Title:

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

Authors:

Matt Abrahamson†, Alessandro Ardito††, Don Han†, Robert Haw†, Brian Kennedy†, Nicholas Mastrodemos†, Sumita Nandi†, Ryan Park†, Brian Rush†, Andrew Vaughan†
† Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109.
†† INAF

Introduction:

The NASA Dawn spacecraft was launched on September 27, 2007 on a mission to study the asteroid belt's two largest objects, Vesta and Ceres. It is the first deep space orbiting mission to demonstrate solar-electric ion propulsion, providing the necessary delta-V to enable capture and escape from two extraterrestrial bodies. At this time, Dawn has completed its science campaign at Vesta and is currently on its journey to Ceres, where it will arrive in mid-2015. The spacecraft spent over a year in orbit around Vesta from July 2011 through August 2012, capturing science data during four dedicated orbit phases. In order to maintain the reference orbits necessary for science and enable the transfers between those orbits, precise and timely orbit determination was required. The constraints associated with low-thrust ion propulsion coupled with the relatively unknown a priori gravity and rotation models for Vesta presented unique challenges for the Dawn orbit determination team. While [1] discusses the prediction performance of the orbit determination products, this paper discusses the dynamics models, filter configuration, and data processing implemented to deliver a rapid orbit determination capability to the Dawn project.

Dawn Spacecraft

Dawn is a 740-kg dry mass spacecraft built by Orbital Sciences Corporation in Dulles, Virginia. The spacecraft bus is attached to 20-m long Gallium Arsenide solar arrays used to power the spacecraft systems at 3 AU from the Sun. Dawn is equipped with three gimbaled NSTAR solar-electric ion engines, known as the Ion Propulsion Subsystem (IPS), for trajectory maneuvers. During Vesta operations, the ion engines were able to provide thrust magnitudes on the order of 40-60 mN based on the available power from the solar arrays [1][4].

The spacecraft's Attitude Control Subsystem (ACS) provided three-axis stabilized control of Dawn during all nominal phases of the Vesta mission. Reaction Wheel Assemblies (RWAs) were used nominally for attitude actuation, and a partially coupled hydrazine Reaction Control System (RCS) was used to de-saturate the angular momentum built up ("desat" event) into the RWAs.

Orbit Phases:

Dawn carries the following scientific instruments on the spacecraft bus for the capture of visible, infrared, and gamma ray spectra emitted by Vesta:

- The visible light Framing Camera (FC).
- The Visible and Infrared Spectrometer (VIR).
- The Gamma Ray and Neutron Detector (GRaND).

In addition, Dawn captures gravity science data via the Doppler shift observed over the high gain antenna (HGA) transmission to Earth. The expected science data was recorded during the following four orbit phases of the Vesta mission with the primary science instrument for each phase indicated:

- Survey Orbit: VIR at 800 m/pixel resolution (July-August 2011)
- High Altitude Mapping Orbit-1 (HAMO-1): FC at 100 m/pixel resolution (October 2011)
- Low Altitude Mapping Orbit (LAMO): GRaND and gravity science (December 2011 - April 2012)
- High Altitude Mapping Orbit-2 (HAMO-2): FC at 100 m/pixel resolution (June-July 2012)

Orbit determination was tasked to support periodic on-board ephemeris updates and orbit maintenance maneuvers during these phases.

Transfer Phases

In addition to the four orbit phases, four mission phases were dedicated to the transfer between each of the science orbits:

- Survey Orbit to HAMO (September 2011)
- HAMO to LAMO (November 2011 – early December 2011)
- LAMO to HAMO-2 (early May 2012 – early June 2012)
- HAMO-2 to Vesta Escape (late July 2012 – September 2012)

The majority of time during the each of the transfer phases was dedicated to IPS thrusting to achieve the necessary delta-V to complete each transfer. The maneuver design cycles were chosen with a 3-4 day turnaround by the mission design team to provide a high confidence of success based on statistical analyses of trajectory perturbations during the transfer. Orbit determination was tasked to provide the trajectory state inputs to mission design to initiate each maneuver design. Due to the rapid maneuver design cycles involved, the timeliness of the orbit determination process was especially critical during orbit transfers.

Orbit Determination Process

The function of the orbit determination (OD) process is to reconstruct the Dawn as-flown trajectory up to the radiometric and optical measurement data cutoff and estimate the best dynamics models to be used for projecting the Dawn trajectory into the future. While [1] discusses the trajectory prediction performance of the OD products, this paper will discuss the models and process necessary to reconstruct the as-flown trajectory from the measurement data and produce the delivery products in a timely manner. In order to fit the Dawn trajectory to the measurement data, several dynamics models were established to describe the Vesta gravity field and orientation, IPS thruster activity, spacecraft attitude profile, and RCS desat events. The a priori models were built based on design inputs from the mission design and attitude control teams, then updated as telemetry of the as-flown performance became available on the ground. The ability to fit the measurement data was influenced by a variety of factors, including the accuracy and order of the a priori models, the modeled fidelity of desat and burn event timing, antenna motion present in the measurement data, filter weights, and the arc length of the measurement data. Often, the estimates for several filter parameters would alias due to lack of observability in the measurement data. To combat this, the filter weights were tuned by computing the statistics of several OD solutions using independent one-week data arcs during each orbiting phase. Once the trajectory was determined, the OD products were built and delivered to the mission design, attitude control, spacecraft, and science teams for implementation of the next maneuver design. In addition to the trajectory reconstruction, the OD products also included estimates of the IPS thruster performance, Vesta gravity field, and Vesta body frame.

Orbit Determination Challenges

A major challenge for the orbit determination process at Vesta was the incorporation of ion propulsion usage in the Dawn mission design and navigation architecture. Due to the low thrust provided by the IPS, the Dawn spacecraft spent a majority of time thrusting during orbit transfers. The result was fewer radiometric and optical measurements for orbit determination due to operational constraints. If tracking were to be enabled during thrusting, a drop in thrust on the order of 3 mN would be needed to route power to the transmitter [1]. During operations at Vesta, thrusting durations were on the order of days and each of the orbit transfers lasted approximately 6 weeks [2][3]. Telemetry playback on the high-gain antenna during transfers was limited to an 8-hour pass every few days. During orbit transfers, the maneuver design process on the ground occurred in parallel with thrusting on the spacecraft, meaning that the n+2 maneuver was designed based on orbit determination knowledge only up to the nth maneuver. The result was a time-constrained, data-limited orbit determination process tasked with providing orbit determination updates in the small periods between long-duration thrust segments.

A second challenge for orbit determination was Vesta gravity, center of mass, pole, and prime meridian estimation given the lack of detailed a priori models. Since the signal from each of these parameters increased in resolution as the spacecraft altitude was reduced, it was important to carefully manage the filter configuration for these parameters during the Survey-to-HAMO, and HAMO-to-LAMO transfers. For gravity, this meant expanding the order of spherical harmonics estimated and for the other parameters it meant updating the nominal values and uncertainties appropriately.

A third challenge for orbit determination was safe mode recovery. During Vesta operations, Dawn entered safe mode five times. Upon safe mode entry, the spacecraft ceased sequenced activities, turned the solar panels toward the Sun, entered a slow spin mode, and communicated to the Earth via the low gain antenna. The recovery process for orbit determination involved advancing the filter epoch past the safe mode entry time, collecting estimates of delta-V events from the attitude control team, modeling the delta-V events as small forces, modeling the spin motion of the antenna, and delivering a rough trajectory to the spacecraft team based on a small amount of radiometric data. Since the telemetry bandwidth is constrained until the high gain antenna is restored, a lack of telemetry for delta-V events added to the difficulty of the task. Each safe mode event required a quick turnaround by orbit determination to assess the mission impact.

Orbit Determination Performance

The requirements levied on the Dawn orbit determination team specified an in-orbit orbit determination capability with the following accuracies:

- 200 m (1-σ) and 10 cm/sec (1-σ) @ 2000 km altitude (Survey)
- 70 m (1-σ) and 3 cm/sec (1-σ) @ 700 km altitude (HAMO-1, HAMO-2)
- 20 m (1-σ) and 0.5 cm/sec (1-σ) @ 200 km altitude (LAMO)

As Dawn ventured to lower altitudes above Vesta, the trajectory could be found with greater confidence due to the increase in dynamic motion apparent in the measurements at lower altitudes. By LAMO, the trajectory could be determined within 20 meters. Figure 1 plots the performance of each orbit determination delivery during LAMO up to the data cutoff as compared to the final trajectory reconstruction. With the exception of one LAMO delivery, all other OD delivered achieved sub-sigma performance.

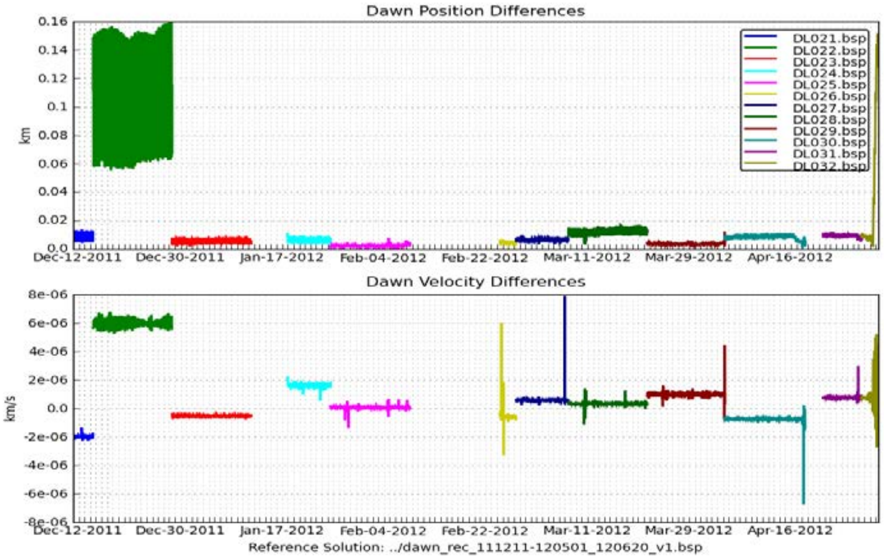

Figure 1: Dawn OD Deliveries Compared to Final Reconstruction During LAMO

This paper will discuss the orbit determination models and processing steps in detail and offer a few specific examples of challenges and surprises that occurred along the way. The paper will explore issues with filter weighting, data editing, arc length, and parameter aliasing. The maneuver design cycle will be discussed, with detail given to the timing and content of interface products exchanged between the OD team and the other subsystems. The paper will also expand upon the discussion of orbit determination knowledge requirements to all phases of the Vesta campaign.

Acknowledgements

The work to be described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Special thanks are extended to the tremendous efforts put forth from our fellow members of the Dawn Spacecraft Team, the Dawn Science Team, the Dawn Project Management and the Personnel of the DSN facilities in Barstow, California; Madrid, Spain; and Canberra, Australia

References

[1] Kennedy, B., *et. al.,* "Dawn Orbit Determination Team: Trajectory and Gravity Prediction Performance during Vesta Science Phases", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Hawaii Kauai, Feb. 10-14, 2013.
[2] Han, D., "Orbit Transfers for Dawn's Vesta Operations: Navigation and Mission Design Experience", 23rd International Symposium on Space Flight Dynamics (ISSFD), October 29-November 2, 2012, Pasadena, California.
[3] Parcher, D.W., and Whiffen, G.J., "Dawn Statistical Maneuver Design for Vesta Operations", AIAA/AAS Astrodynamics Specialist Conference, New Orleans, Louisiana, Feb. 13-17, 2011.
[4] Garner, C., Rayman, M., "Performance of the Dawn Ion Propulsion System Through Operations at Vesta", 23rd AAS/AIAA Spaceflight Mechanics Meeting, Hawaii Kauai, Feb. 10-14, 2013.