Gravity investigations at gas giants and their icy moons with the Cassini and Juno missions

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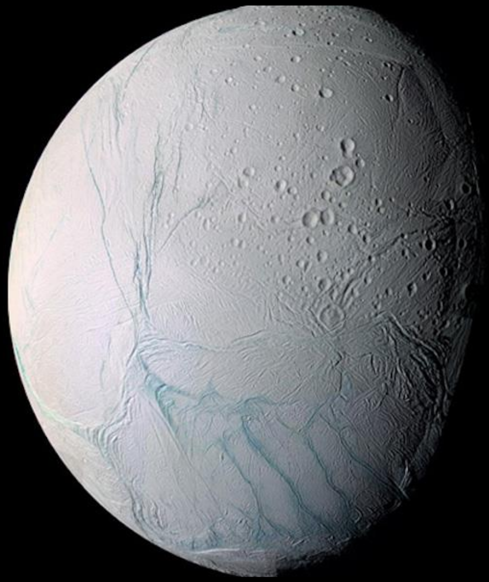
Seminar overview

- Why do we carry out Gravity Science experiments on inter-planetary missions?
- The instrument
- Observables and orbit determination
- Gravity science with the Cassini mission
  - Detection of a subsurface ocean underneath the ice shell of Enceladus
  - Re-orientation of Rhea's principal axes in the quadrupole field
- Juno gravity science
  - Determination of the Great Red Spot's depth with past and future flyovers
- Questions?

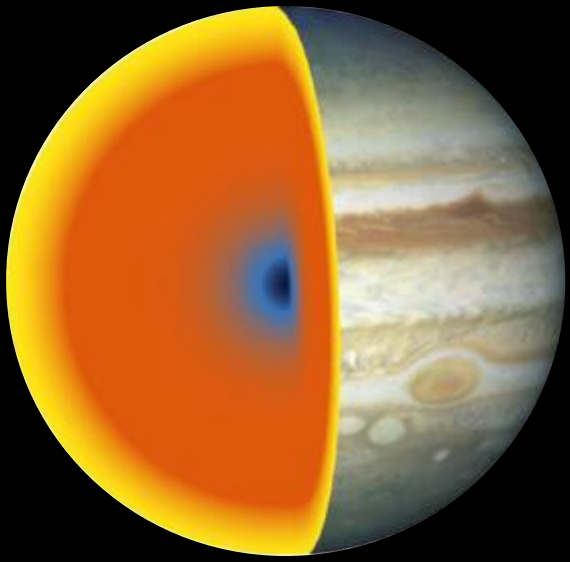


Gravity Science Experiments

The main goal of gravity science experiments is to learn about the interior structure of planets and satellites.

Celestial bodies are very diverse and so are the investigations based on gravity measurements:

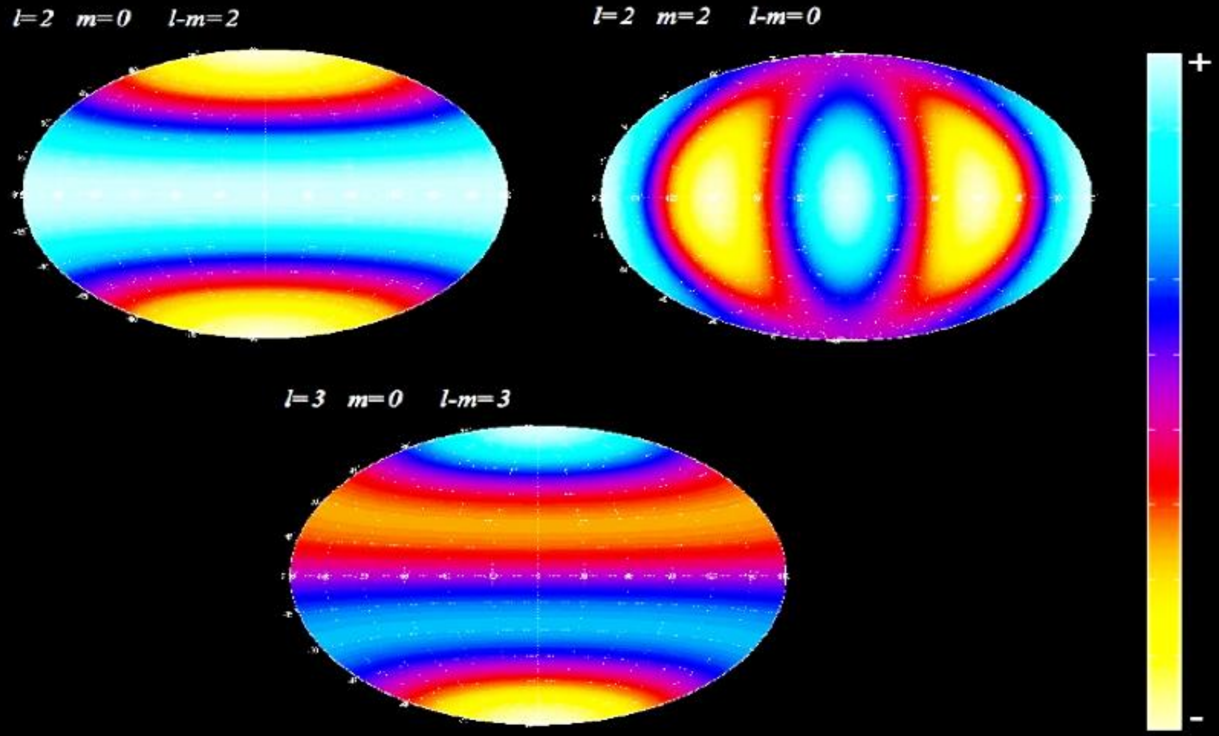
- determination of the moment of inertia
- determination of the mass and size of a planetary core
- detection of water reservoirs
- study of deep zonal flows at gas giants
- determination of the rotational state
- measurement of the tidal response of a body



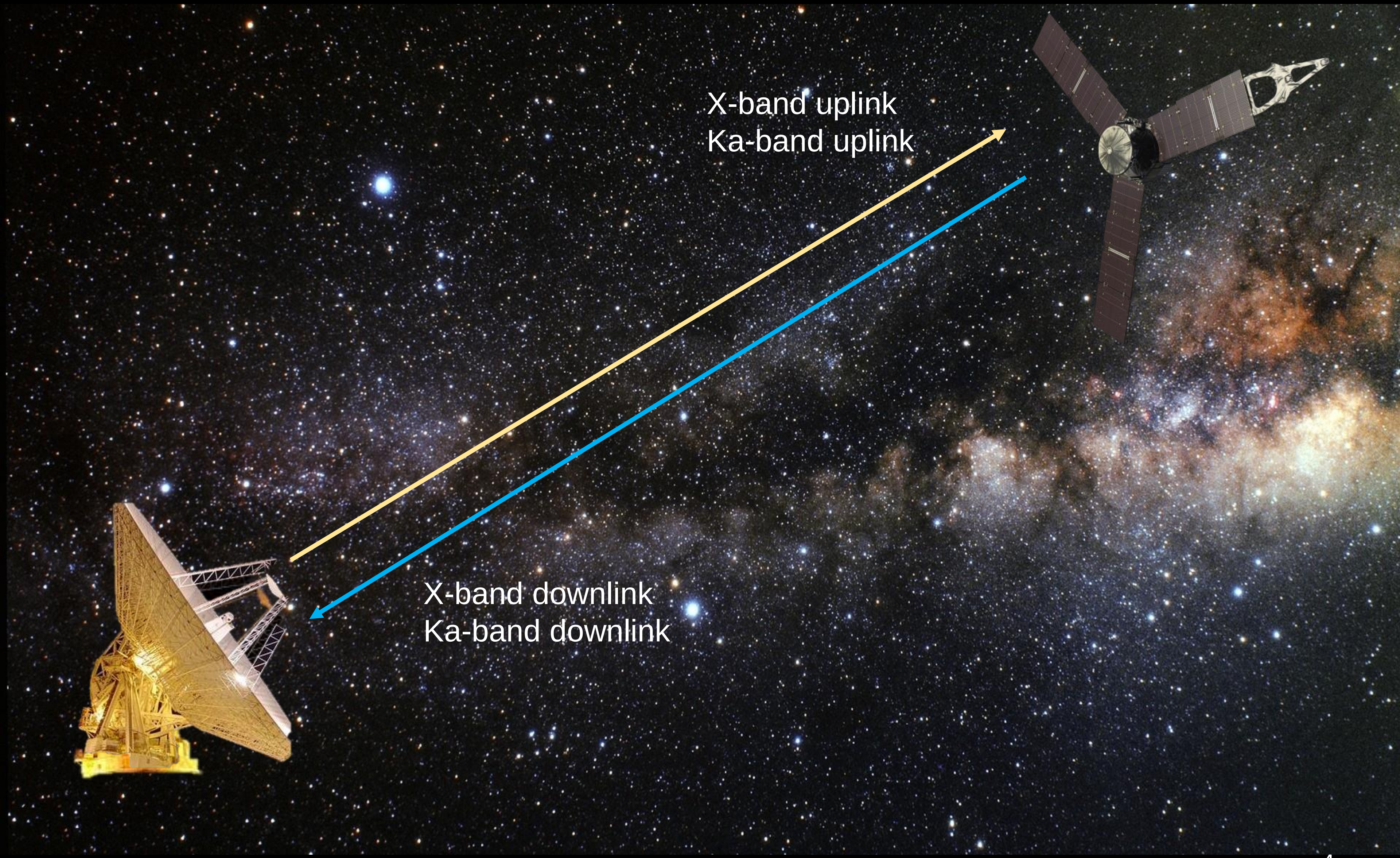
Spherical harmonics

Gravitational potential of a body:

$$V(r,\vartheta,\lambda)=\frac{\mu}{r}\left(1+\sum_{l=2}^{\infty}\left(\frac{R}{r}\right)^{l}\sum_{m=0}^{l}P_{lm}(\sin\vartheta)\left[C_{lm}\cos m\lambda+S_{lm}\sin m\lambda\right]\right)$$



Gravity Science instrument



Observables

- Doppler - frequency shift in the carrier (Δf), measures the range rate of the spacecraft relative to Earth:

$$\frac{\Delta f}{f} = \frac{\dot{\rho}}{c}$$

  - Cassini used X and Ka Doppler tracking of the spacecraft with accuracies down to 0.02 mm/s at 60 s integration time;

- Range - Measurement of the round trip light time:

$$\rho = c(t_R - t_T) + \varepsilon$$

  - Range typical accuracy of 20 cm (60s) - subject to long term, systematic effects

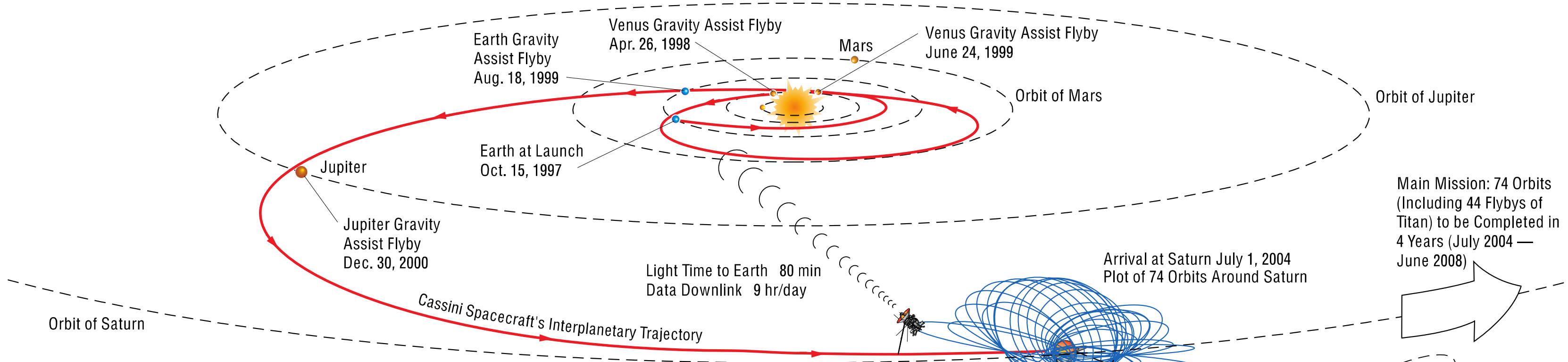
- Angular Observables – ΔDOR

DSS-25 Water Vapor Radiometer

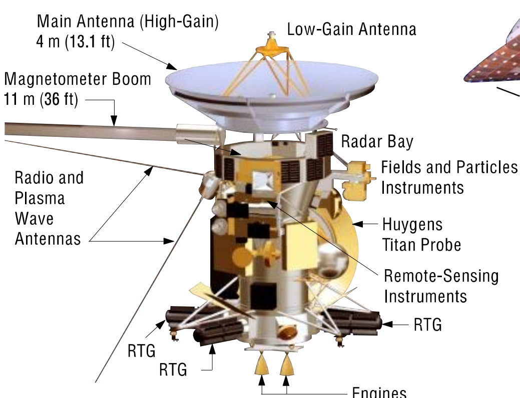
The Advanced Media Calibration System for tropospheric dry and wet path delay corrections.

The 34m beam waveguide tracking station DSS 25, NASA's Deep Space Network, Goldstone, California

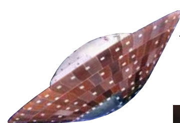
The Cassini Mission to Saturn



The Cassini Spacecraft



- Launch Mass
  - Spacecraft — 2,442 kg (5,384 lb)
  - Propellant — 3,132 kg (6,905 lb)
  - Total Mass — 5,574 kg (12,288 lb)
- Propulsion: Two engines, 445 Newton (100 lb) thrust each
- Electrical Power Source: Three radioisotope thermoelectric generators (RTGs)
- Optical Remote-Sensing Instruments: Will determine temperatures, chemical composition, structure, and chemistry of Saturn, its rings, moons, and their atmospheres; will measure the mass and internal structure of Saturn and its moons; will photograph Saturn, its rings, and moons in visible, near-infrared, and ultraviolet wavelengths.
- Radar: Will map Titan and measure heights of surface features.
- Field and Particles Instruments: Will map the magnetic field of Saturn; detect charged particles and plasmas; study interactions between solid bodies and the solar wind; investigate ice and dust, plasma waves, and radio waves.



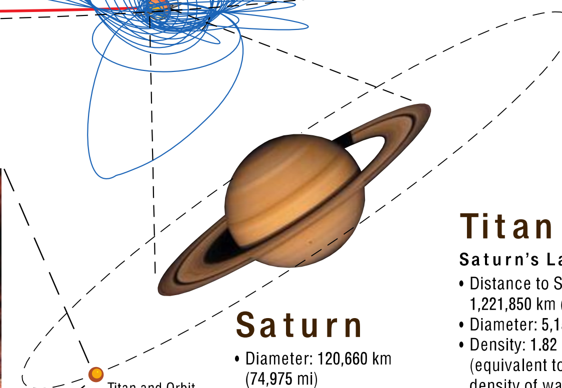
Huygens Titan Probe

Touchdown on Titan — Nov. 27, 2004

During 3 hours of science observation and measurements, the Huygens Probe instruments will:
- Collect aerosols for chemical analysis.
- Make spectral measurements and take pictures of Titan's surface and atmosphere.
- Measure wind speeds using the Doppler effect.
- Identify constituents in atmosphere.
- Measure physical and electrical properties of the atmosphere.
- Measure physical properties of the solid or liquid surface of Titan.

Cassini Partners

The Cassini mission is a joint effort of the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and Italian Space Agency (ASI). The mission is managed for NASA by the Jet Propulsion Laboratory, California Institute of Technology. Partners include the U.S. Air Force (USAF), Department of Energy (DOE), and academic and industrial participants from 19 countries.



Saturn

- Diameter: 120,660 km (74,975 mi)
- Density: 0.69 g/cm^3
- Length of Day: 10 hr 40 min
- Length of Saturn Year: 29.42 Earth Years
- Rings: 7
- Moons: 18
- Composition of Atmosphere:
  - Hydrogen (H_2)
  - Helium (He)
  - Methane (CH_4)
  - Ammonia (NH_3)
  - — and numerous other hydrocarbons

Titan

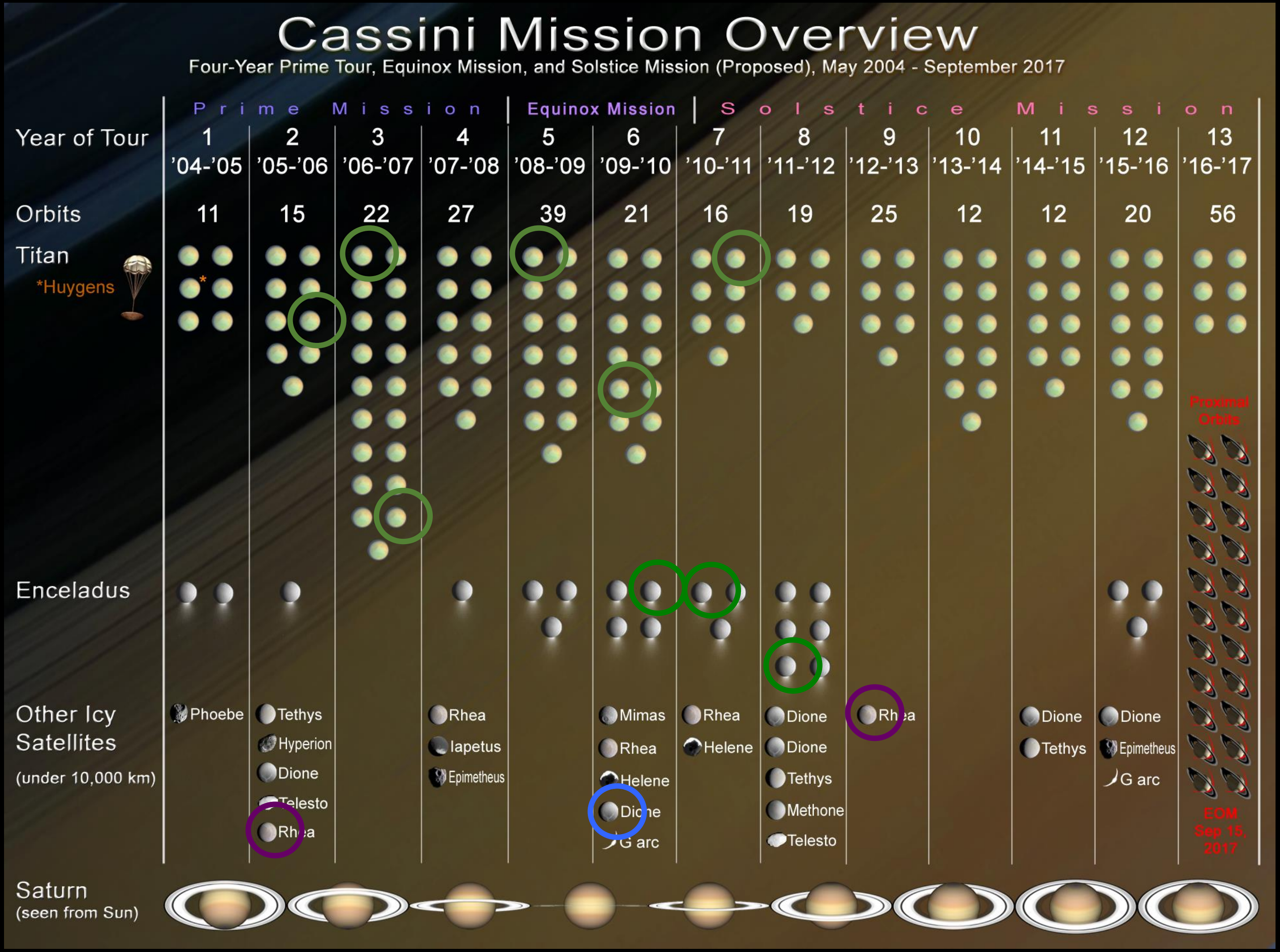
Saturn's Largest Moon

- Distance to Saturn: 1,221,850 km (759,200 mi)
- Diameter: 5,150 km (3,199 mi)
- Density: 1.82 g/cm^3 (equivalent to 1.82 times the density of water)
- Surface Temperature: –181 °C (–294 °F)
- Surface Pressure: 1.5 bars (approximately 1.5 times surface pressure at sea level on Earth)
- Composition of Atmosphere:
  - Nitrogen (N_2)
  - Methane (CH_4)
  - — and other hydrocarbons and nitriles

World Wide Web (WWW): http://www.jpl.nasa.gov/cassini

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
JPL 400-843 10/99

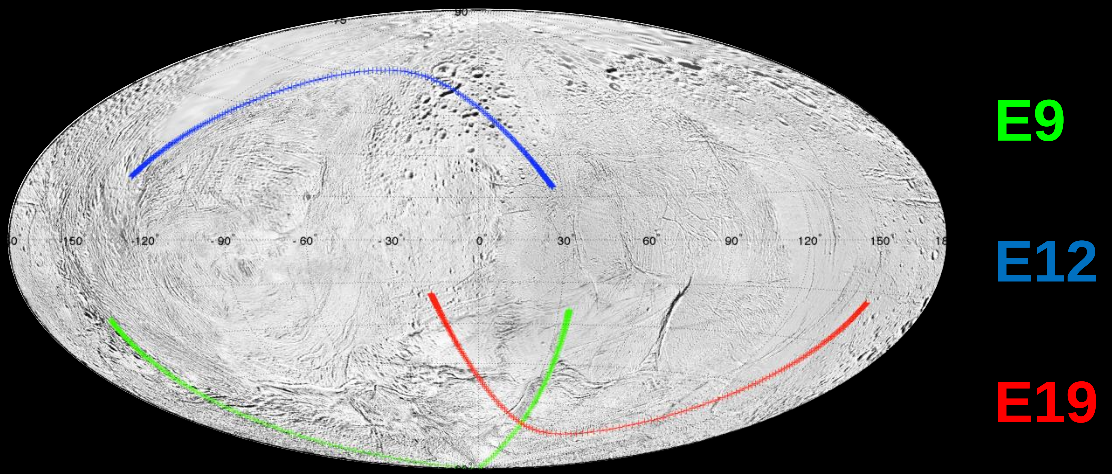
Cassini tour of the Saturnian System



Gravity flybys: Titan (10) Enceladus(3) Rhea(2) Dione(1)

Enceladus gravity flybys characteristics

E9	E12	E19
C/A: APR-28-2010 00:10:51 UTC Altitude: 100 km C/A latitude: -89° SEP angle: 141° Observation time: -> 7h continuous tracking around C/A: 2-way Doppler data only Relative velocity: 6.5 km/s	C/A: NOV-30-2010 11:53:59 UTC Altitude: 48 km C/A latitude: 62° SEP angle: 54° Observation time: -> 3h continuous tracking around C/A: 3-way tracking data at C/A Relative velocity: 6.3 km/s	C/A: 2-MAY-2012 09:31:29 UTC Altitude: 70 km C/A latitude: -72° SEP angle: 162° Observation time: -> 3h continuous tracking around C/A: 3-way tracking data at C/A Relative velocity: 7.5 km/s



Enceladus’s plumes

E9

$\rho_M = 3.78 \times 10^{-12}\ kg/m^3$	$\rho_M = 1.03 \times 10^{-11}\ kg/m^3$
$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.27\ mm/s$	$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 1.5\ mm/s$

$0.30\ mm/s \leq \Delta V \leq 1.5\ mm/s$

E19

$\rho_M = 6.46 \times 10^{-13}\ kg/m^3$	$\rho_M = 4.85 \times 10^{-12}\ kg/m^3$
$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.06\ mm/s$	$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.48\ mm/s$

$0.10\ mm/s \leq \Delta V \leq 0.50\ mm/s$

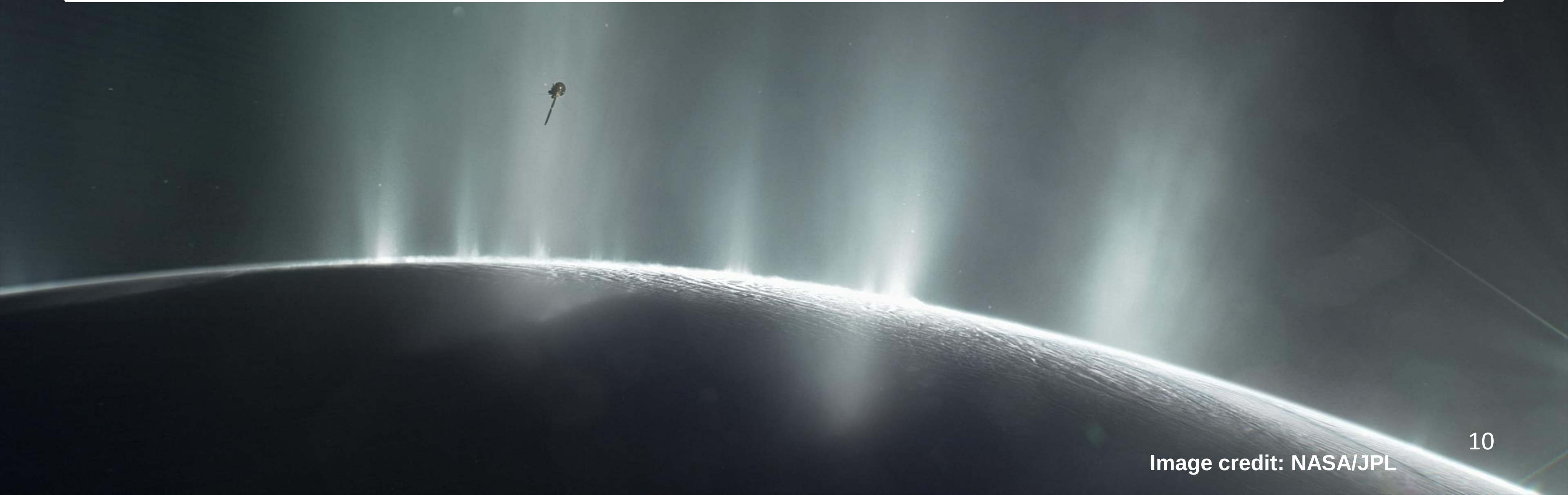
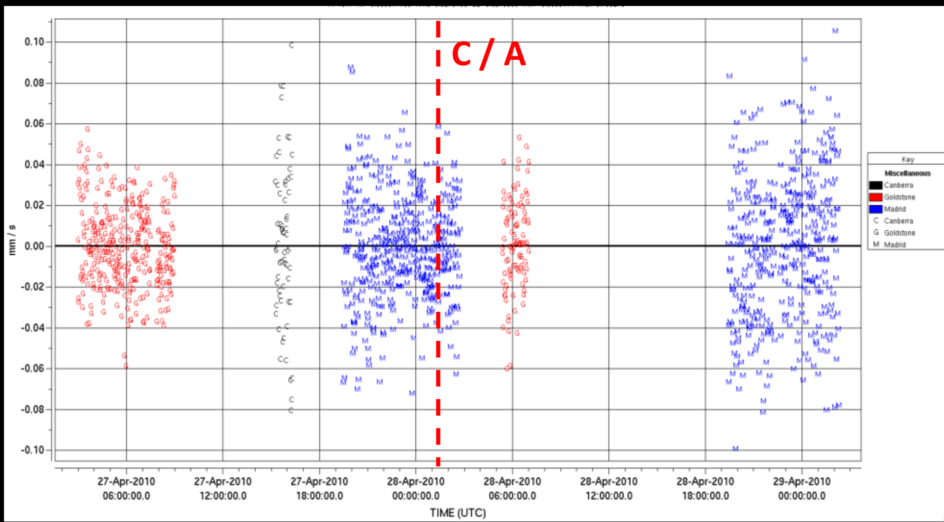
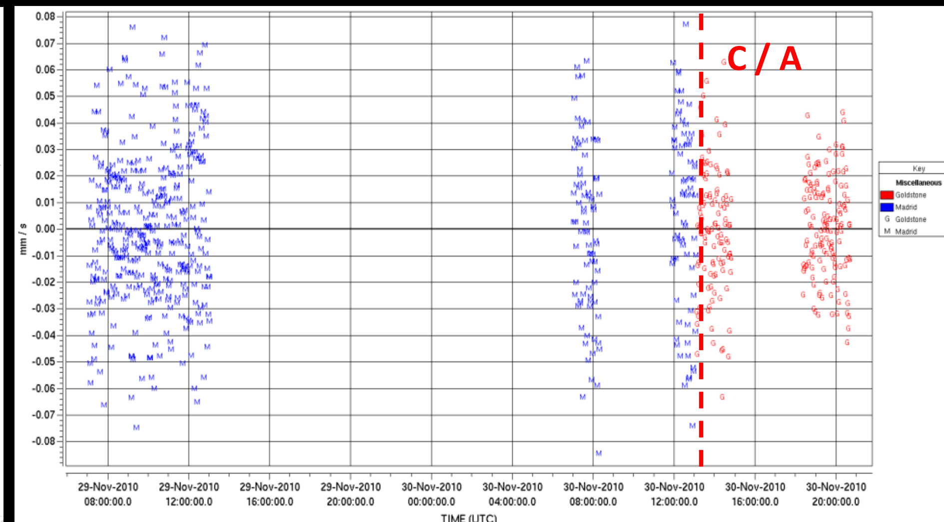


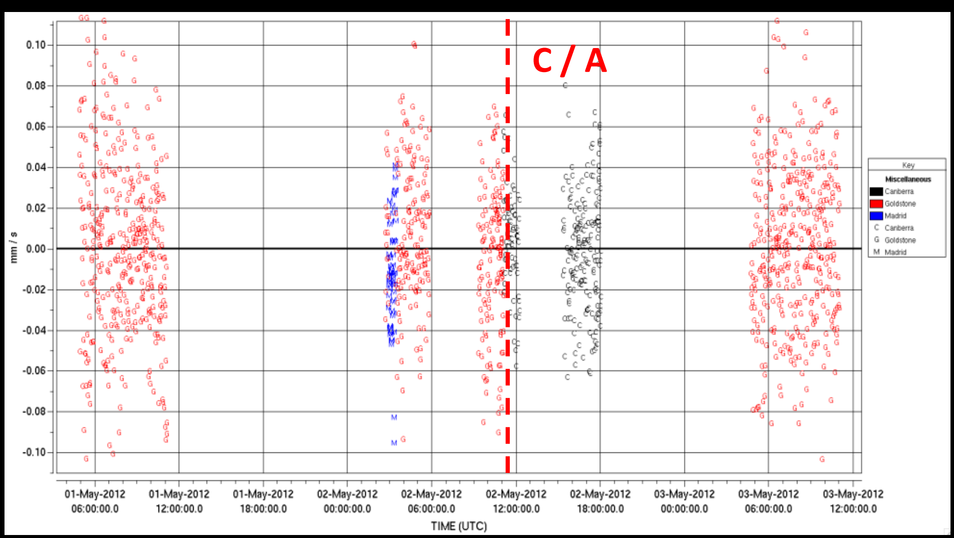
Image credit: NASA/JPL

Enceladus flybys: Doppler residuals





(X/X and X/Ka)
@ 60 sec

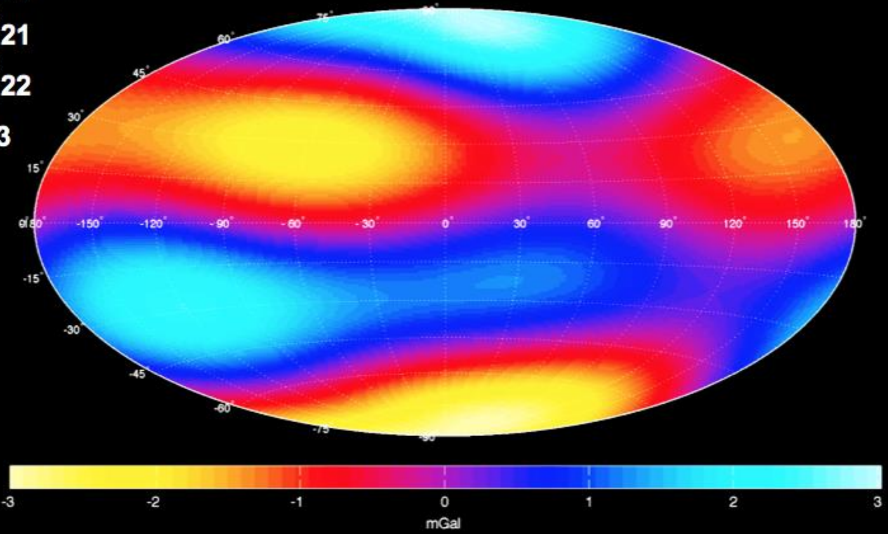


Multiarc solution for the gravity field of Enceladus

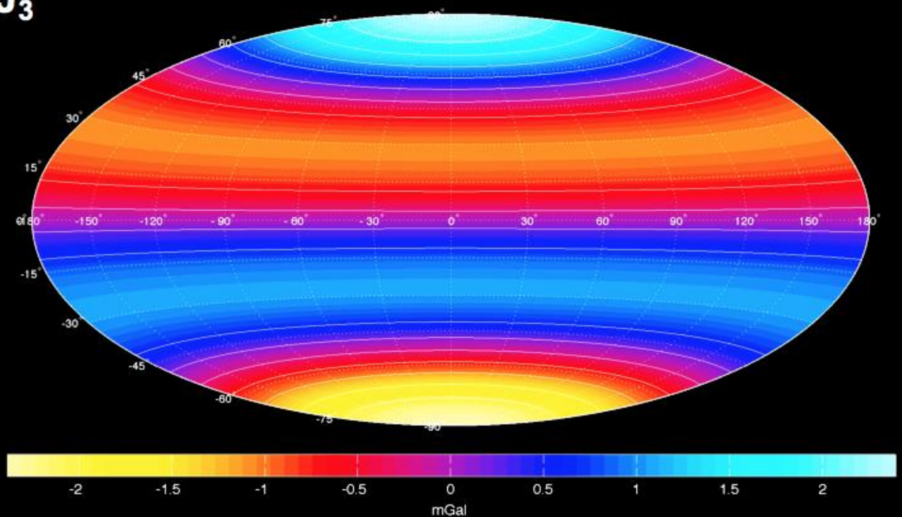
Coeff.	Sol DELTAV	
	Central value (x10^6)	Formal uncertainty (x10^6)
J_2	5435.2	34.9
C_{21}	9.2	11.6
S_{21}	39.8	22.4
C_{22}	1549.8	15.6
S_{22}	22.6	7.4
J_3	-115.3	22.9
ΔV (E9)	0.23 mm/s (96% in the direction of –V)	
ΔV (E19)	0.25 mm/s (87% in the direction of –V)	
J_2/C_{22}	3.51 ± 0.05	
corr(J_2,C_{22})	-0.28	
C/MR^2 (Radau-Darwin from C_{22})	0.339	

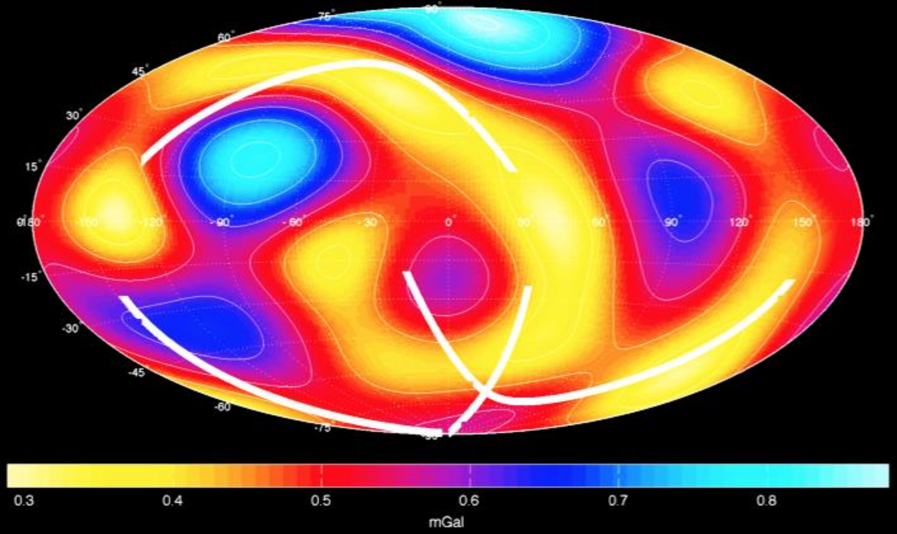
Gravity disturbances

C_{21}
S_{21}
S_{22}
J_3

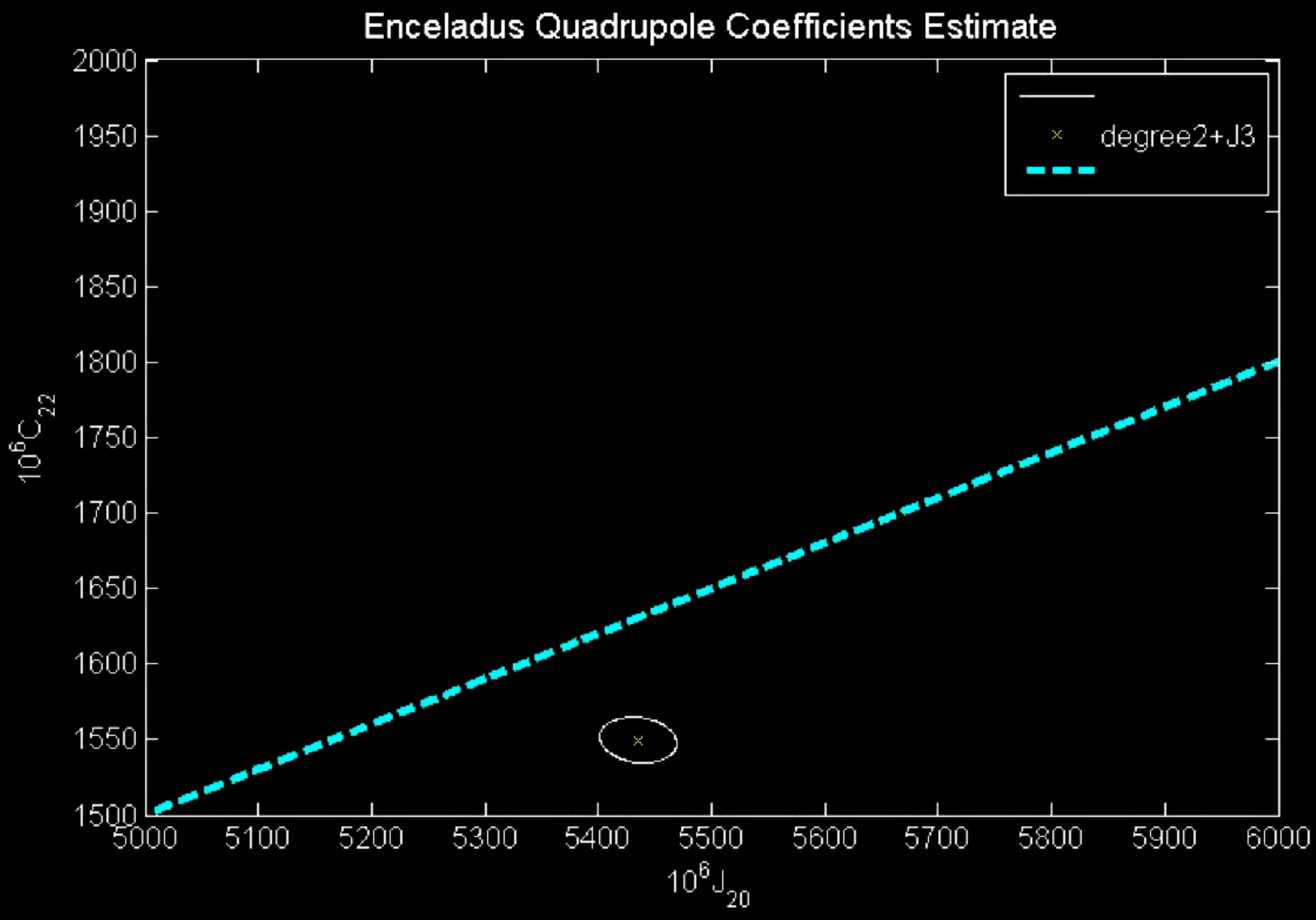


J_3

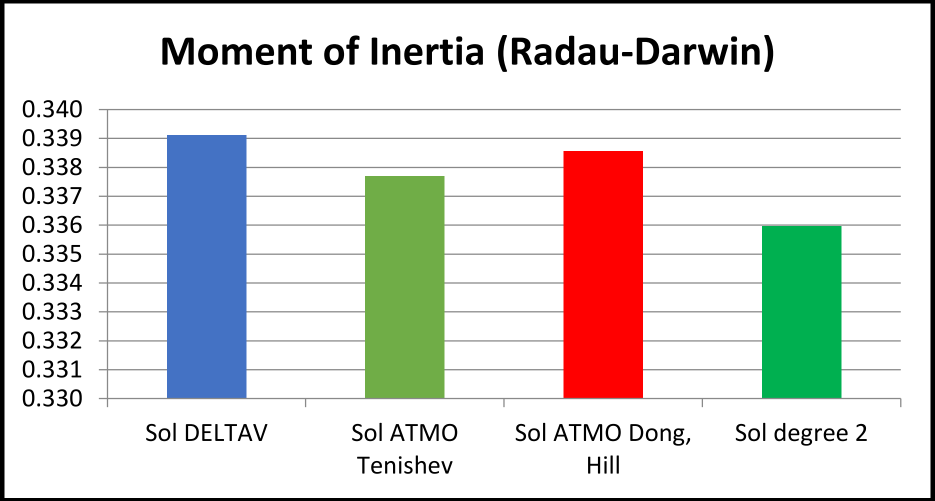




J_2/C_{22} vs hydrostatic equilibrium



Enceladus as a differentiated body



Radau-Darwin equation can be used to compute the MoI only when the body is found in hydrostatic equilibrium.
For Enceladus, corrections must be applied in order to compute the actual MOI.

The true MOI is 0.33 → fully differentiated body.

J_2 and C_{22} present a tidal and rotational distortion Δ, associated only to the core of the body. This is the memory of when Enceladus was rotating faster and closer to Saturn, while the ice layer has no memory of that time and can be considered hydrostatic.

Non-hydrostatic component of the gravity field

$C_{22} = (1+\Delta)^* C_{22,h}$ → Δ is the distortion of core only

$J_2 = (1+\Delta)^* J_{2,h} + J_{2,nh}$ → Δ is the distortion of core + axial-symmetric non-hydrostatic effect at degree 2

$J_{2,h} / C_{22,h} = 10/3$

$J_{2,h} = 10/3\ C_{22,h}$

$J_{2,h}\ (1+\Delta) = 10/3\ (1+\Delta)\ C_{22,h} = 10/3\ C_{22}$

$10^6\ J_{2,nh} = J_2 - (1+\Delta)^* J_{2,h} = 283 \pm 86$

$10^6\ J_3 = -115 \pm 23$

Interpretation of the Enceladus gravity data

The assumption of a negative point mass at the South pole leads to:

$$J_{2,nh}/J_3 = -1$$

While:

$$(J_{2,nh}/J_3)_{observed} = -2.4\ (+1.5;-1)$$

The assumption of a negative cap that extends out 200 km from the pole leads to:

$$J_{2,nh}/J_3 = -2$$

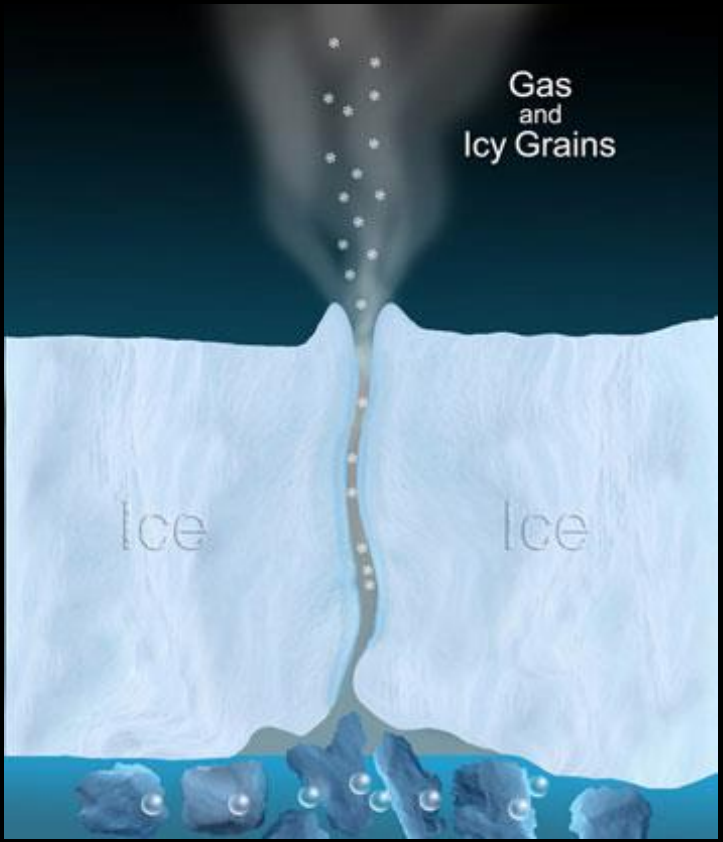
This time the observed ratio is compatible with the assumption.

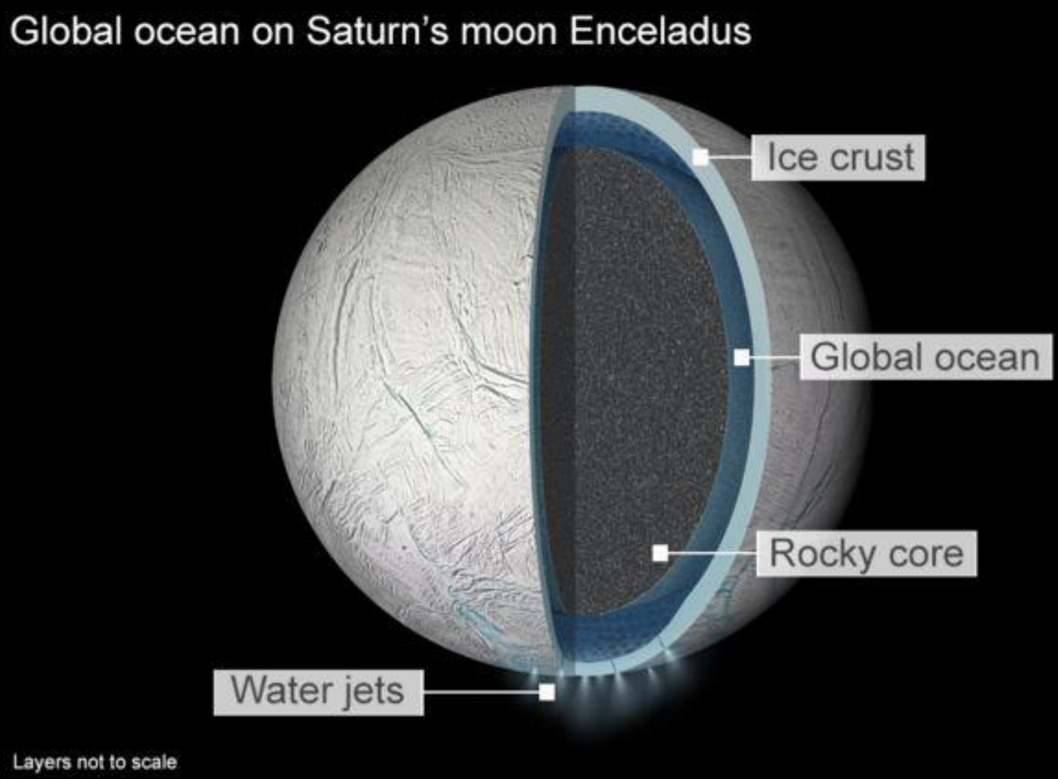
Another physical model compatible with the observed ratio is composed of two caps centered at the South pole:

1) ~ 1 km thickness of missing ice at the top;
2) ~ 10 km thickness of water ocean at ~ 40 km depth

For a fully differentiated core of density 2.6 g/cm^3, the thickness of the outer shell (ice +water) is only ~50km.

Enceladus's ocean





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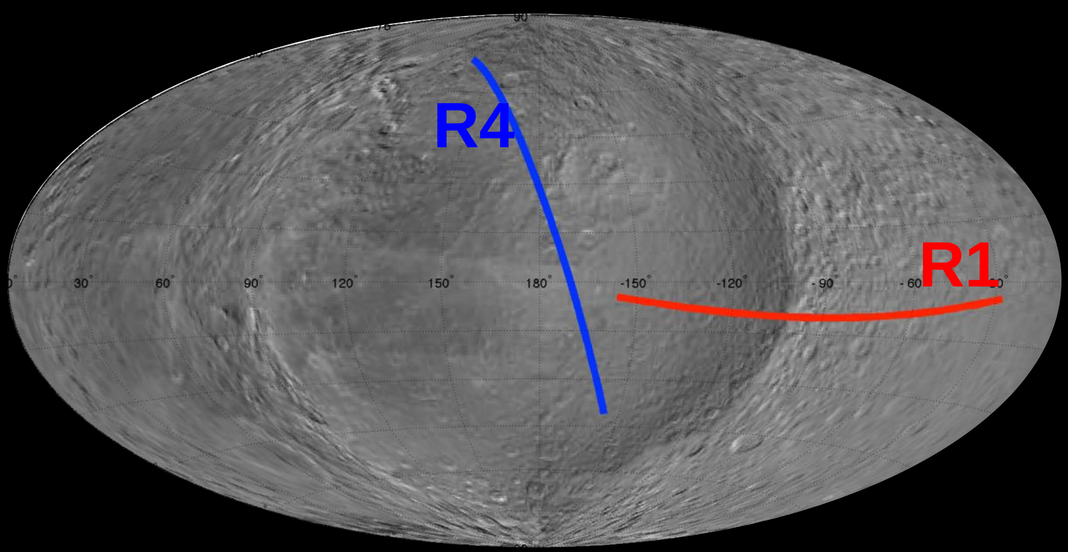
"The Gravity Field and Interior Structure of Enceladus"

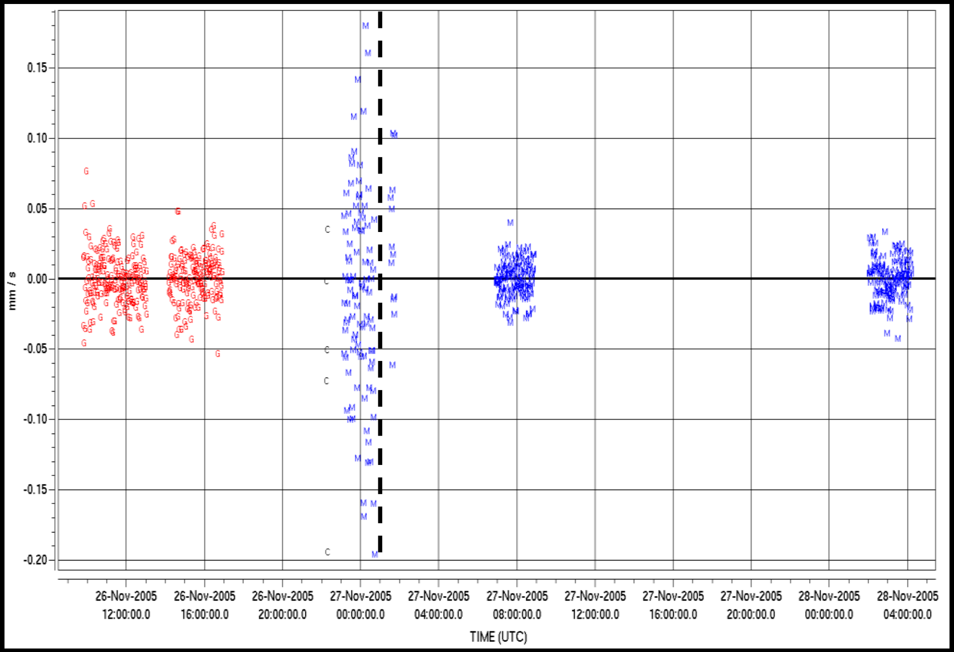
Cassini's gravity flybys of Rhea

R1	R4
C/A: 26-NOV-2005 22:37:36.0000 UTC Altitude: 500 km C/A latitude: -10.3° SEP angle: 113.5° Observation time: -> 4h continuous tracking around C/A: 2-way and 3-way Doppler data Relative velocity: 7.3 km/s	C/A: Altitude: 1000 km C/A latitude: 18.3° SEP angle: 128.1° Observation time: -> 3h continuous tracking around C/A: 2-way Doppler data only Relative velocity: 9.3 km/s

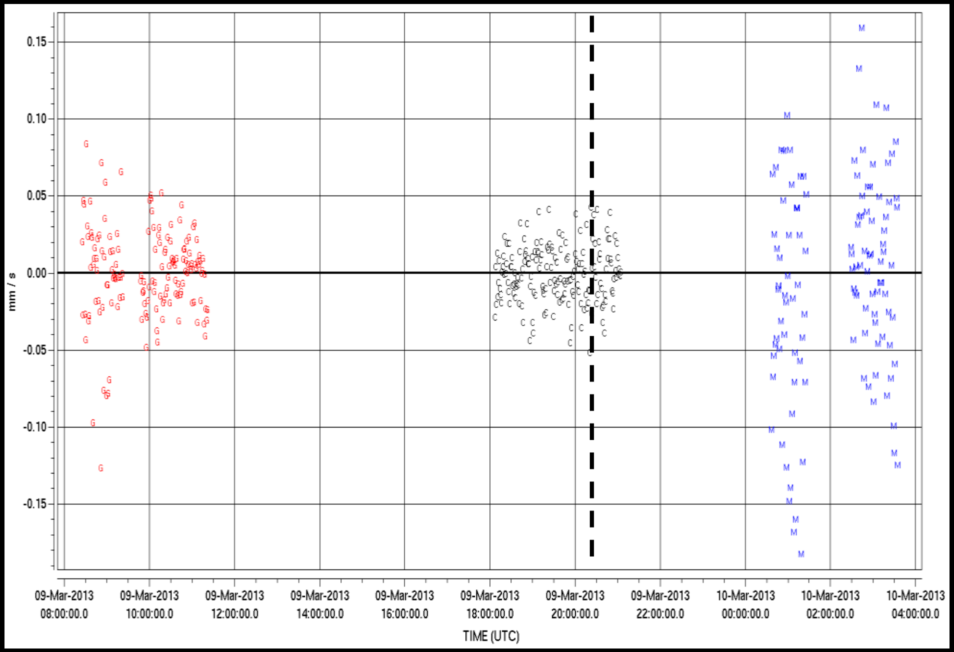


R1 and R4 Doppler residuals

R1 – November 2005 - RMS = 32 μm/s



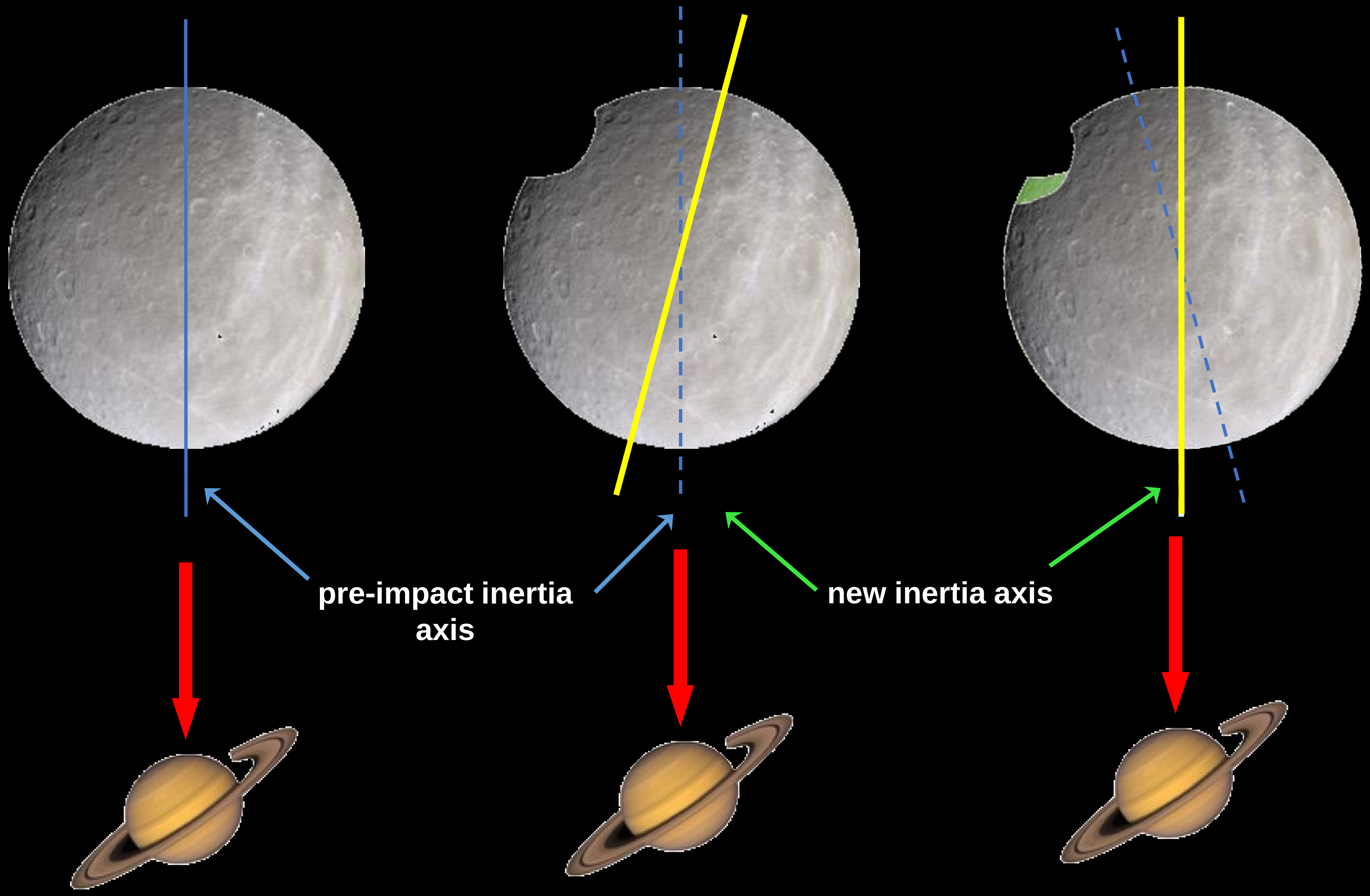
R4 – March 2013 - RMS = 39 μm/s



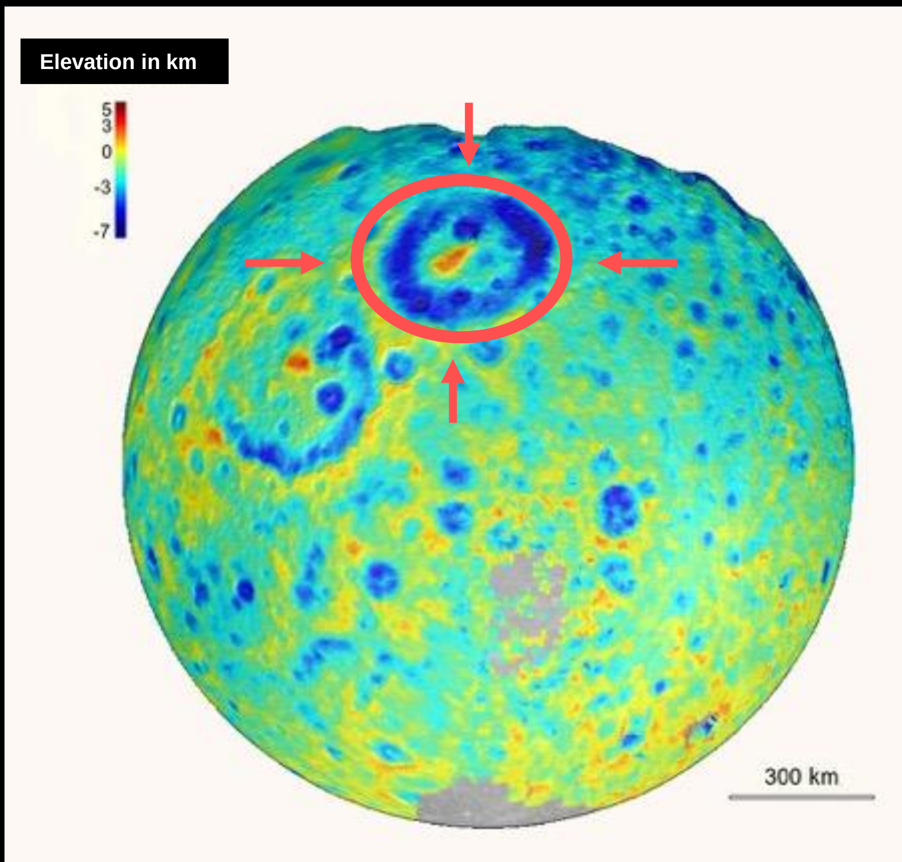
Multiarc solution for the gravity field of Rhea

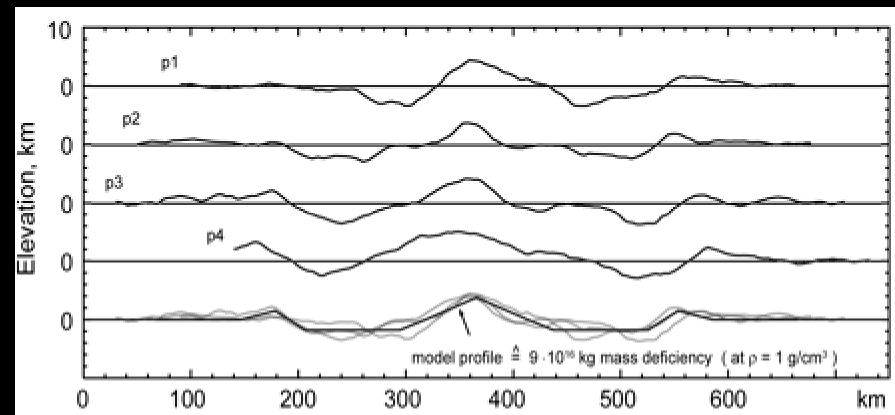
Coefficient	Central value ($x10^6$)	Formal uncertainty ($x10^6$)
C_{20}	- 953.4	14.5
C_{21}	- 9.6	11.7
S_{21}	-28.1	28.7
C_{22}	231.5	6.2
S_{22}	- 15.2	5.3
J_2/C_{22}	4.12 ± 0.15	
corr J_2 - C_{22}	-0.63	
C/MR^2 (Radau-Darwin from C_{22})	0.37	

The re-orientation scenario



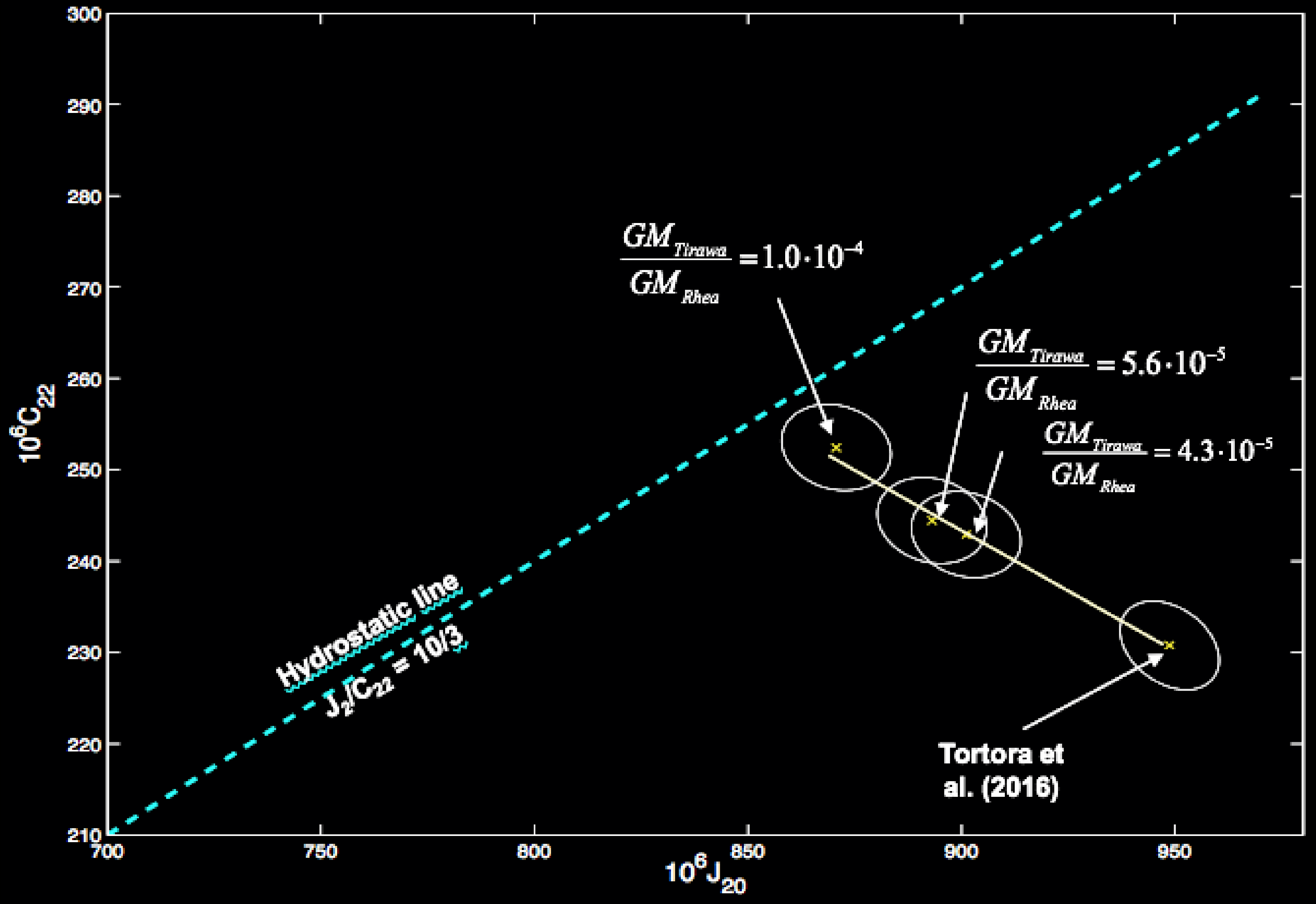
The Tirawa crater





	Mass	GMTirawa/GMRhea
Minimum	$1.0 \cdot 10^{17}$ kg	$4.3 \cdot 10^{-05}$
Best	$1.3 \cdot 10^{17}$ kg	$5.6 \cdot 10^{-05}$
Maximum	$2.3 \cdot 10^{17}$ kg	$1.0 \cdot 10^{-04}$

A non-hydrostatic Rhea



Re-orientation of the principal axes (1)

Quadrupole gravity field can be written using the quadrupole tensor Q

$$\mathbf{Q} = \frac{1}{3}\iiint_V \left[3(\mathbf{r}'\mathbf{r}') - \mathbf{1}r'^2\right]\rho(\mathbf{r}')dV$$

MacCullagh formula relates the quadrupole tensor Q and the inertia tensor I:

$$\mathbf{Q} = \frac{1}{3}\mathbf{1}Tr(\mathbf{I}) - \mathbf{I}$$

⇒

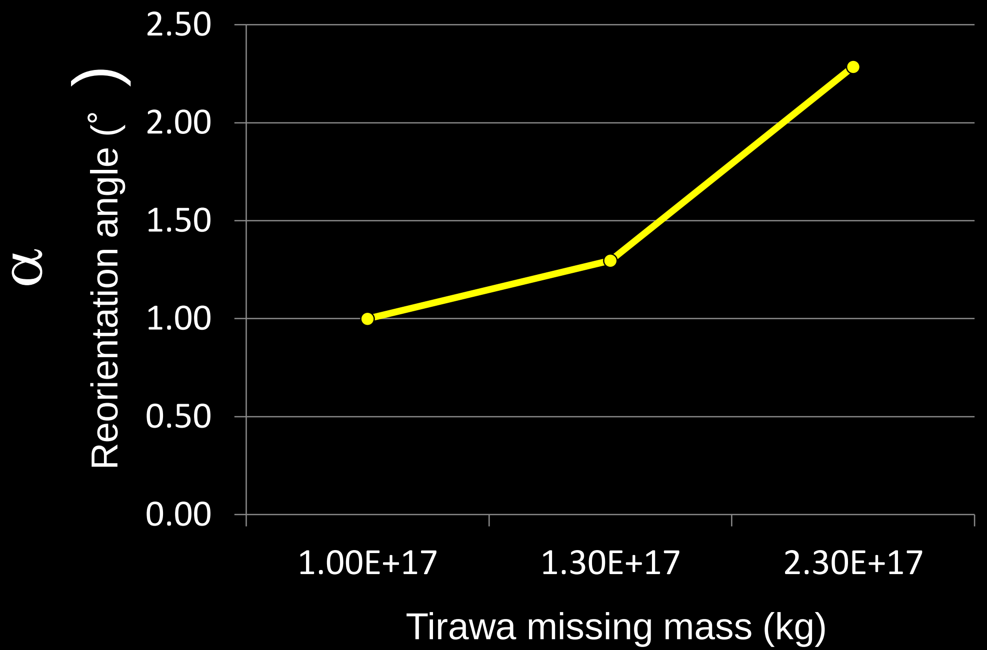
I and Q share the same eigenvectors

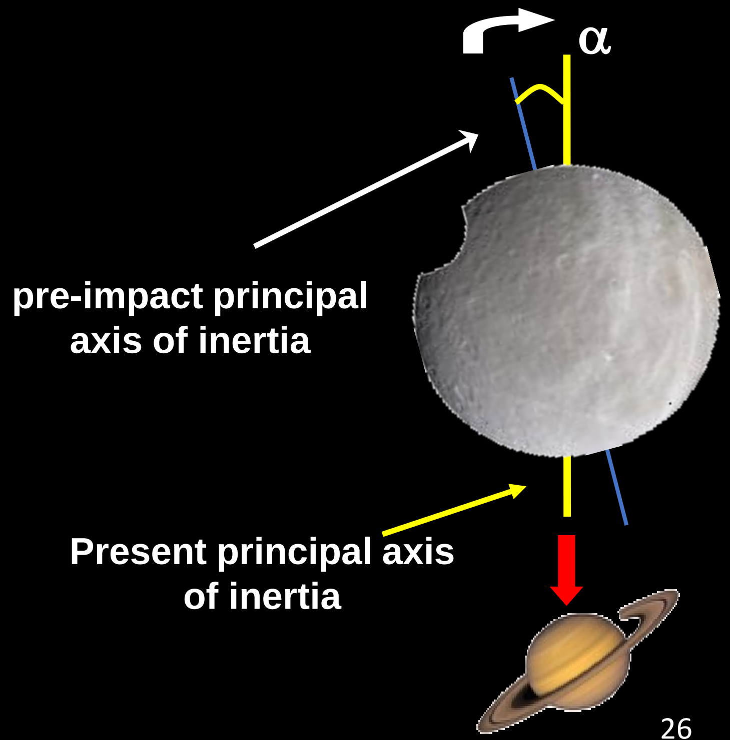
$$\mathbf{Q} = \frac{\sqrt{5}}{3}MR^2\begin{pmatrix} -(C_{20} - \sqrt{3}C_{22}) & \sqrt{3}S_{22} & \sqrt{3}C_{21} \\ \sqrt{3}S_{22} & (C_{20} + \sqrt{3}C_{22}) & \sqrt{3}S_{21} \\ \sqrt{3}C_{21} & \sqrt{3}S_{21} & 2C_{20} \end{pmatrix}$$

Re-orientation of the principal axes (2)

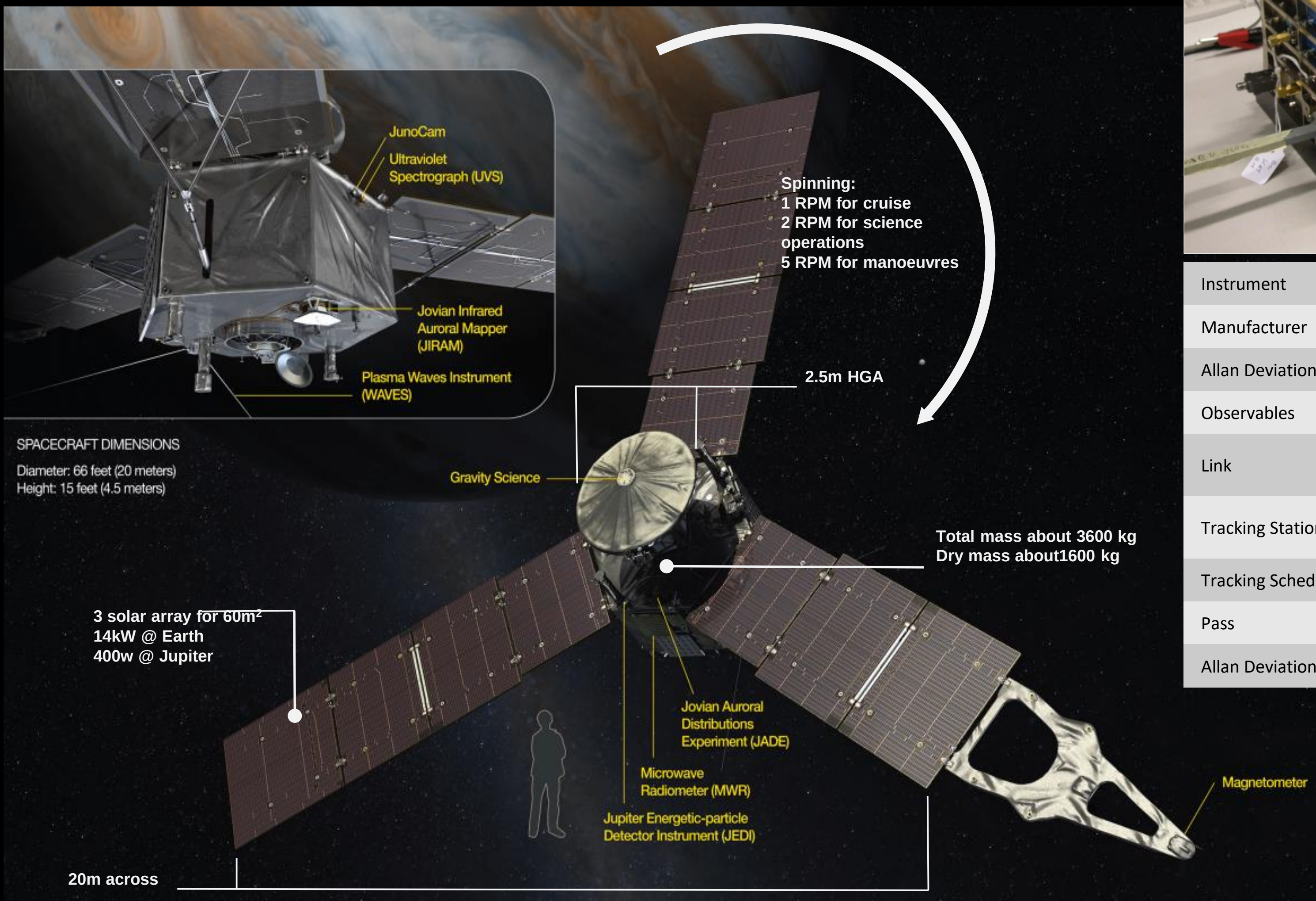
Quadrupole tensor eigenvectors (computed only with J_2, C_{22} e S_{22}) gives the pre-impact principal axes of inertia.

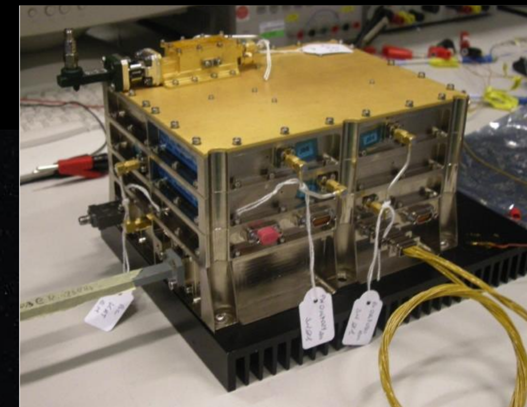
Present principal axes of inertia are given by the eigenvectors of the complete quadrupole tensor (computed with J_2, C_{22}, S_{22} + Tirawa's gravity field)





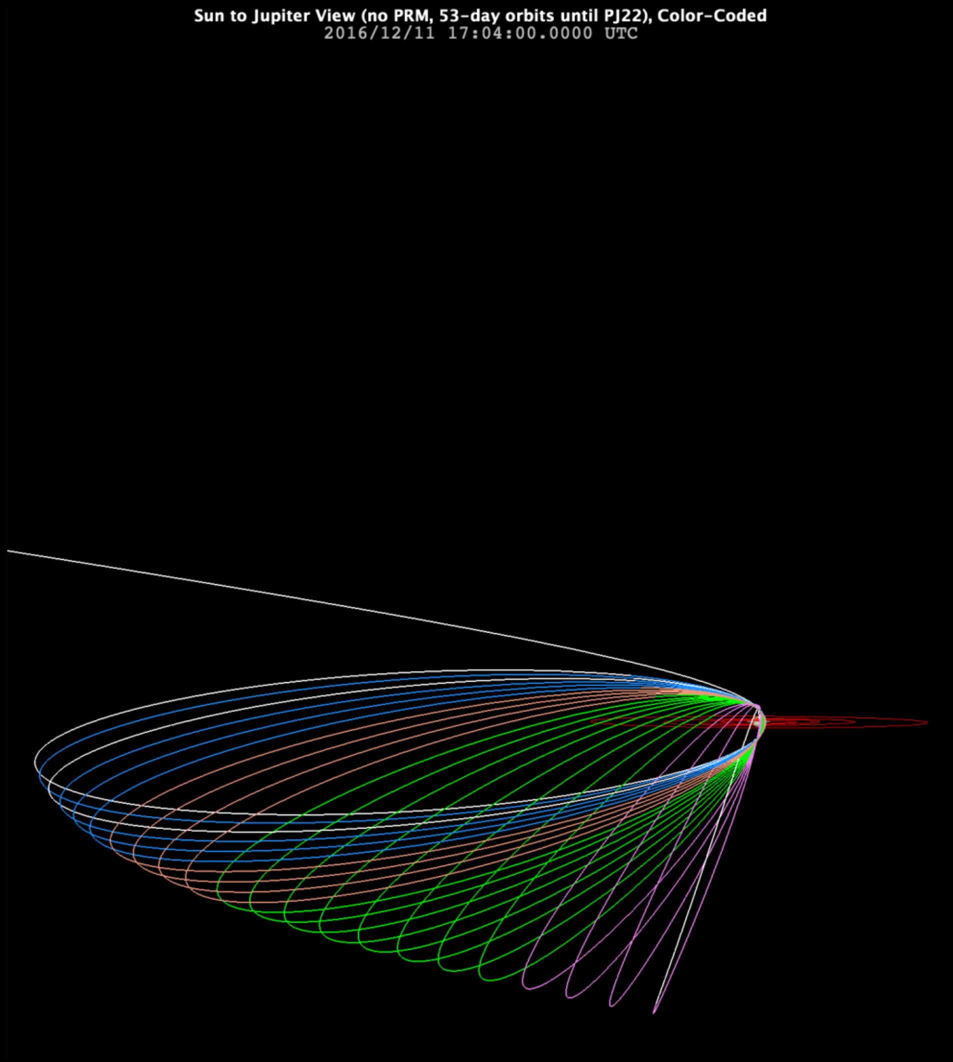
The Juno mission and the gravity science instrument

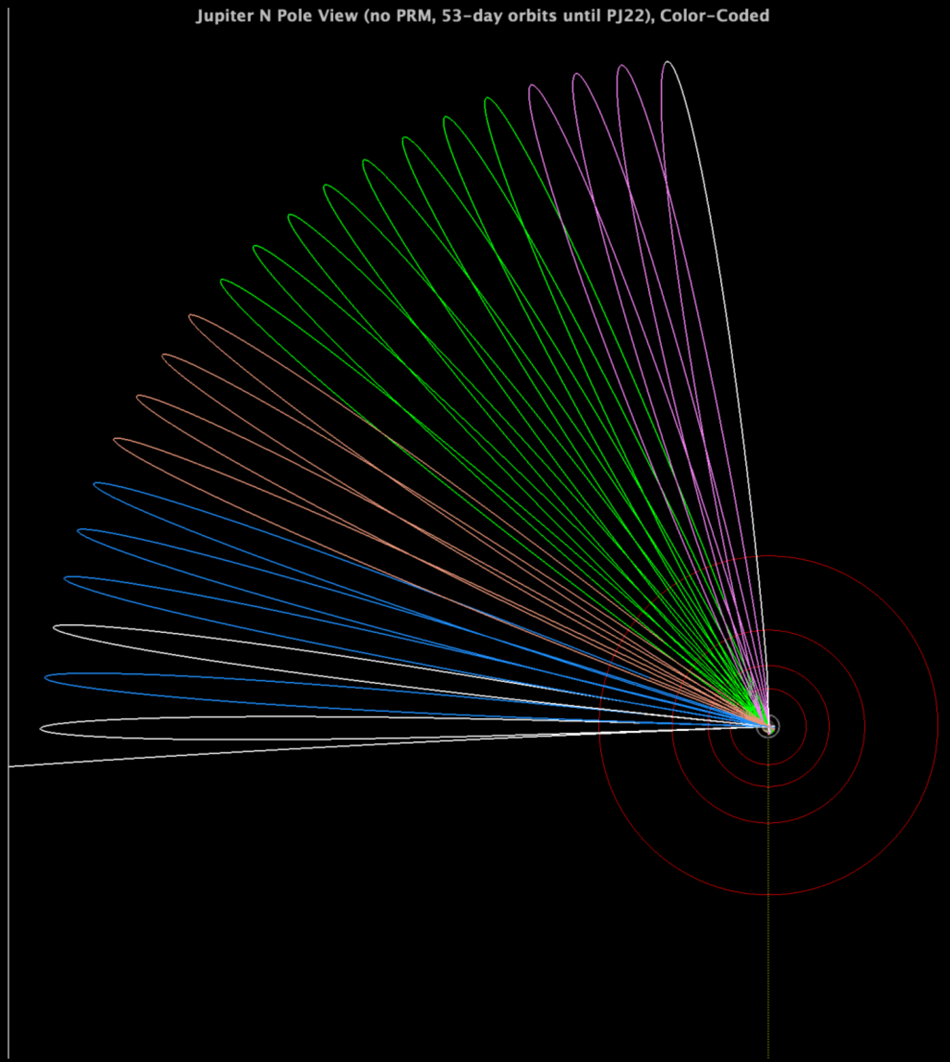




Instrument	KaTS
Manufacturer	Thales Alenia Space - Italia
Allan Deviation	$4x10^{-16}$ @ 1000s
Observables	2-way Doppler
Link	Ka/Ka (34Ghz up / 32.5 GHz down)
Tracking Station	DSS25 34m BWG – Goldstone DSN
Tracking Schedule	C/A +/- 3h
Pass	25 out of 32
Allan Deviation	< 10^{-14} @ 1000s end to end

The 53-day Juno orbit



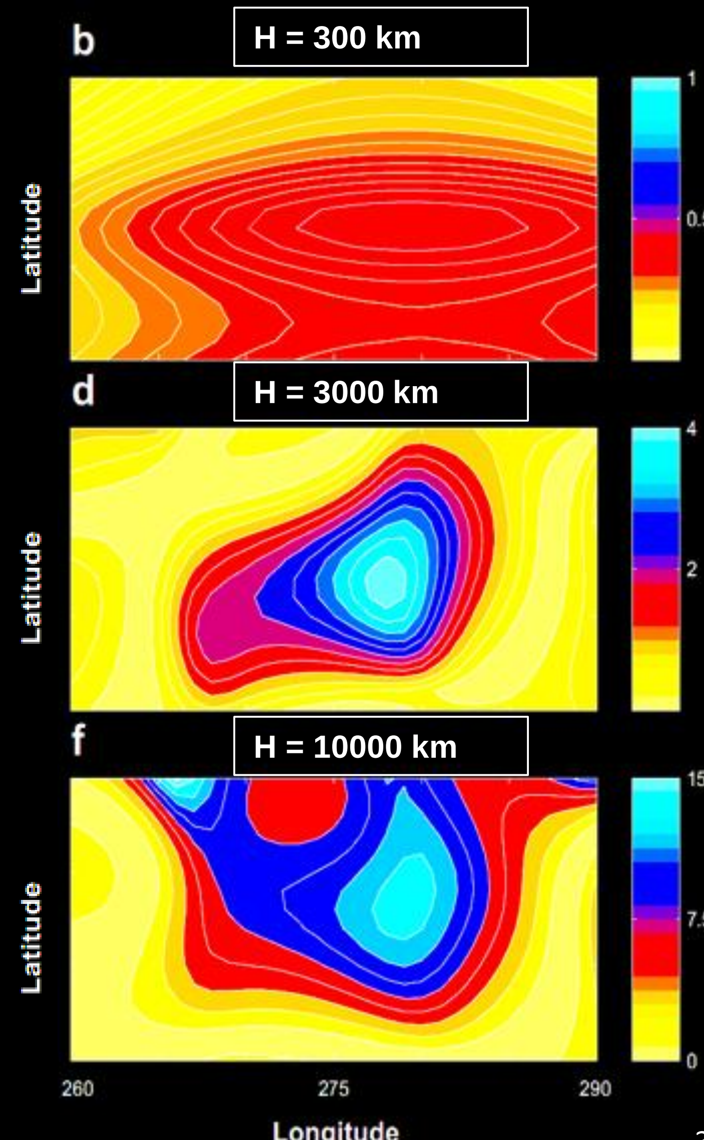


The Juno gravity experiment: goals

- Juno Gravity Science main goal is to learn about the interior mass distribution of Jupiter
- Specific Gravity Science measurements include:
  - Core size
  - Deep zonal flow – motion of gas on series of concentric cylinders
  - Precession – change in direction of Jupiter spin axis from solar torque, which gives indication on the size and mass of the core
  - Tidal response – change in mass distribution due to position of Io
- However, the surface gravity field does not determine a unique interior.
  - All golf balls have the same external gravity but different interiors.

Jupiter’s Great Red Spot

- July 11th 2017
- MWR tilt attitude
- X/X data
- 5400 km altitude
- Lat 9.5 ° N
- SEP 86°



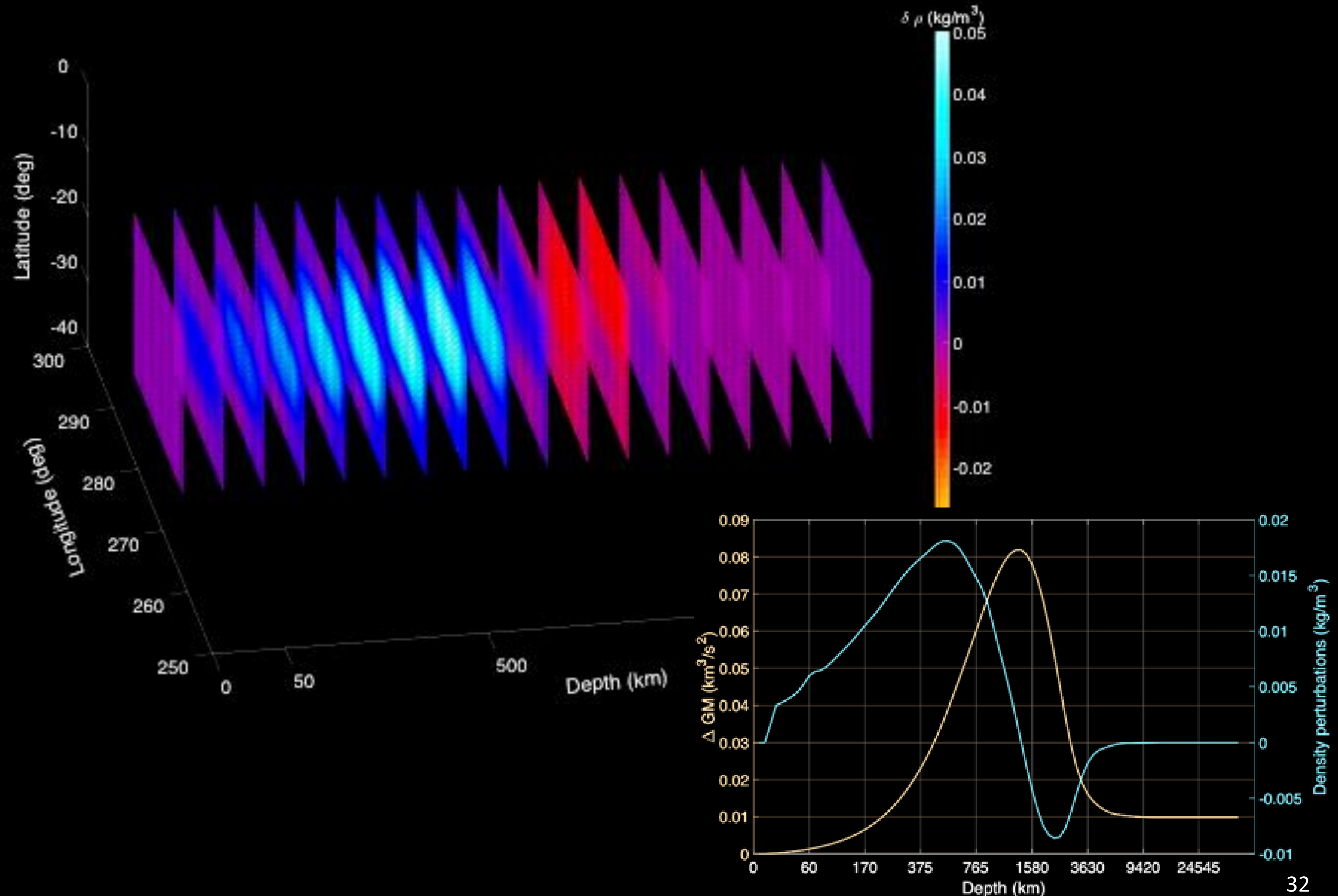
From Parisi et al. (2016), Icarus

GRS additional overflights

- PJ7 in July was over the GRS in MWR attitude.
  - Spin artifacts on X-band Doppler on MGA but noise has been brought down through optimal data compression and de-spinning calibrations.
  - Io plasma torus calibrations from models are still being worked.
- PJ21 is planned in 2019 in GRAV attitude with HGA.
- More overflights can be achieved by changing longitude order.
  - Changes time of filling longitude grid for MAG.
  - MAG team was strongly opposed to changing PJ12, probably PJ17 (it completes the grid of first 16).

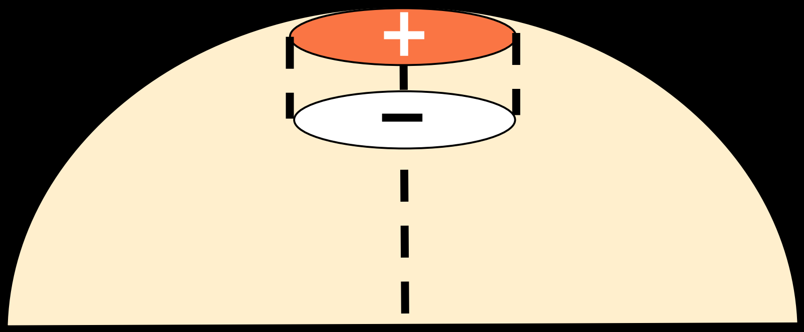
Perijove	GRS Δlon	Decision Date
PJ7	0.2°	Complete
PJ21	-5.2°	Planned
PJ18 (PJ23)	2.9°	Sep-18
PJ22 (PJ33)	1.6°	Sep-18
PJ27 (PJ32)		
PJ31 (PJ19)	0.8°	Sep-18

Thermal wind model of the GRS



Mascons in the OD software

- We model the GRS ‘bubble’ as two thin circular flat disk mascons at different altitude.
  - With equal masses of opposite sign.
  - Center of mascons at the GRS lat and long.
  - Radius of 8,000 km equal to longitudinal radius of GRS.
  - Vertical separation of 1,000 km.

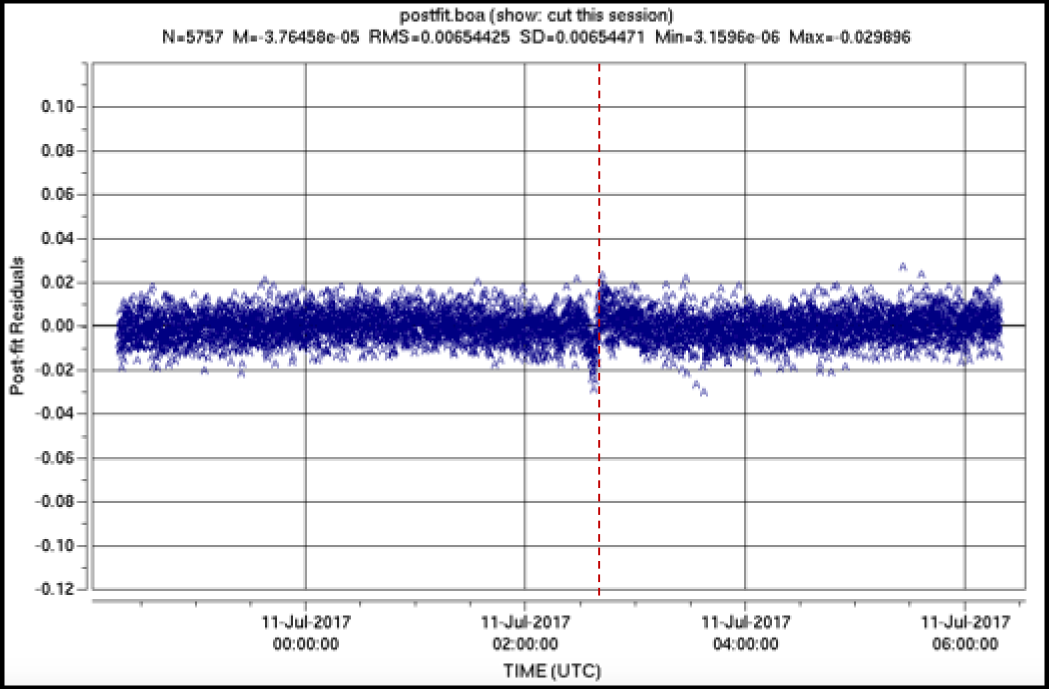


- Numerical simulations were carried out using different numbers of possible GRS over-flights. Expected uncertainty in GM of positive (upper) and negative (lower) change to mass of bubble at GRS.
- Leaving out PJ12 changes results by only ~2%.
- Adding 3/4 more over-flights to PJ7 improves accuracy by ~x2.

GRS perijoves	σ(GM), km^3/s^2
PJ7	0.0935
PJ7+PJ21	0.0752
PJ7+PJ21+PJ22	0.0618
PJ7+PJ21+PJ22+PJ31	0.0503
PJ7+PJ12+PJ21+PJ22+PJ31	0.0495

PJ7 data status

- PJ7 Doppler residuals after estimating only the Juno state for each single arc
- A new position for the MGA is estimated
- PJ1-8 multiarc solution used for the gravity field, pole position, precession rate, Love numbers (only k_{22} was estimated in the multiarc, the others are held to Wahl's values)
- No plasma calibrations for the Io torus applied



Conclusions and publications

- The measure of interesting parameters can be performed by means of radio science experiments, that otherwise would be very difficult

- Many inferences on the interior structure of a body can be made on the basis of gravity analysis

- Gravity interpretations are not univocal

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