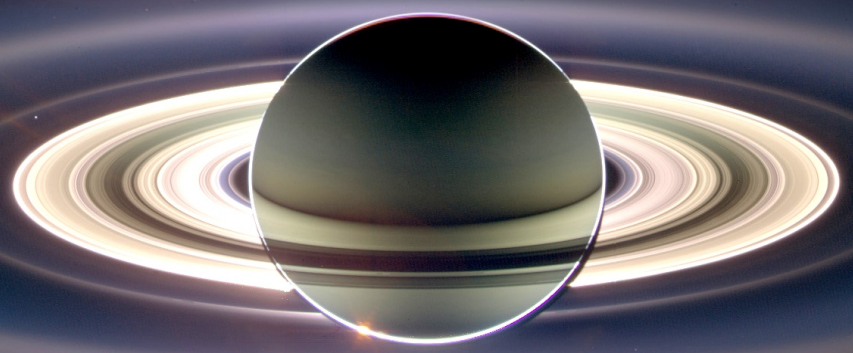
Optical Navigation During Cassini's Solstice Mission



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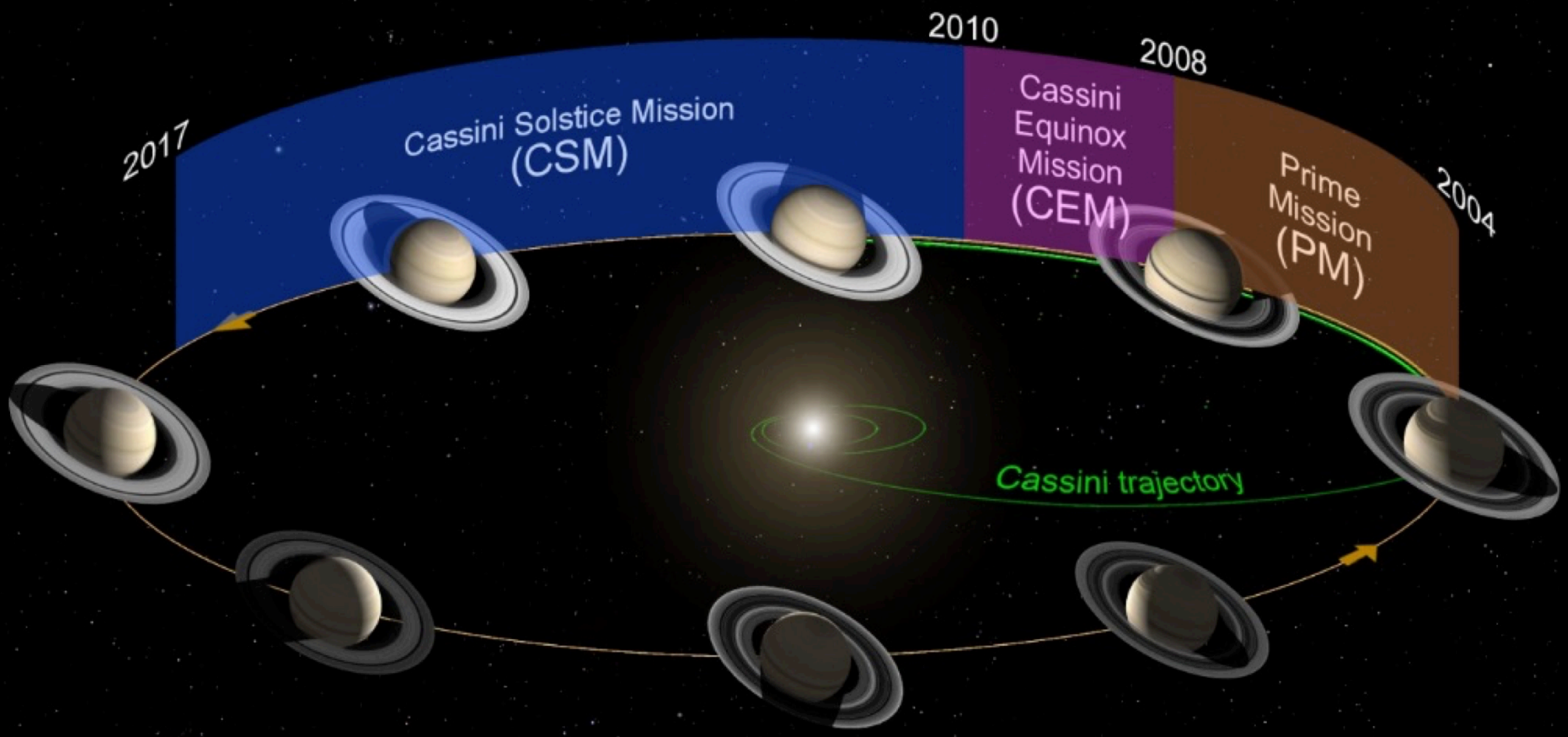
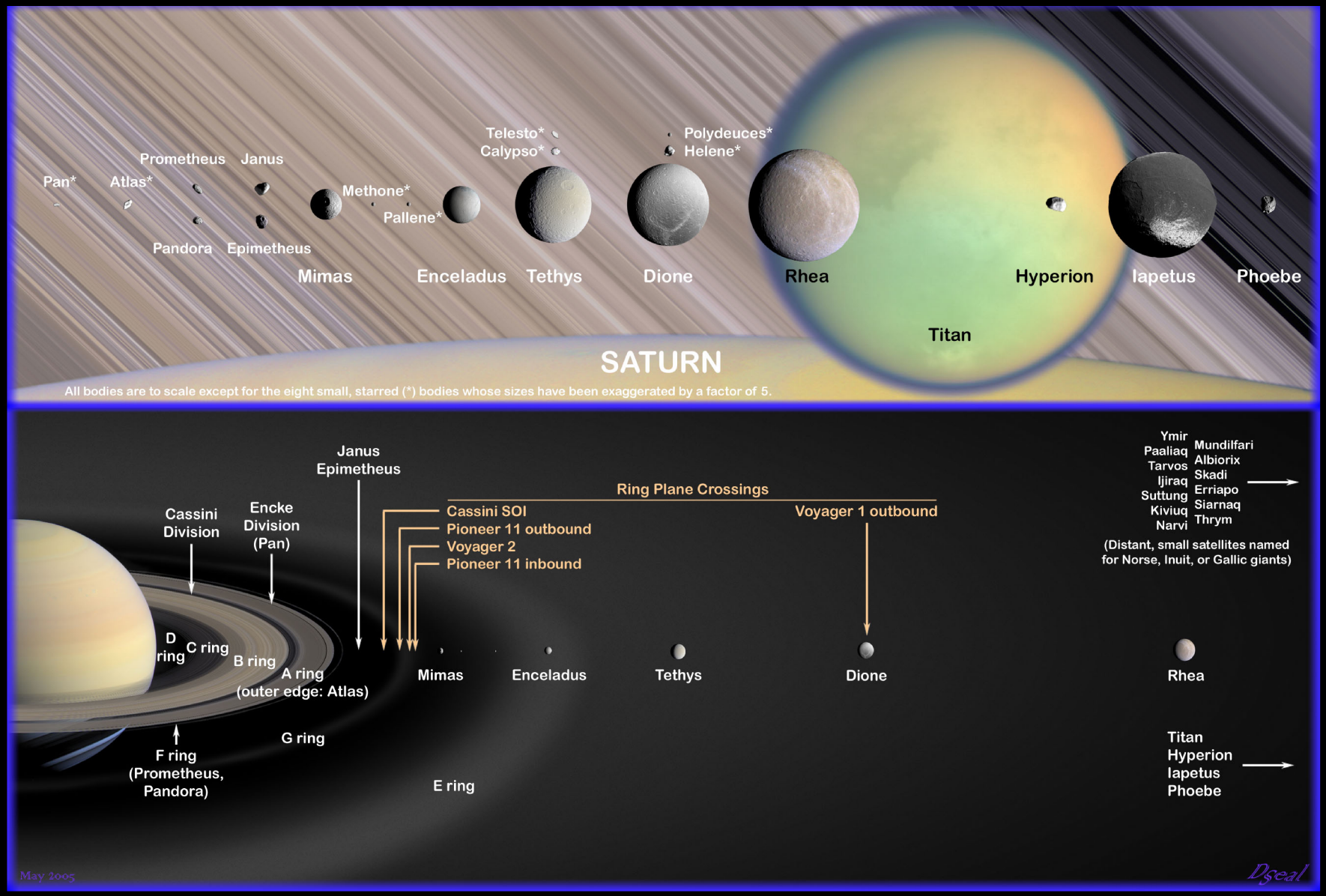
Agenda

- Cassini & Saturn Overview
- Optical Navigation Overview
- Early Mission Opnavs
- Late Mission Flybys & Opnavs
- Orbit Determination Results
- Where are we now?

A Brief History of Cassini



The Saturnian System



Optical Navigation Overview

- Use of onboard imaging for spacecraft navigation
- Must include at least 1 moon & 2 bright catalogued stars
- Stars provide inertial attitude of camera boresight
- Allowing determination of inertial direction from the spacecraft to the satellite, corrected for light-time
- Opnav images augment the radiometric Doppler & range data
- Same strategy used for Voyager & Galileo

Cassini Diagram

ISS: Imaging Science Subsystem
- NAC: Narrow Angle Camera
- WAC: Wide Angle Camera

VIMS: Visual & Infrared Mappings Spectrometer

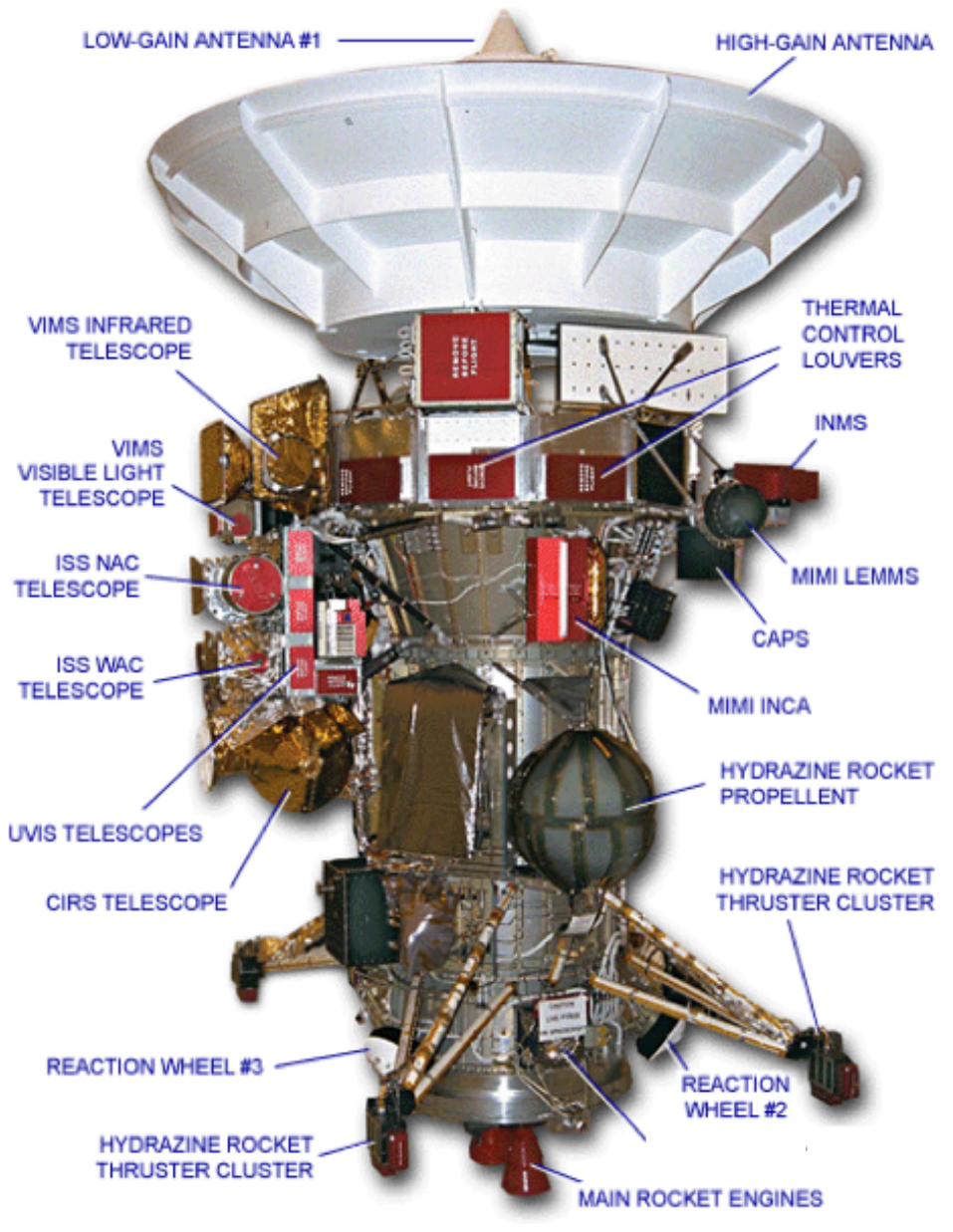
UVIS: Ultra Violet Imaging Spectrograph

CIRS: Composite Infrared Spectrometer

INMS: Ion & Neutral Mass Spectrometer

MIMI: Magnetospheric Imaging Instrument

CAPS: Cassini Plasma Spectrometer



Camera Characteristics

NARROW-ANGLE CAMERA

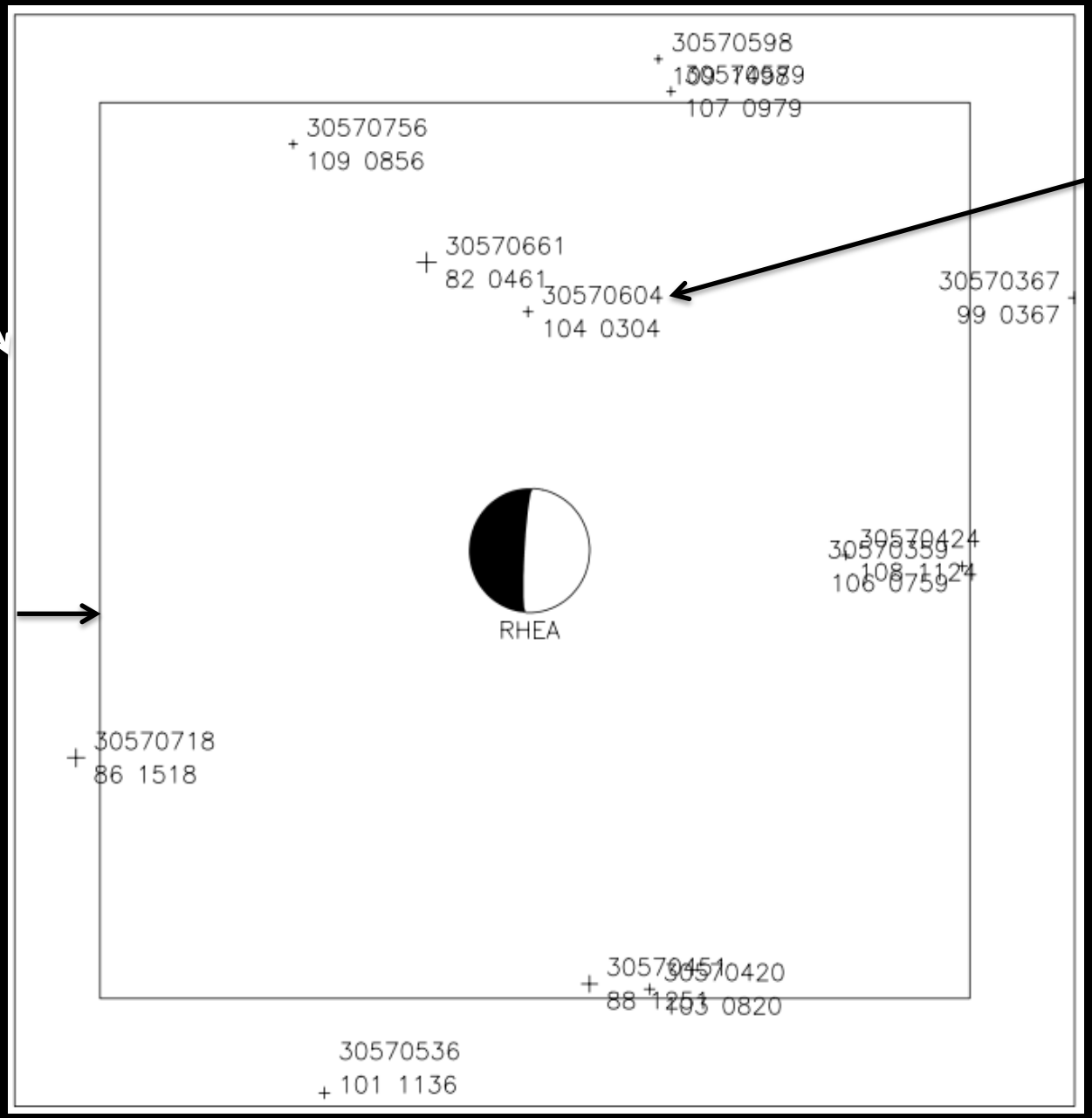
Parameter	Value	Sigma
Focal length (mm)	2002.703	0.017
Pixel width (μm)	12.0	(assumed)
Pixel height (μm)	11.99863	0.00015
Cubic radial distortion (mm^{-2})	8.28E-6	0.06E-6
Tip/tilt in x (mm^{-1})	5.45E-6	0.34E-6
Tip/tilt in y (mm^{-1})	−19.67E-6	0.30E-6

WIDE-ANGLE CAMERA

Parameter	Value	Sigma
Focal length (mm)	200.7761	0.0061
Pixel width (μm)	12.0	(assumed)
Pixel height (μm)	11.99888	0.00045
Cubic radial distortion (mm^{-2})	60.88E-6	0.16E-6
Tip/tilt in x (mm^{-1})	5.28E-6	0.61E-6
Tip/tilt in y (mm^{-1})	−71.86E-6	0.61E-6

- The NAC provided almost all of the opnav images, 1024 x 1024 pixels

Sample of an Opnav Planning Image



WAC frame

NAC frame

Star catalogue number & magnitude (10.4)

Cassini's last planned opnav: Sept 20, 2016 16:30:06.200 ET

Exp time: 0.0800 s

RA: 156.546
DEC: -32.346
Twist: -115.732522

N1853084193

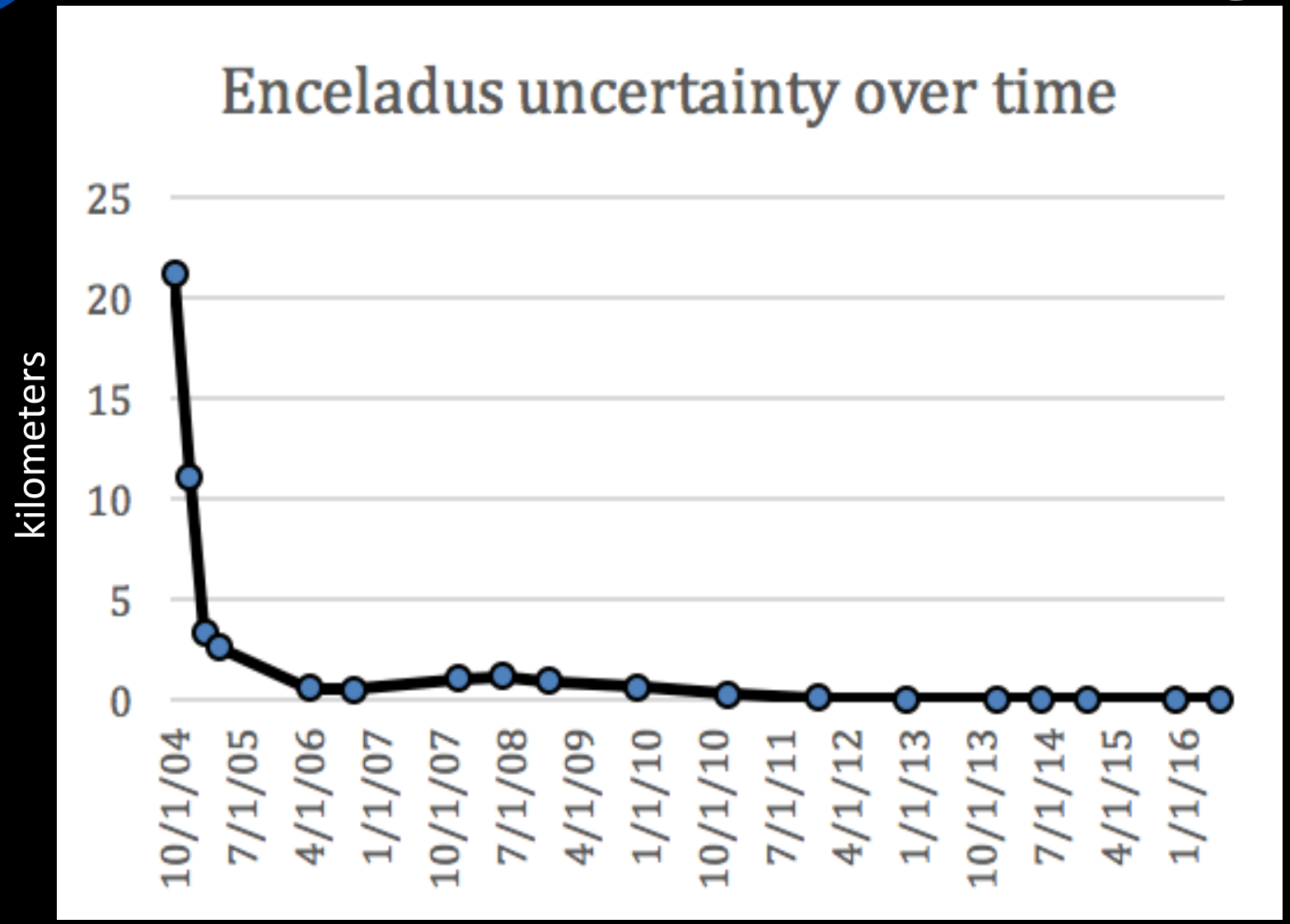
Opnavs by Satellite and Mission Phase

Satellite	Pre-SOI	Prime	Equinox	Solstice	Total
Mimas	62	301	47	14	**424**
Enceladus	58	317	44	12	**431**
Tethys	57	267	48	12	**384**
Dione	61	286	42	13	**402**
Rhea	67	292	32	14	**405**
Titan	49	119	0	4	**172**
Hyperion	42	196	2	8	**248**
Iapetus	46	189	3	7	**245**
Phoebe	95	46	0	0	**141**
Total	**537**	**2013**	**218**	**84**	**2852**

Incorporating the Opnavs

- Early opnavs of Saturn's moons helped reduce their large position uncertainties
- Daily rate of 8 opnav images for the first two years of Prime Mission
- Rate reduced to 3-6 images per week for remainder of Prime Mission
- Rate reduced to about 9 per month for Equinox Mission
- Rate further reduced to 1 per month for Solstice Mission
- Opnavs of Titan were less effective due to Titan's thick atmosphere and the difficulty this caused the limb fitting and center-finding algorithms, halted after June 2006
- Prior to Saturn Orbit Insertion, Phoebe was intensely imaged ahead of its only planned flyby, hence it wasn't imaged much beyond July 2004

Opnav Benefit to Moon Position Uncertainties



One sigma RSS of position uncertainty over time, was as high as 465 km prior to SOI

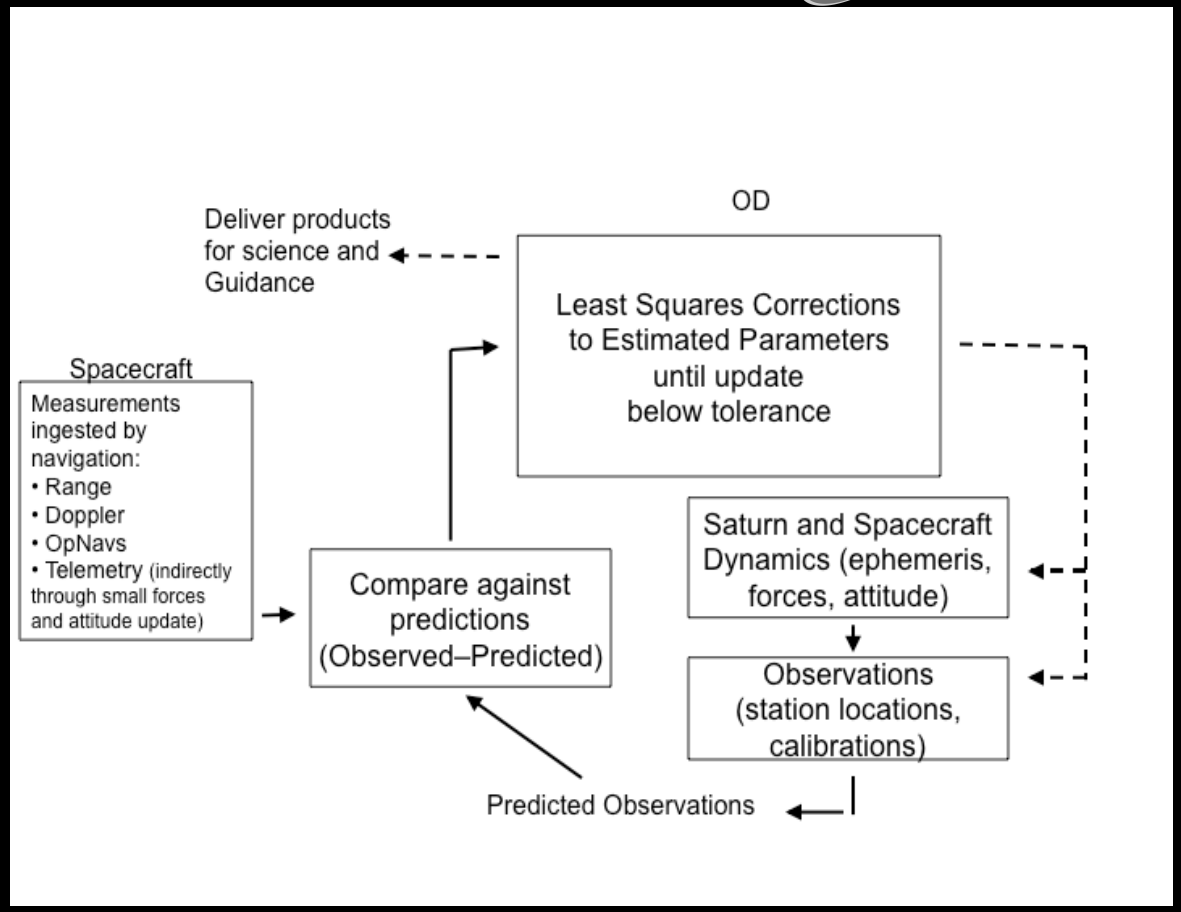
Navigation Role & Orbit Determination Process

Maintain Cassini close to a reference trajectory

Timing & Geometry of targeted flybys are tightly controlled

OD Team provides orbit predictions to maintain trajectory, provide updates for science observations & reconstructions

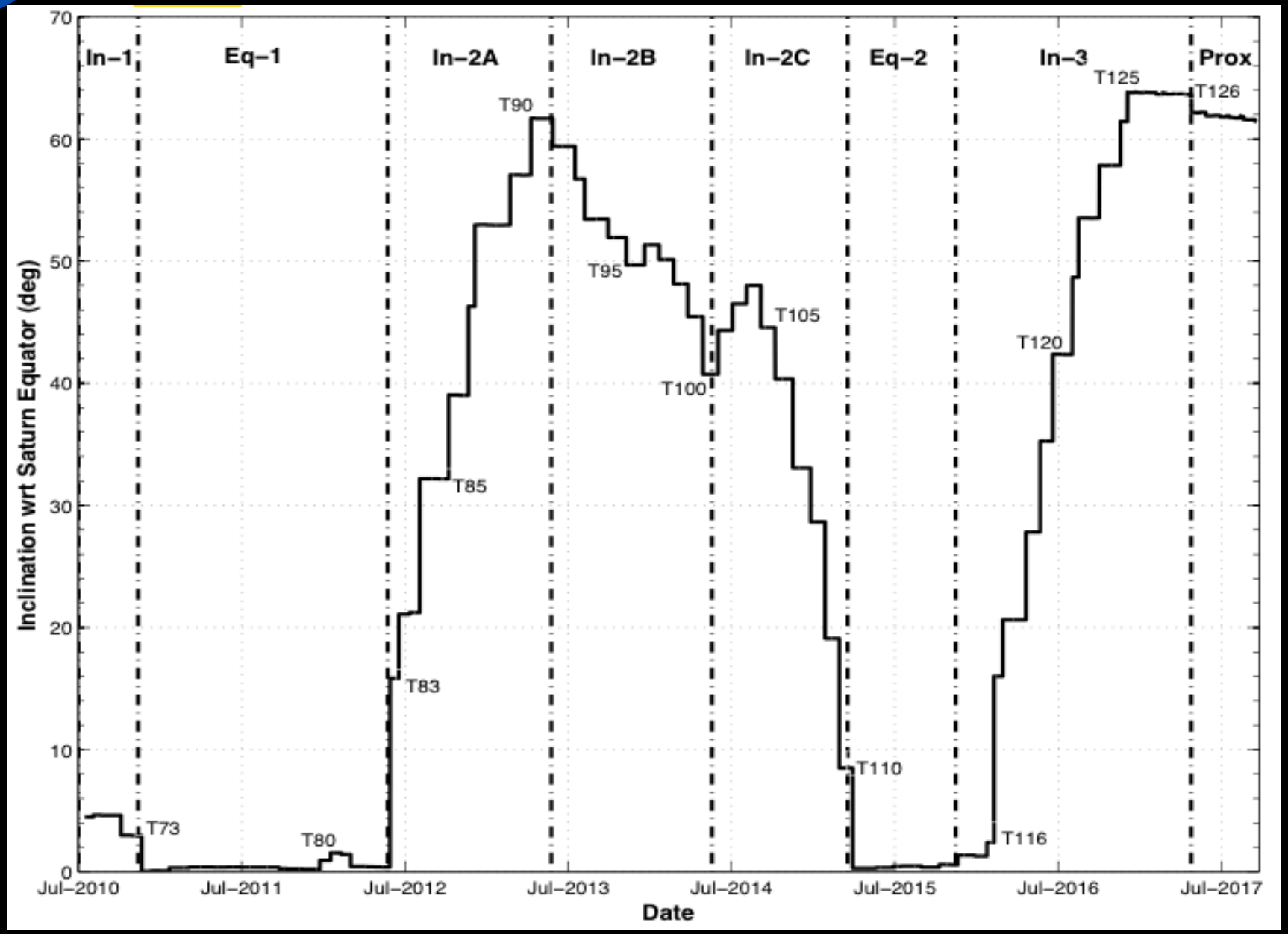
OD process incorporates refined model of Saturnian system, spacecraft, opnavs, tracking data, media calibrations, small forces and other dynamical events



JPL's Solar System Dynamics Group provides updates to the Saturnian system ephemerides and covariance data with data spanning four decades (global fit)

OD Team can toggle on/off estimation of Saturnian system ephemerides as needed (local fit)

Solstice Mission Inclination vs Saturn Equator



Solstice Mission Icy Moon Targeted Flybys

- Eq-1 spanned July 2010 – May 2012
  - 10 icy moon flybys planned
- Eq-2 spanned March 2015 – Jan 2016
  - Final 5 icy moon flybys planned after a 3-year gap
  - Concerned about down-track component of a moon's orbit uncertainty accumulation
  - 1 mm/s velocity uncertainty could grow to ~100 km

Moon	Date	Altitude (km)
Enceladus-12	30-Nov-2010	50
Enceladus-13	21-Dec-2010	50
Rhea-3	11-Jan-2011	75
Enceladus-14	01-Oct-2011	100
Enceladus-15	19-Oct-2011	1236
Enceladus-16	06-Nov-2011	500
Dione-3*	12-Dec-2011	100
Enceladus-17	27-Mar-2012	75
Enceladus-18	14-Apr-2012	75
Enceladus-19	02-May-2012	75
Dione-4	16-Jun-2015	517
Dione-5	17-Aug-2015	474
Enceladus-20	14-Oct-2015	1840
Enceladus-21	28-Oct-2015	50
Enceladus-22	19-Dec-2015	5000

* Part of a dual flyby w/ targeted Titan-79

Solstice Mission Icy Moon Targeted Flybys

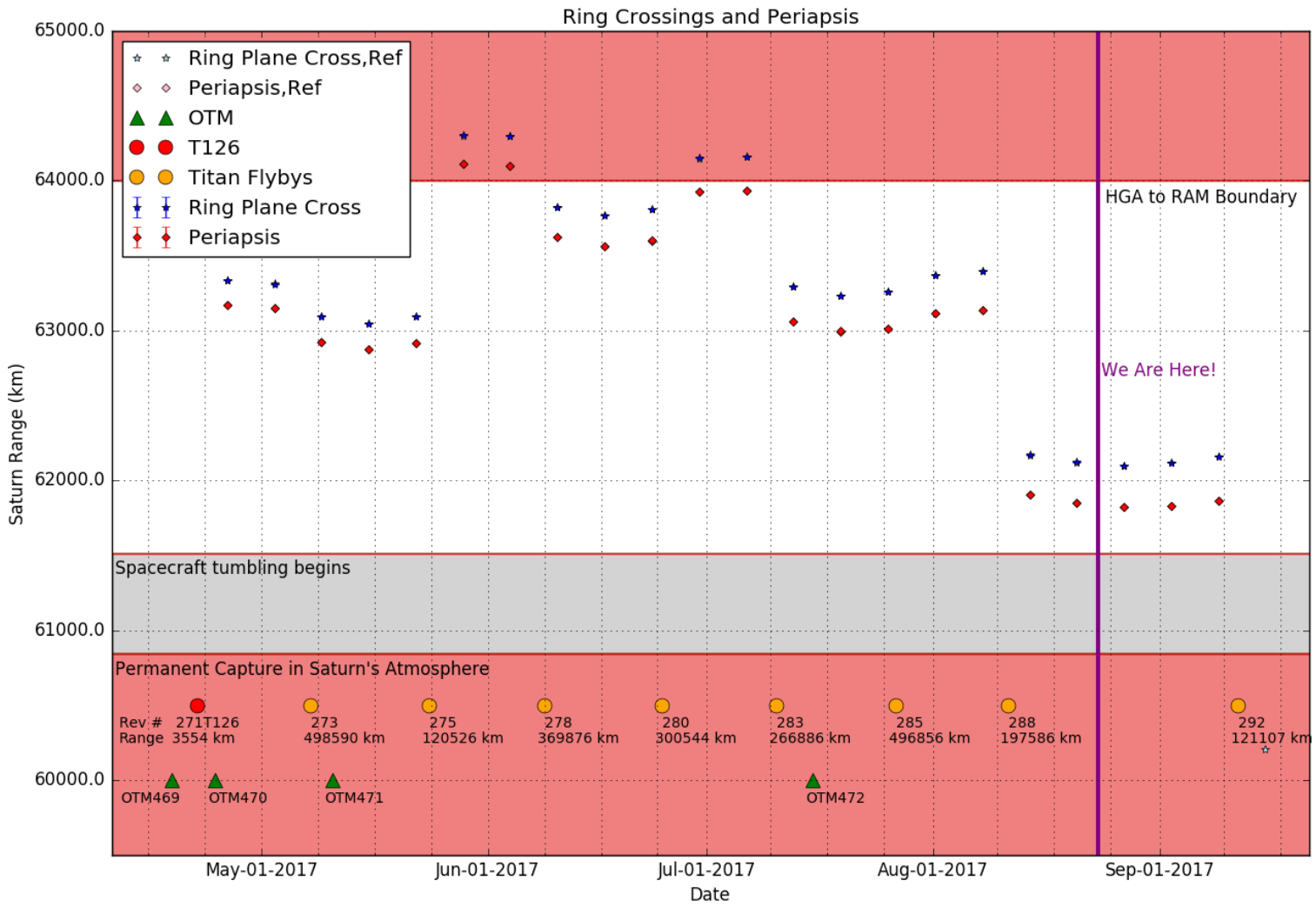
- In the Spring of 2015, the Navigation team was preparing for final icy moon encounters, especially the 50 km flyby of Enceladus
- Final opnavs of the moons appeared to be keeping their runoff errors in check, but were there enough planned
  - Dione's last image prior to its flybys in June & August was in March 2015
  - Enceladus's last image prior to its flybys in October & December in May 2015
- After the opnavs arrived, various filter strategies were tested to better quantify potential runoff errors
  - Estimating the Saturn pole, gravity and satellite ephemerides against the baseline case without these modeled was a primary concern
  - Proved to be only 0.5 km apart in the Dione-4 B-plane, only two-sigma
- In September 2015, science images of Dione & Enceladus confirmed the errors for these moons were on the order of 1-2 km
- Monthly opnav images proved to keep the moon ephemeris errors in check, provided peace of mind, and insured mission objectives would be met

OD Performance of Eq-2 Phase Flybys

Target	Date	Altitude (km)	3-D Error (km)	3-D Sigma
Dione-4	16-Jun-2015	516	0.74	1.8
Titan-112	07-Jul-2015	10953	0.34	1.4
Dione-5	17-Aug-2015	475	0.42	1.4
Titan-113	28-Sep-2015	1036	0.13	0.7
Enceladus-20	14-Oct-2015	1840	1.68	2.4
Enceladus-21	28-Oct-2015	50	0.91	1.4
Titan-114	13-Nov-2015	11920	1.21	9.9
Enceladus-22	19-Dec-2015	5000	0.14	0.4

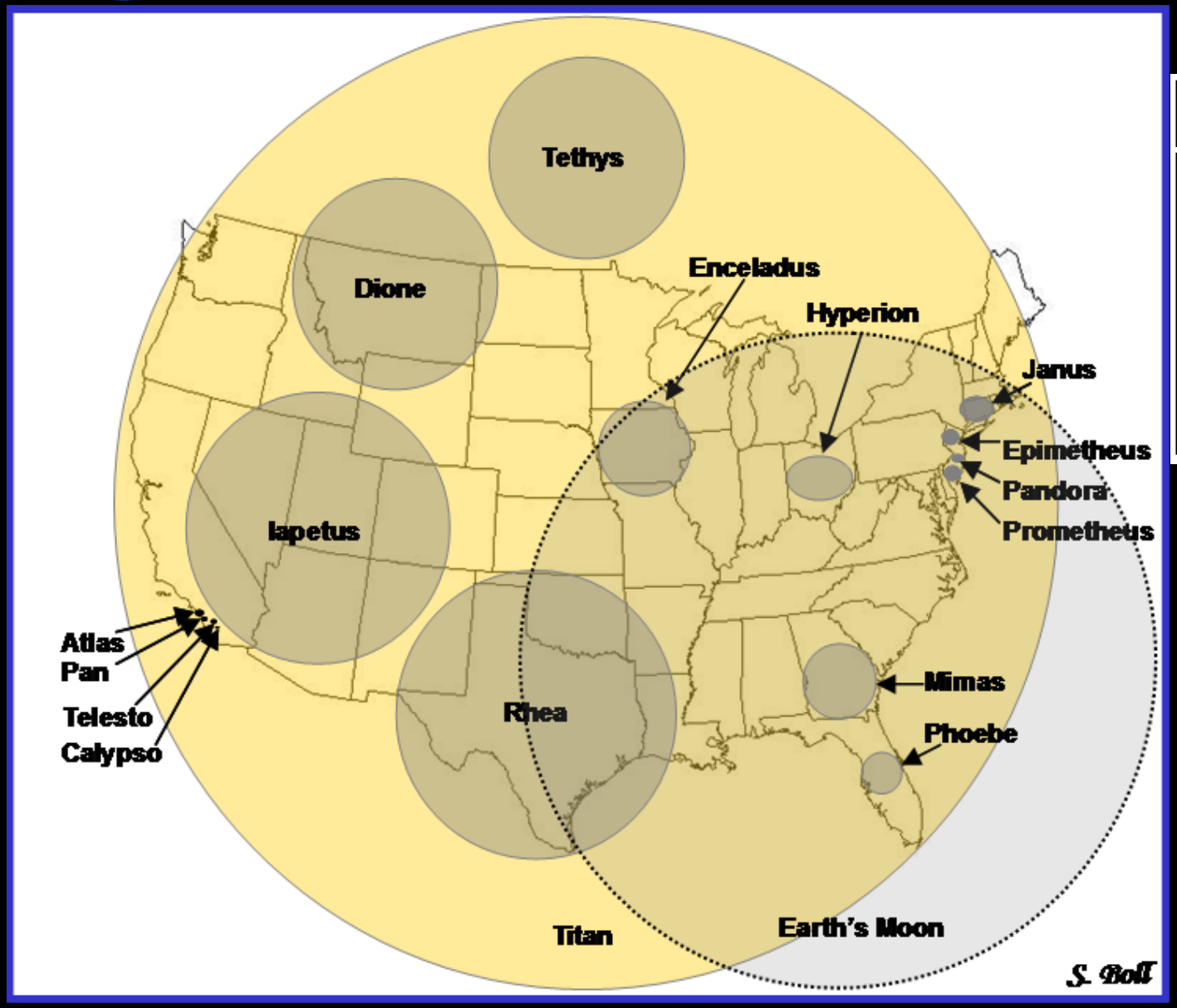
Where are we now?

The Grand Finale: the last 22 orbits



Backup Slides

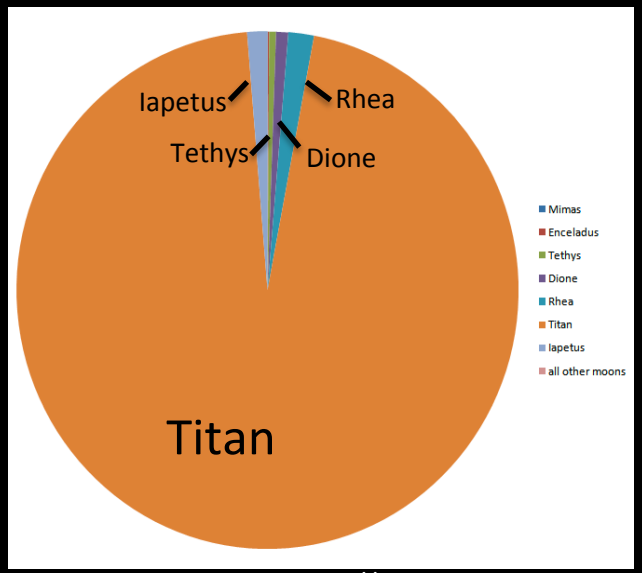
Relative Sizes of Saturn's Primary Moons



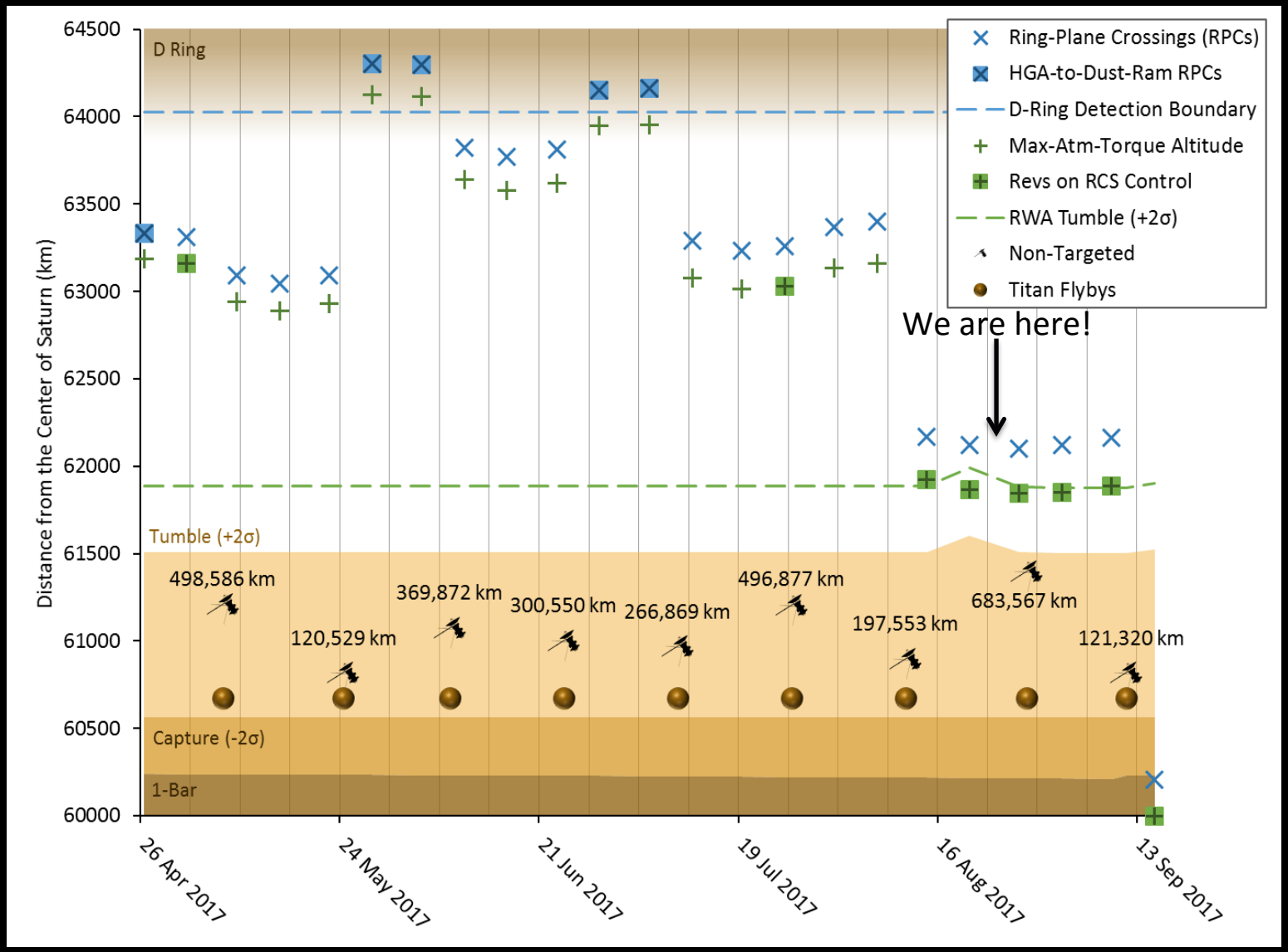
- Mean Radius and Period

Moon	Mean Radius (km)	Period (days)
Mimas	198.2	0.94
Enceladus	252.1	1.37
Tethys	531.1	1.89
Dione	561.4	2.74
Rhea	763.8	4.52
Titan	2575.5	15.95
Hyperion	135	21.28
Iapetus	734.5	79.32
Phoebe	106.5	550.56

- Relative masses



Credit: https://en.wikipedia.org

Where are we now?

The Grand Finale: the last 22 orbits