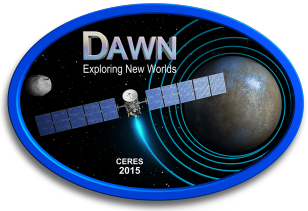

HYDRAZINE CONSERVATION FOR THE DAWN SPACECRAFT OPERATIONS AT THE DWARF PLANET CERES

Ryan S. Lim
Jet Propulsion Laboratory
California Institute of Technology
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OUTLINE

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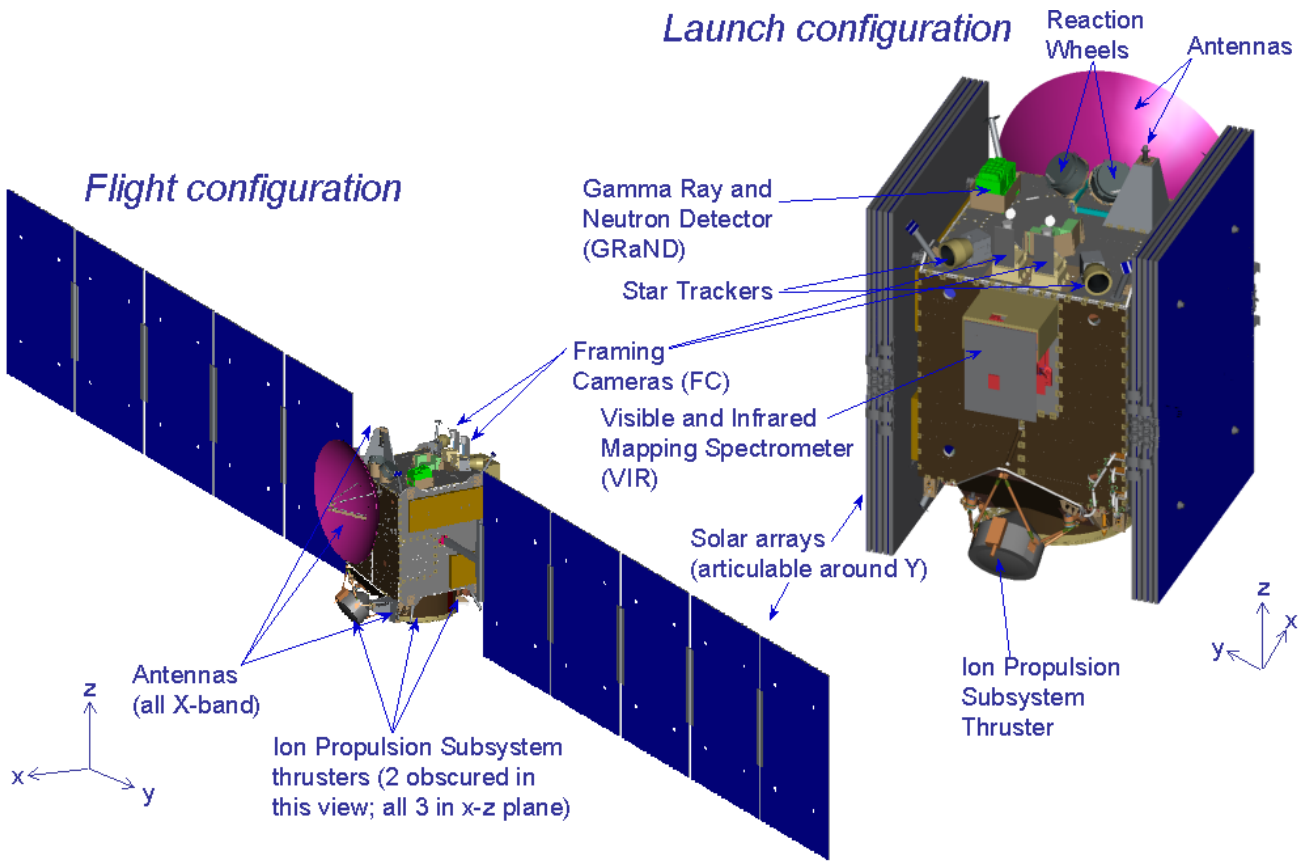
- Hydrazine Conservation Efforts
  - Prior to Vesta Departure
  - During Cruise to Ceres
  - At Ceres
- Dawn Ceres Extended Mission
- Summary & Future Considerations

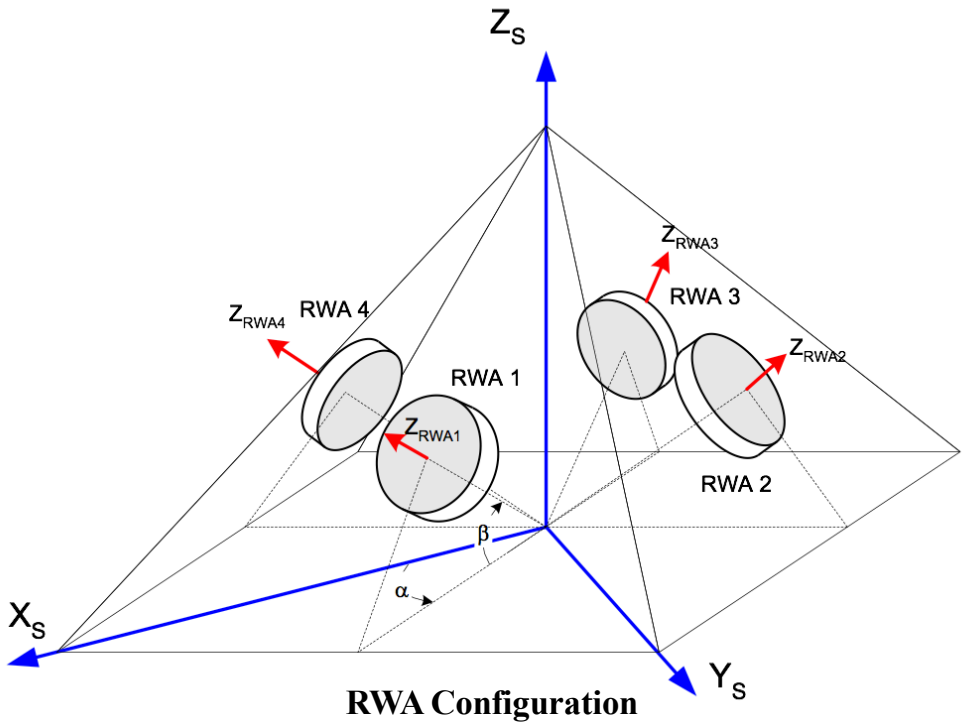
Introduction: the Dawn Mission

- NASA's 9th Discovery Mission
- Launch (Sep 2007), Vesta Prime Mission (July 2011 - Sep 2012), Ceres Prime Mission (Mar 2015 – June 2016), Ceres Extended Mission (July 2016 – Scheduled to end in June 2017)
- Low-thrust interplanetary mission using ion propulsion system
- First spacecraft to orbit two extraterrestrial (and non-solar) bodies

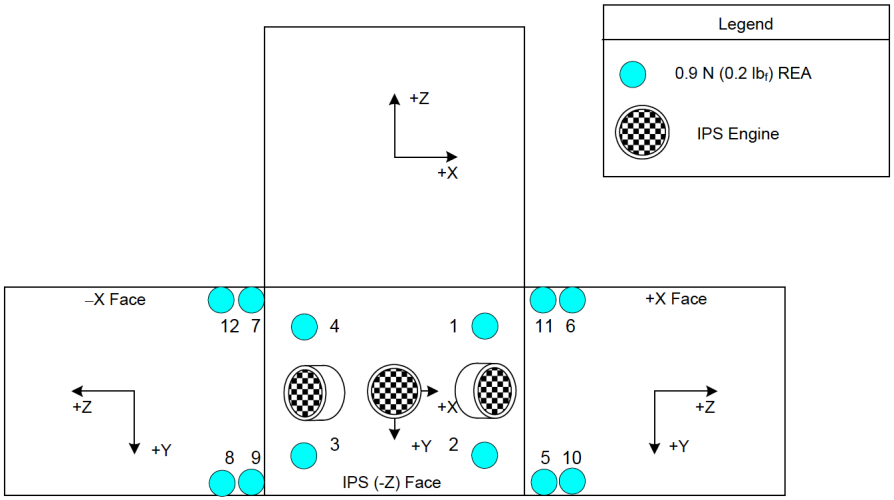


Introduction: Dawn Actuators

- 3-axis attitude control using reaction wheel assemblies (RWA) and hydrazine-based reaction control system (RCS)
- When thrusting with ion propulsion engine, 2-axis control is provided by engine gimbal and 3rd axis is controlled by either RWA or RCS
- RWA-4 Fault in 2010, RWA-3 Fault in 2012
  - Hydrazine conservation efforts began to ensure successful Vesta & Ceres mission



RWA Configuration



RCS Configuration

Hydrazine Conservation Efforts: Prior to Second RWA fault during Vesta Departure

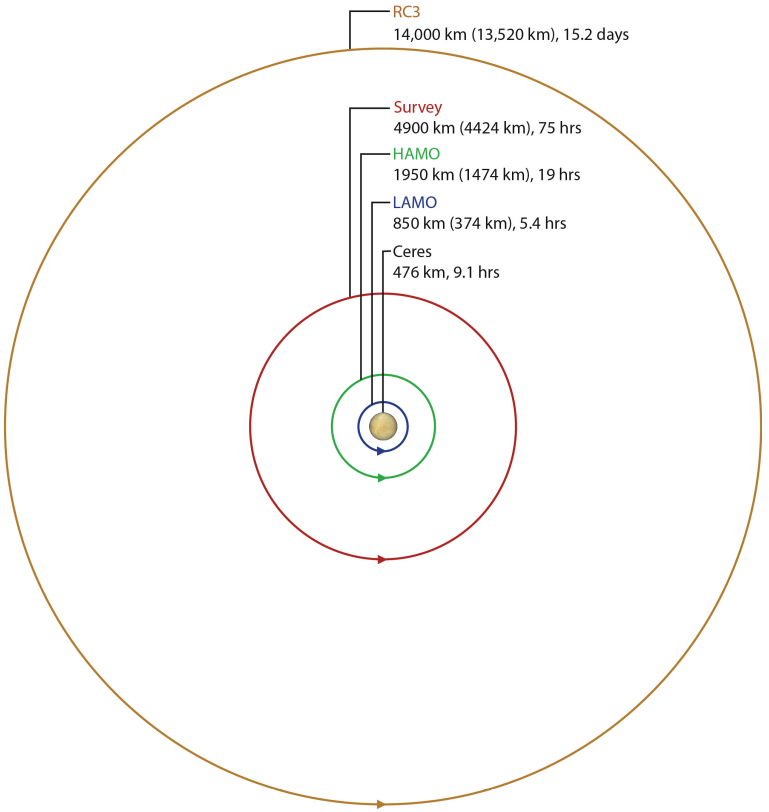
- The first RWA fault with RWA-4 occurred in June 2010
  - Approximately one year before the start of the Vesta mission
  - Premature failure after accumulating only ~25% (0.5 billion revolutions) of the expected lifetime of 2 billion revolutions (very conservative lifetime limit compared to the original lifetime limit of 8 billion revolutions)
- Three remaining RWAs were turned off to save lifetime
  - Remaining cruise to Vesta was done in all-RCS control
- In Nov 2010, new attitude control gains were implemented (loosened deadbands)
- Slew rate was reduced from 0.1 º/s to 0.05 º/s
- Hybrid control capability was developed and implemented in April 2011
  - 3-axis control using two RWAs and RCS thrusters
- The remaining three RWAs were turned on in May 2011 for Vesta operations
- The second RWA fault with RWA-3 occurred in Aug 2012
  - Failure occurred at ~1.1 billion revolutions
- Remaining hydrazine status at the second RWA failure
  - Launch: 42.7 kg, When RWA-3 faulted: 29.6 kg
  - Projected hydrazine at Ceres arrival at the time: 18 kg (if no changes were made to the mission operations plan without any further anomalies). The expectation, at the time, was that 18 kg was not enough to have a successful Ceres science campaign → More hydrazine savings needed !

Hydrazine Conservation Efforts: During Cruise to Ceres

- Number of turns was reduced
  - Dawn has to turn to point the High Gain Antenna (HGA) to Earth for each high-rate Deep Space Network (DSN) communication session
  - One of the most hydrazine-costly activities is turning
- Slew rate was further reduced from 0.05 º/s to 0.025 º/s
- Ceres science plan was re-architected
  - Original Ceres science plan assumed RWA use, which was no longer a possibility
  - Re-architecture focused on meeting science requirements even without further use of the two remaining reaction wheels
  - Number of turns was reduced (Ceres planned turns = 1/5 of Vesta planned turns)
    - Vesta plan had frequent communication turns when science data was not being acquired
    - Ceres plan included turns only when they were absolutely necessary: when onboard data storage was full or when it was necessary to conduct other engineering activities
- Remaining hydrazine status at Ceres arrival: 27.8 kg
  - Significantly better than 18 kg we would have had if none of the hydrazine saving efforts were implemented
  - Newly architected Ceres science plan would require ~17 kg of hydrazine expenditure for the Ceres prime mission

Science Orbits at Ceres

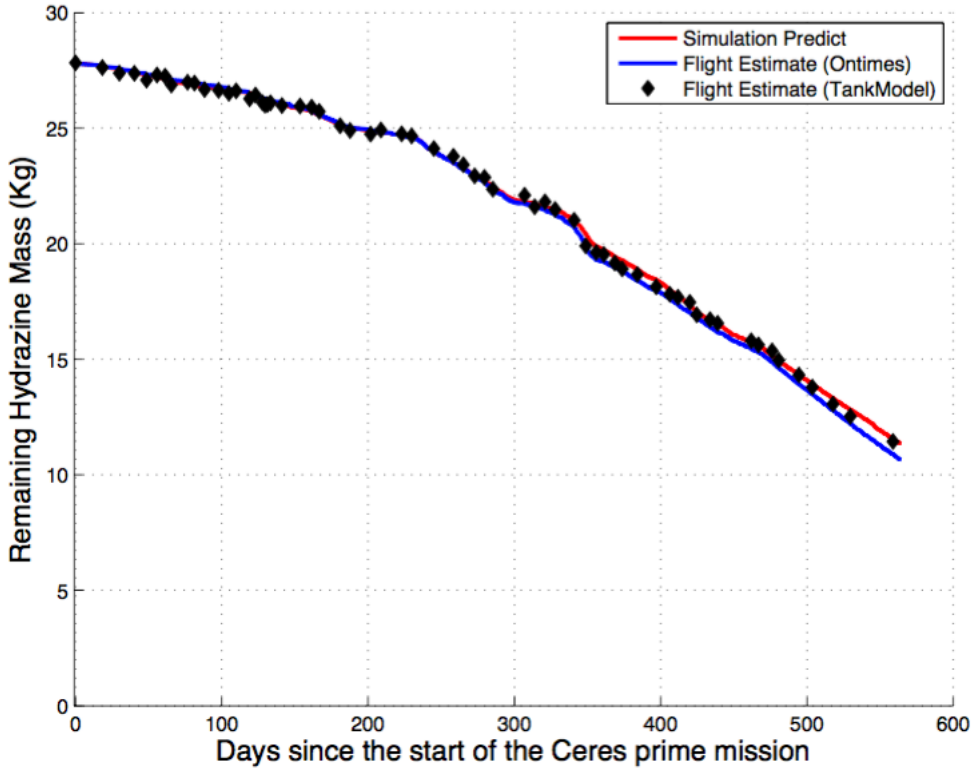
- Dawn began its Ceres prime mission in Dec 2014 shortly before being captured into orbit around Ceres in March 2015
- 4 main science orbits at Ceres
  - Rotational Characterization Orbit 3 (RC3), Survey, High Altitude Mapping Orbit (HAMO), Low Altitude Mapping Orbit (LAMO)



Ceres Science Orbits (Orbit Radius and Orbit Altitude)

Hydrazine Conservation Efforts: at Ceres (1/7)

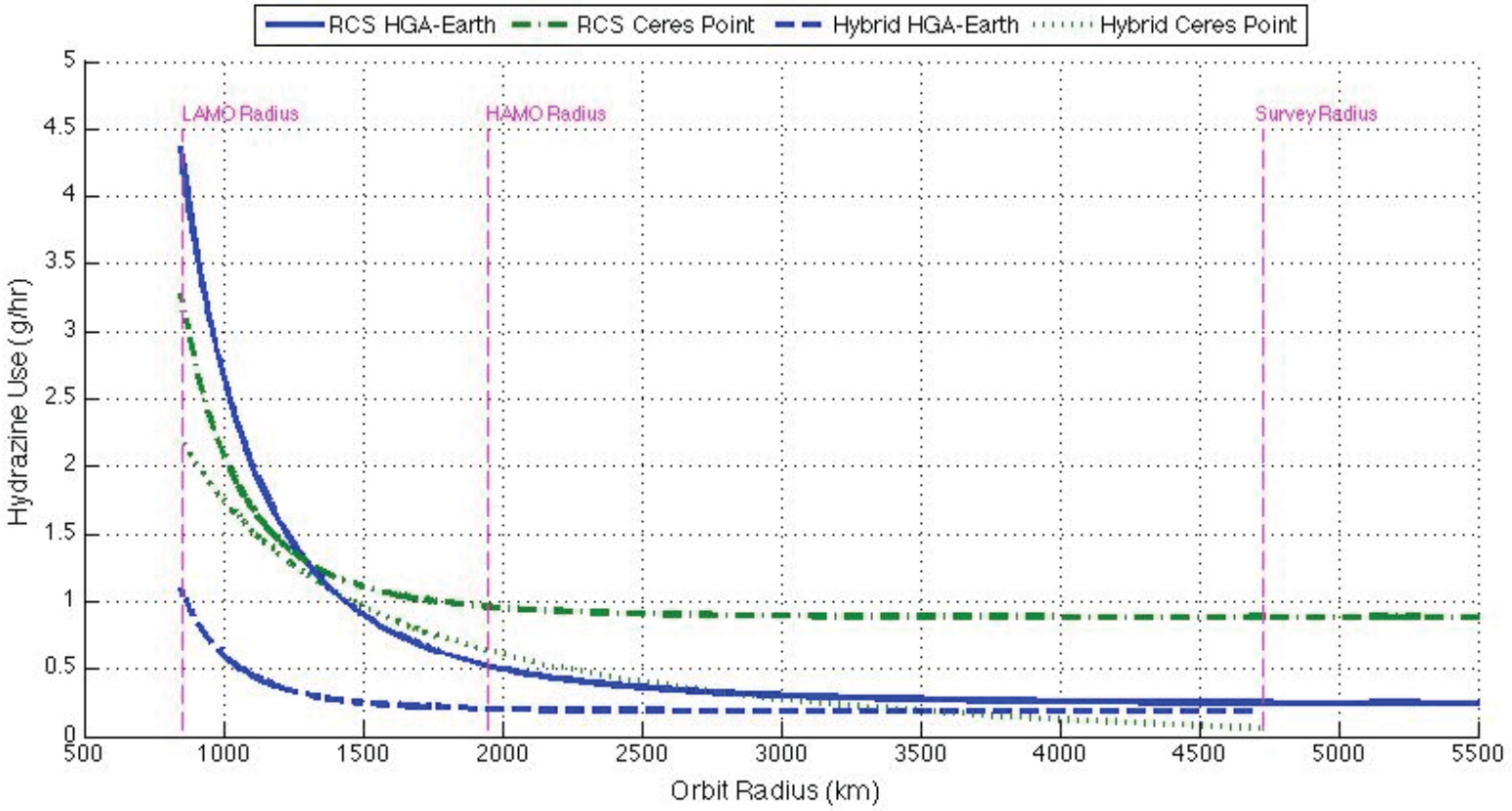
- Hydrazine conservation efforts still continued at Ceres
  - Mission Design and Navigation (MDNAV) team delivered transfer trajectory designs that would minimize the amount of coasting
    - When coasting, the ion propulsion thrusting is stopped and hydrazine-based thrusters are used to maintain attitude → 0.3 g/hr to 0.6 g/hr saving by keep thrusting instead of coasting
  - Hydrazine consumption was tracked on a weekly basis and compared to the simulation predictions. Simulation models were updated with flight experience



Hydrazine Consumption for the Entire Ceres Prime Mission

Hydrazine Conservation Efforts: at Ceres (2/7)

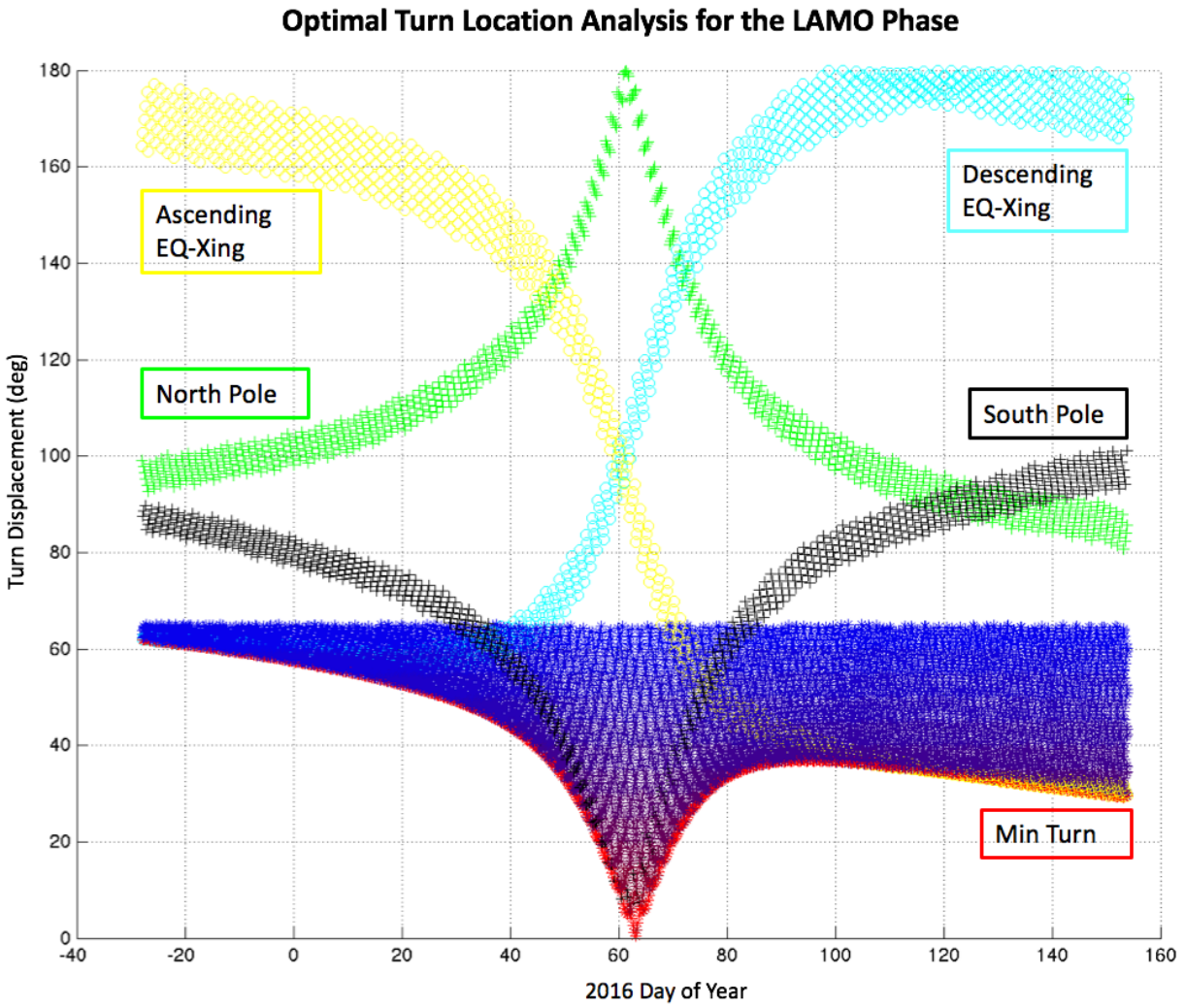
- Decision was made to wait until the LAMO orbit before using the hybrid control
  - The confidence in the remaining lifetimes of the two remaining RWAs was low
  - LAMO provides the greatest hydrazine savings



Hydrazine Cost vs. Orbit Radius

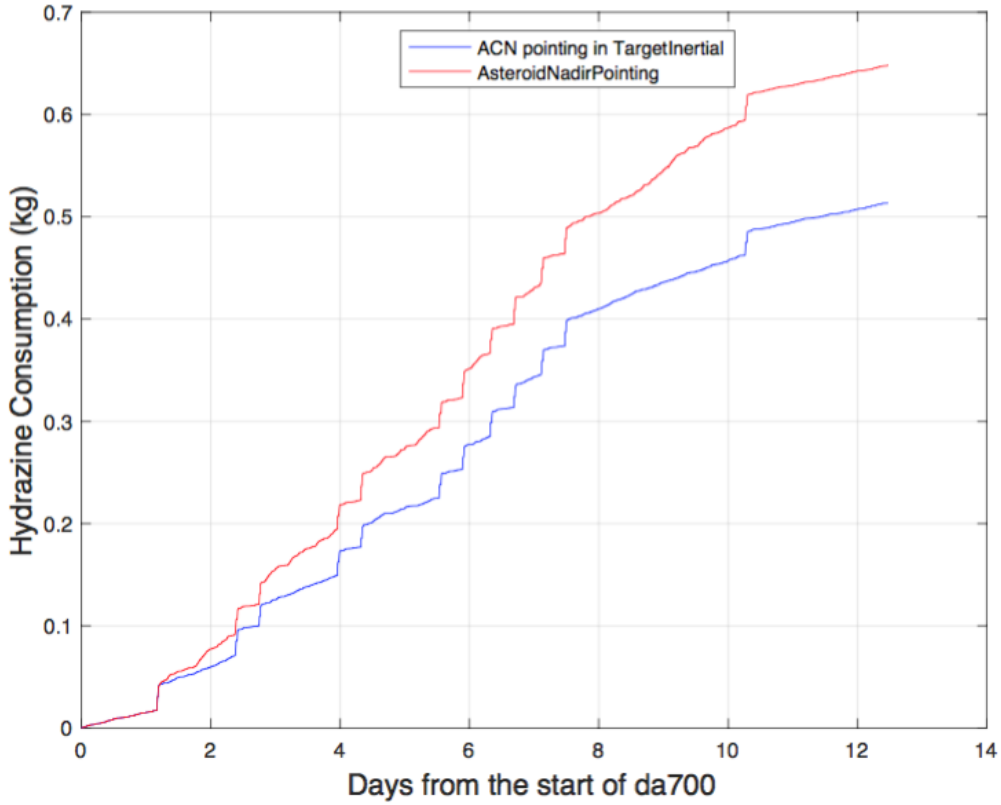
Hydrazine Conservation Efforts: at Ceres (3/7)

- Turns were placed optimally where turn displacements can be reduced



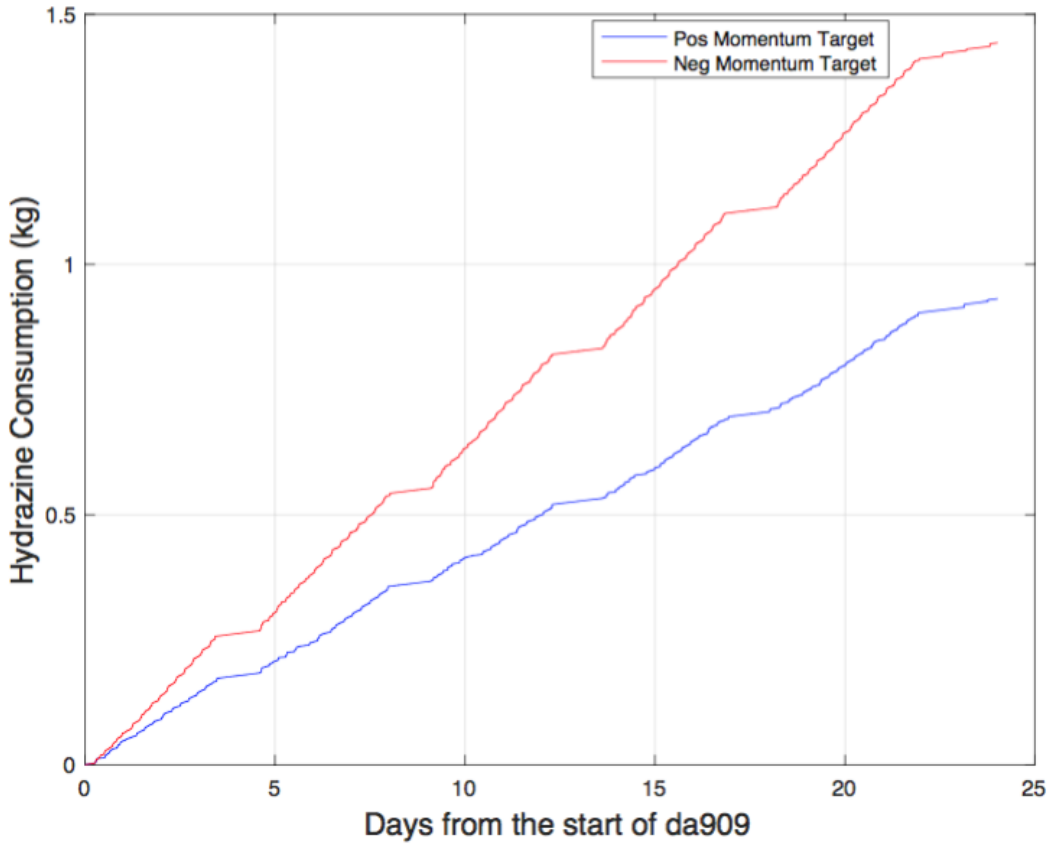
Hydrazine Conservation Efforts: at Ceres (4/7)

- Ahead Cross Nadir (ACN) pointing in "TargetInertial" mode used for nadir pointing instead of using "AsteroidNadirPointing" mode
  - Ahead: Velocity Direction, Cross: completes the right hand orthonormal coordinate system with Nadir direction. ACN pointing in "TargetInertial" mode with [0, 0] deg target achieves same pointing as nadir pointing in "AsteroidNadirPointing" mode. Hydrazine saving comes from the special filtering algorithm that reduces excessive thruster firings in all-RCS "TargetInertial" mode. "AsteroidNadirPointing" mode does not have this special filtering algorithm as it assumes to use RWA
  - More than 100 g saving for da700, the first HAMO cycle



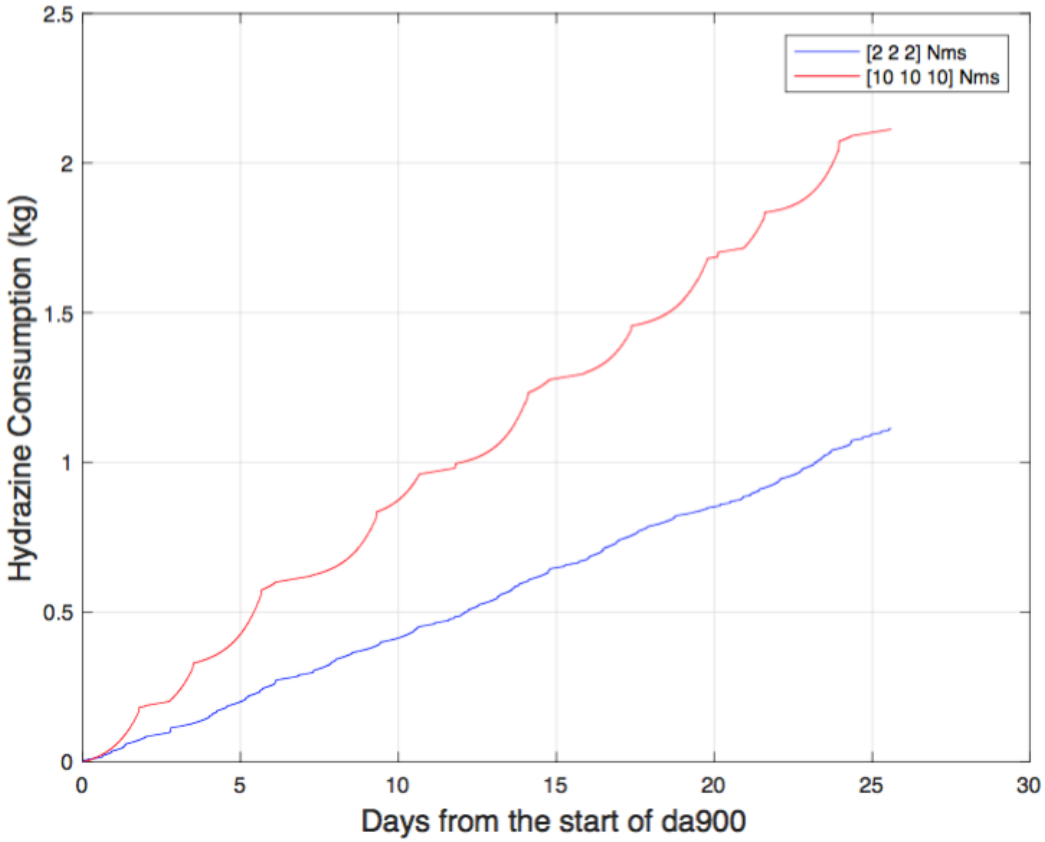
Hydrazine Conservation Efforts: at Ceres (5/7)

- RWA parameter optimization: Angular momentum adjust target
  - Polarity of the spacecraft angular momentum adjust target, either [0.0, 0.81, 1.15] Nms or [0.0, -0.81, -1.15] Nms was carefully chosen to minimize number of momentum unloadings
  - During a momentum unloading, RCS thrusters produce counter torque to cancel the resulting RWA torque on the body. Fewer momentum unloadings translates into conserving more hydrazine
  - (Ex) ~500g could be saved for da909, the last LAMO sequence of the Ceres prime mission



Hydrazine Conservation Efforts: at Ceres (6/7)

- RWA parameter optimization: Angular momentum error high threshold
  - [2.0, 2.0, 2.0] Nms were used instead of using a larger threshold on the order of [10.0, 10.0, 10.0] Nms. (Full RWA control used [6.0, 11.5, 11.5] Nms)
  - Momentum stored in each reaction wheel is minimized by using smaller error high threshold → less RWA gyroscopic stiffness that the RCS thruster controlled axis has to overcome
  - ~ 1 kg saving for da900, the first LAMO cycle



Hydrazine Conservation Efforts: at Ceres (7/7)

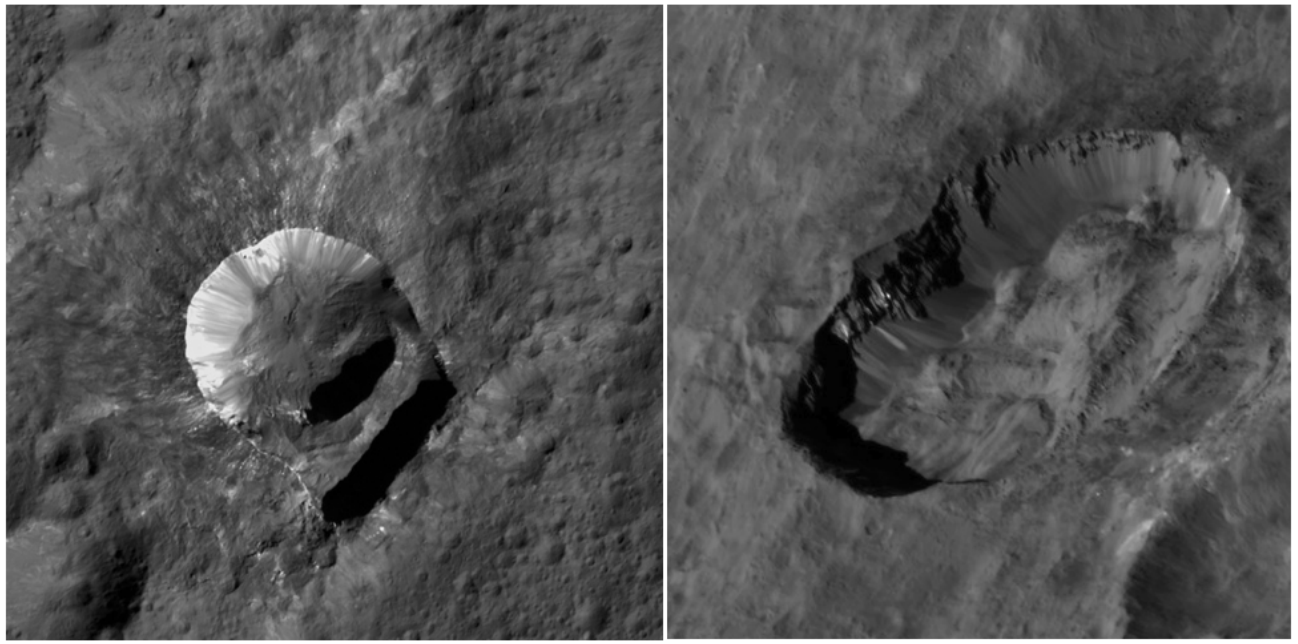
- Choosing hydrazine friendly off-nadir ACN targets for the LAMO topography campaign
  - Mapping Ceres with off-nadir pointing
  - Collaboration between Attitude Control Subsystems Team and Science Operations Support Team
  - (ex) ACN target of [0, -5] costs five times less hydrazine than [-7, 7]

Cross Angle (deg) \ Ahead Angle (deg)	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
7	1773							1582							
6		1669						1502							
5			1552					1474					1628		
4								1453							
3	1619							1358							1680
2								1315							
1								1176							
0	1538	1561	1566	1432	1296	1209	1202	1146	1220	1282	1374	1455	1445	1557	1611
-1								1093							
-2								1037							
-3	1407							786							1439
-4								346							
-5			1043					342					1048		
-6								360							
-7	1158							386							1250

Hydrazine Cost (in grams) for Various Off-Nadir ACN Targets in the LAMO orbit

Dawn Extended Mission

- Dawn operations has been extended until June 30, 2017
- Extended Mission Orbit 1 (XMO1): improving and wrapping up science campaign at the 385 km LAMO orbit
- Extended Mission Orbit 2 (XMO2): observation of the Oxo and Juling craters at 1500 km orbit

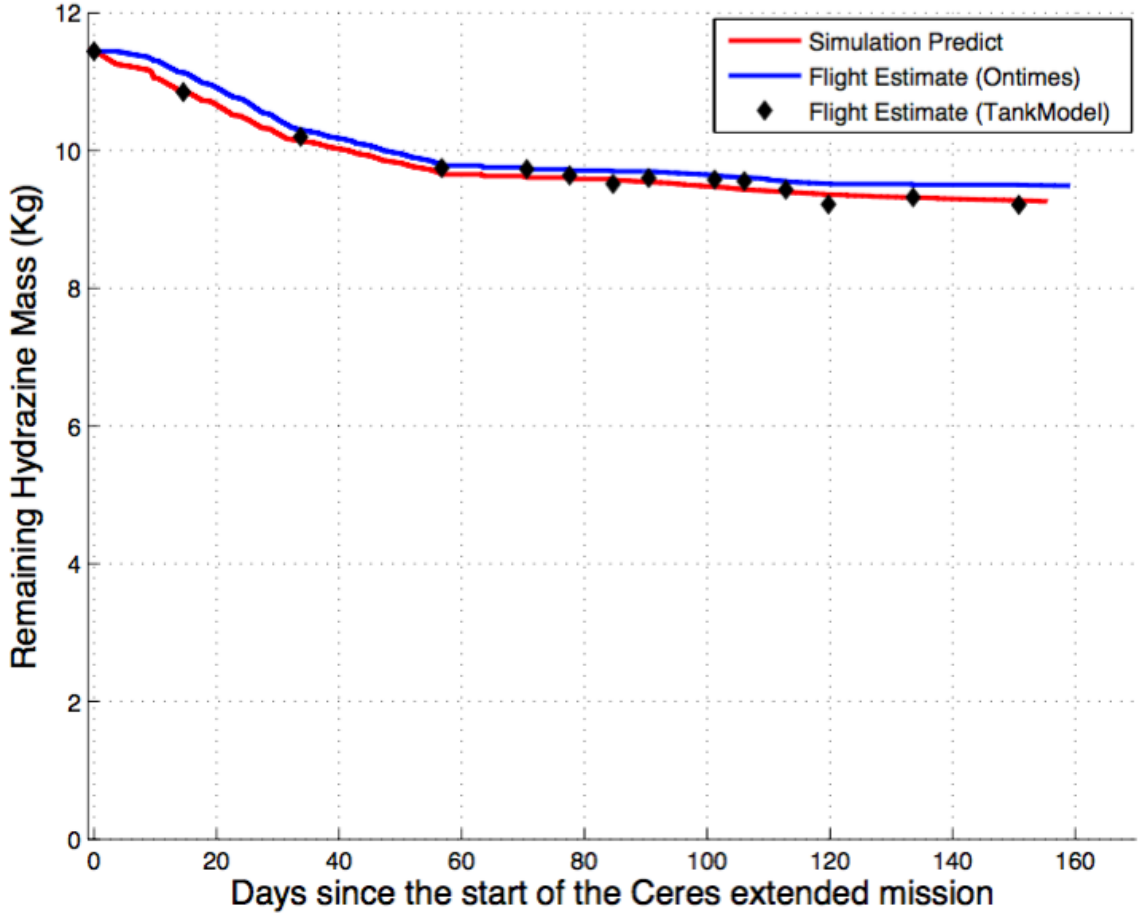


Oxo crater (left) and Juling crater (right)

- Extended Mission Orbit 3 (XMO3): >7200 km orbit, background spectra for the gamma ray and neutron detector (GRaND) instrument are being continuously obtained

Hydrazine Status as of Dec 2016

- Dawn started the Ceres Extended Mission with 11.4 kg of remaining hydrazine
- At the beginning of XMO3 in Dec 2016, there was 9.2 kg of remaining hydrazine



Ceres Extended Mission Hydrazine Consumption through the Start of XMO3 (Dec 2016)

Summary and Future Considerations

- Dawn has successfully completed the Vesta and Ceres prime mission
- After a series of reaction wheel faults, the project had to promptly undertake a major campaign to conserve hydrazine
- The two remaining reaction wheels have been working flawlessly

- If another RWA fault occurs:
  - Will have to transition to all-RCS control
  - Opening up deadbands further to the maximum allowable values while still maintaining acceptable HGA pointing would reduce hydrazine consumption
  - The spacecraft slew rate, which was changed to 0.05 º/s for Ceres operations after completing Cruise to Ceres at 0.025 º/s, can be set back to 0.025 º/s

- Current estimates predict that there will still be significant hydrazine left at the end of the extended mission
  - Another extended mission is a real possibility

QUESTIONS

BACK UP

Dawn Extended Mission Schedule