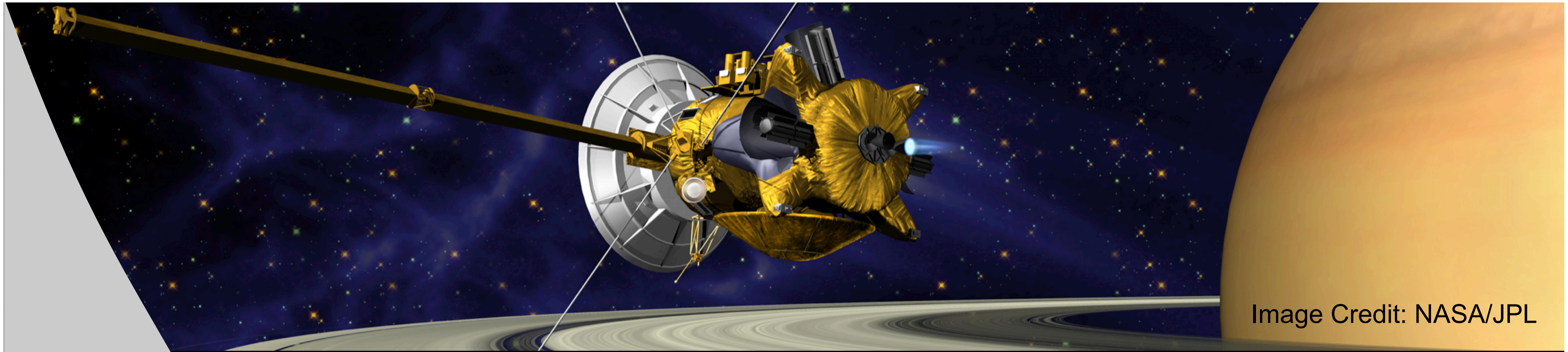

Enceladus' Gravity Field From Cassini Radio Science

Sami Asmar & Aseel Anabtawi

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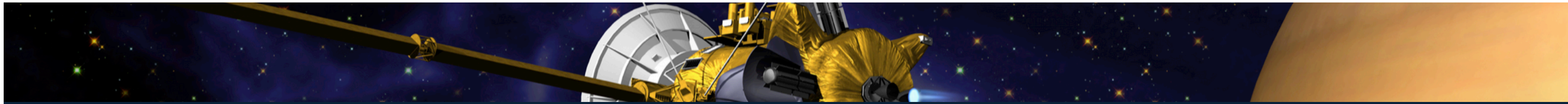


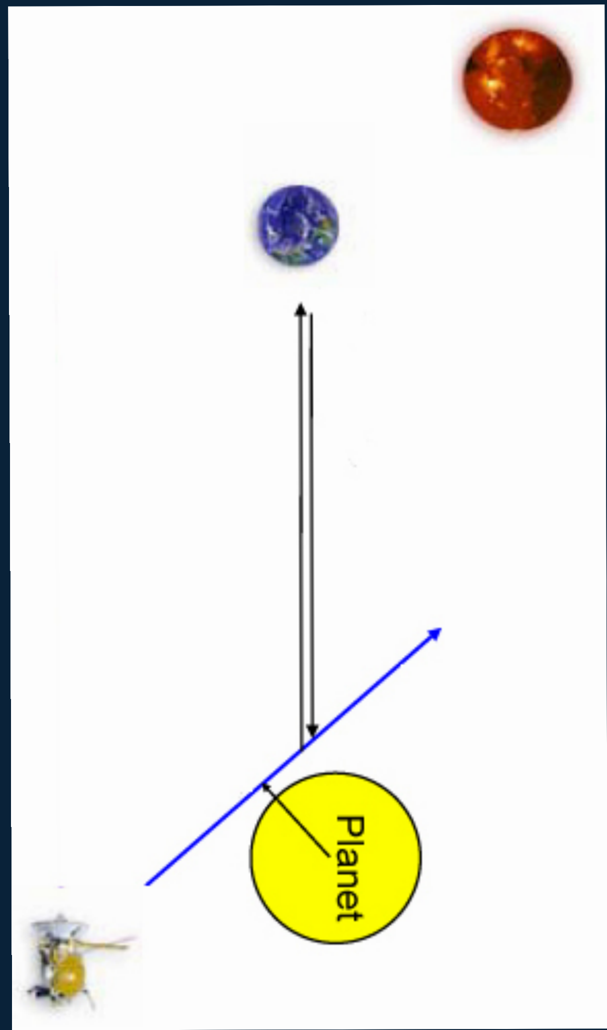
Radio Science Investigations

- Utilize the telecommunication links between spacecraft and Earth to examine changes in the phase/frequency, amplitude, and polarization of radio signals to investigate:

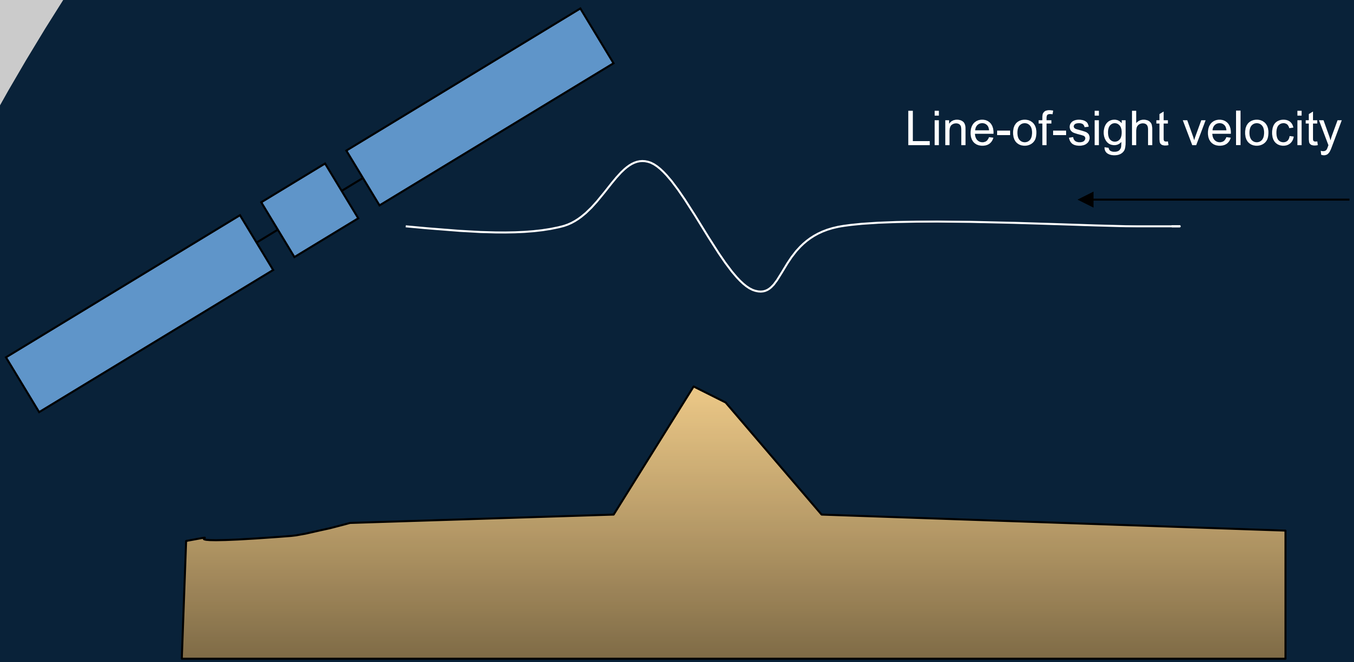
- Planetary atmospheres
  - Temperature-pressure profiles
  - Composition of ionospheres
  - Winds speeds and directions
  - Scintillations & magnetic fields
  - Planetary shapes
- Planetary interiors
  - Masses and mass distribution
  - Precision orbits
- Planetary rings
- Planetary surfaces
- Solar corona and wind
- Comet mass flux and particle distribution
- Fundamental Physics

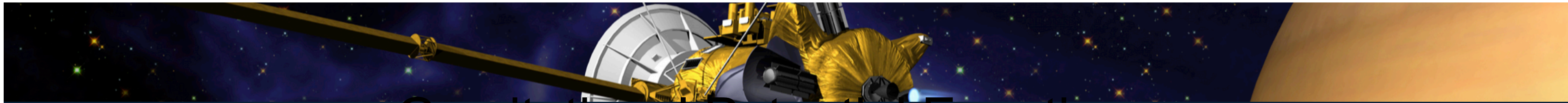
Gravity and Planetary Interiors

- Determine the mass and mass distribution
  - GM of body or system (planet + satellites)
  - Gravity field: higher order expansion of mass distribution
- Constrain models of internal structure
  - Examples: ocean on Europa
- Improve orbits and ephemeredes
- Doppler and range
  - Doppler accuracy to ~ 0.01mm/s at X-band and better at Ka-band
  - Ranging accuracy to ~ 1 meter



Doppler Measurement of Gravity Perturbations





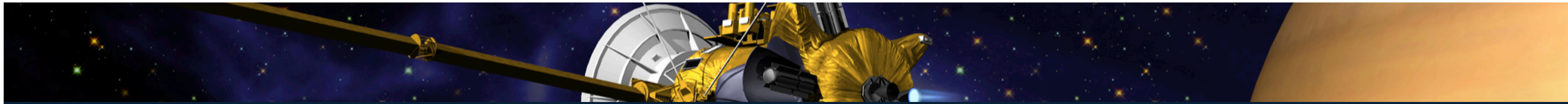
Gravitational Potential Equation

Gravitational Potential

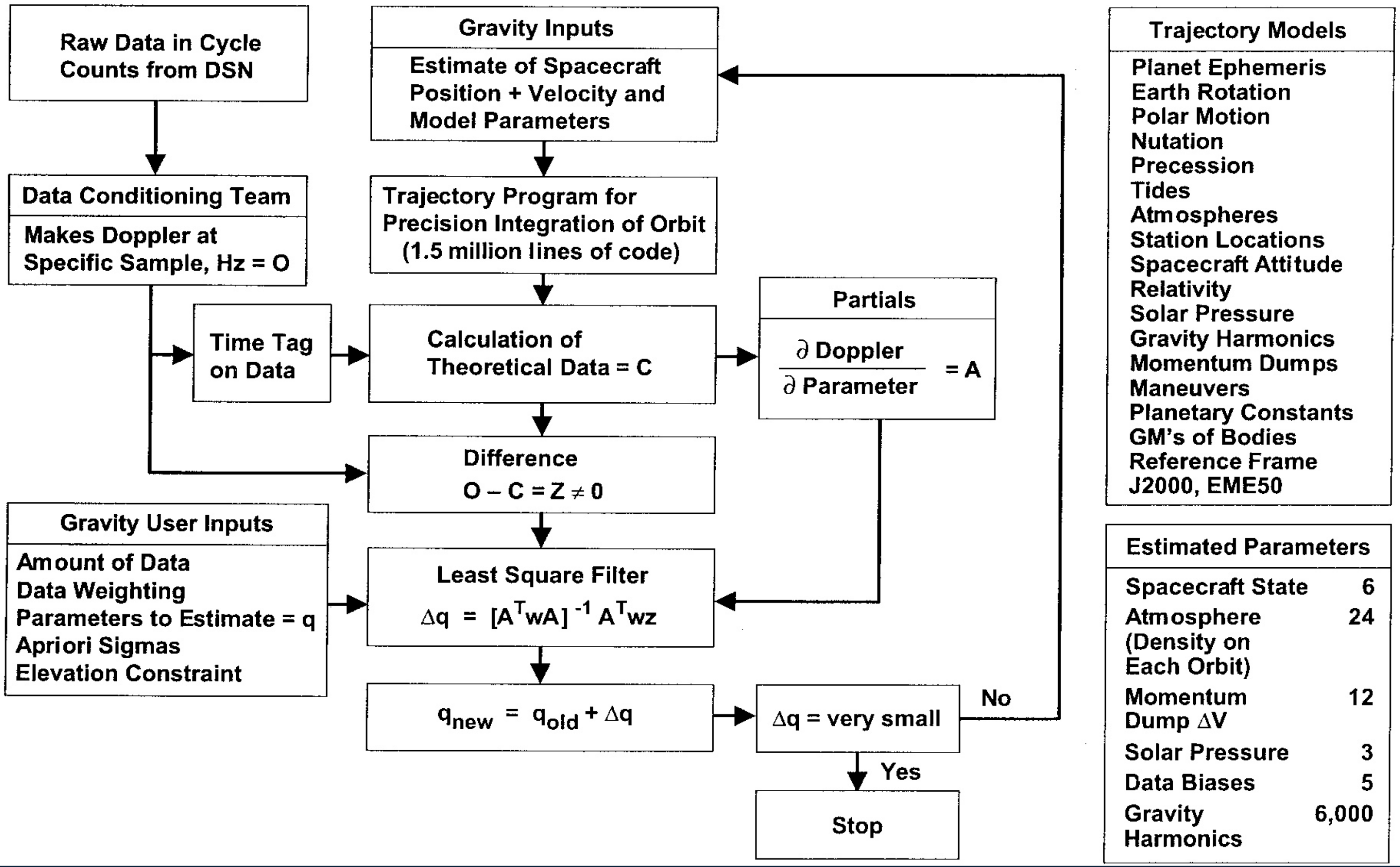
$$U = \frac{GM}{r} + \frac{GM}{r}\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{R_e}{r}\right)^n \overline{P}_{nm}(\sin\phi_{lat})\left[\overline{C}_{nm}\cos(m\lambda) + \overline{S}_{nm}\sin(m\lambda)\right]$$

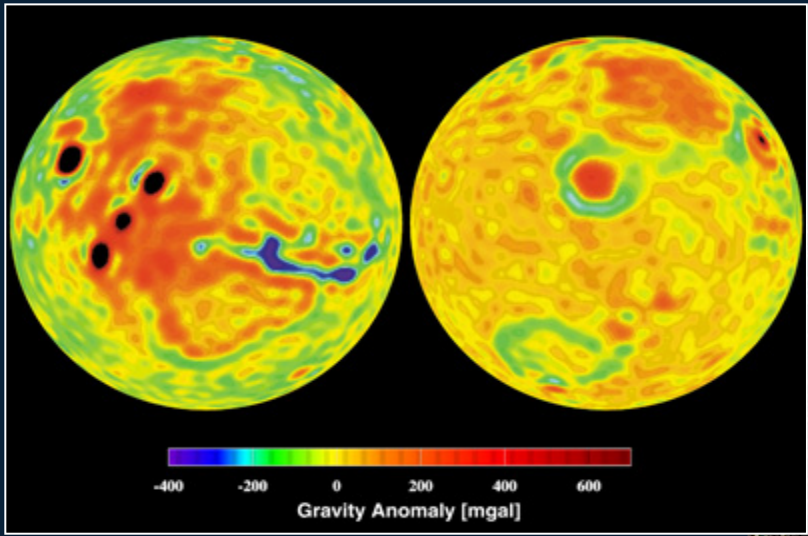
Normalization of Spherical Harmonic Coefficients:

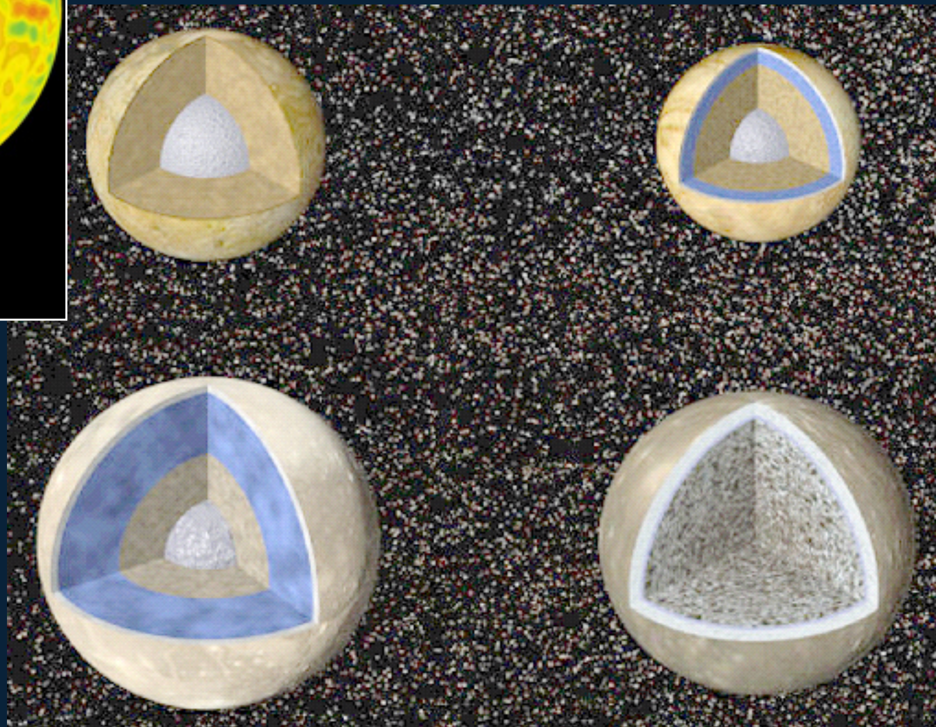
$$\begin{pmatrix} C_{nm} \\ S_{nm} \end{pmatrix} = \left[\frac{(n-m)!(2n+1)(2-\delta_{0m})}{(n+m)!}\right]^{1/2}\begin{pmatrix} \overline{C}_{nm} \\ \overline{S}_{nm} \end{pmatrix} = f_{nm}\begin{pmatrix} \overline{C}_{nm} \\ \overline{S}_{nm} \end{pmatrix}$$

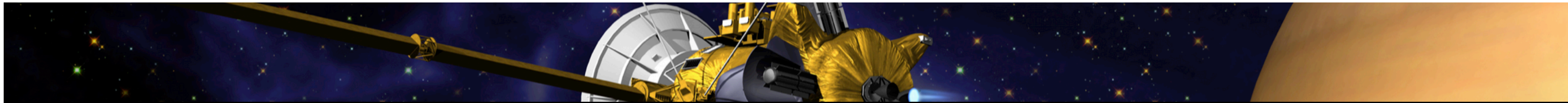


FLOW DIAGRAM FOR GRAVITY DATA REDUCTION




-400
-200
0
200
400
600
Gravity Anomaly [mgal]



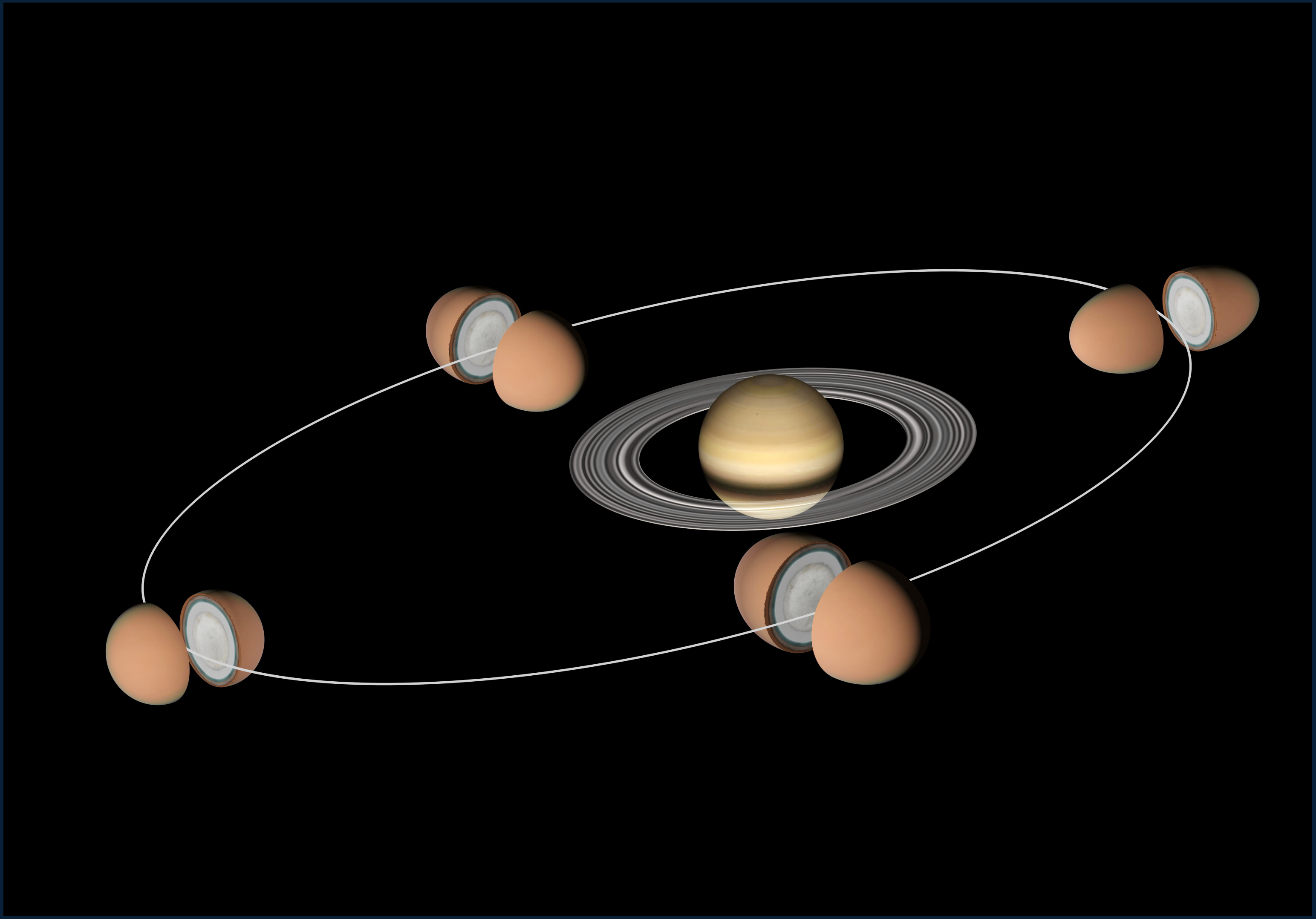


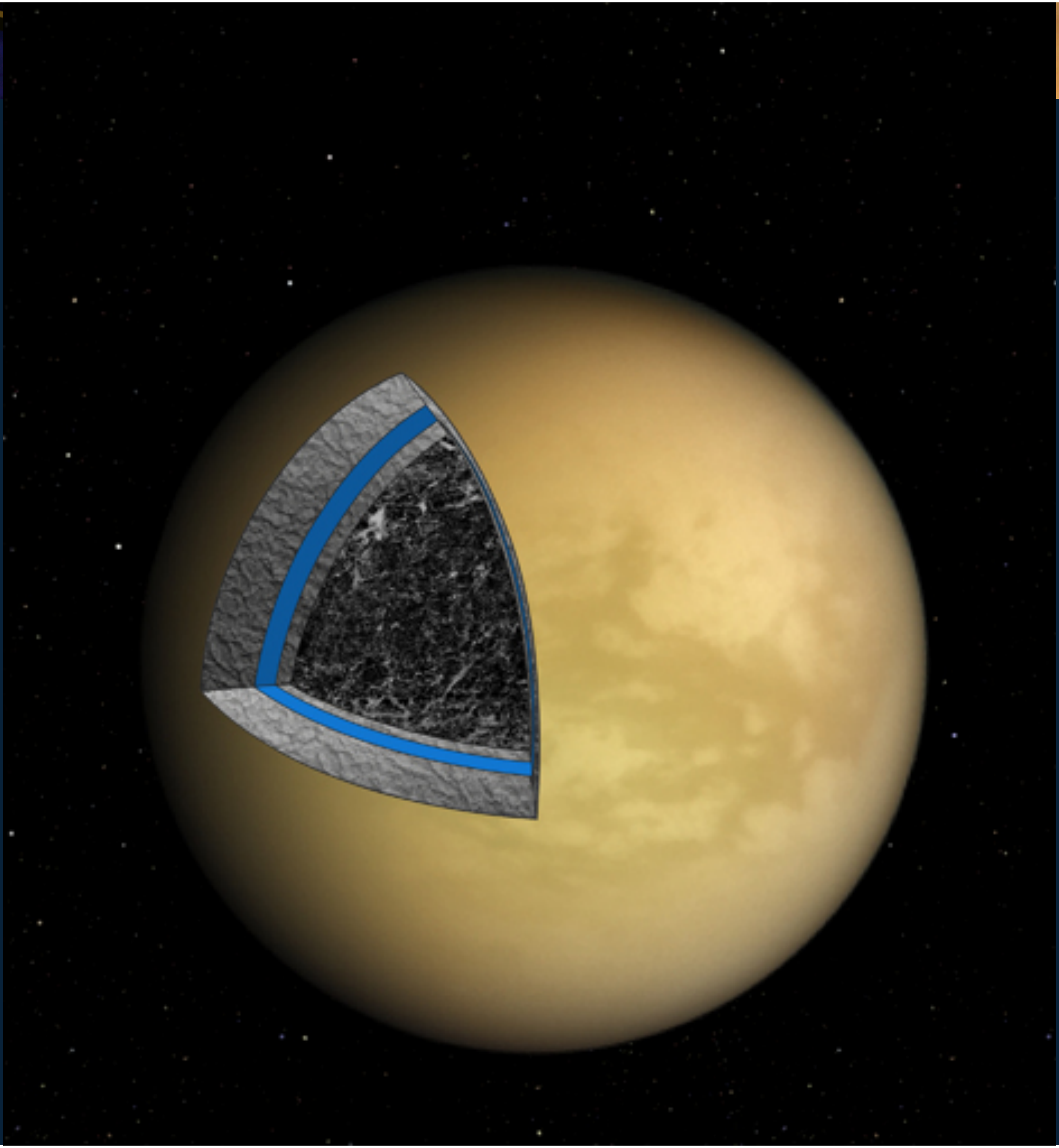
Enceladus: facts

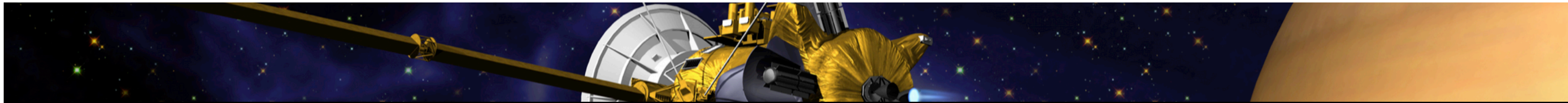
- **Sixth largest moon of Saturn**
- **Orbit semi-major axis ≈ 240,000 km**
- **Orbit velocity (average) ≈ 12.6 km/s**
- **Orbit eccentricity ≈ 0.005**
- **Orbit inclination ≈ 0.01°**
- **Mean radius ≈ 252 km**
- **Mean density ≈ 1.61 g/cm^3**

- **Water vapor jets from the south pole discovered in 2005**

Tidal Forces: Titan

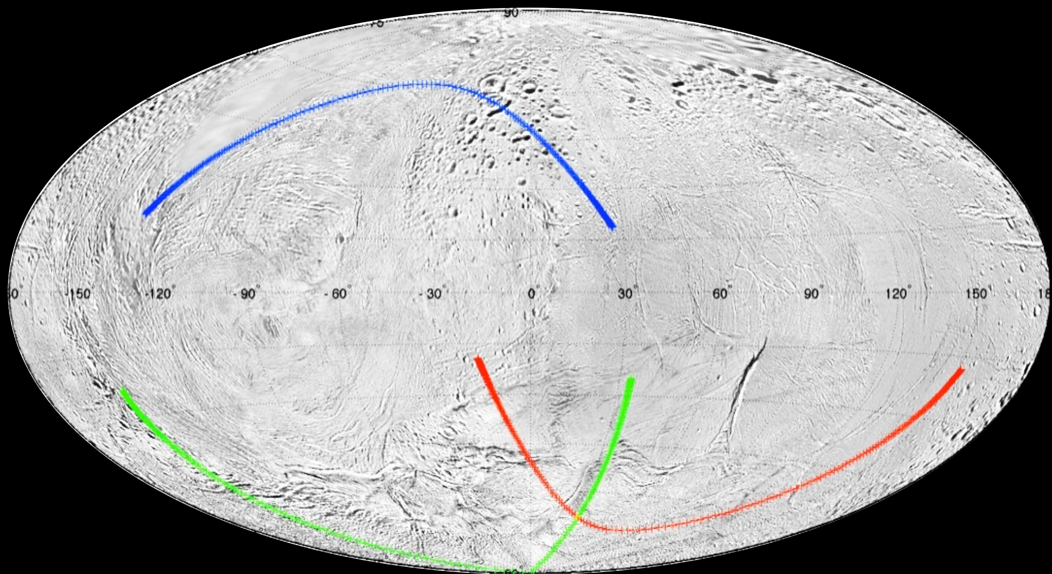






Enceladus: gravity flybys characteristics

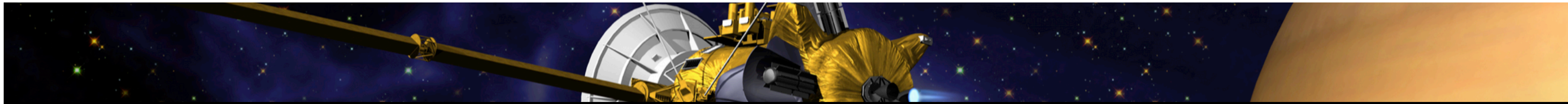
E9	E12	E19
C/A: APR-28-2010 00:10:51 UTC Altitude: 100 km C/A latitude: -89° SEP angle: 141° Observation time: -> 7h continuous tracking around C/A: 2-way Doppler data only Relative velocity: 6.5 km/s	C/A: NOV-30-2010 11:53:59 UTC Altitude: 48 km C/A latitude: 62° SEP angle: 54° Observation time: ->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



E9

E12

E19

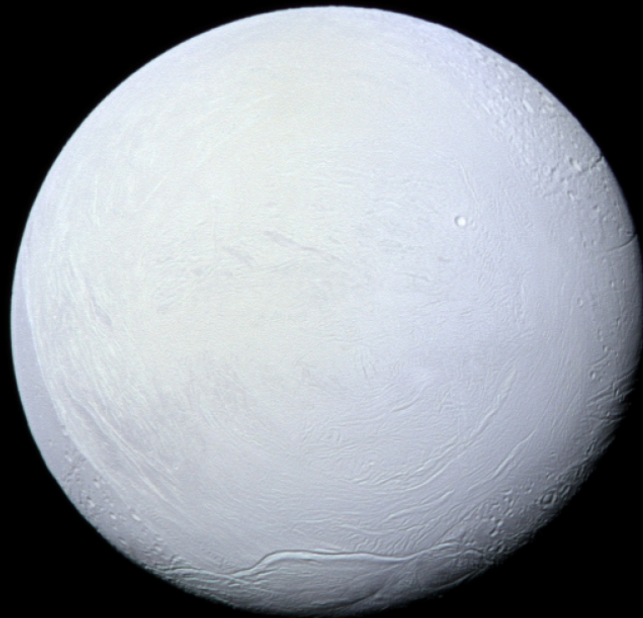


Measurement sensitivity: gravitational accelerations

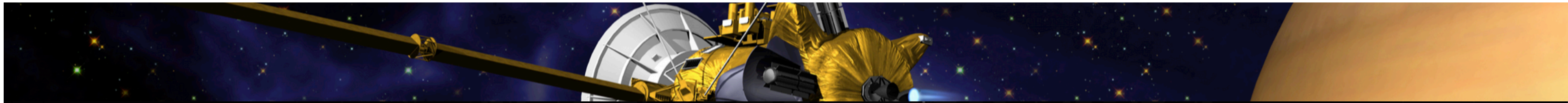
Monopole: $\delta V^{(0)} \approx (GM/rV)$

Degree-2: $\delta V^{(2)} \approx (GM/rV)\,(R/r)^2\,J_2$

Degree-3: $\delta V^{(3)} \approx (GM/rV)\,(R/r)^3\,J_3$



	E9	**E12**	**E19**
$\delta V^{(0)}$ (km/s)	3.2×10^{-3}	3.9×10^{-3}	3.0×10^{-3}
$\delta V^{(2)}$ (km/s)	9.0×10^{-6}	15.0×10^{-6}	10.0×10^{-6}
$\delta V^{(3)}$ (km/s)	2.0×10^{-7}	3.0×10^{-7}	2.0×10^{-7}



Measurement sensitivity: Enceladus' plume

The velocity variations caused by the atmospheric drag can be predicted using different models of Enceladus' plume density profile
(red boxes: Tenishev, DPS 2012; yellow boxes: Dong et al. 2011)

E9

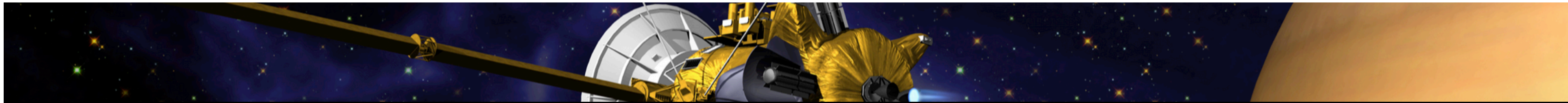
Yellow box (Dong et al. 2011)	Red box (Tenishev, DPS 2012)
$\rho_M = 3.78 \times 10^{-12}$ kg/m^3	$\rho_M = 1.03 \times 10^{-11}$ kg/m^3
$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.27$ mm/s	$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 1.5$ mm/s

$0.27 \text{ mm/s} \leq \Delta V \leq 1.5 \text{ mm/s}$

E19

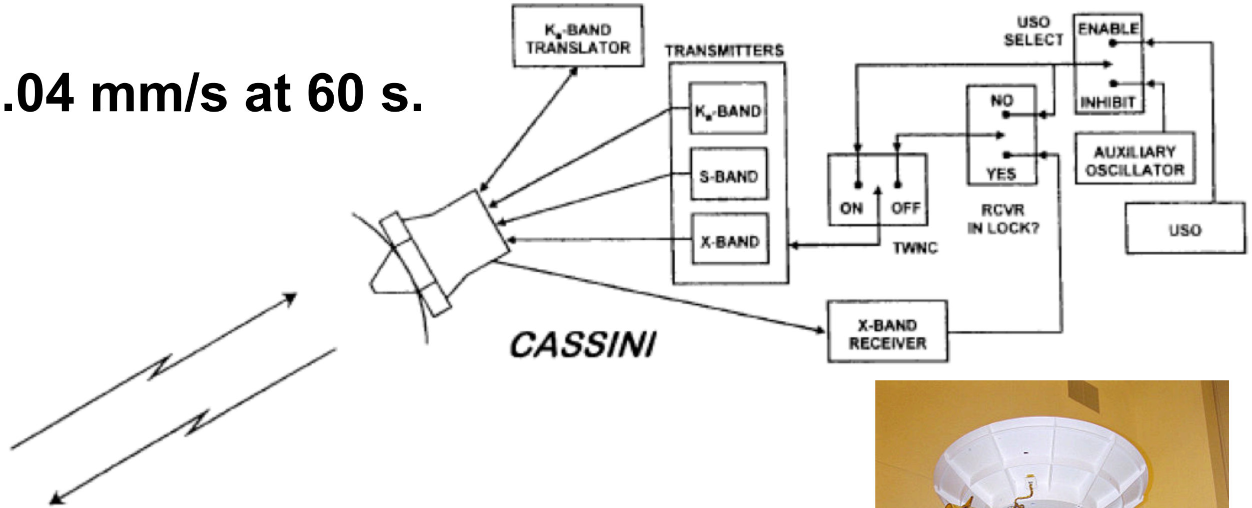
Yellow box (Dong et al. 2011)	Red box (Tenishev, DPS 2012)
$\rho_M = 6.46 \times 10^{-13}$ kg/m^3	$\rho_M = 4.85 \times 10^{-12}$ kg/m^3
$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.06$ mm/s	$\Delta V \cong 1/2\ (\rho_M/m_C)\ A\ C_D\ V^2\ \Delta t = 0.48$ mm/s

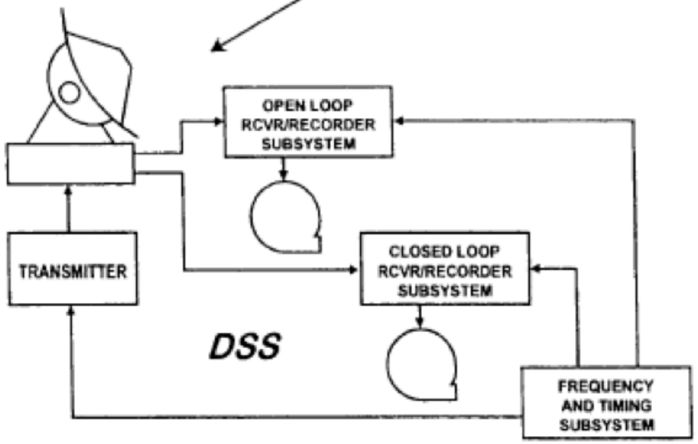
$0.06 \text{ mm/s} \leq \Delta V \leq 0.48 \text{ mm/s}$

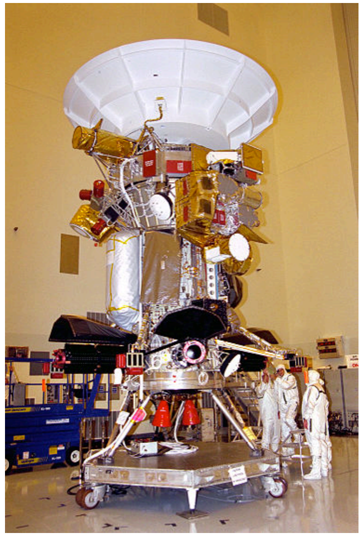


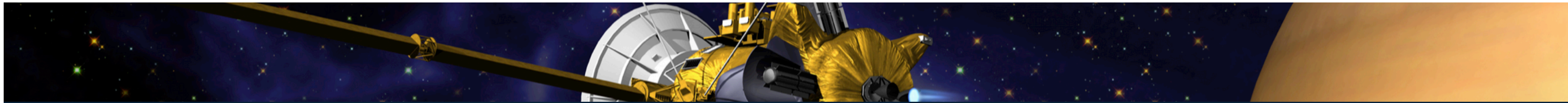
Cassini Radio Science Subsystem

Two-way and three-way Doppler using X-X and X-Ka radio links.
Data accuracy ~ 0.02 – 0.04 mm/s at 60 s.

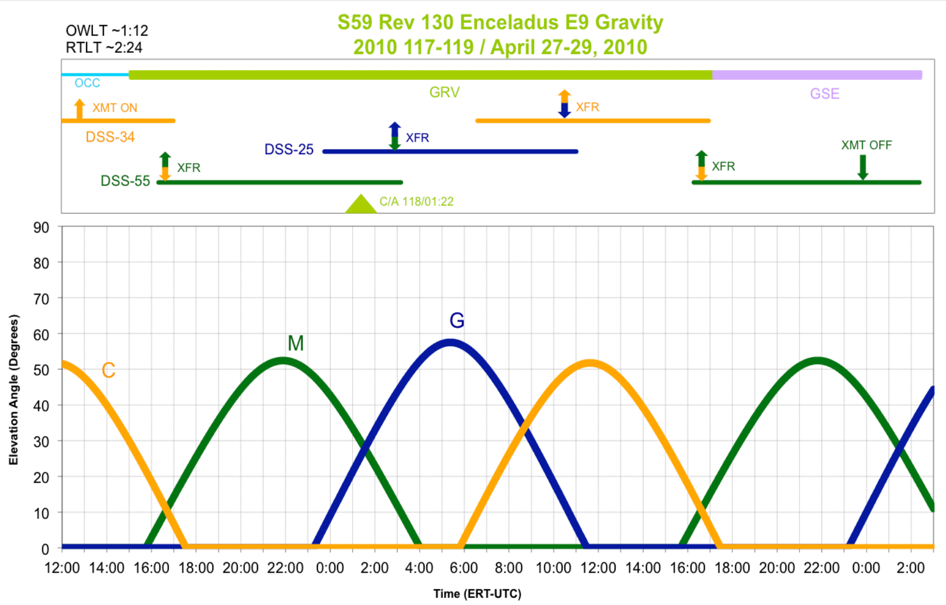


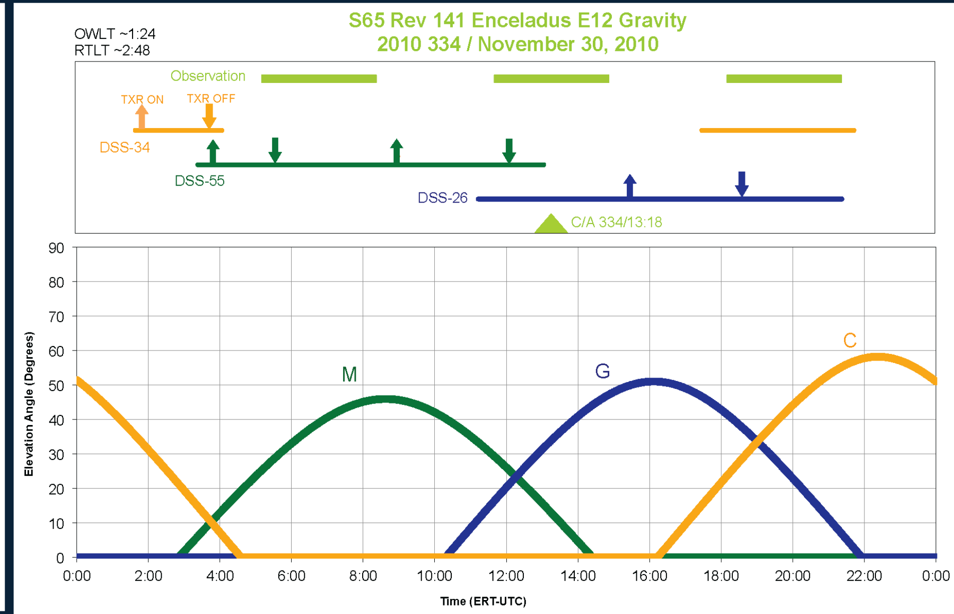


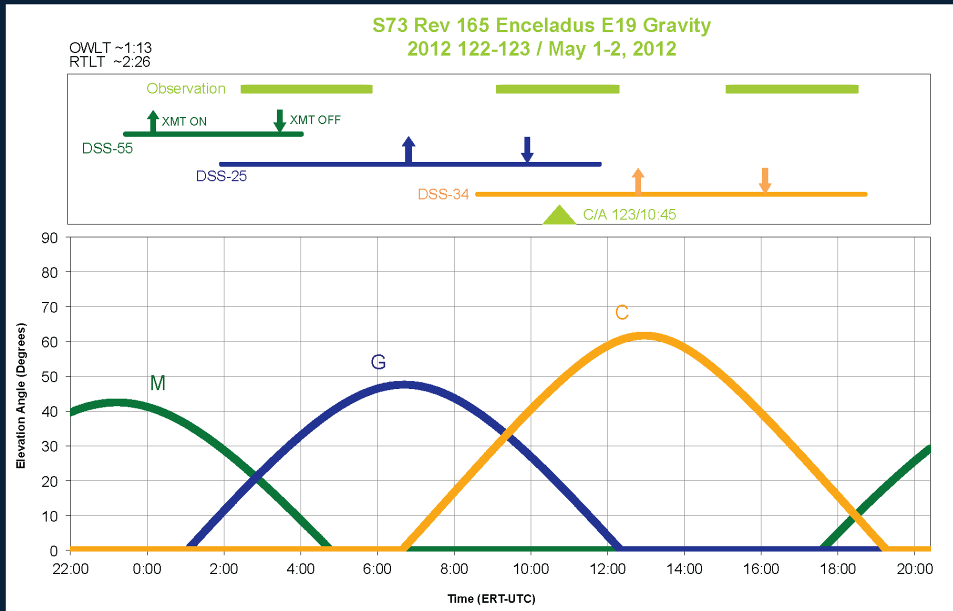


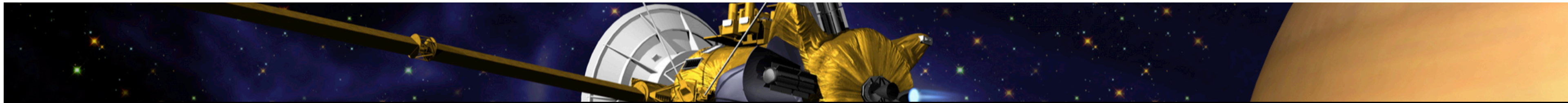


Deep Space Network (DSN) Coverage And Elevation Plots



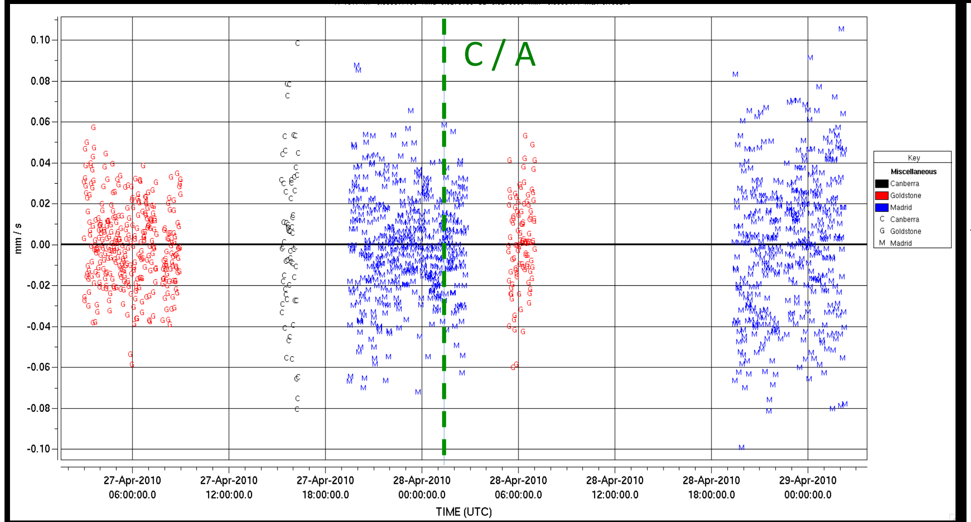




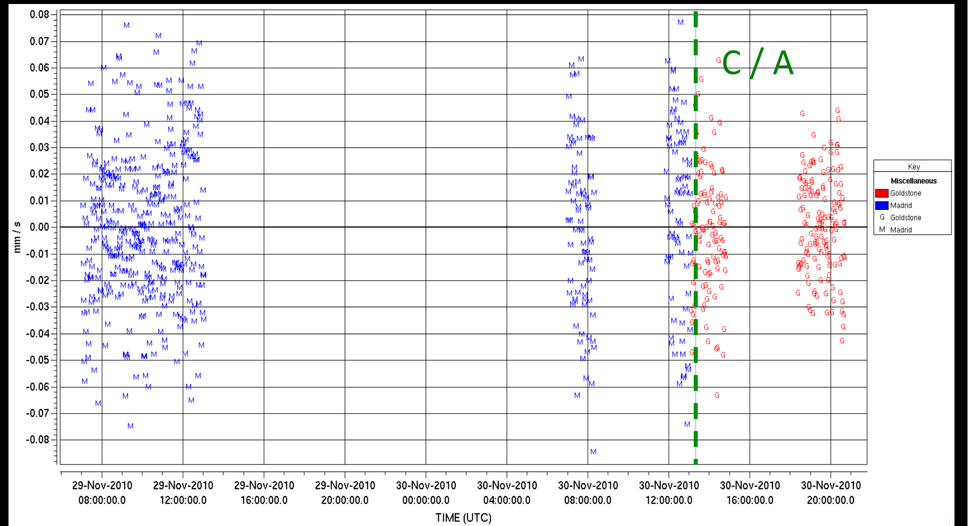


Multiarc solution with Monte – Doppler residuals (X/X and X/Ka) @ 60 sec

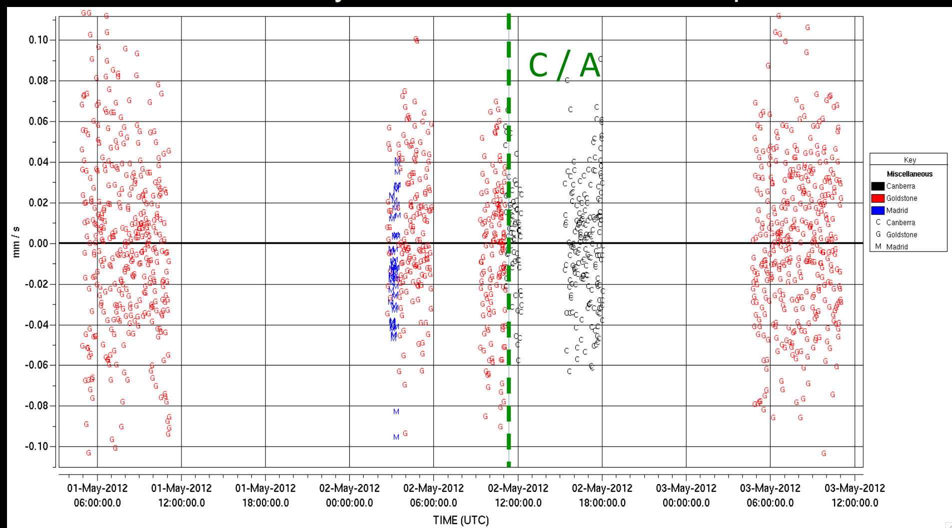
E9 – April 2010 RMS = 28 μm/s

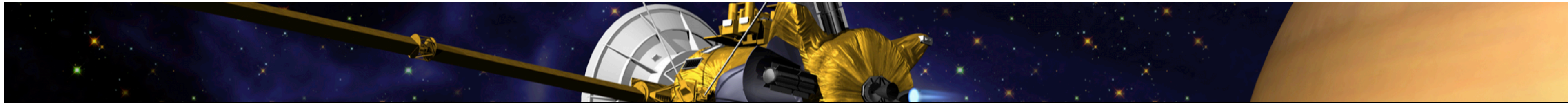


E12 – November 2010 RMS = 27 μm/s



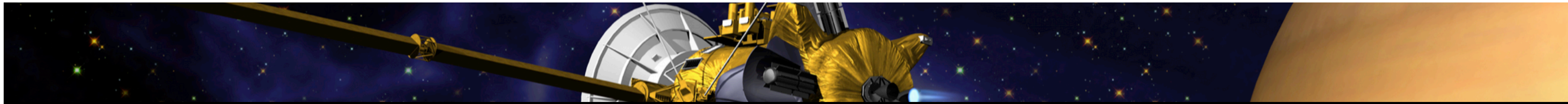
E19 – May 2012 RMS = 37 μm/s





Multiarc solution for global parameters

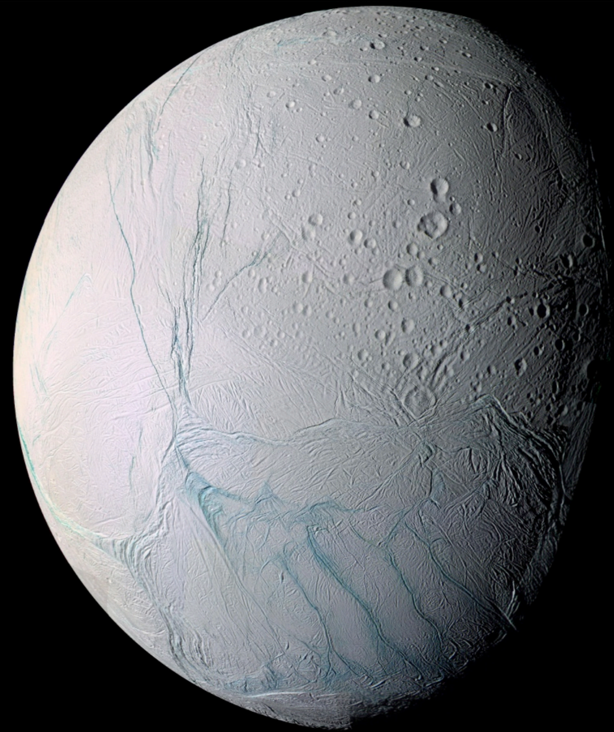
Coefficient	Central value (x10^6)	Formal uncertainty (x10^6)
J_2	5435.2	34.9
C_{21}	9.2	11.6
S_{21}	39.8	22.4
C_{22}	1549.8	15.6
S_{22}	22.6	7.4
J_3	-115.3	22.9
ΔV (E9)	0.25 mm/s (92% in the direction of –V)	
ΔV (E19)	0.26 mm/s (91% in the direction of –V)	
J_2/C_{22}	3.51 ± 0.05	

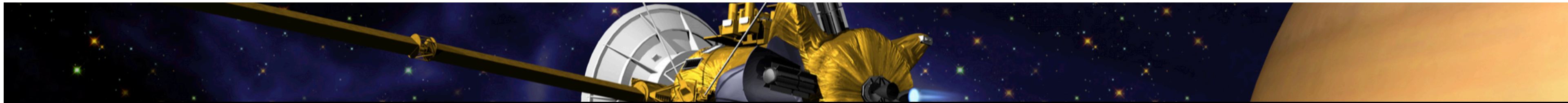


Implications from gravity data

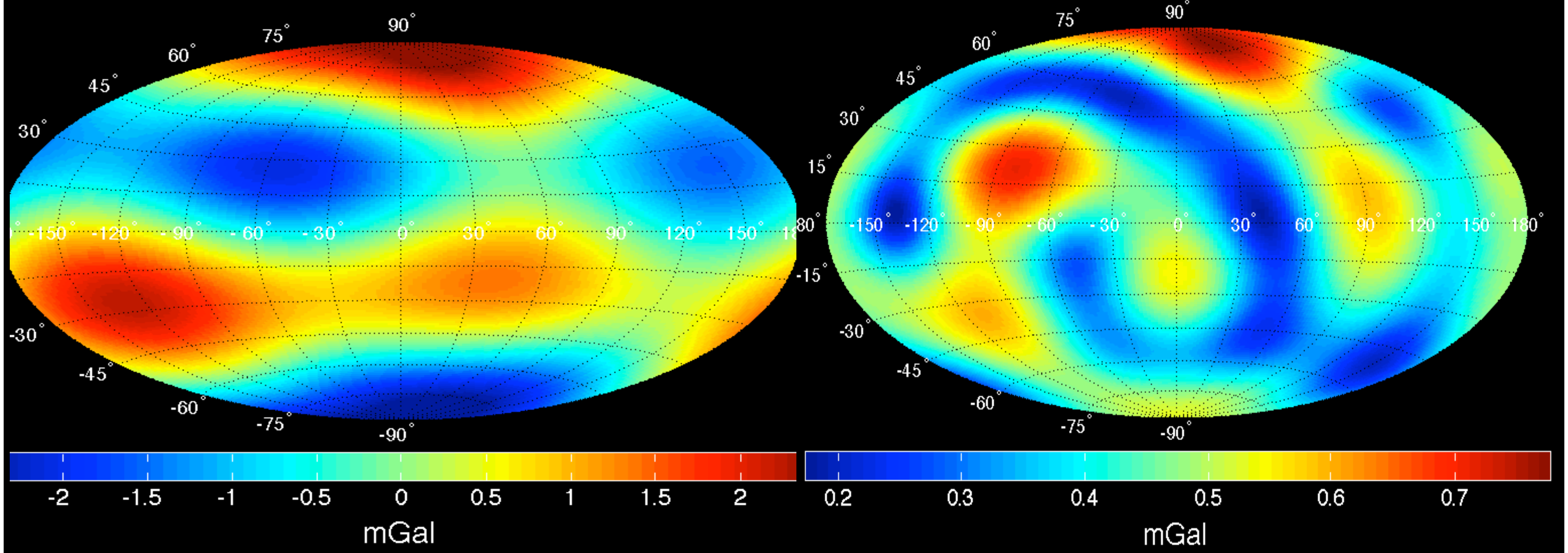
Estimated gravity field of Enceladus indicates:

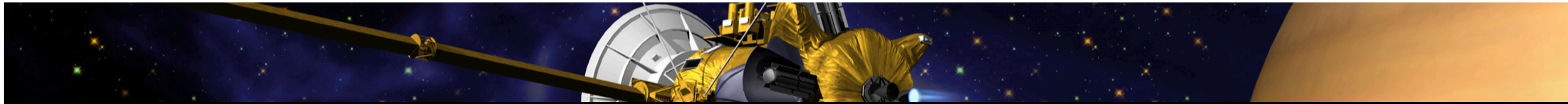
- predominance of the quadrupole terms J_2 and C_{22} (as expected)
- existence of a remarkable asymmetry between northern and southern hemispheres
- mild deviation of the body from hydrostatic equilibrium (~6%), the non-hydrostatic contributions might be small because of compensation
- small non degree-2 contributions ($J_3 \sim 0.02\ J_2$)
- MOI of about 0.335-0.336 MR^2 compatible with a low core density of ~ 2.4 g/cm^3 and a H_2O mantle of density 1 g/cm^3 and 60 km thickness





Gravity anomalies: values and uncertainties

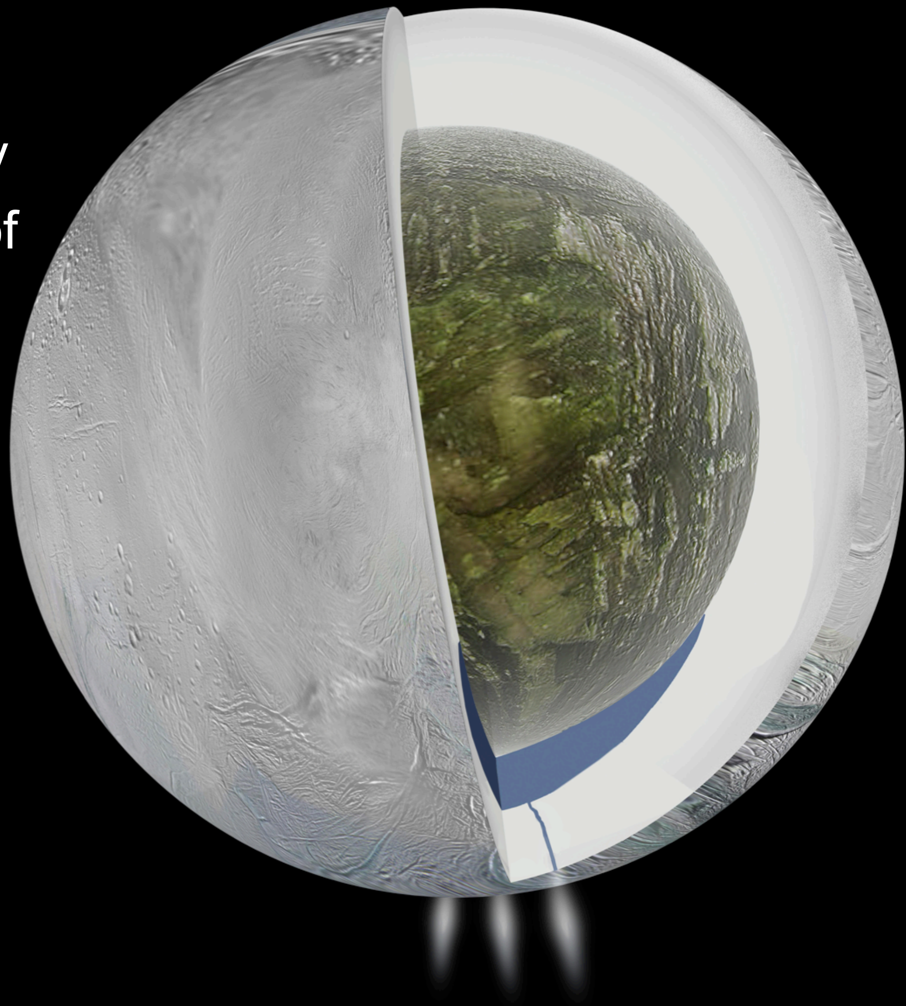


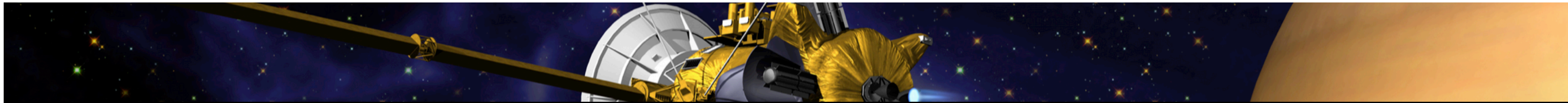


Gravity measurements: interpretation (1)

We inferred the presence of a liquid water reservoir at depth in the proximity of the south pole, based on a number of considerations:

- the estimated gravity anomaly is not large enough to explain the 1.2 km depression at the south pole
- this region dominance in the heat output
- the plumes activity
- the need for decoupling of the ice shell and tidal heating

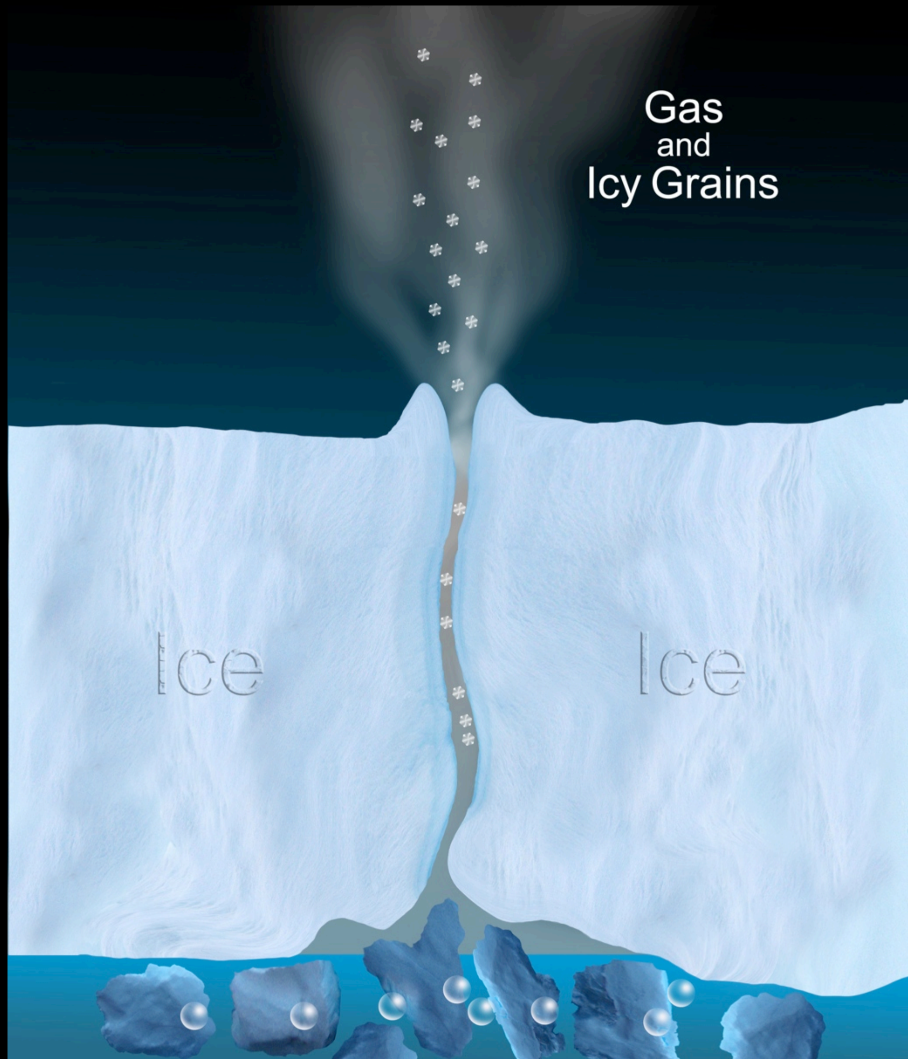


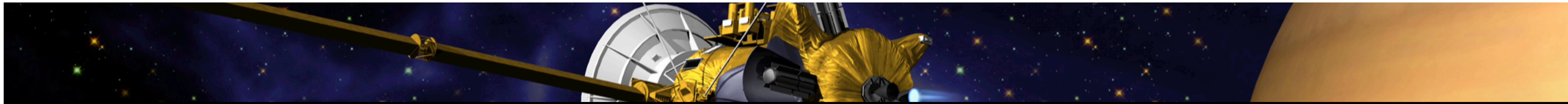


Gravity measurements: interpretation (2)

Additional information concerning the ocean characteristics can be extrapolated:

- A liquid water layer (8% denser than ice) of 10 km thickness at depth would explain the observed gravity
- the regional ocean is likely to extend out to about 50° south latitude
- the moon is too small to have an internal energy source capable of melting the ice, tides must be the main heat source
- The water ocean is directly in contact with the rocky core





Conclusions

- A very fitting interpretation of Cassini gravity measurements is the presence of a regional liquid water ocean underneath the icy crust of Enceladus at the south pole
- The water pocket functions as a tank that supplies the jests made of water-ice particles
- A potentially habitable environment has been found in an unexpected place of the solar system, where the energy needed to produce liquid water from ice is not provided by solar radiation
- The greater concentration of water beneath the surface at the south pole, inferred from our gravity data, fits with our understanding if how Enceladus can be active