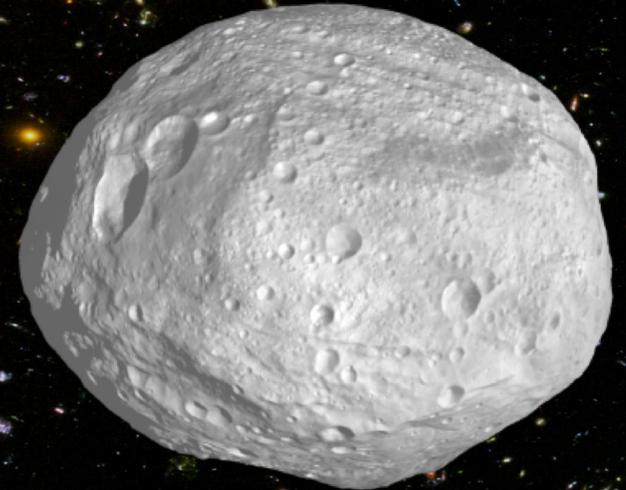
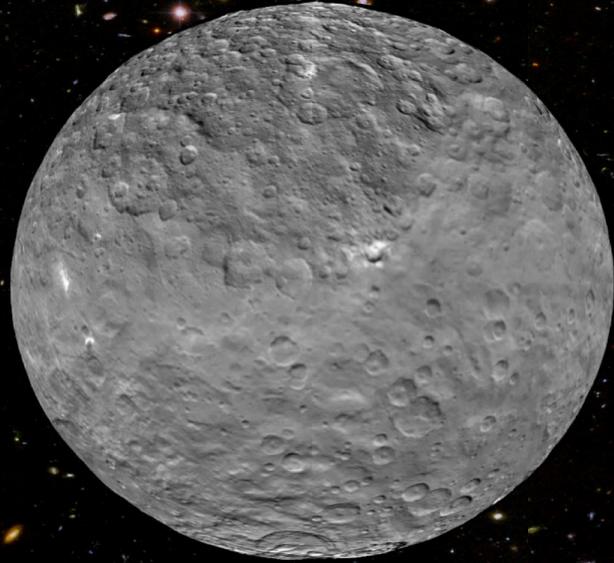


# Dawn's Final Mission at Ceres: Navigation and Mission Design Experience

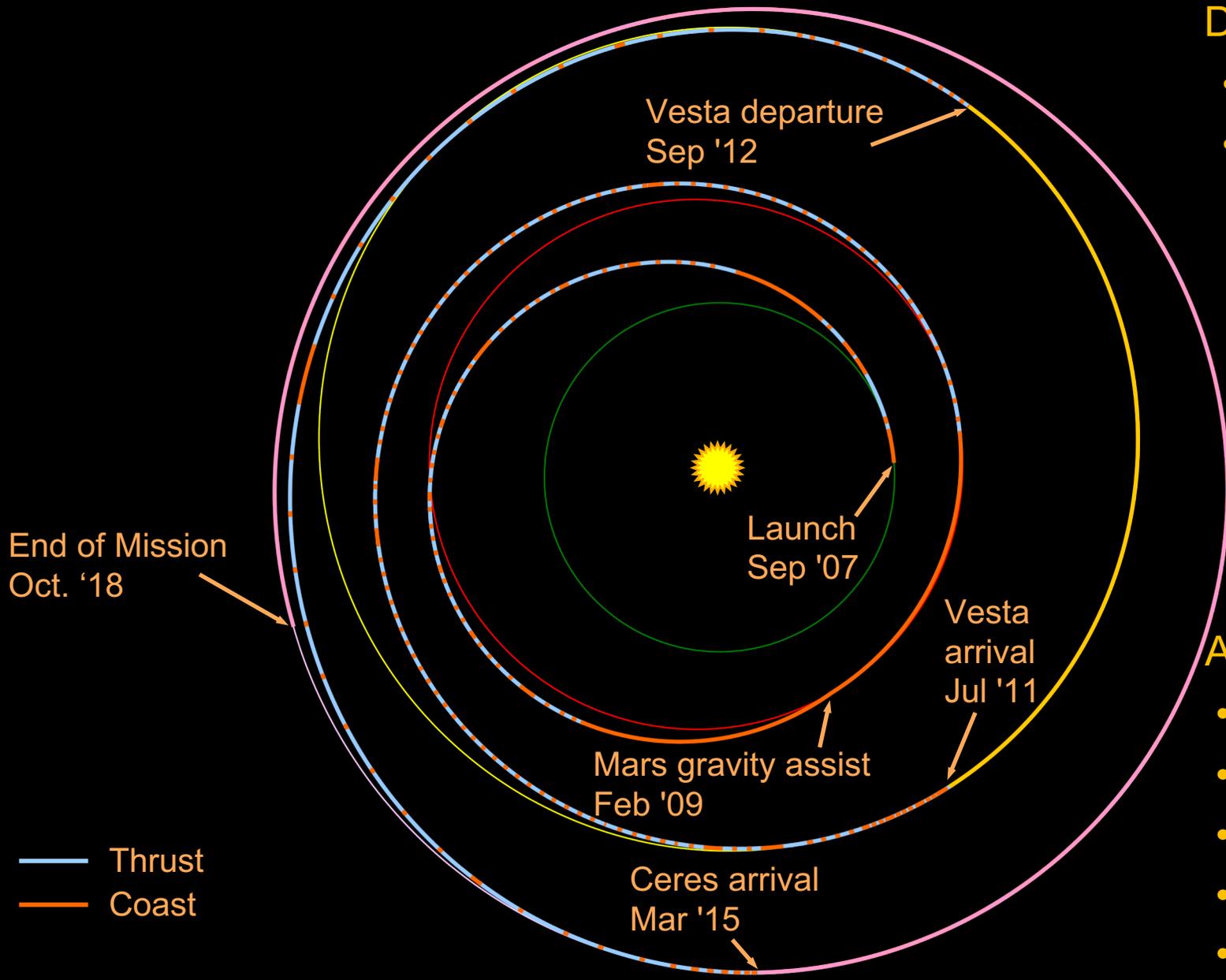


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Dongsuk Han  
Jet Propulsion Laboratory  
California Institute of Technology

*Credit: Marc Rayman*



## Dawn:

- NASA's Discover Program
- The first mission ever to orbit two different extraterrestrial bodies

## At Vesta and Ceres, Dawn:

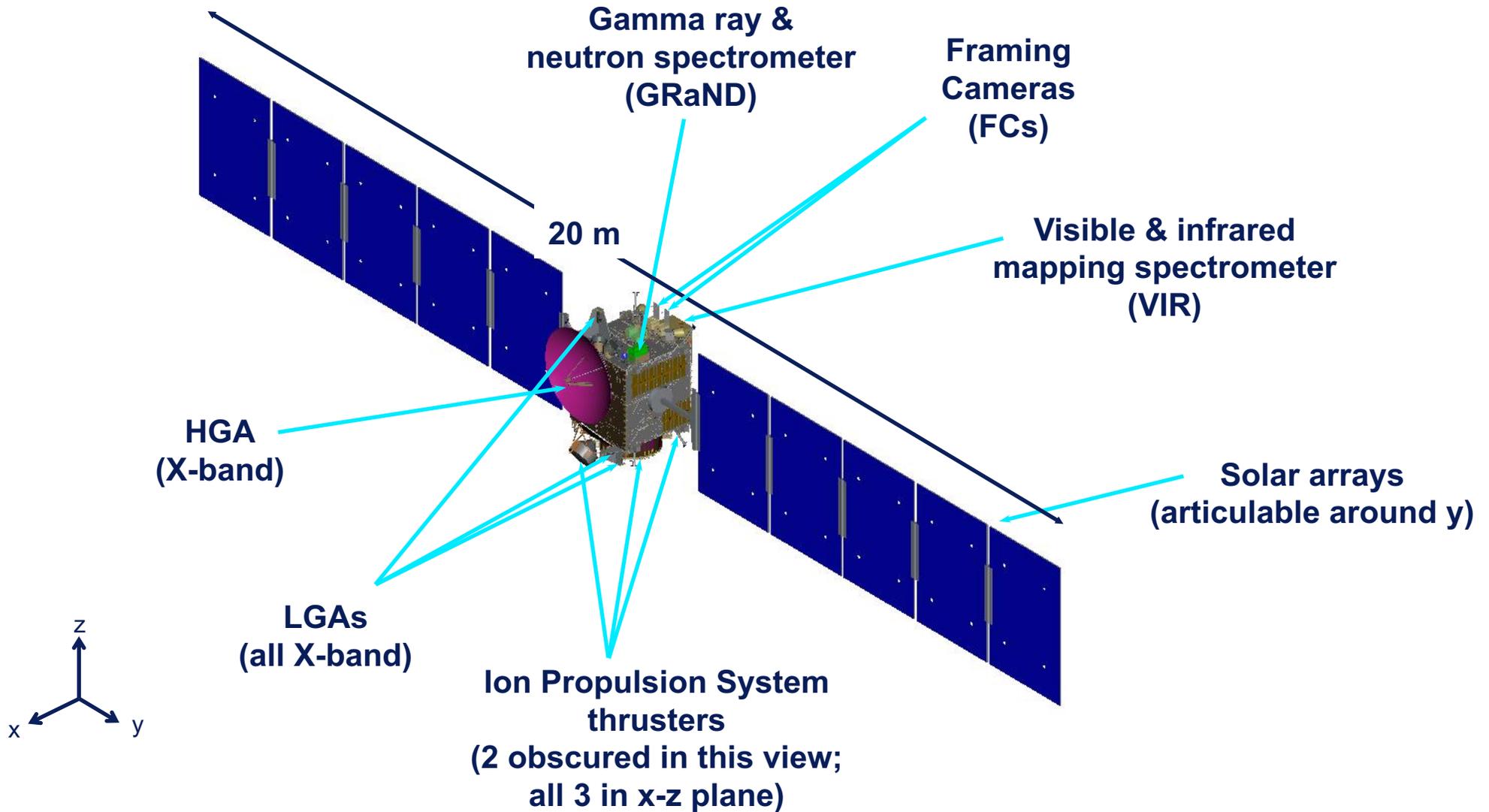
- Mapped the surface in color
- Acquired stereo imagery
- Mapped the elemental composition
- Mapped the mineralogical composition
- Measured the gravity field
- Searched for moons



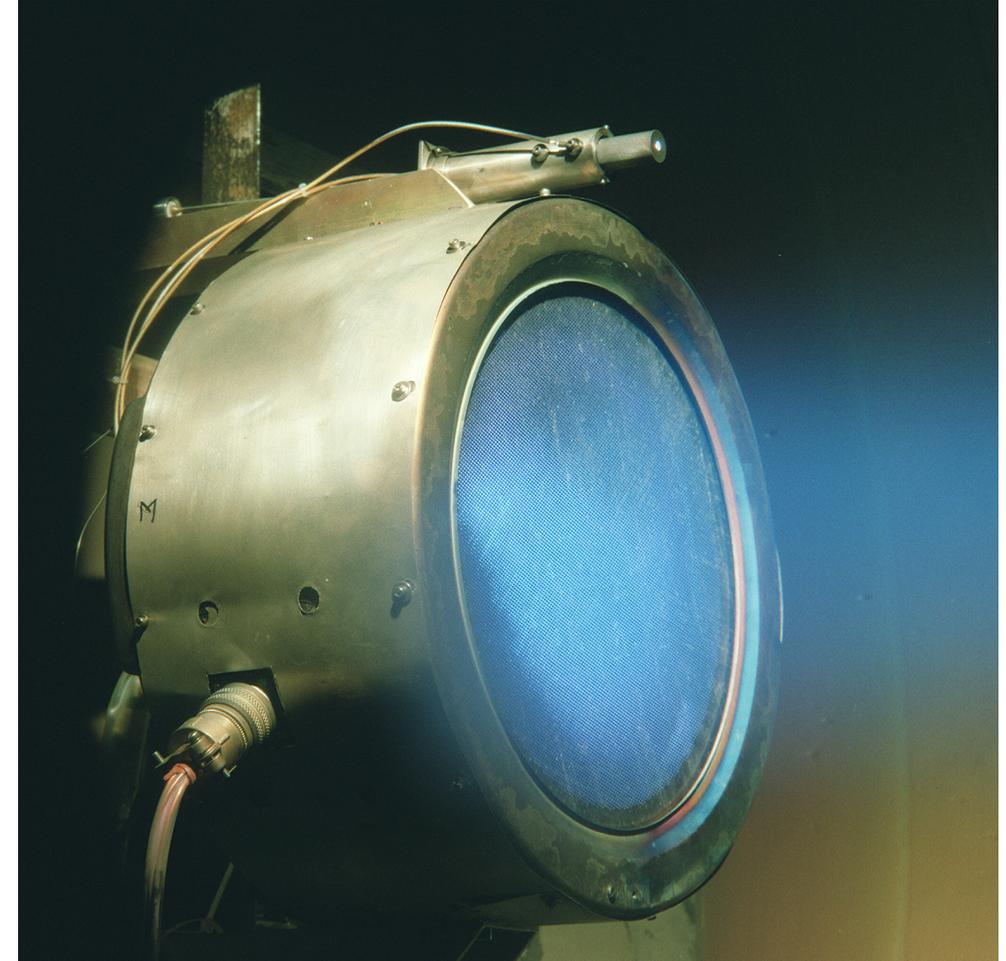
# Dawn Flight System Configuration



Dawn



- Dawn's Ion Propulsion System (IPS) is inherited directly from the design proven on Deep Space 1.
- IPS  $\Delta V = 11.5 \text{ km/s} > \text{Delta 7925H } \Delta V$
- Dawn's IPS has been on for 51,385 hours (5.87 years).
- The IPS has been used for all nominal post-launch trajectory control, including TCMs, orbit transfers, and Orbit Maintenance Maneuvers.
- Maximum thrust 91.6 mN, 76 – 46 mN at Vesta, 25 – 18 mN at Ceres
- Overall duty cycle since launch  $\approx 53 \%$



## Prime Mission

### Rotation Characterization 3 (RC3)

- 14,000 km radius, 15 days, 1 orbit
- Nadir rotation movies, high phase observations

### Survey

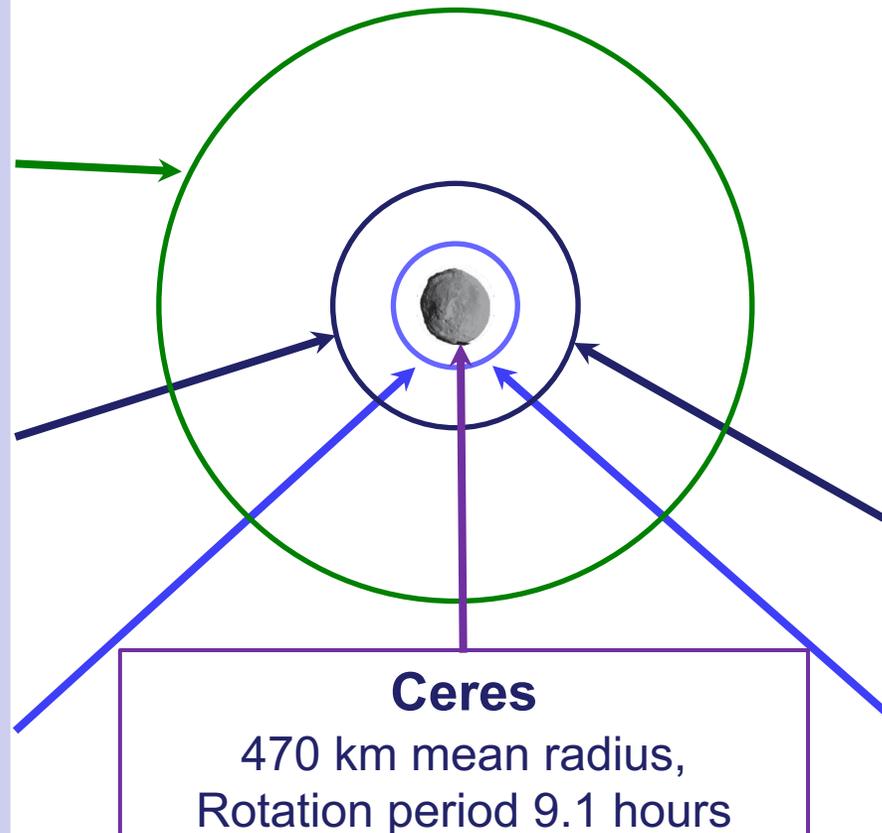
- 4900 km radius, 75 hrs, 7 orbits (22 days)
- Nadir mapping, limb observations

### HAMO

- 1950 km radius, 19 hrs, 6x14 orbits (56 days)
- Nadir and fixed off-nadir mapping

### LAMO

- 850km radius, 5.4 hrs, 404 orbits (92 days)
- Mapping gravity field & elemental composition (GRaND)



## Extended Mission 1 (XM1)

### XMO 5

- Jun. 24, 2017 – Apr. 15, 2018
- Orbit period 30 days, staging orbit
- GRaND background measurement

### XMO 4

- Apr. 27, 2017 – Jun. 3, 2017
- Altitude < 20,000 km
- Occator measurement at low phase

### XMO 3

- Dec. 6, 2016 – Feb. 22, 2017
- Altitude > 72,000 km
- GRaND background measurement

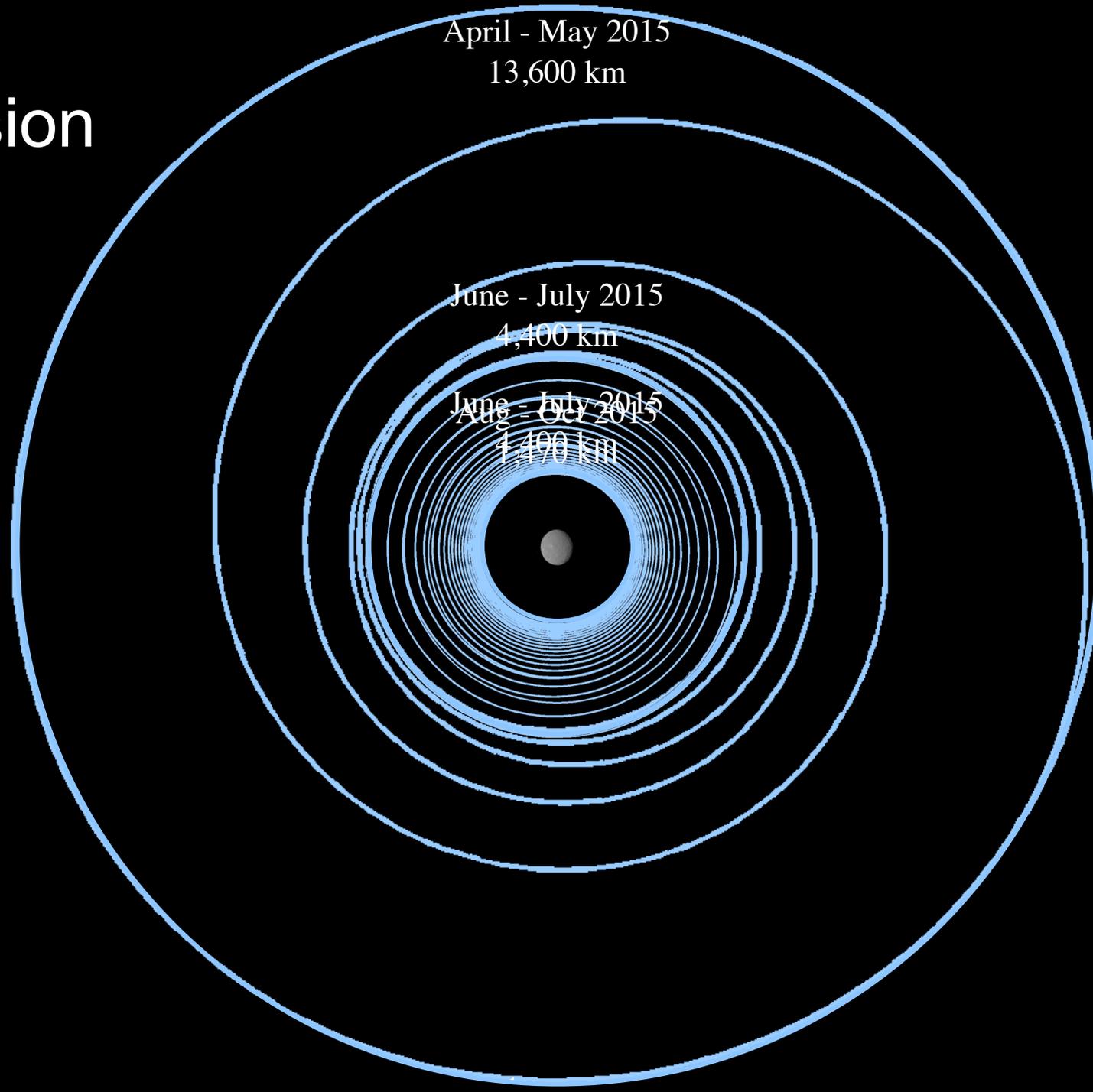
### XMO 2

- Oct. 6, 2016 – Nov. 3, 2016
- VIR's Juling Observation

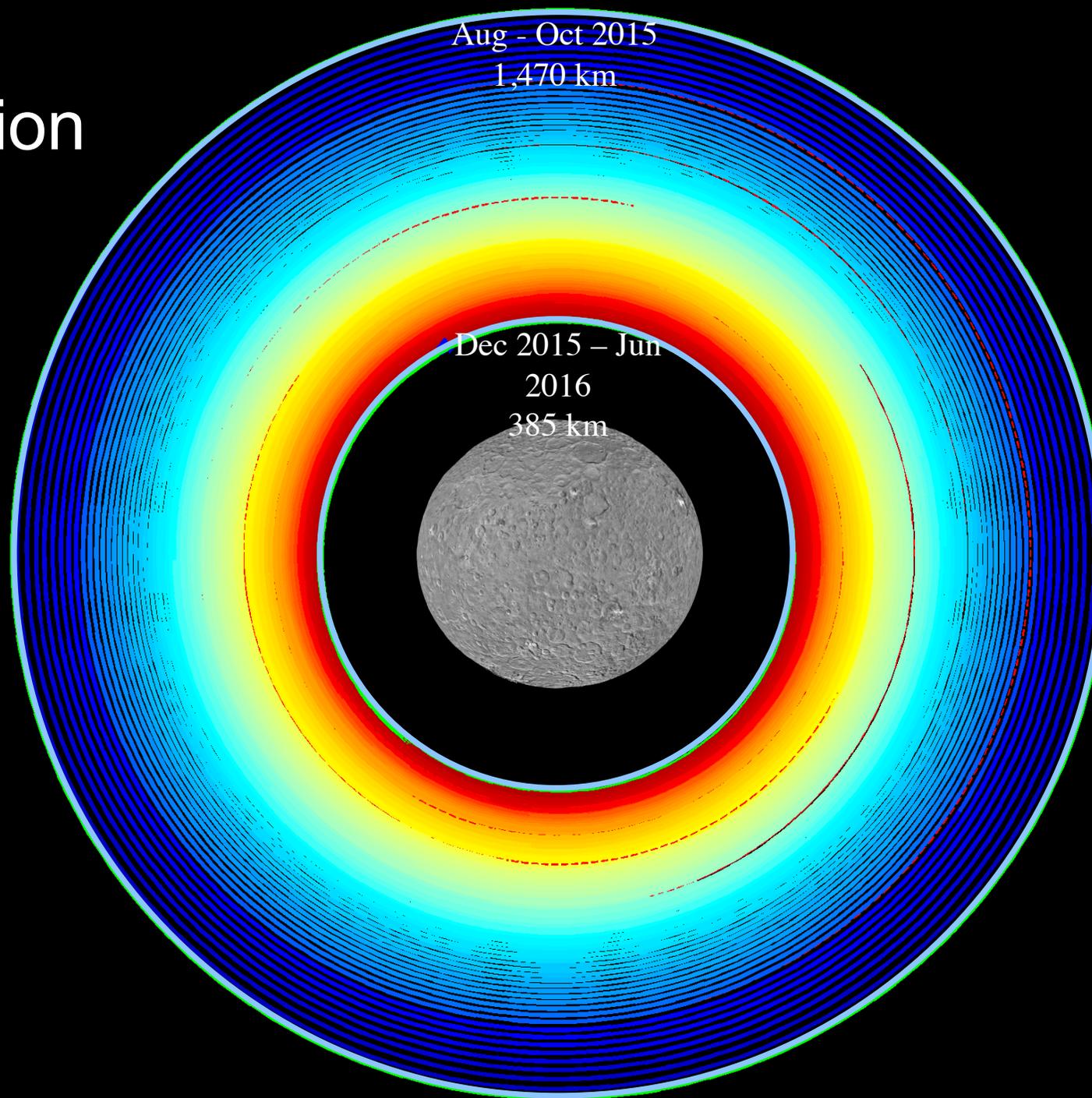
### XMO 1

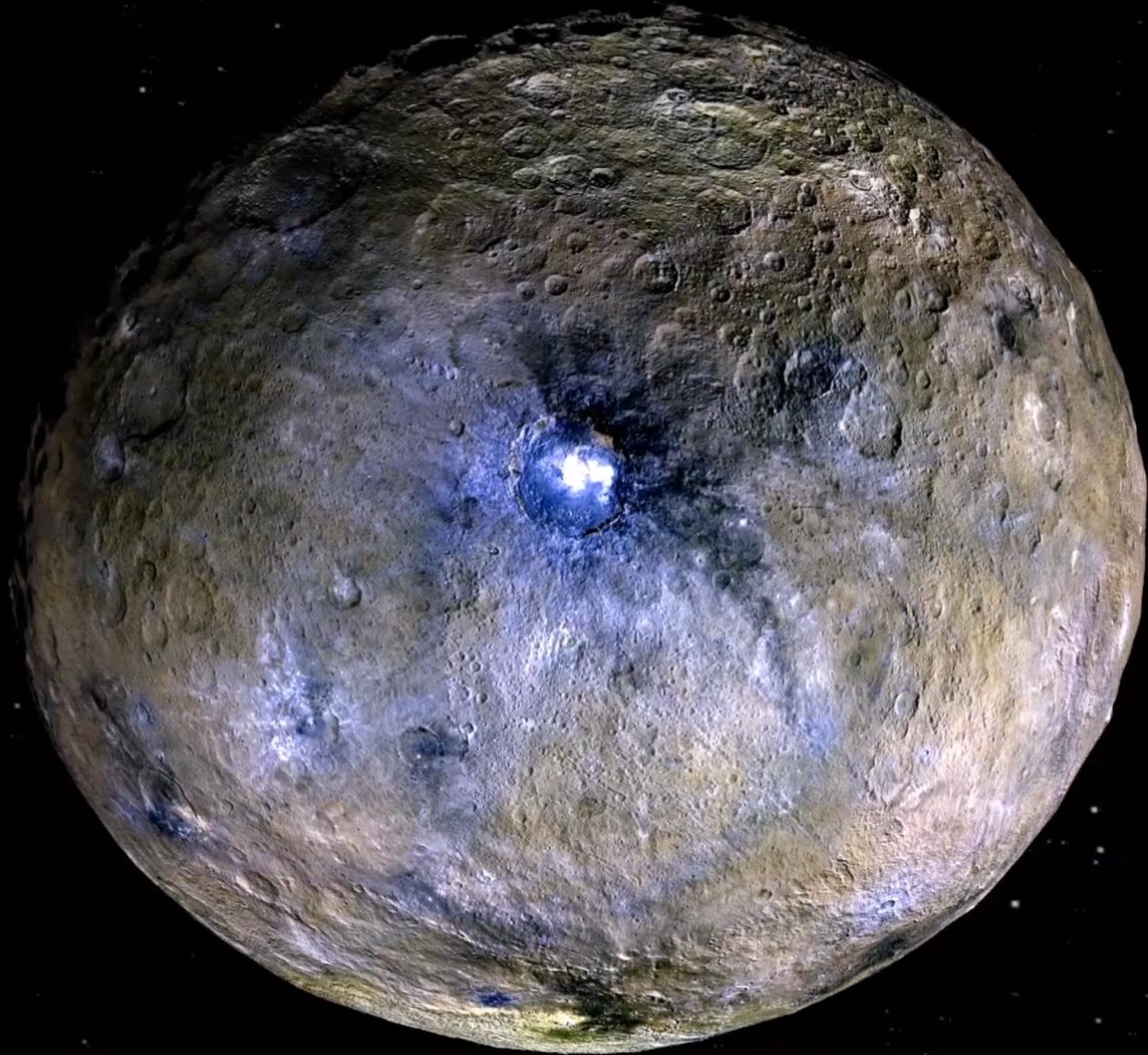
- July 1, 2016 – Sep. 1, 2016
- GRaND & Gravity

# Ceres Prime Mission

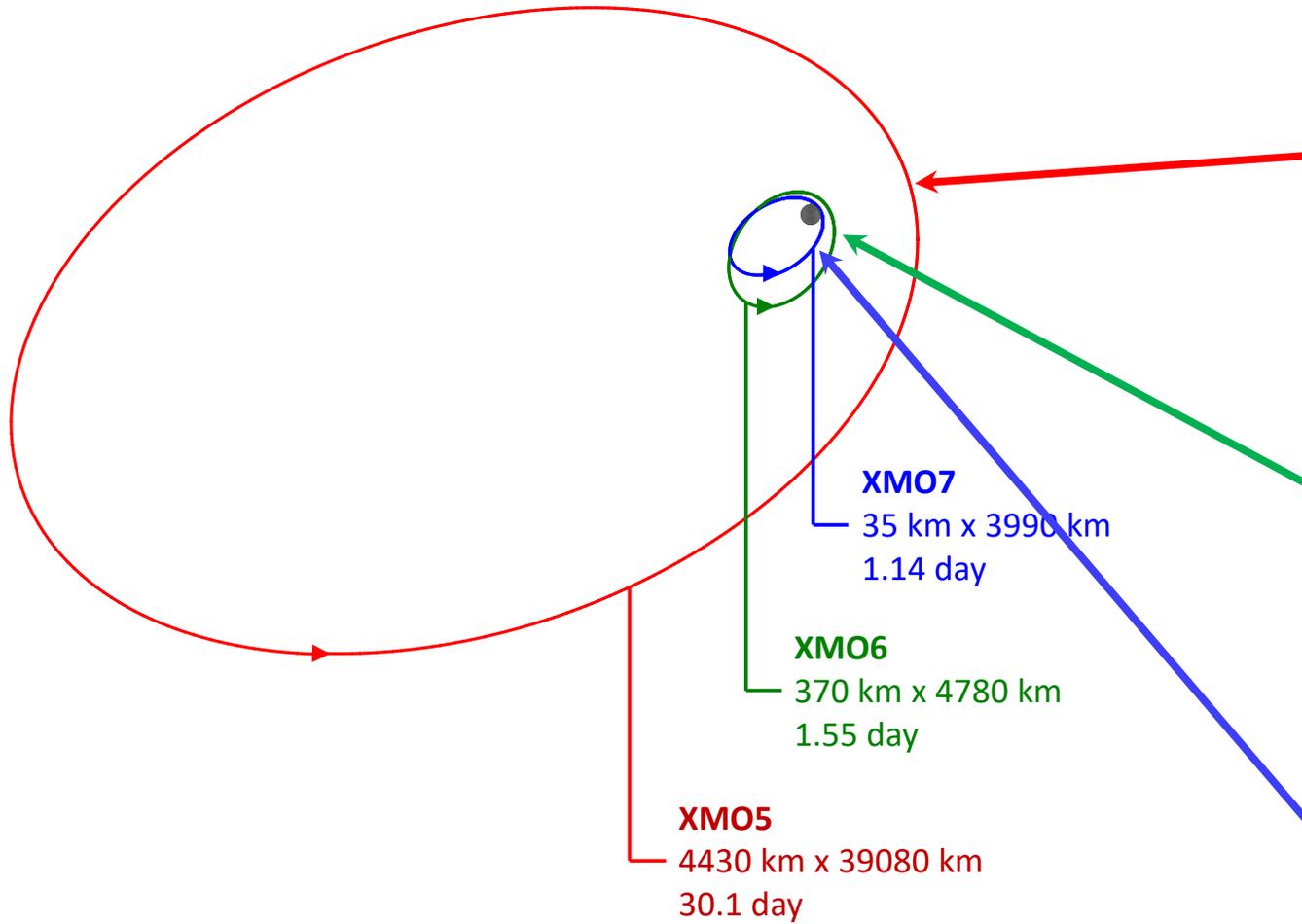


# Ceres Prime Mission





Dawn



## Extended Mission 2 (XM2)

**XMO 5**

- Jun 24, 2017 – Apr 15, 2018
- Orbit Period 30 days
- Staging orbit for XM2
- GRaND background measurement

**XMO 6**

- May 15, 2018 – May 31, 2018
- Intermediate orbit
- VIR southern observation
- VIR Juling observation

**XMO 7**

- Jun 6, 2018 – Oct 31, 2018
- GRaND observation in low altitude
- Occator imaging



# Navigational Challenges in XM2

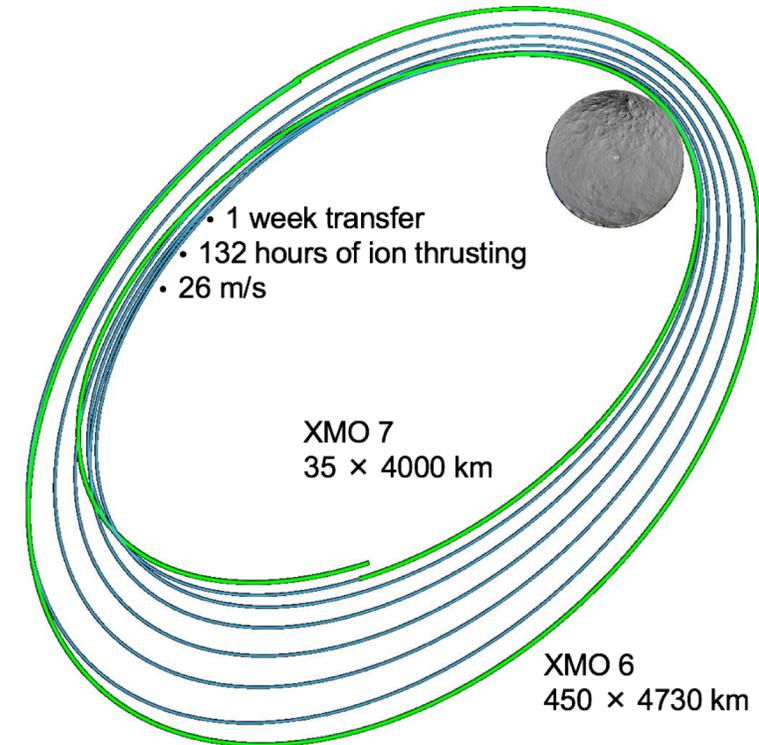
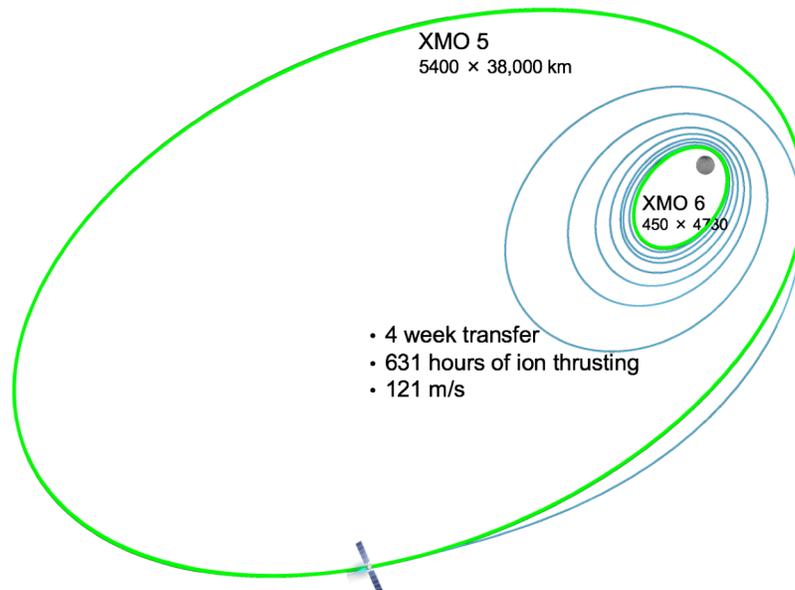


Dawn

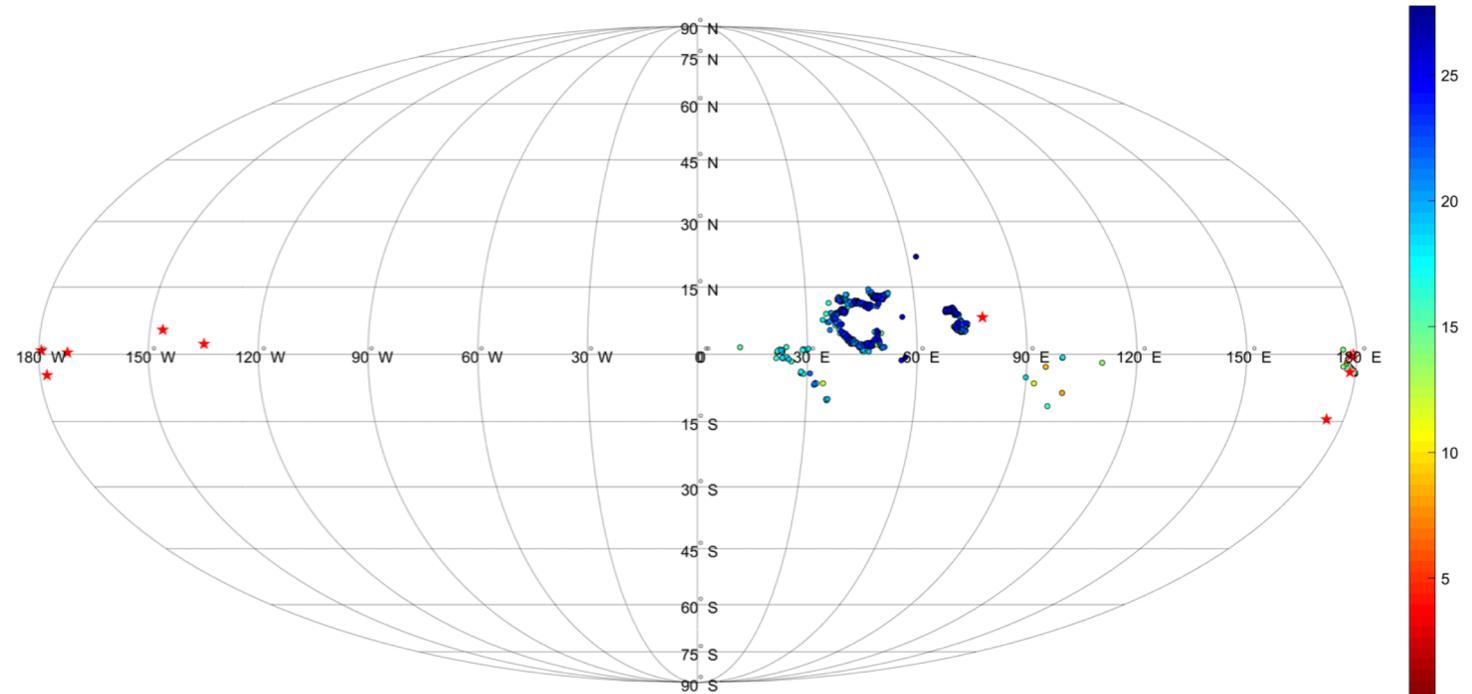
- Orbit disturbances due to  $\Delta V$  exerted by RCS control
  - After reaction wheel failures, attitude was controlled by small thrusters using hydrazine
- Increasingly limited hydrazine stores
  - Hydrazine became limiting source defining end of mission
- Meeting Planetary Protection requirements with the final orbit
  - Spacecraft orbital lifetime around Ceres of greater than 20 years post-orbital-insertion
- Highly elliptical orbit, new to Dawn flight team
  - Final orbit XMO7 was 4000 km x 35 km
- Targeted fly-over
  - Dawn's prime mission was mapping mission.
  - Juling (XMO 6) and Cerealia Facula (XMO 7) fly-over were requested
- Limited preparation time
  - Six months of preparation time for XM2

- XM2's prime objective was to reach periapsis below 200 km (or as low as possible)
  - The final orbit must fulfill NASA's planetary protection requirement
  - Balance between hydrazine consumption in each orbit and number of periapsis passes was key for choosing orbits
  - Target Juling fly-over in XMO 6
  - Target Cerealia Facula fly-over in XMO 7

Dawn

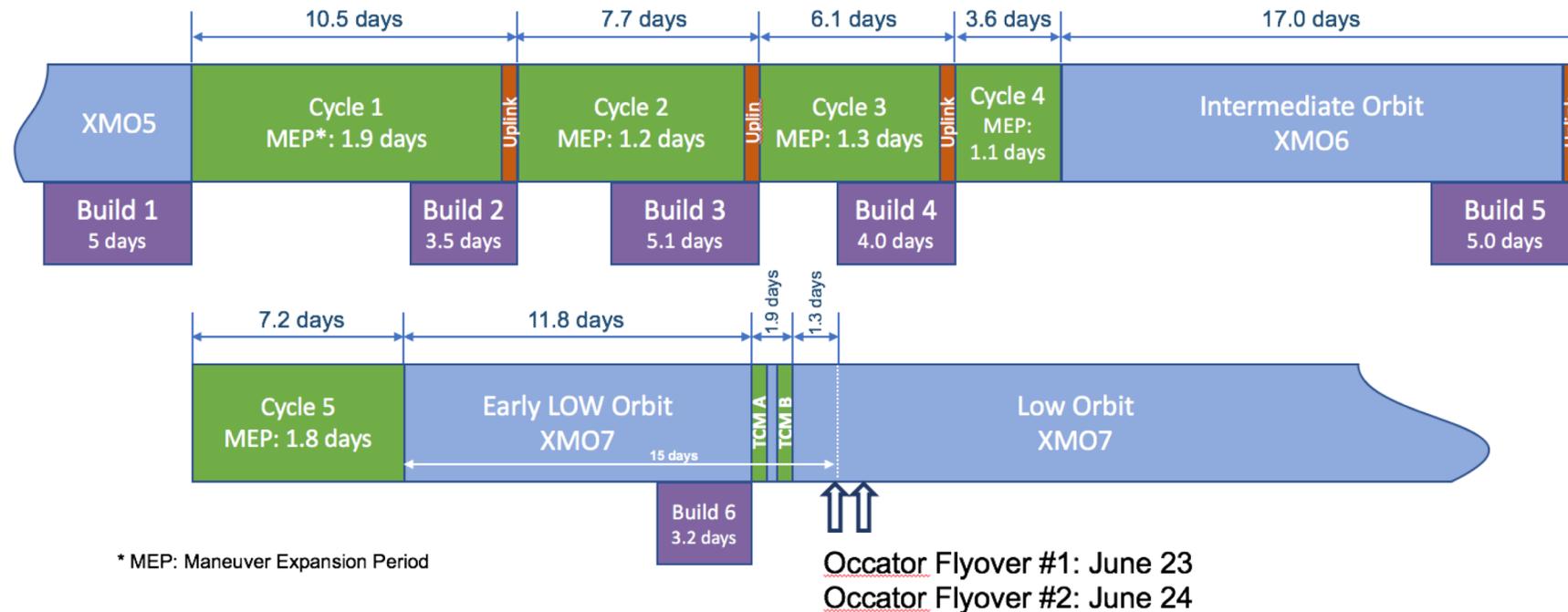


- Because of its substantial inventory of water, organic materials and other compounds, and internal heat, Ceres is subject to planetary protection.
- Dawn's orbital lifetime is required to be  $\geq 20$  years.
- The final orbit was chosen to ensure compliance.
- Monte Carlo studies show lifetime  $> 20$  years
- Lifetime  $> 50$  years with  $> 99\%$  confidence



Location of Minimum Altitude and Unlikely Impact Sites for 50-yr Monte Carlo Study  
Impact locations indicated by red stars

- Transfer architecture is built by Monte Carlo maneuver analysis tool (Veil)
- Number of thrust cycles, build duration for thrust cycle, statistical maneuver duration (MEP) are key factors in designing the architecture



Dawn

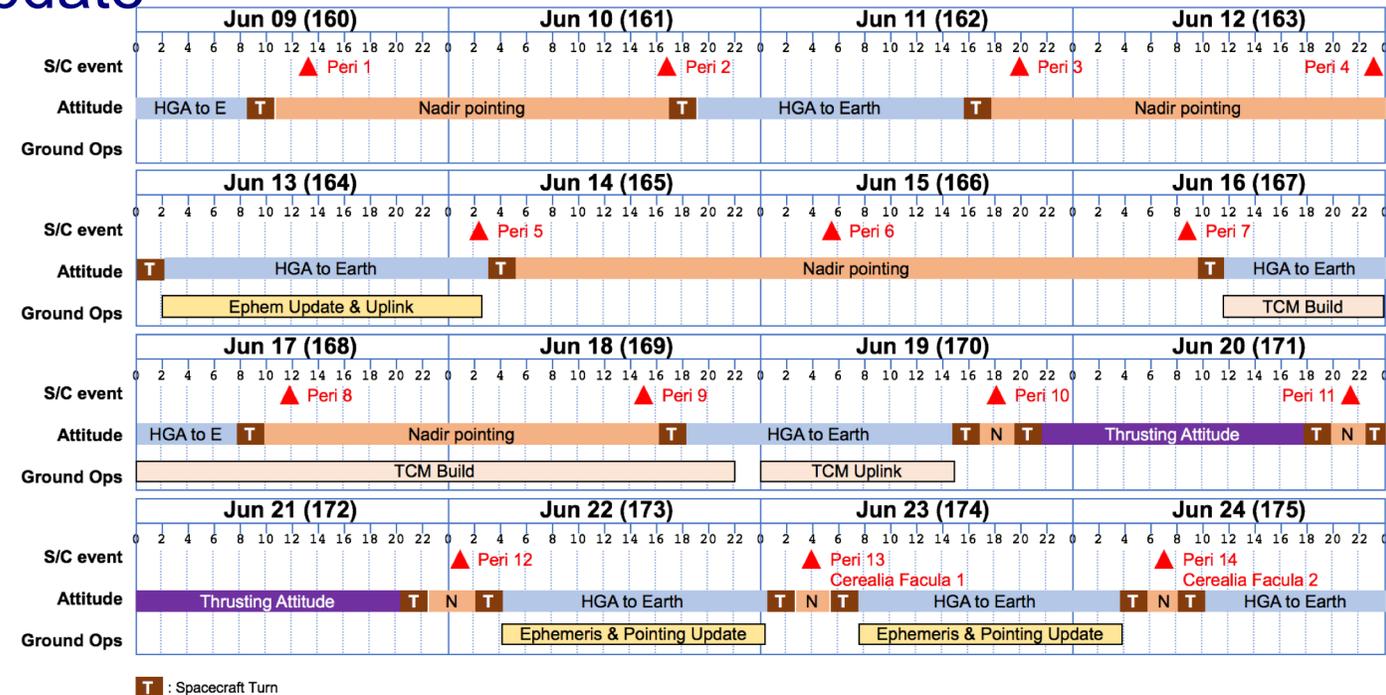


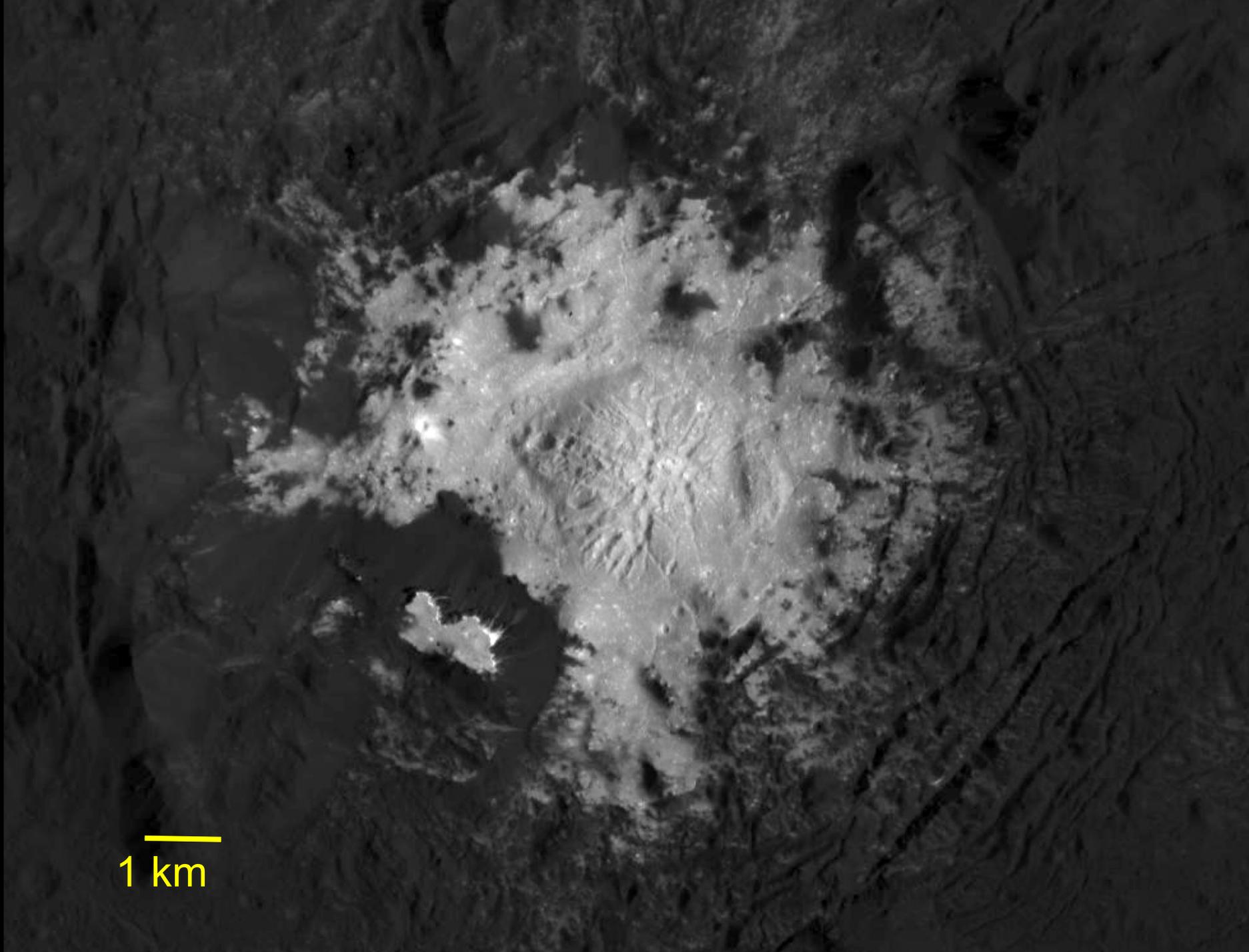
# Improving Target Observation Accuracy



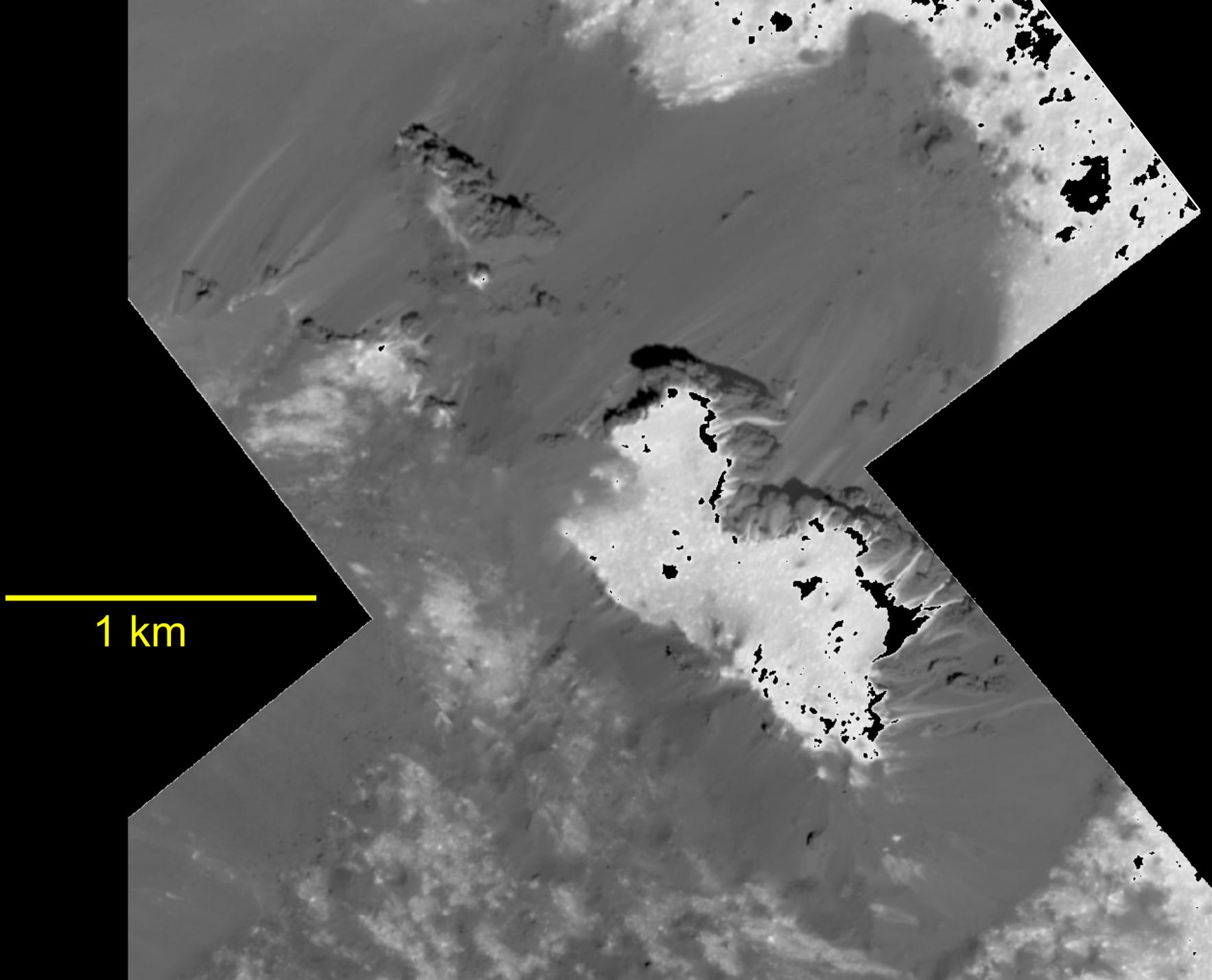
- Short build cycle of thrust sequence
- Short duration thrust sequence
- On-board ephemeris update
- Sequence timing update
- Sequence science pointing update

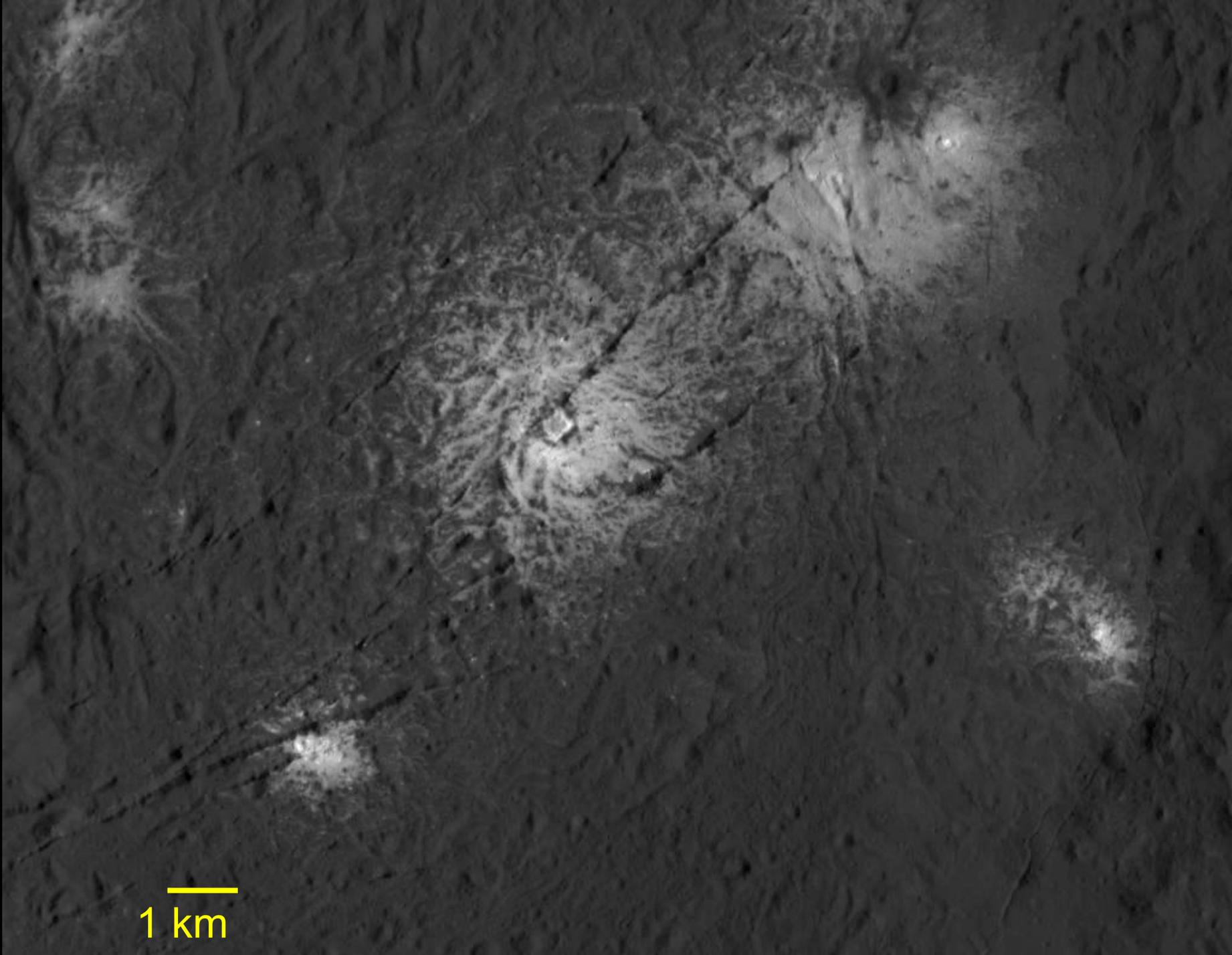
Dawn



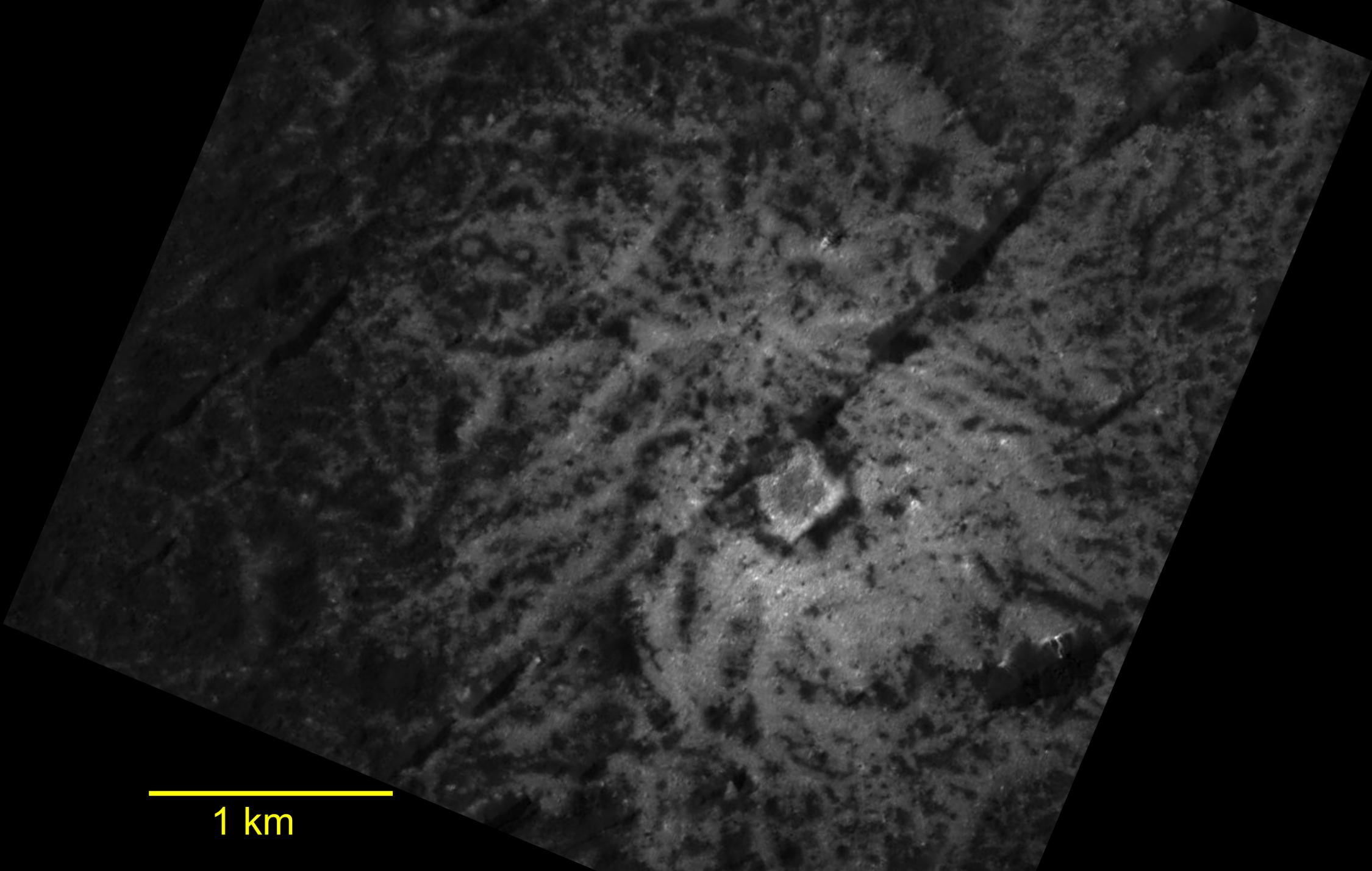


1 km

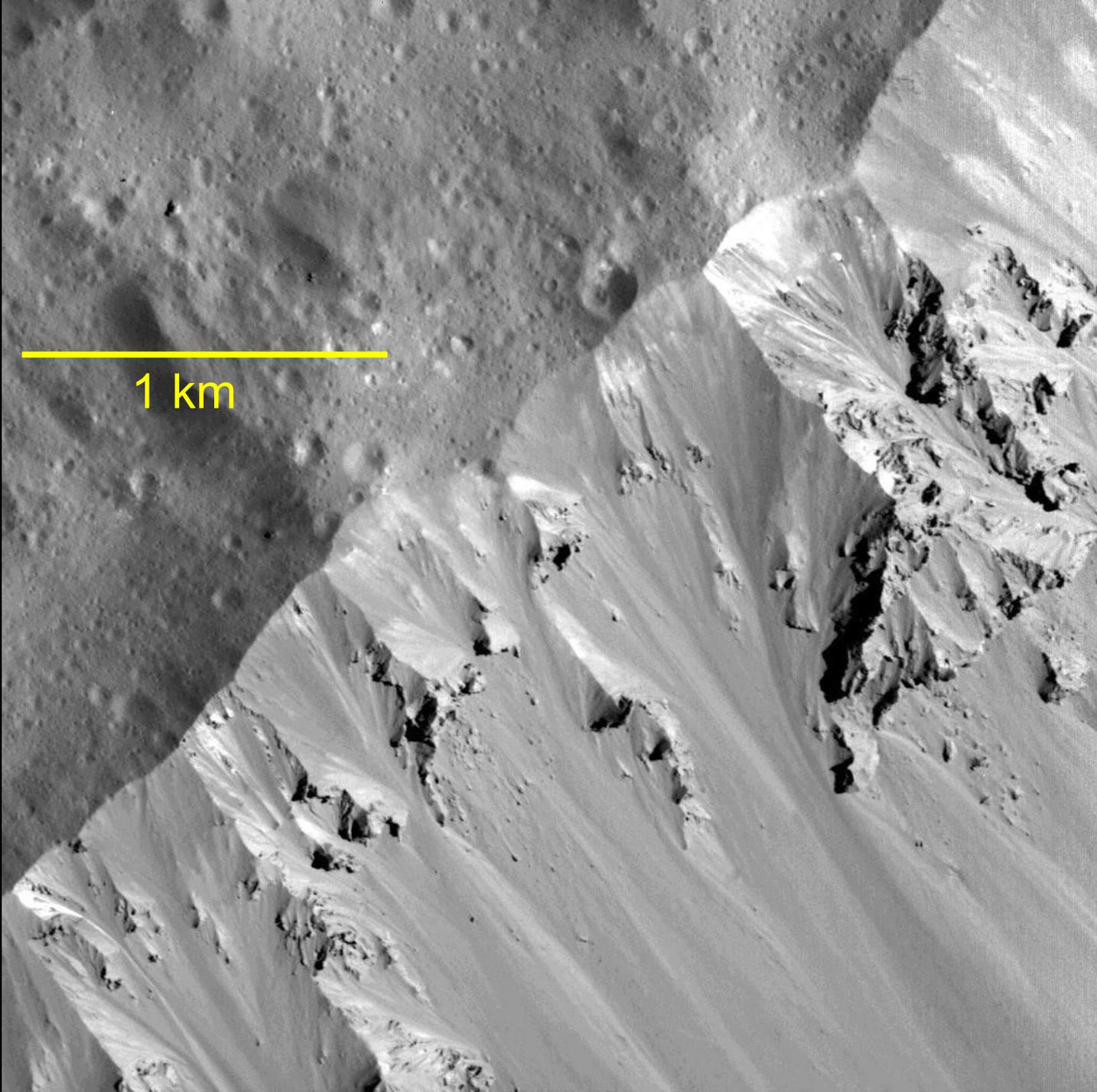




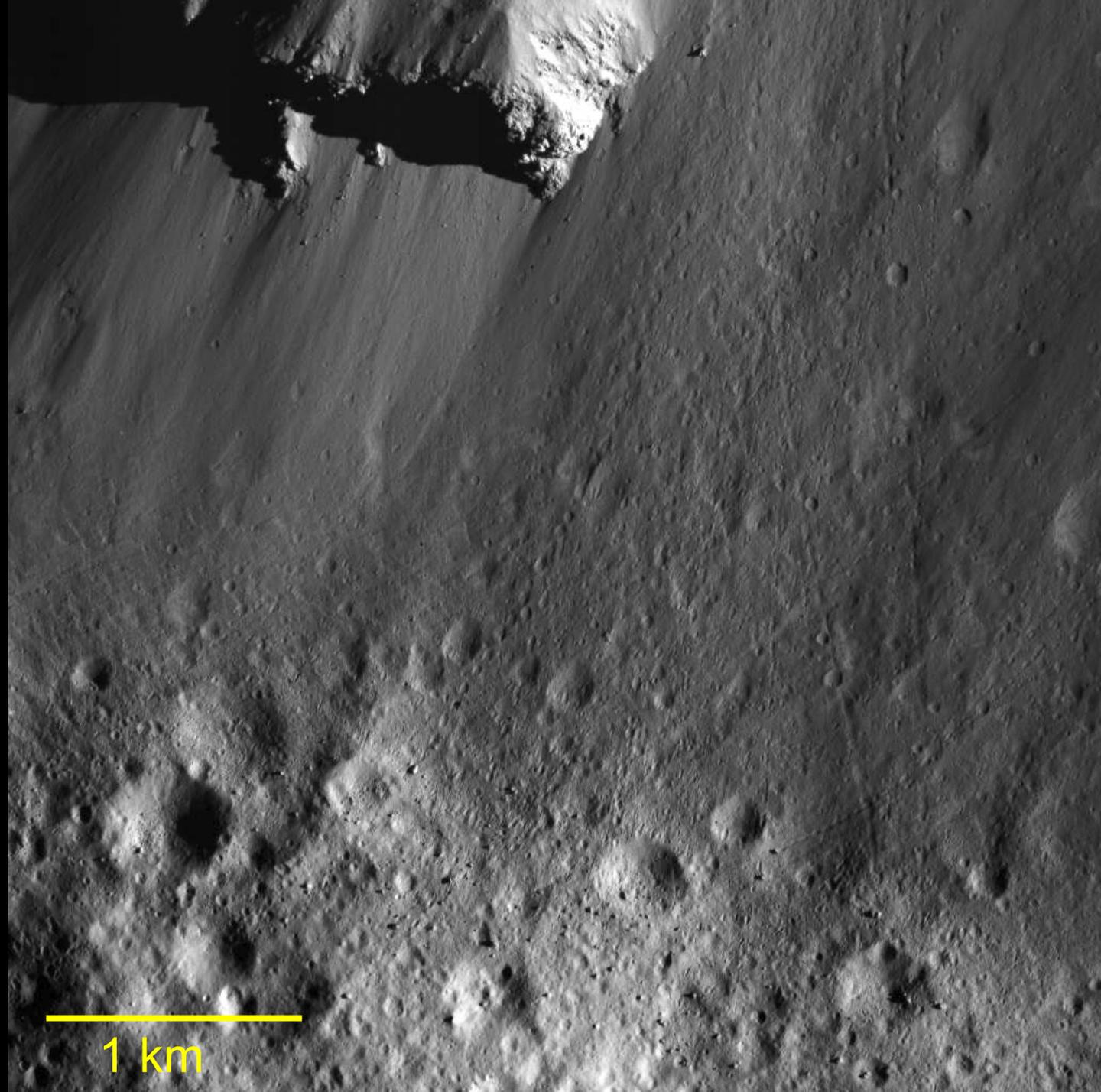
1 km



1 km



1 km



1 km



# Conclusions



Dawn

- Dawn mission was ended on Oct. 31, 2018 losing attitude control with hydrazine all depleted.
- Final reference orbit met all science team's objectives and comply with NASA's planetary protection requirement.
- Orbit transfer architecture and operational plan led to accurate fly-over Juling and Cerealia Facula.
- Dawn's final mission at Ceres accomplished all science objectives, and mission design & navigation team played a key role.