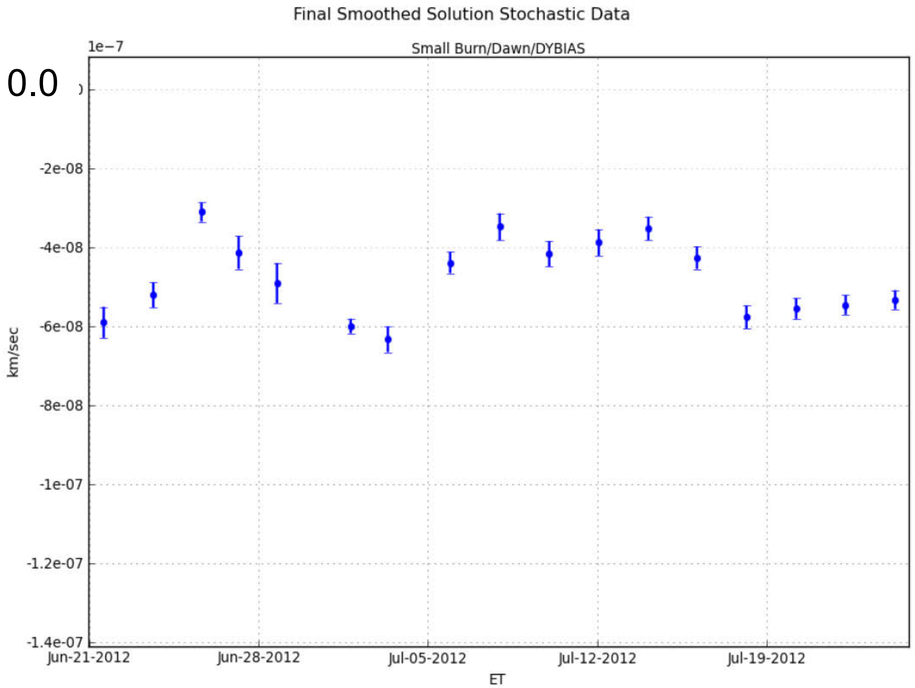
- During thrust cycles, the trajectory was dispersed from the reference target by modeling errors and execution errors
  - Modeling errors were due to the thrust design not modeling RCS (desat) events or the IPS Diode Mode (warmup)
  - Execution errors were due to RCS (desat) and IPS over-performance or under-performance in flight
- Ellipsoid plot shows modeling errors (“IPS_SFF” from “Ref”) and execution errors (“Recon” from “IPS_SFF” at the DL032 interface state
- In general, executions errors were below levels of modeling errors, indicated good performance prediction

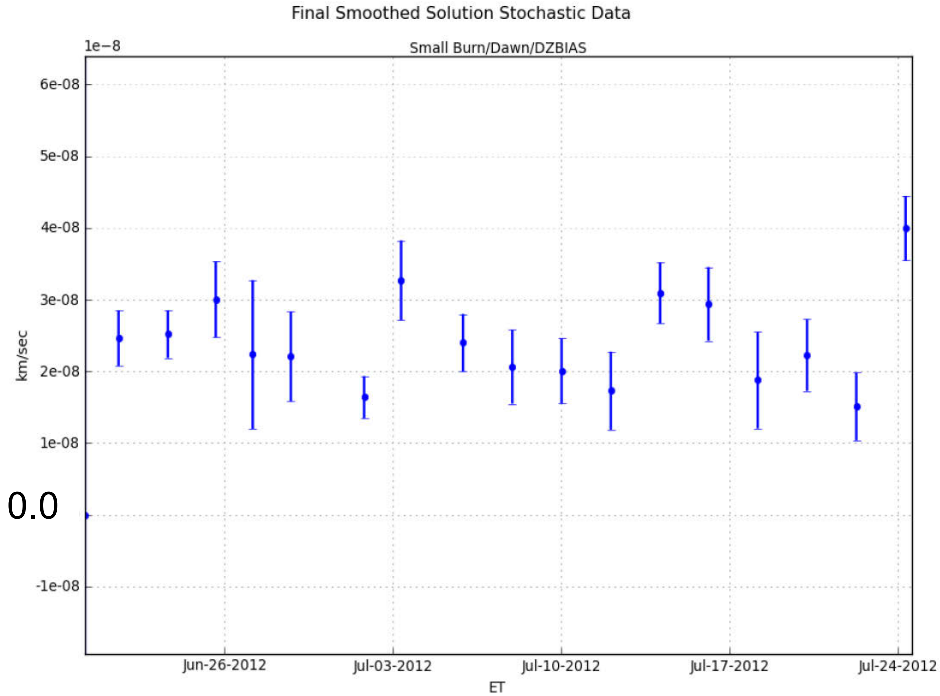


Thrust Design Cycle	Waypoint Epoch (11:25 UTC)	Throttle Level	IPS Scale Factor Adjustment	Total Dispersion from Reference (km)	Desat and Diode Mode Modeling Dispersions (km)	IPS/Desat Execution Dispersions (km)
DL031	04-MAY-2012	51	-0.2%	26.0 Downtrack	23.7 Downtrack	2.3 Downtrack
DL032	10-MAY-2012	51	0%	12.5 Downtrack	8.5 Downtrack	4.0 Downtrack
DL033	13-MAY-2012	51	0%	10.0 Downtrack	6.8 Downtrack	3.2 Downtrack
DL034	15-MAY-2012	50	0%	6.9 Downtrack	7.0 Downtrack	0.1 Uptrack
DL035	19-MAY-2012	50	-0.15%	8.8 Uptrack	5.8 Downtrack	14.6 Uptrack
DL036	23-MAY-2012	50	0%	37.6 Downtrack	33.9 Downtrack	3.7 Downtrack
DL037	27-MAY-2012	50	0%	65.2 Downtrack	36.2 Downtrack	29.0 Downtrack
DL038	31-MAY-2012	49	+0.2%	28.0 Downtrack	23.0 Downtrack	5.0 Downtrack
DL039	04-JUN-2012	49	0%	11.8 Uptrack	30.5 Downtrack	42.3 Uptrack
DL040	09-JUN-2012	49	-0.15%	17.5 Downtrack	14.3 Downtrack	3.2 Downtrack

Desat Bias Errors

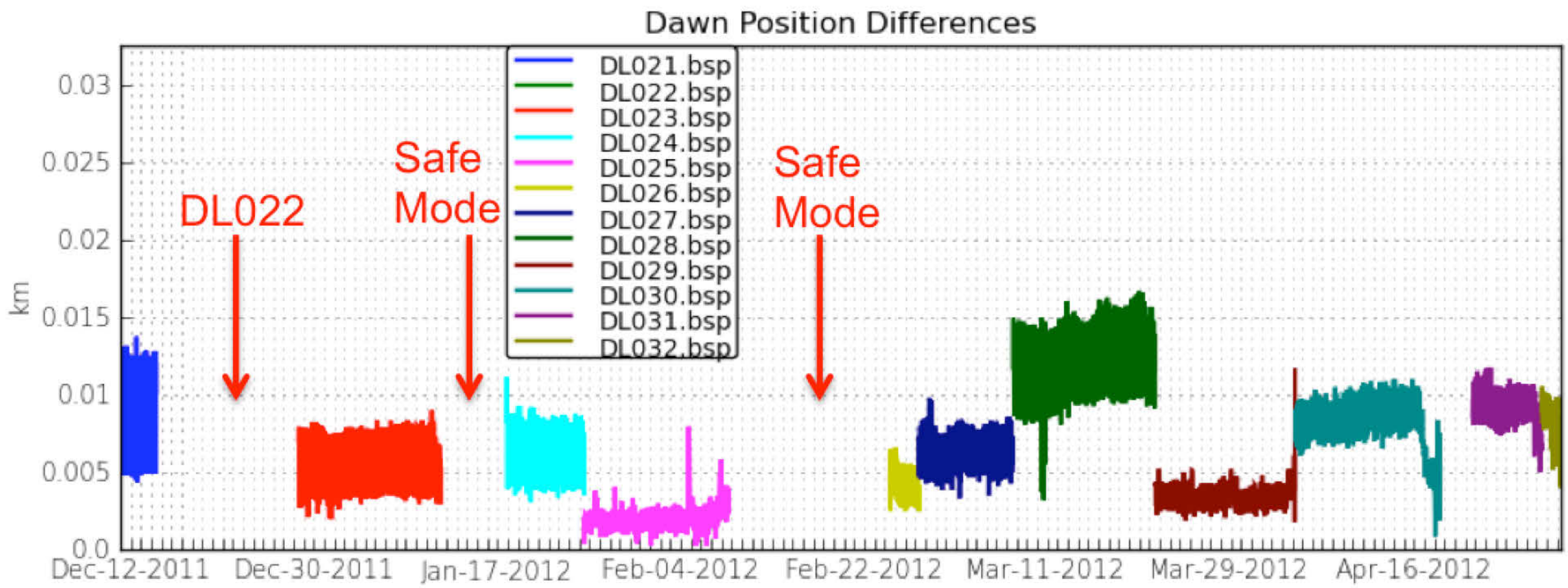
- Desat estimation can indicate biases in the SFF telemetry records.
- Estimates of the Z-axis RCS corrections indicated an underprediction of 0.02 to 0.03 mm/s in the SFF records delivered by telemetry.
  - Since each desat consisted of 10-15 records, this indicated desat over performance of 0.2-0.5 mm/s.
- A Y-axis RCS bias of -0.04 to -0.06 mm/s per record indicated an error of 0.4-1.0 mm/s per desat
  - This is particularly noteworthy since it may indicate an RCS thruster misalignment of a few degrees.





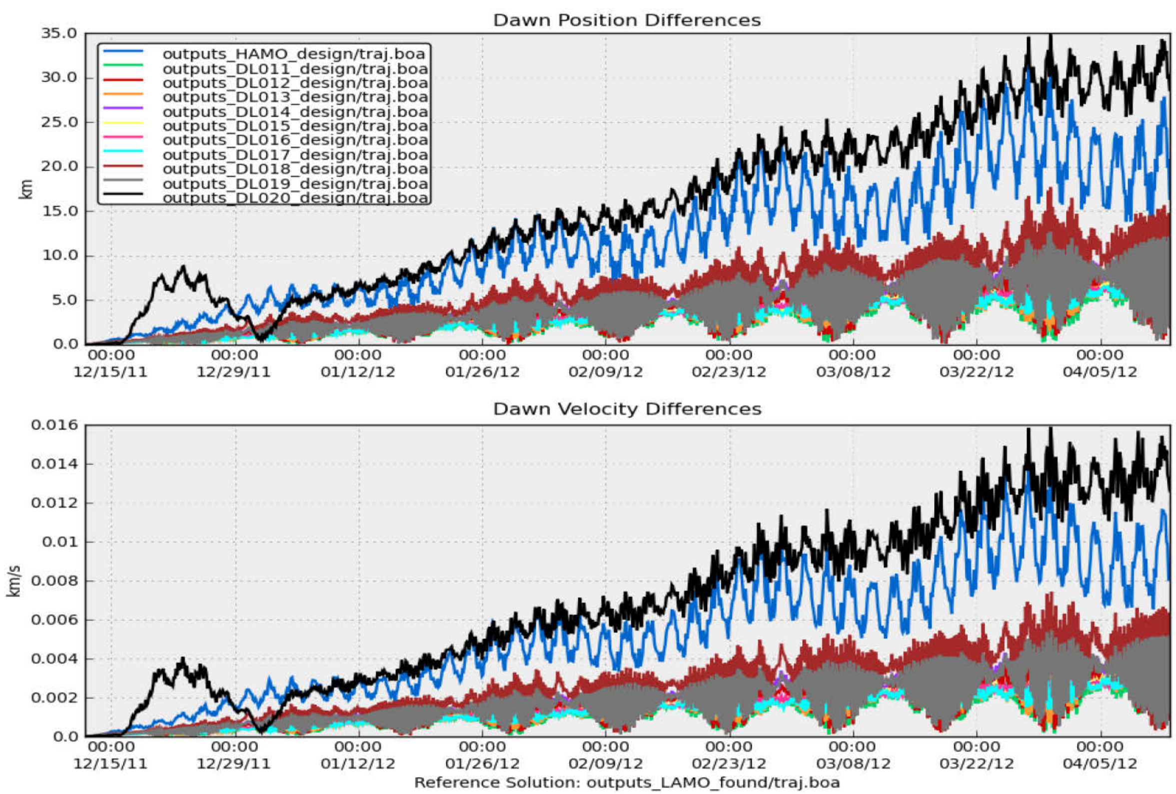
Trajectory Reconstruction Accuracy

- Intermediate trajectory reconstructions at LAMO compared to final LAMO reconstruction
- Maximum error shown here is 15 meters, meeting project requirement of 20 meters (1-σ)
- Three exceptions are two safe modes, and during DL022.
  - DL022 the only intermediate delivery at LAMO to merge radiometric and optical measurements
  - This will be discussed in later presentation.



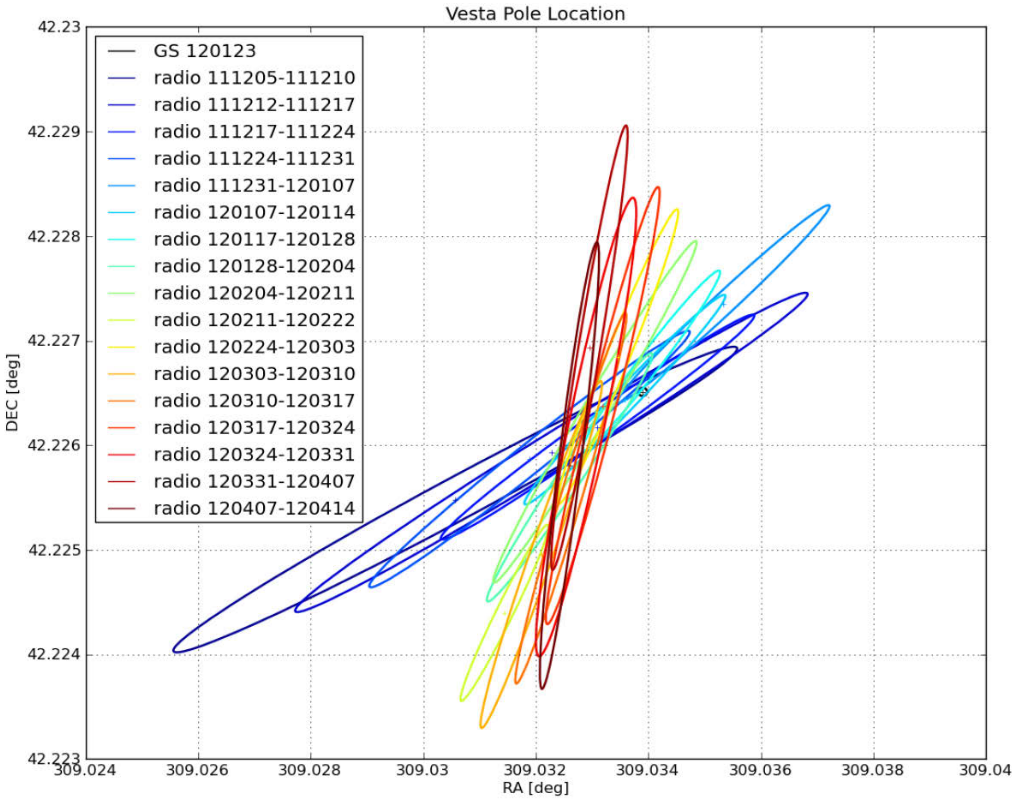
Gravity Field Stability

- To assess consistency of gravity field deliveries, each delivered gravity field during the HAMO to LAMO transfer was used to propagate the Dawn trajectory over LAMO
- In comparison to the LAMO reconstruction, the HAMO-delivered gravity field would have only caused a maximum trajectory dispersion of 30km and 1.4 m/s during LAMO
- All other delivered gravity fields would have dispersed the trajectory no more the 15 km, expect for the DL020 gravity field, which was solved with limited data after a safe mode



Vesta Frame Orientation Reconstruction

- This set of consecutive week-long Radio-only solutions from LAMO (blue) orient the pole at 42.226º Dec and 309.033º RA with uncertainty on the order of $\pm 0.005^{\circ}$
- This is within a millidegree of an estimate from Dawn Gravity Science



Conclusions

- At Vesta, the OD team was able to provide the necessary support to engineer the Vesta Mission and help return more than enough data to exceed level-1 requirements.
- OD experienced many exciting moments during the Vesta mission, including:
  - Supporting recovery from five safings
  - Supporting the numerous three-day design cycles during the HAMO to LAMO transfer and the LAMO to HAMO-2 transfer
  - Providing late breaking determination of Vesta parameters to support design of upcoming science orbits
    - Vesta Pole orientation on pproach (results discussed in a later presentation)
    - Vesta gravity from 3000 km, applied to 950 km (results in later presentation)
    - Vesta gravity from 950 km, applied to 475 km (results in later presentation)