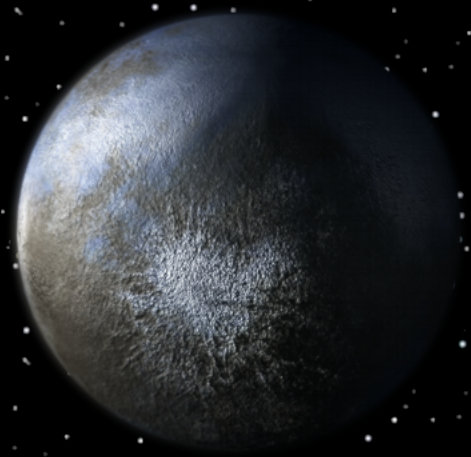
39th AAS Guidance & Control Conference

Determination of Ceres Physical Parameters Using Radiometric and Optical Data.



Brian Kennedy*
Nicholas Bradley*
Dongsuk Han*
Reza Karimi*
Nicholas Mastrodemos*
Brian Rush*
Yu Takahashi*

*Jet Propulsion Laboratory/California Institute of Technology

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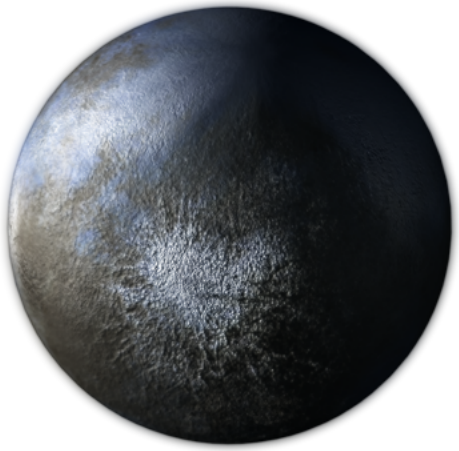
Agenda

Dawn

- Overview
  - Mission
  - Spacecraft
  - Science
- Navigation
  - Subteams
  - Data types
  - Physical Parameters
- Parameter Predictions
  - Performance
  - Follow up analysis
- Conclusions



Dawn Mission

Dawn

- Launched: September, 2007.
- Mission: orbit two of the largest asteroids in the main asteroid belt, Vesta and Ceres.
  - Vesta: July, 2011 through September, 2012.
  - Ceres: January, 2015 and onward.
- For both targets, science goals include
  - Surface mapping using a visible light Framing Camera
  - Infrared spectroscopy
  - Gamma ray and neutron counts
  - Gravity science using radiometric tracking data
- A low-thrust ion engine is used to target the asteroid encounters and to change orbit altitudes.

Dawn Mission Trajectory

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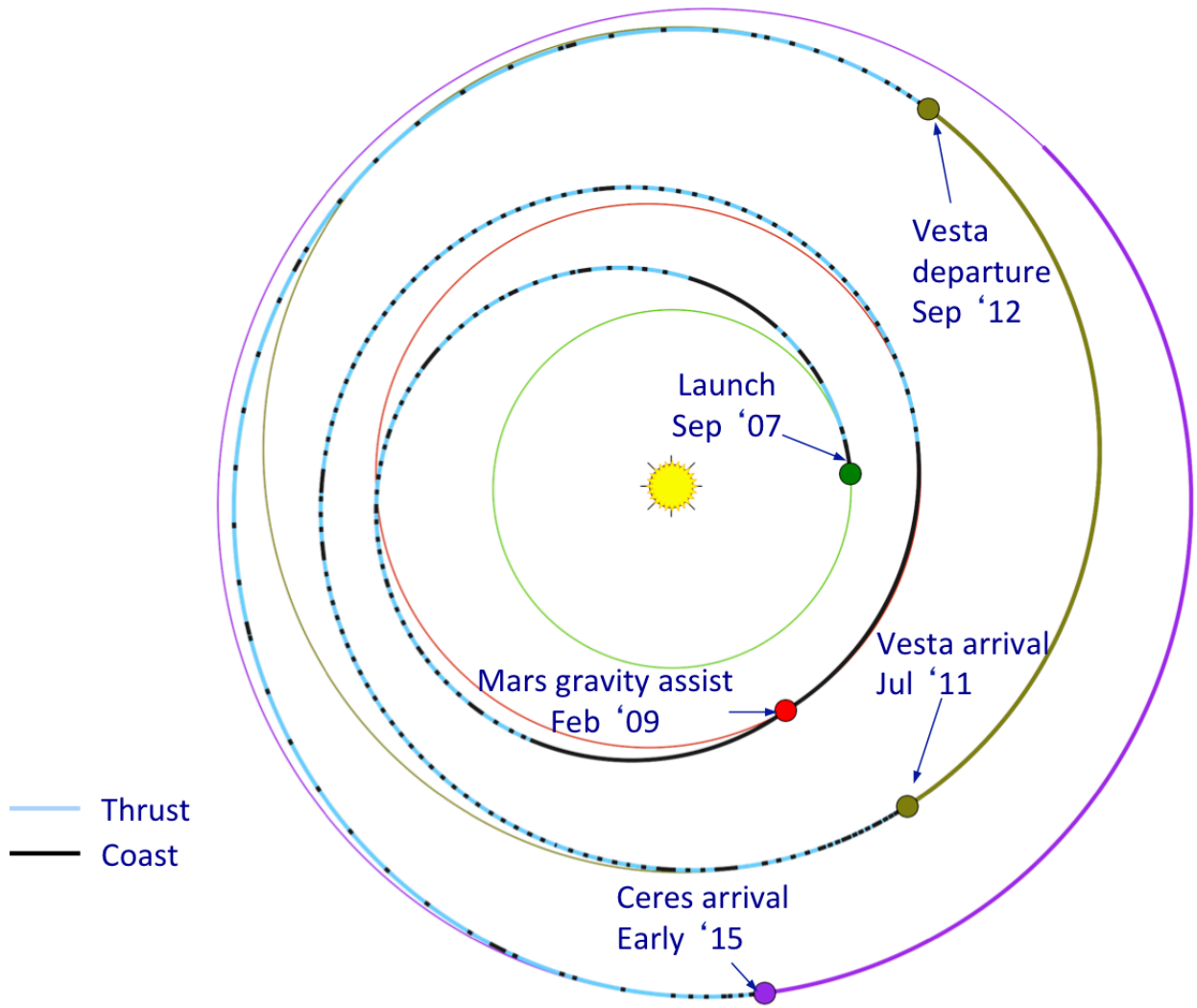
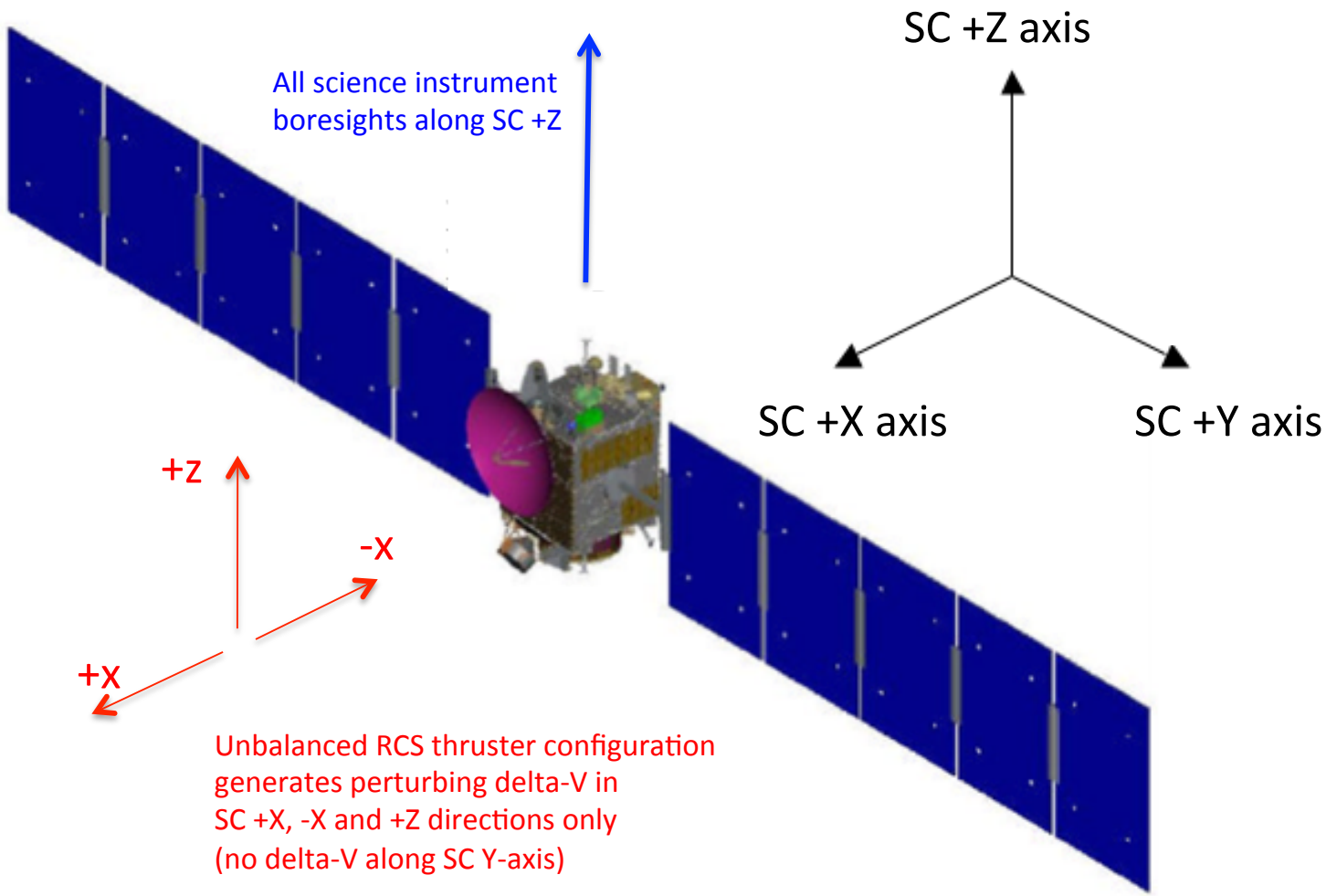


Dawn Spacecraft



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Dawn ACS

- Dawn is a three-axis stabilized spacecraft
- Attitude can be controlled using Reaction Wheel Assemblies (RWAs) or the Reaction Control System (RCS).
- Due to the loss of two of the four RWAs earlier in the mission, science operations at Ceres are conducted in one of two modes:
  - Full Reaction Control System (RCS) control
  - Hybrid RCS and RWA control, where the remaining two RWAs are used concurrently with the RCS.

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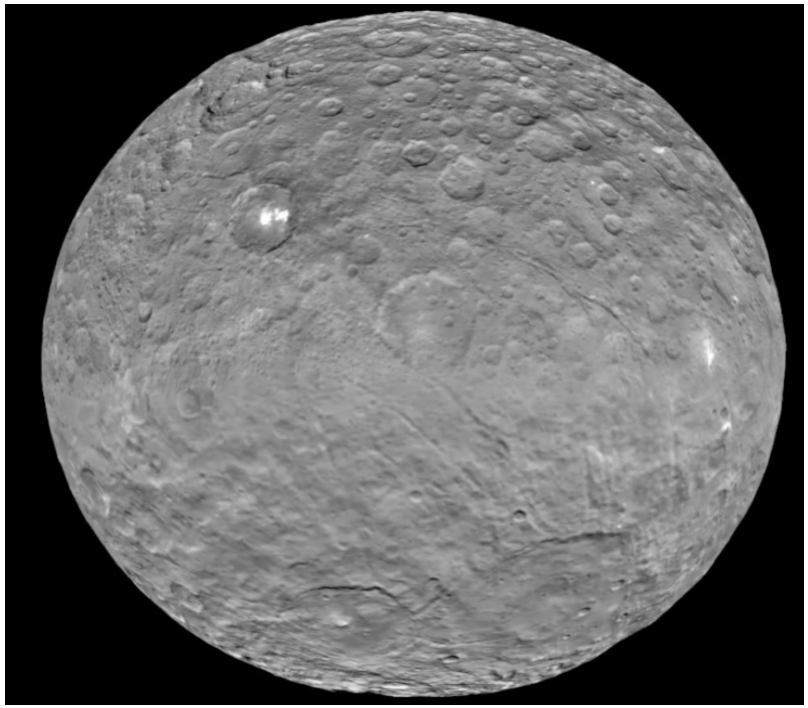
Ceres

- The asteroid/dwarf planet Ceres is located in the main asteroid belt between Mars and Jupiter.
  - Orbital period: 4.6 years
  - Rotational rate: 9.07 hours
  - GM: 62.63 km^3/sec^2
  - Average radius: ~470 km



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Ceres Science Phases

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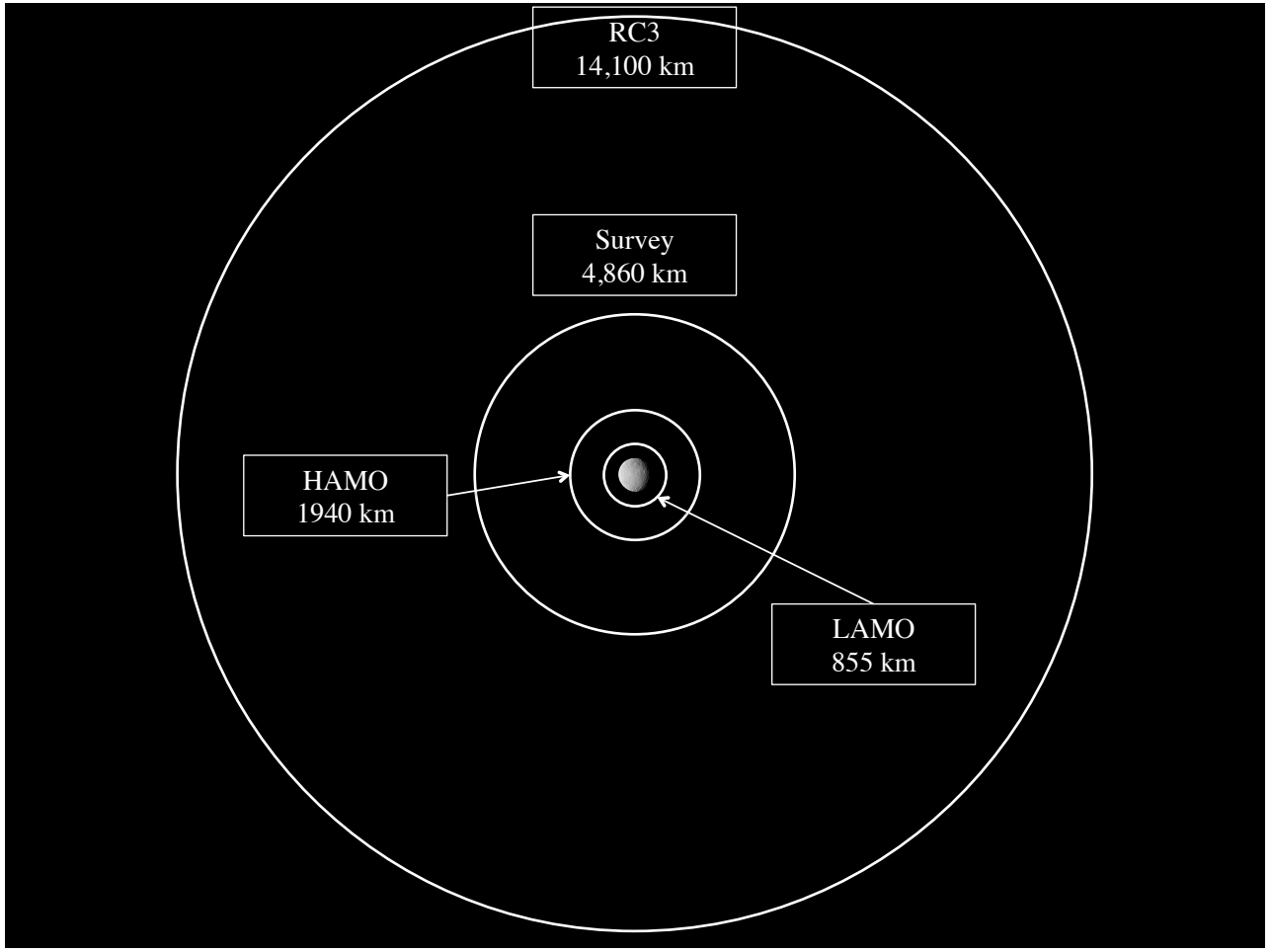
Phase	Distance from Ceres (km)	Orbit period	Dates	ACS mode	# Of orbits
Approach	1500000 to 4860	N/A	Dec, 2014 to Mar, 2015	All-RCS	-
RC1	87000	N/A	Feb 12th, 2015	All-RCS	-
RC2	49000	N/A	Feb 19th, 2015	All-RCS	-
RC3	14100	~14 days	Apr 23rd – May 9th, 2015	All-RCS	~1
Survey	4860	~3 days	June 3rd, 2015 – July 15st, 2015	All-RCS	8
High Altitude Mapping Orbit (HAMO)	1940	~19 hours	August 13th, 2015 – October 23rd, 2015	All-RCS	80
Low Altitude Mapping Orbit (LAMO)	855	~5 hours	December 7th, 2015, - EOM	Hybrid	400+

Ceres Science Phases



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Dawn Navigation

- Dawn Navigation consists of three teams:
  - Dawn Mission and Maneuver Design (MD) Team
    - Designs orbit for each of the four science phases: RC3, Survey, HAMO and LAMO
    - Designs thrust profile needed to transfer to the next phase
  - Dawn Orbit Determination (OD) Team
    - Reconstructs past trajectory and predicts future trajectory
    - Provides estimates of Ceres physical parameters for design of each of the four science orbits
  - Dawn Optical Navigation (Opnav) Team
    - Determines shape model and surface landmarks
    - Reduces science imagery into optical data observations for OD team

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Dawn OD Data

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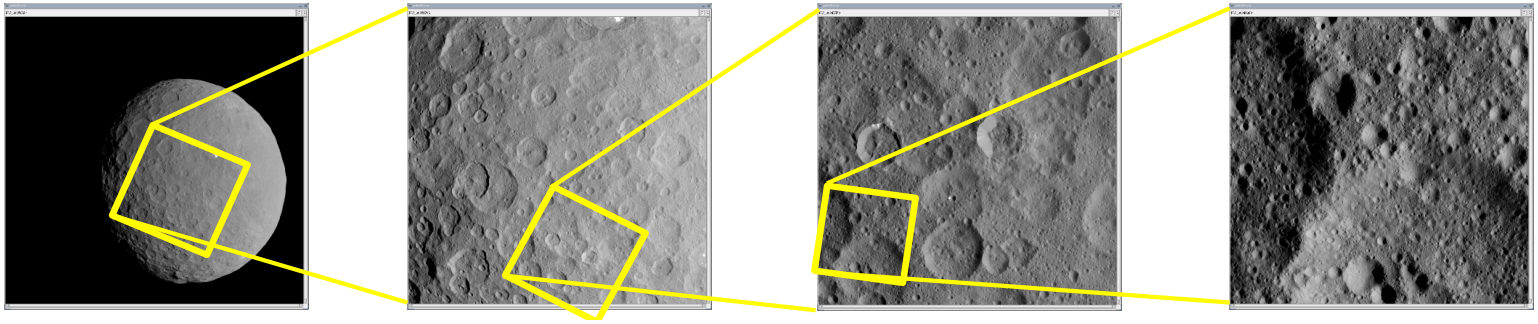
- The Dawn OD team uses two data sources to estimate the trajectory and Ceres
  - Radiometric data from the Deep Space Network (DSN)
    - Spacecraft velocity measurements ("Doppler")
    - Space distance measurements ("range")
  - Optical data reduced from science imagery
    - Vectors from spacecraft camera to locations on surface
    - Relative resolution of Ceres at each mission phase shown below

RC3	Survey	HAMO	LAMO
5/04/2015	6/21/2015	10/01/2015	12/25/2015
Range = ~14,100 km	Range = ~4860 km	Range = ~1940 km	Range = ~855 km
1 Pixel = ~1.3 km	1 Pixel = ~450 m	1 Pixel = ~180 m	1 Pixel = ~79 m
FOV = ~1330 km	FOV = ~460 km	FOV = ~185 km	FOV = ~81 km



Estimated Parameters

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- The OD team fits the radiometric and optical data using a square root information filter.
- Trajectory parameters in the filter
  - IPS thrusting
  - RCS pulses
  - Solar radiation pressure (SRP)
  - State at start of trajectory.
- Ceres parameters in the filter
  - Orientation of Ceres rotational pole
  - Rotational rate
  - GM
  - Gravity field, modeled using the standard spherical harmonics representation described in Kaula's *Theory of Satellite Geodesy*

Parameter Visibility

- Both radiometric and optical data are required to realize the complete set of Ceres parameters.
- Gravity field: best seen with radiometric data.
- GM: seen using either radiometric or optical data, with optical data reporting a higher confidence.
- Pole orientation and rotational rate: almost entirely seen using optical data.
  - Interestingly, radiometric data does have some visibility into the pole at sufficiently low altitudes, as shown on the table below.

	Pole R.A uncertainty (º, 1- σ)		Pole Dec. uncertainty (º, 1- σ)		Rate uncertainty (º/year, 1-σ)	
Phase	Radio only	Merged	Radio only	Merged	Radio only	Merged
RC3	N/A	0.007	N/A	0.004	N/A	0.08
Survey	1.0	0.002	0.06	0.0016	30	0.04
HAMO	0.24	0.0007	0.012	0.0003	1.5	0.011
LAMO(2 wks.)	0.02	0.0016	0.004	0.0004	2.0	0.07

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Parameter Estimation Accuracy

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- Monte Carlo (MC) studies were performed in preparation for Ceres operations.
- These MC studies demonstrated that the spacecraft could be transferred to the next science orbit, and that the orbit would meet coverage requirements.
- The OD team performed covariance studies to provide the MD team with a full correlated covariance for the spacecraft state and the Ceres parameters.
- To demonstrate robustness, the formal one-sigma uncertainties in the covariance were all inflated by a factor of five.
- The design of all four science orbits was tested in this fashion.

Parameter Prediction Performance

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- During Ceres operations, the OD team provided the MD team with four estimates of the Ceres physical parameters; one for the design of each of the four science orbits.
  - March 18th, 2015: delivery for design of RC3
  - May 5th, 2015: delivery for design of Survey
  - July 9th, 2015: delivery for design of HAMO
  - October 1st, 2015: delivery for design of LAMO
- The current best estimates of the Ceres parameters have been compared with these deliveries.
- As one metric for success, the differences are compared with the covariance inputs to the pre-Ceres MC studies.

Estimation performance

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- RC3 design: GM and Pole
  - None of the estimates exceeded the inflated uncertainties.
- Survey design: GM, Pole and 3rd degree/order harmonics
  - Pole Right Ascension (RA) error of 0.23º exceeded the inflated uncertainty by a factor of 4.
- HAMO design : GM, Pole and 4th degree/order harmonics
  - GM exceeded the inflated uncertainty by a factor of 1.
  - S4,3 exceeded the inflated uncertainty by a factor of 1.
  - C4,4 exceeded the inflated uncertainty by a factor of 2.
- LAMO design: GM, Pole and 5th degree/order harmonics
  - Pole RA error of 0.003º exceeded the inflated uncertainty by a factor of 3.
  - Pole Declination error of 0.005º exceeded the inflated uncertainty by a factor of 13.
  - C5,5 and S5,5 exceeded the inflated uncertainty by a factor of 1.
- While none of the gravity terms exceeded “3-sigma” for the MC study, they still reflect a statistically significant error since the formal sigmas were inflated by 5.
- Pole errors are the most noteworthy. In practice, the actual errors did not result in any coverage issues or orbit plane issues.

Parameter Current Best Estimates (12/31/15)

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- After two weeks of observations in LAMO, the current best estimates (CBE) of Ceres GM, pole and zonal harmonics are shown here. (For brevity, values for sectoral harmonics are not shown.)
- The relatively poor knowledge of GM using radio data is due to having to allowing RCS thruster activity.

Parameter	Value (radio-only)	Value (radio+optical)
GM	62.63 ± 0.12 km^3/s^2	62.6307 ± 0.0009 km^3/s^2
Ceres Pole Right Ascension	291.44 ± 0.02º	291.419 ± 0.002º
Ceres Pole Declination	66.762 ± 0.004º	66.7616 ± 0.0004º
J[2]	1.15114e-2 ± 7e-7	1.15101e-2 ± 3e-7
J[3]	-3.96e-5 ± 2e-7	-3.95e-5 ± 2e-7
J[4]	-5.408e-4 ± 3e-7	-5.404e-4 ± 3e-7
J[5]	3e-7 ± 3e-7	1e-7 ± 3e-7
J[6]	2.07e-5 ± 4e-7	2.10e-5 ± 5e-7

Estimation performance

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- One other metric of gravity estimation performance is to model the predicted field against the reconstructed trajectory.
- The two primary sources of error in staying with the designed orbit are gravity prediction and RCS activity.
- The table below shows that RC3, HAMO and LAMO, the RCS activity resulted in phase errors that were significantly larger than what would be expected from gravity prediction errors.

Phase	Span	Error due to Gravity (º/day)	Error due to Gravity and RCS perturbation (º/day)
RC3	April 24th – May 9th, 2015	0.004	0.044
Survey	June 3rd – June 30th, 2015	0.016	0.035
HAMO	August 14th - October 23rd, 2015	0.038	0.358
LAMO	January 10th – February 8th, 2015	0.065	0.332

Estimation performance

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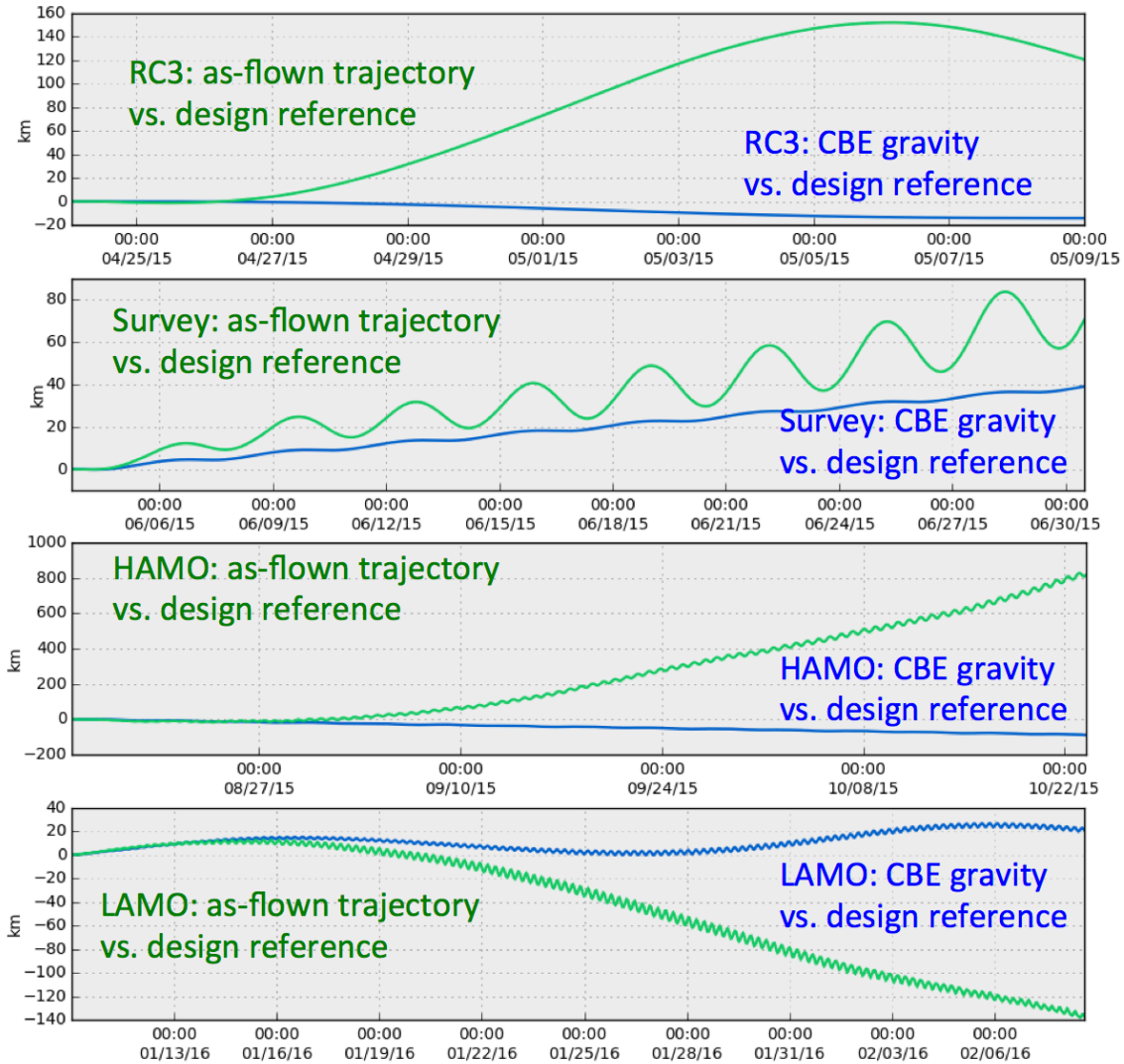
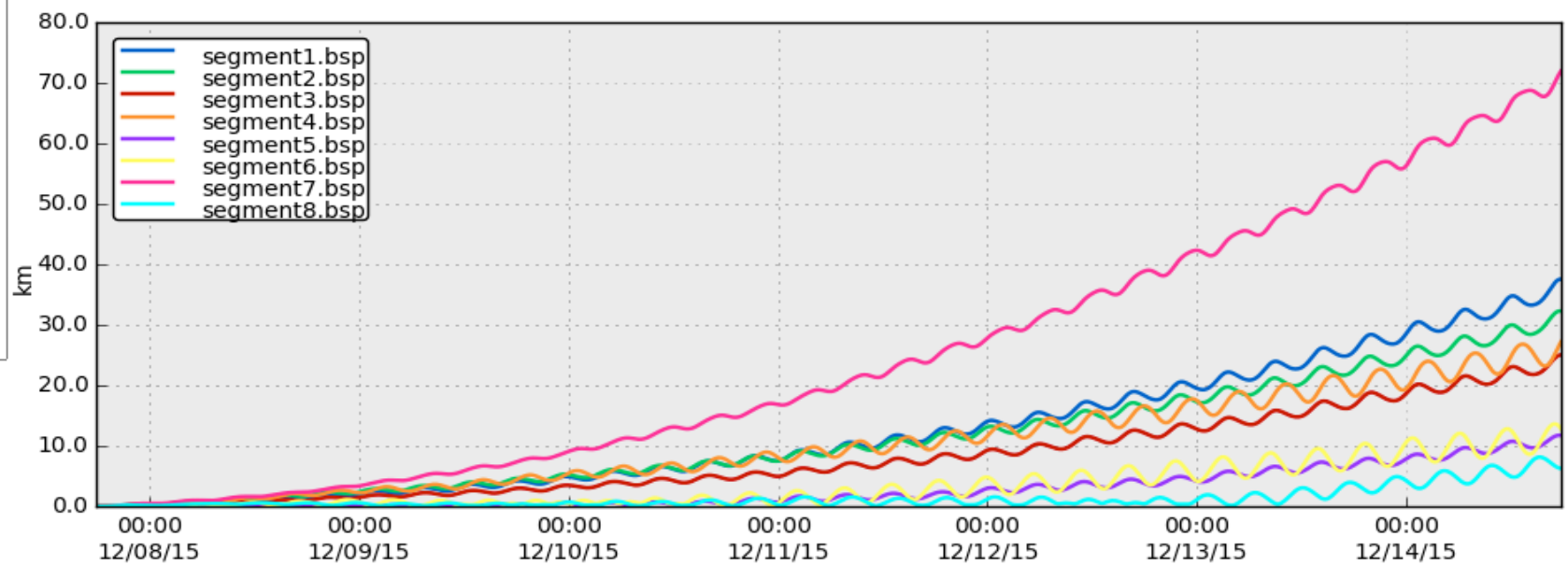


Gravity during Transfers

- Comparison of trajectories propagated through each of the gravity fields estimated for the 8 thrust segments in the HAMO to LAMO transfer.
- For the 7th segment (pink) the gravity estimate was poor due to underestimation of the field.
- For the 8th segment (light blue), a field estimated field with increased size gave the best agreement with the CBE gravity field.



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Post-transfer analysis

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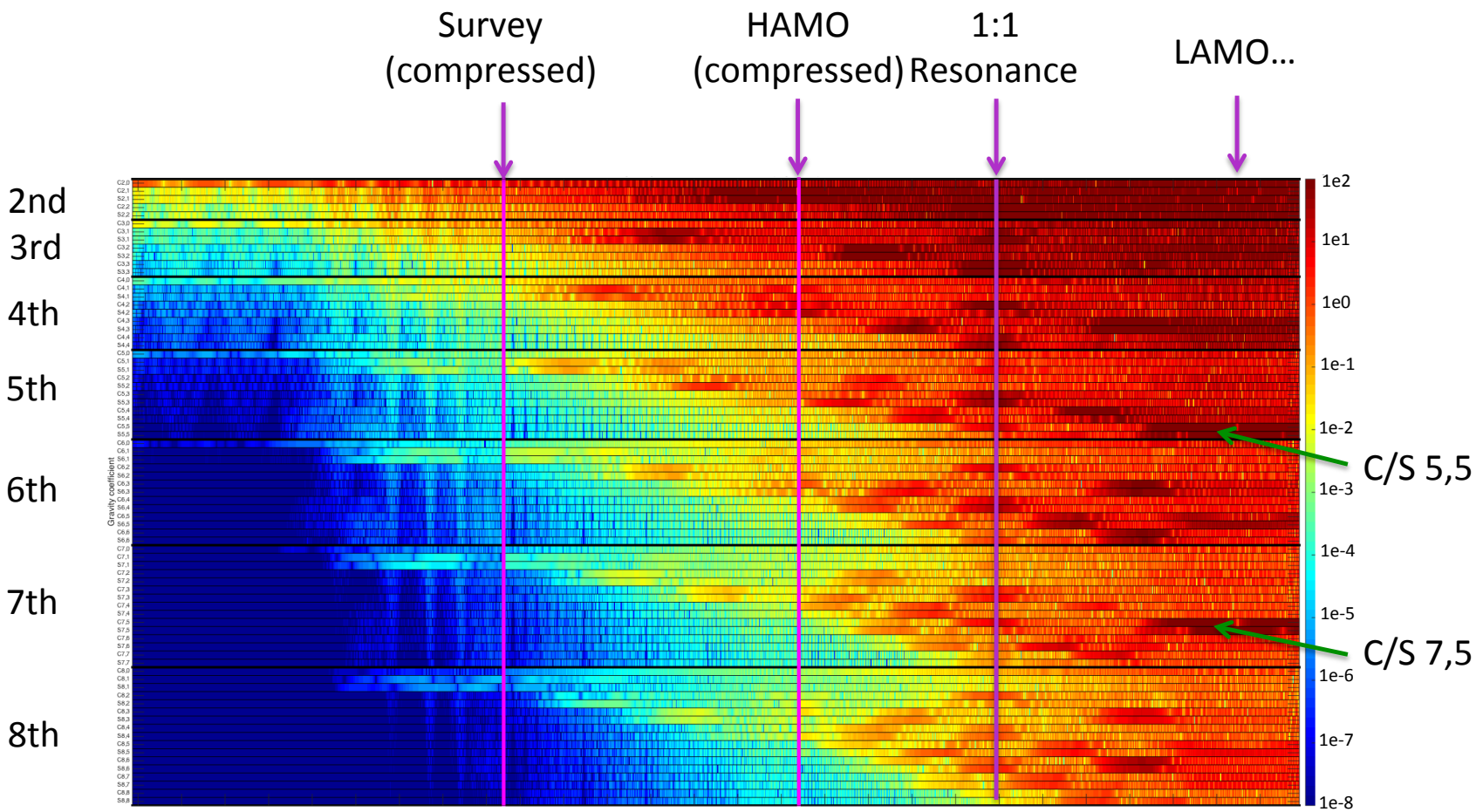
- Post-transfer analysis of the mathematical relationship between the downtrack position and the gravity field parameters showed a sensitivity to C5,5, S5,5, C7,5 and S7,5 at the altitudes during which segment 7 was designed and flown.
- Comparing the segment 7 and segment 8 gravity fields shows that parameters C5,5 and S5,5 were quite different.
- Since only up to degree/order 6 was estimated for segment 7, the signal for C7,5 and S7,5 was not modeled, and the field was mismodeled by using only parameters C5,5 and S5,5. This was corrected in segment 8 by estimating up to degree/order 8.

Sensitivity of downtrack position to parameters in gravity field



Transfer to SURVEY Transfer to HAMO Transfer to LAMO

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Lagrange's Planetary Equations

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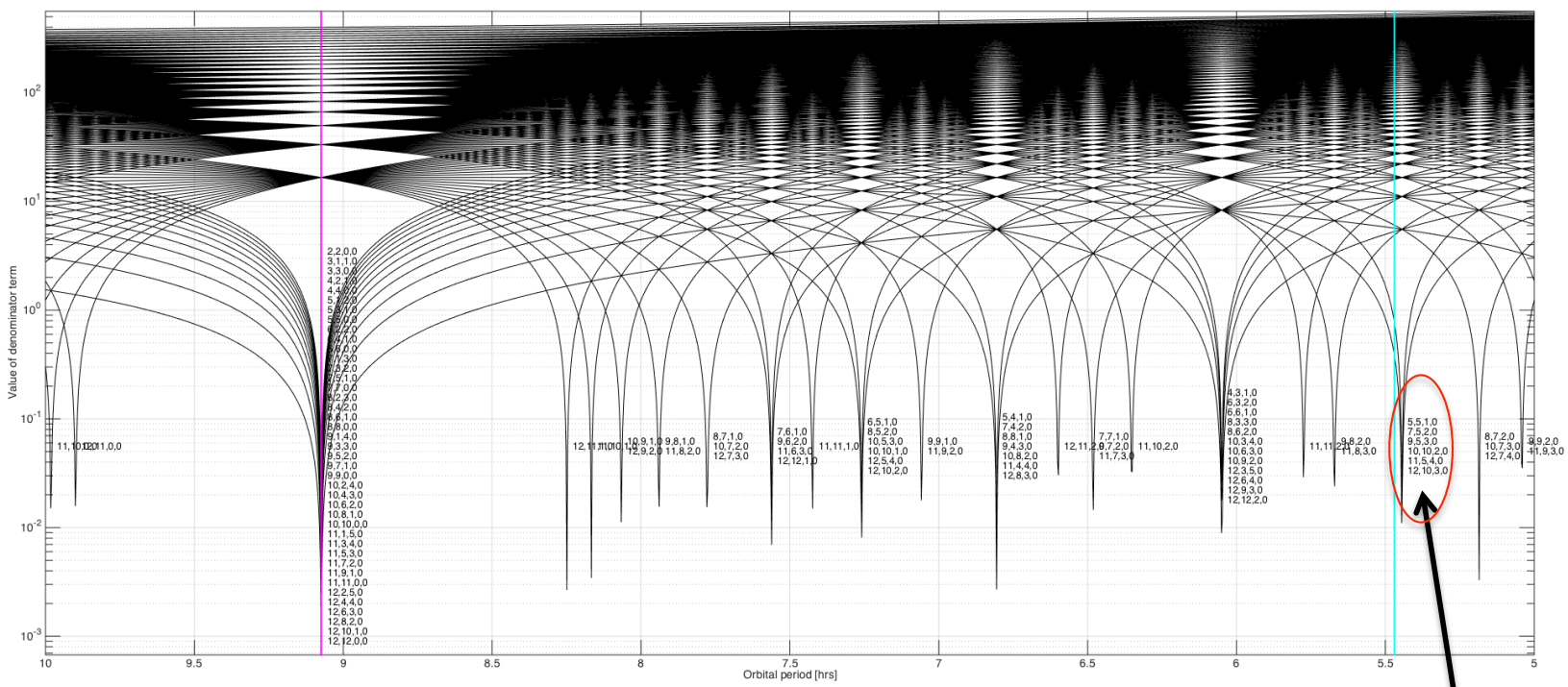
- Kaula's form of the Lagrange's Planetary Equations can also be used to identify sensitivities to specific parameters in the field.
- These equations can be used to compute the linearized sensitivity of classical orbital elements to specific gravitational harmonics parameters.
- One such equation, for semi-major axis, is shown here.
- *l, m, n* and *q* represent indices in the infinite summation that represents the gravity field potential.
- The following plot of the denominator shows where semi-major axis is sensitive to particular combinations of l, m, n and q.

$$\Delta a_{lmpq} = \mu R^l \frac{2F_{lmp}G_{lpq}(l-2p+q)S_{lmpq}}{na^{l+2}\left[(l-2p)\dot{\omega} + (l-2p+q)\dot{M} + m(\dot{\Omega} - \dot{\theta})\right]}$$

Orbital element sensitivity

1:1 resonance

LAMO altitude



Sensitivity to 5-5, 7-5, 9-3, …

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Conclusions

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- As of January 2016, all of the Ceres science orbits have been entered into successfully, and the mission requirements for science data collection have so far been met.
- When considering errors in OD estimation of physical parameters, it is useful to inflate the formal errors by at least a factor of five.
- At Ceres, observations of the gravity at high altitudes are sufficient to design precision orbits at lower altitudes.
- In most cases, RCS perturbations were a larger source of error than gravity field estimation errors.
- When descending into the gravity field, overestimation of the gravity field is recommended.
- Pre-encounter analysis of the mathematical state/field relationships or orbit element sensitivities is useful in identifying gravitational parameters that might prove to be problematic.