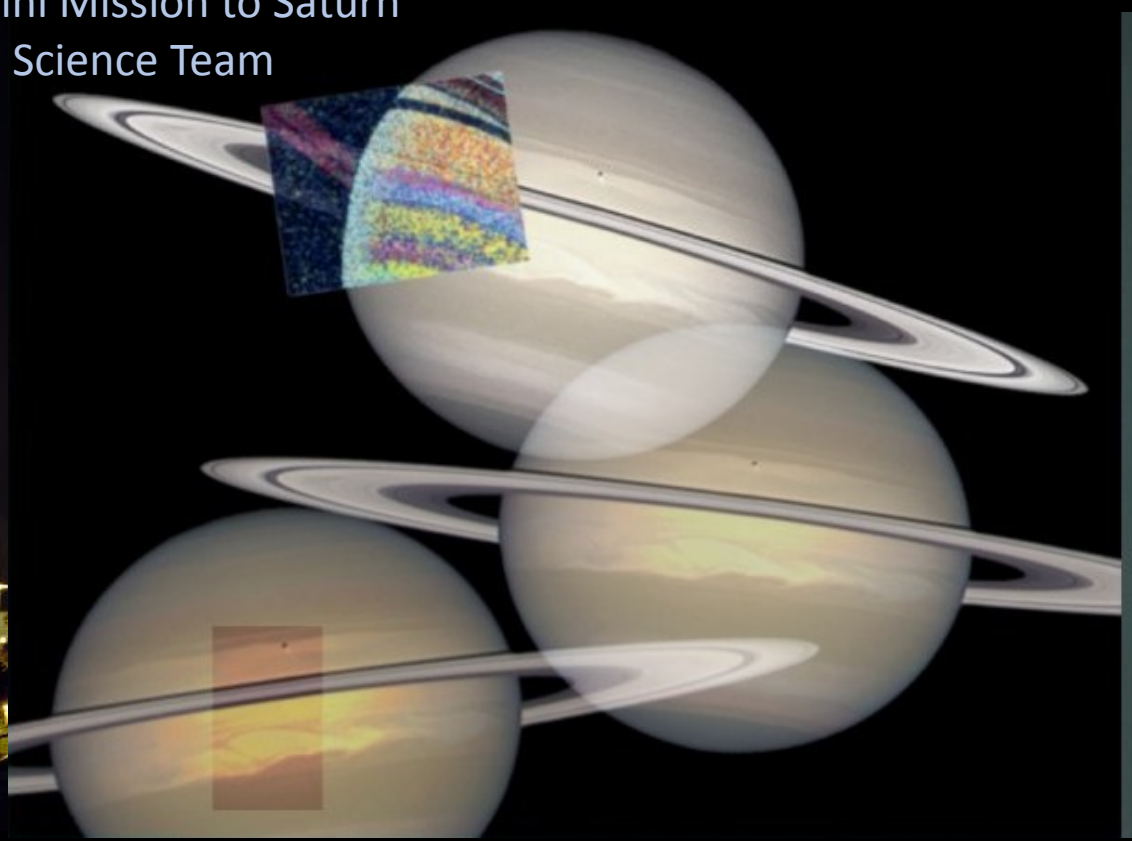
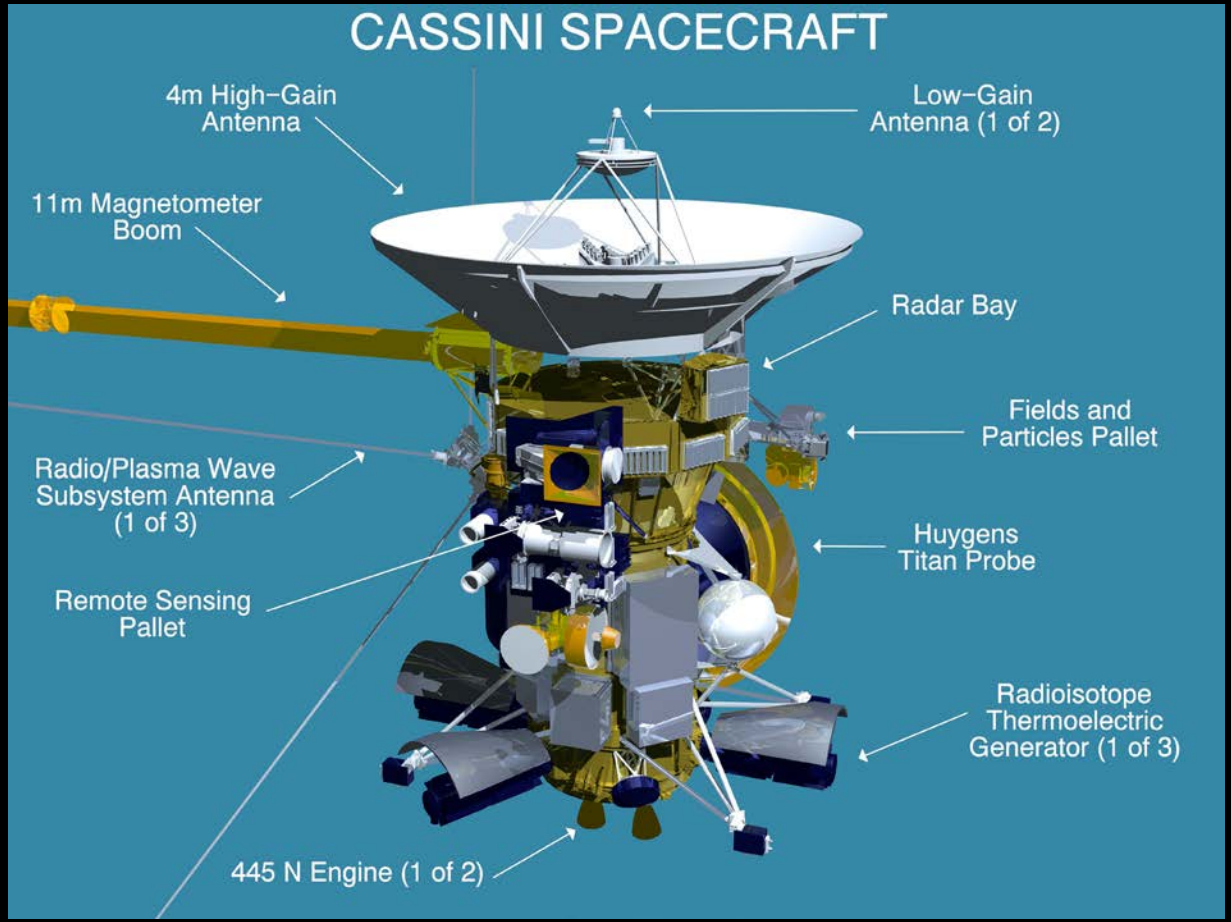
Highlights of the Cassini Mission to Saturn from the Radio Science Team

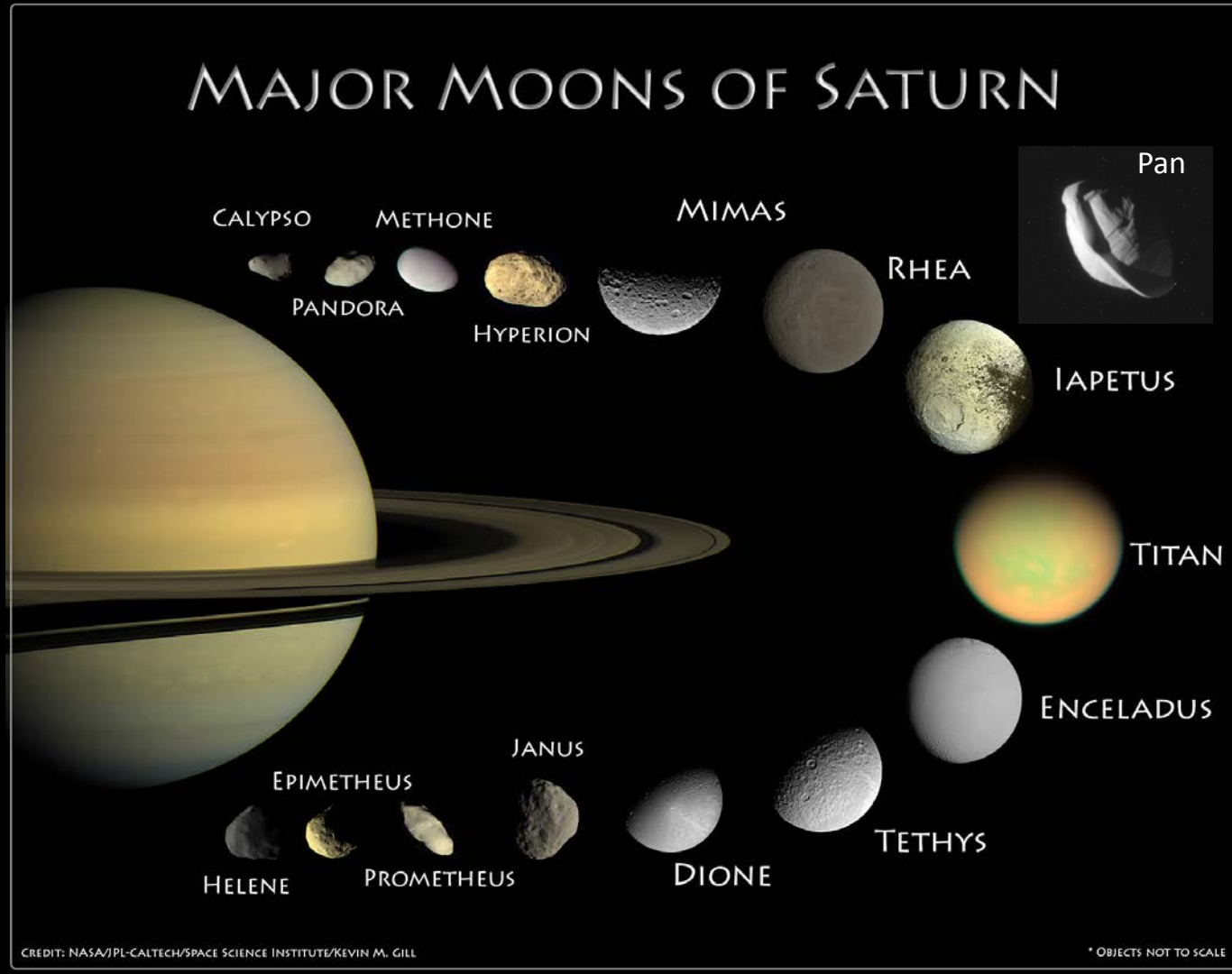


Richard French, Cassini Radio Science Team Leader

NEROC – November 16, 2018


CASSINI SPACECRAFT
4m High-Gain Antenna
Low-Gain Antenna (1 of 2)
11m Magnetometer Boom
Radar Bay
Fields and Particles Pallet
Radio/Plasma Wave Subsystem Antenna (1 of 3)
Huygens Titan Probe
Remote Sensing Pallet
Radioisotope Thermoelectric Generator (1 of 3)
445 N Engine (1 of 2)

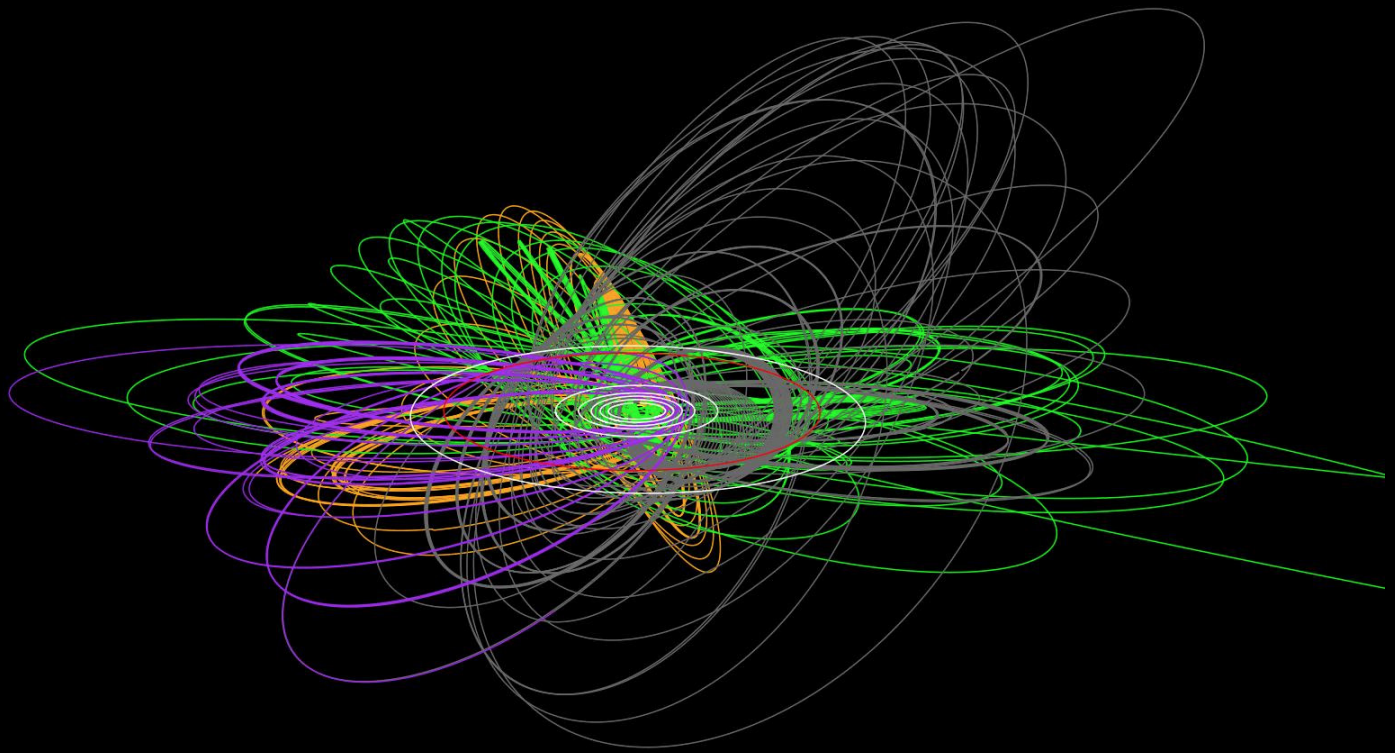
Major Moons of Saturn



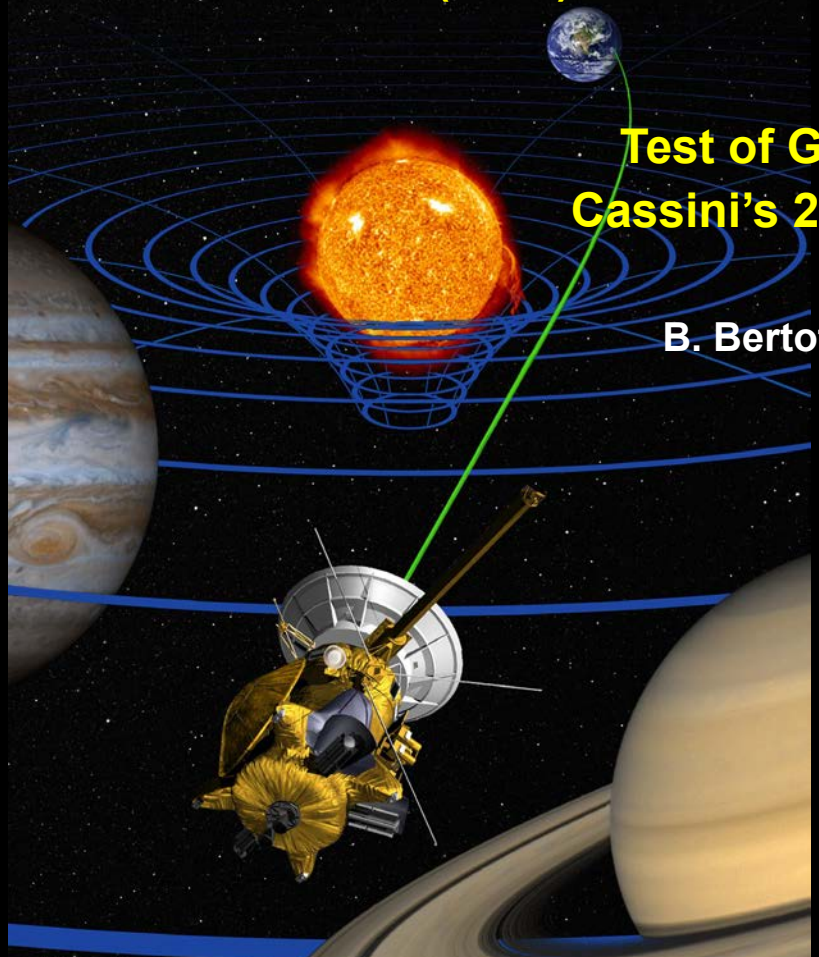
Credit: NASA/JPL-Caltech/Space Science Institute/Kevin M. Gill

* Objects not to scale

Optimized tour for occultations, gravity, bistatic observations



Nature 425, 374 (2003) – 1067 citations and counting!



Test of General Relativity during Cassini's 2002 Superior Conjunction

B. Bertotti[1], L. Iess[2] , P. Tortora[3],

[1] Università di Pavia, Italy

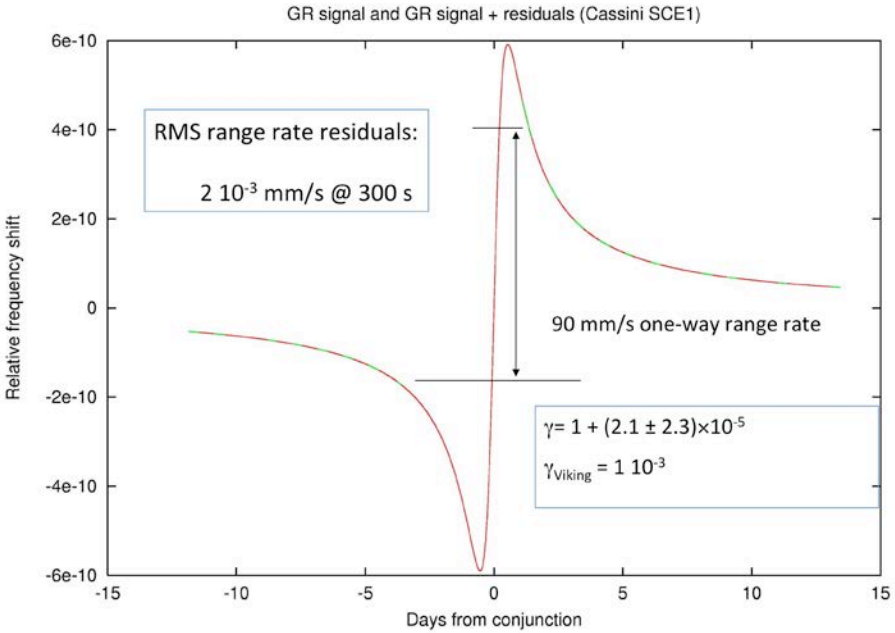
[2] Università di Roma "la Sapienza", Italy

[3] Università di Bologna, Italy

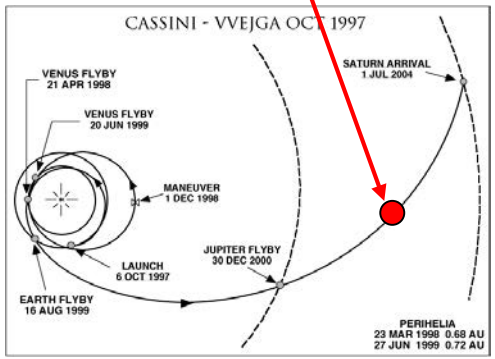
“Moonlighting Satellite Vindicates Einstein”

Science now

24 Sept. 2003



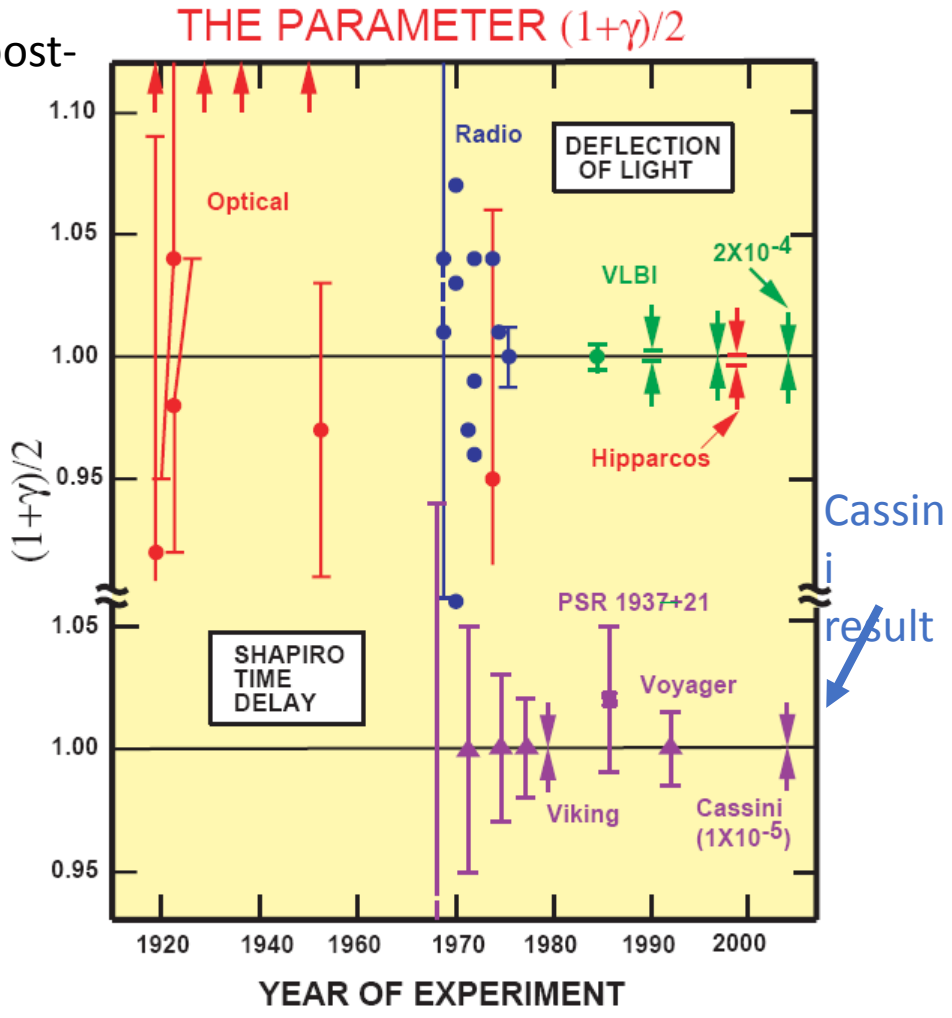
30 days coverage from DSN (June 6 to July 5, 2002) at 8.4 and 32.5 GHz



PPN – Parameterized post-Newtonian formalism

γ = space curvature g_{ij} per unit rest mass

γ = 1 for GR



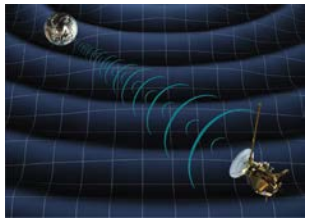
Results and Conclusions

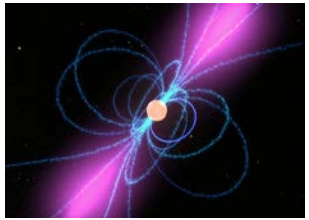
$$\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$$

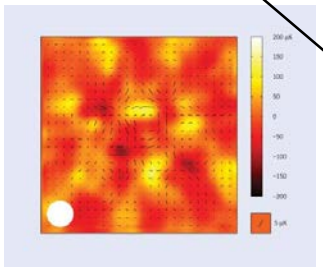
- An improvement of a factor of **50** over previous experimental estimates
- Our result approaches a sensitivity at which, theoretically, deviations from General Relativity are expected. No detailed theory is available about the expected amounts of these violations, but $\gamma - 1$ should be negative and, possibly, in the range $10^{-5} - 10^{-7}$
- The Cassini result is still the strongest limit on γ
- GAIA and BepiColombo should reach a level of accuracy of 2×10^{-6}

Using Cassini to search for Gravitational Waves (40 days and 40 nights…)

- HF (~10-1000 Hz): laser interferometers (e.g. LIGO)
- LF (~10^{-6} to 0.1 Hz): Cassini Doppler tracking (LISA in the future)
- VLF (~10^{-9} to 10^{-6} Hz): pulsar timing
- ELF (~10^{-18} - 10^{-15} Hz): CMB intensity and polarization



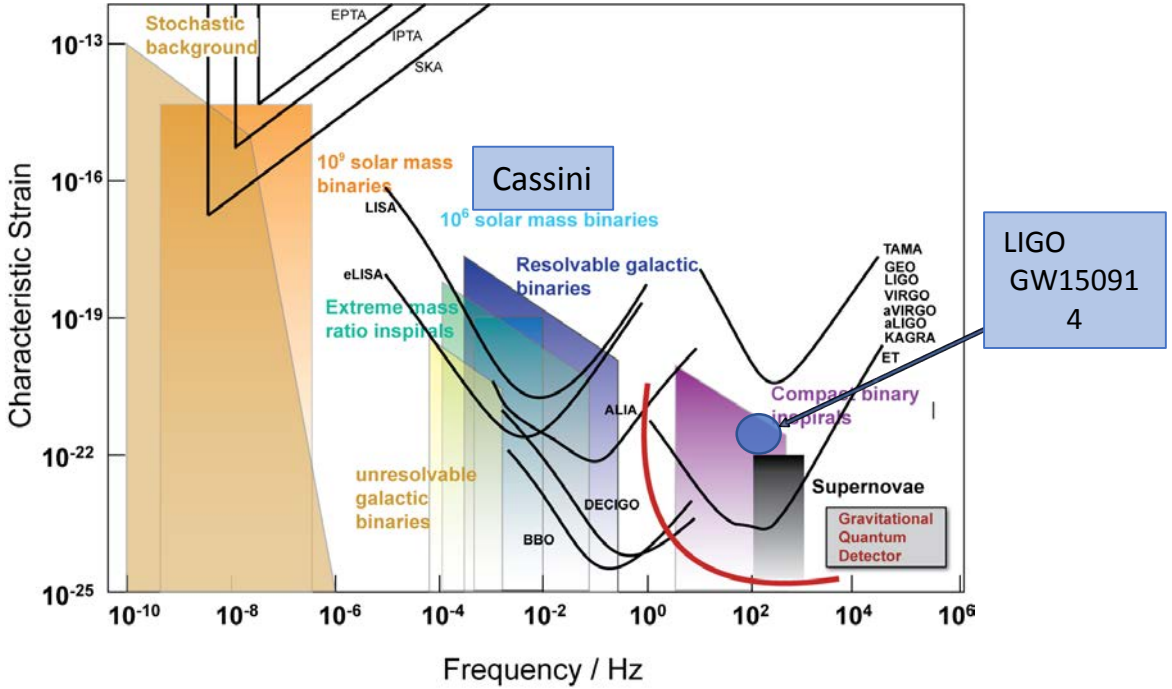




*http://cajagwr.caltech.edu/scripts participating_projects.html

illustration credits: NSF/NASA/JPL/DASI

Cassini GW Limits in Context

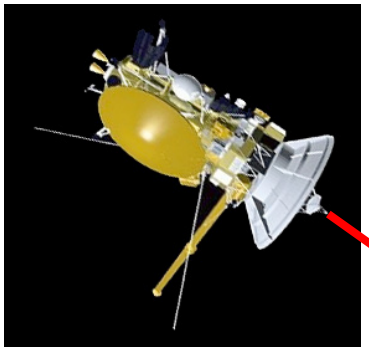


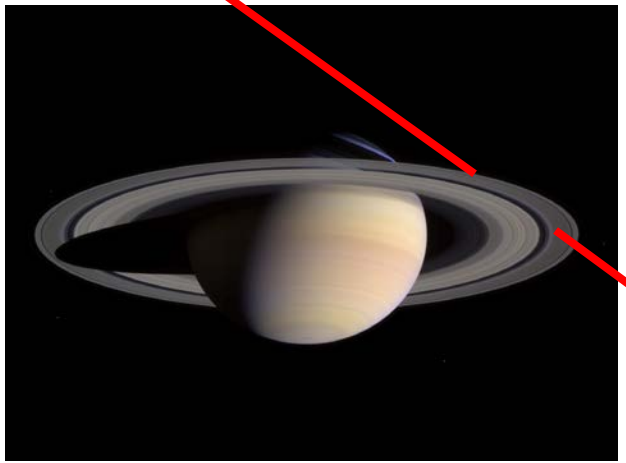
Cassini Ring Occultations

Radio Science Team

+

Radio Science Operations Team

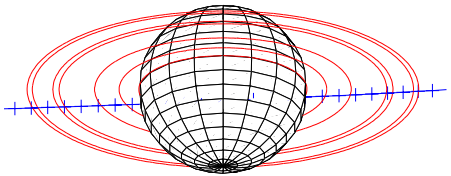




Typical Ring Occultation Track Geometry (15 m tick-marks)

(rev 7) 2005 MAY 3,

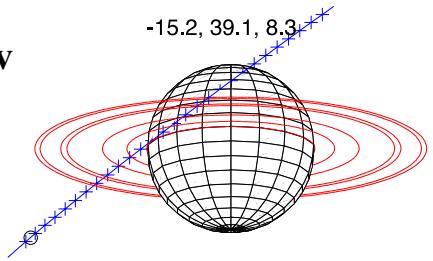
-23.6, 21.9, 5



(rev 44) 2007 MAY 10,

-15.2, 39.1, 8.3

Rev 44



Occultation Sequence: revs 7 to 14

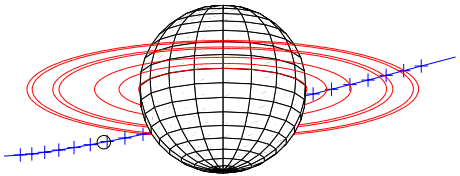
$20 \leq B \leq 24°$

180° Transfer Sequence: revs 44, 46

$B \sim 15°$

(rev 46) 2007 JUN 11,

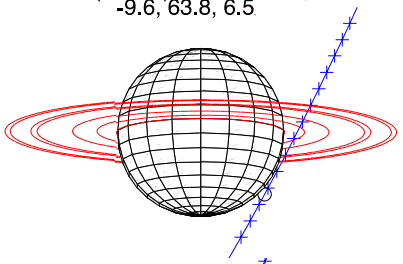
-14.4, 18.4, 5.3



(rev 63) 2008 APR 1,

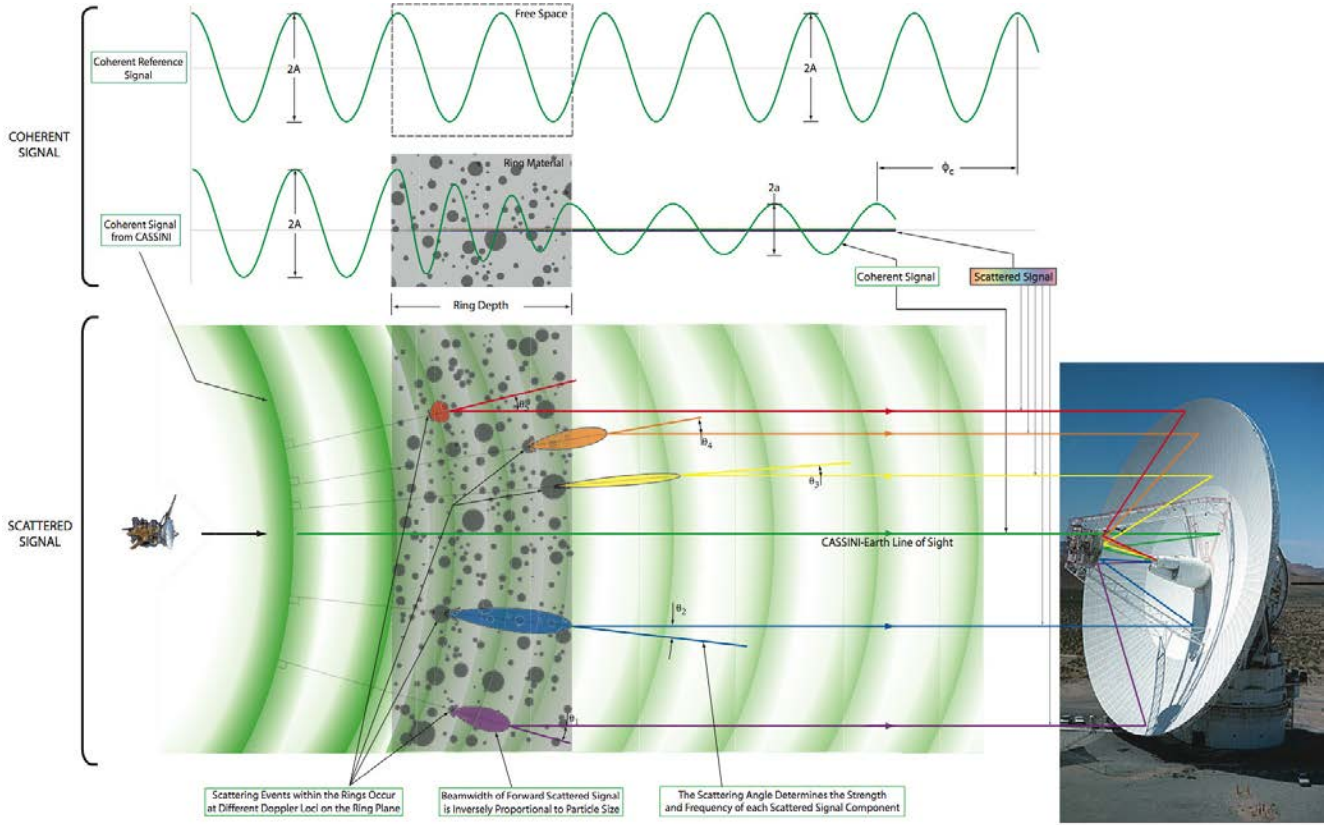
-9.6, 63.8, 6.5

Rev 63



High Inc Sequence Orbits 56 to 67

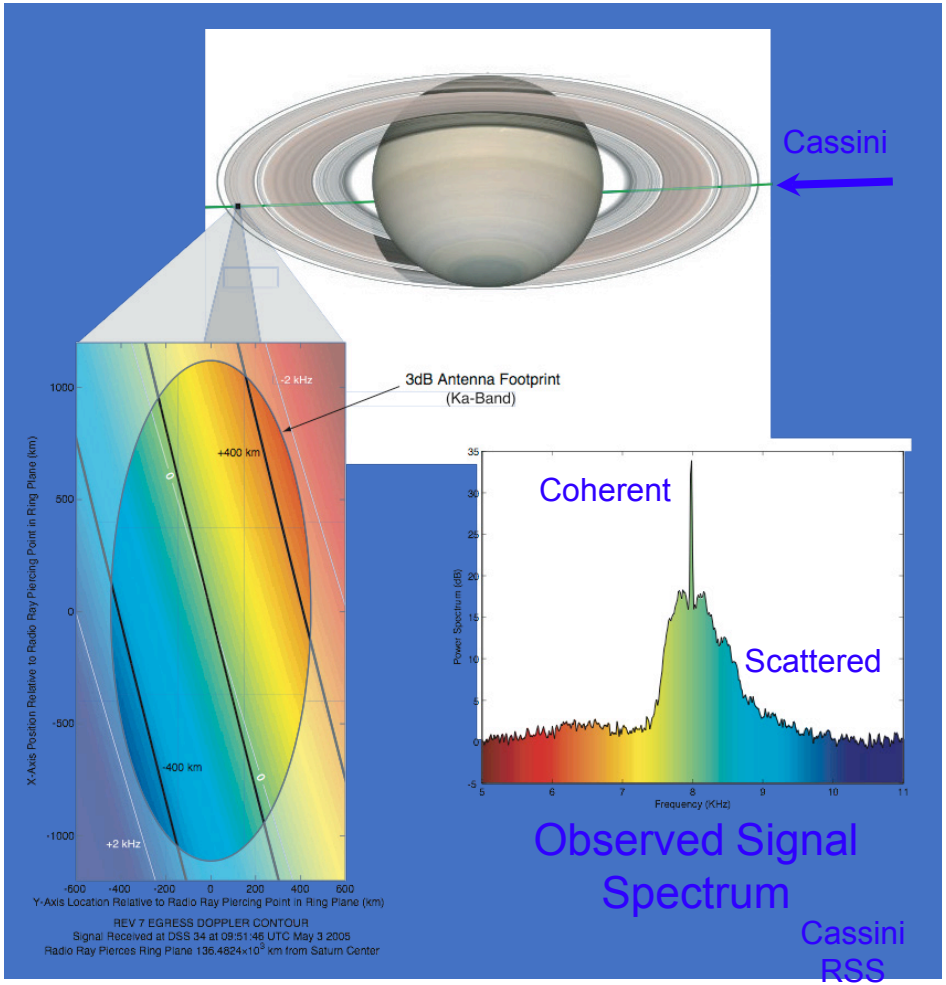
The Coherent (Direct) & Scattered Signals



Cassini RSS

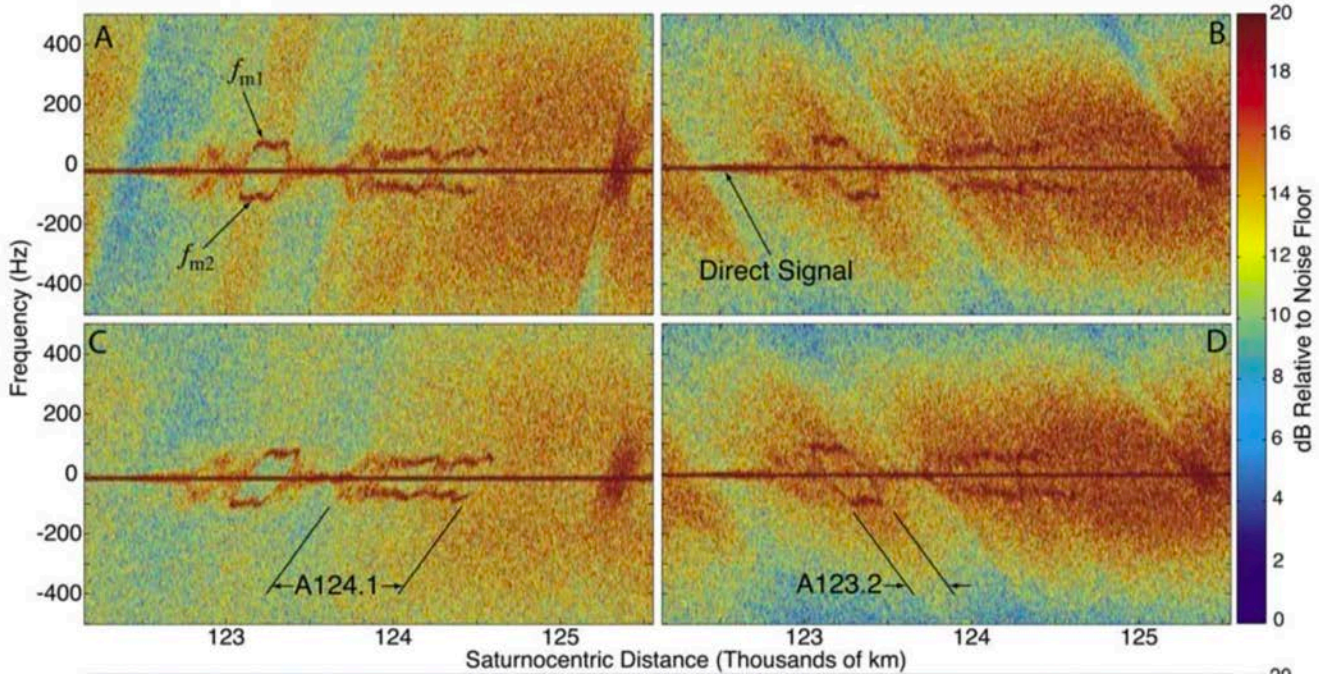
Observables

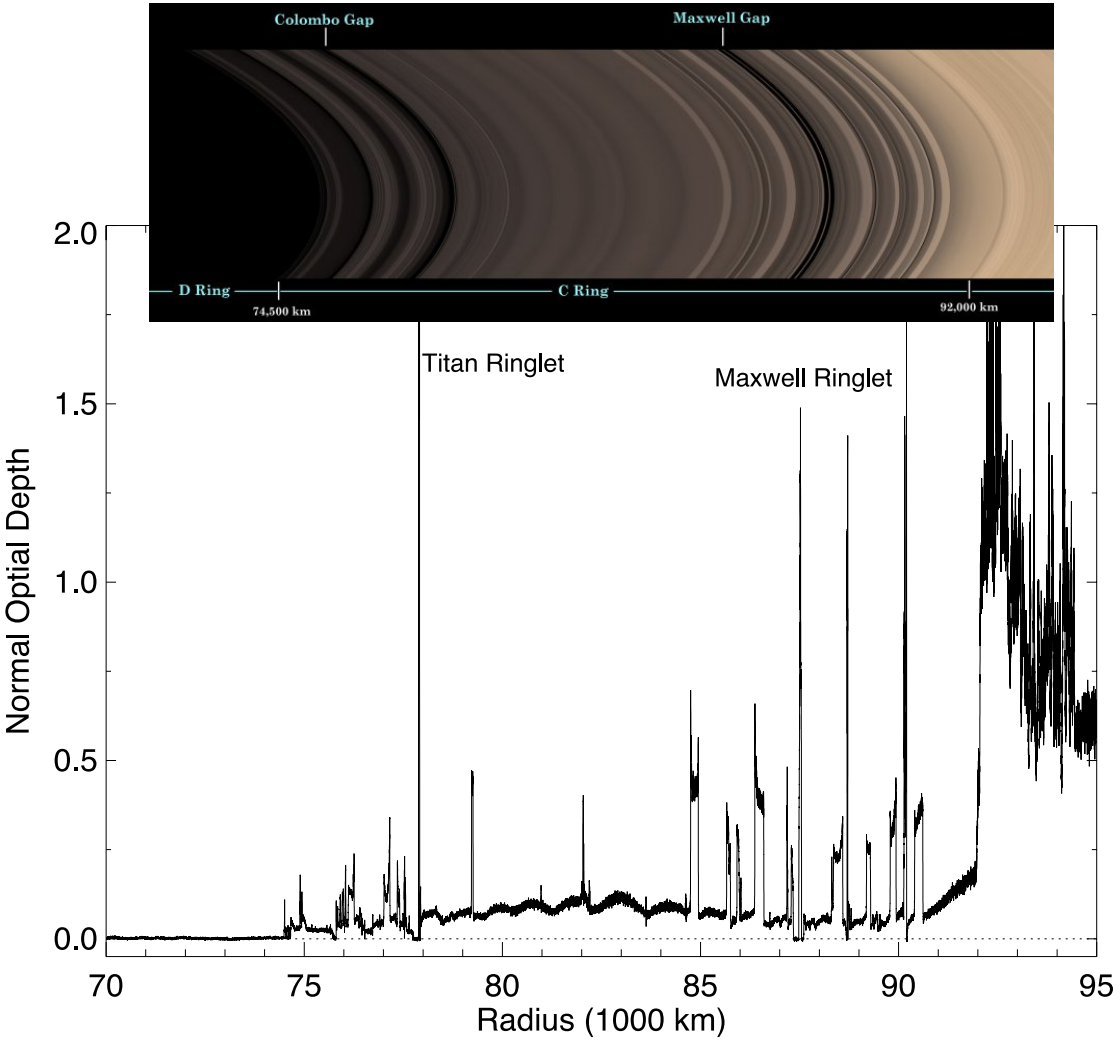
Direct (Coherent) & Scattered signals



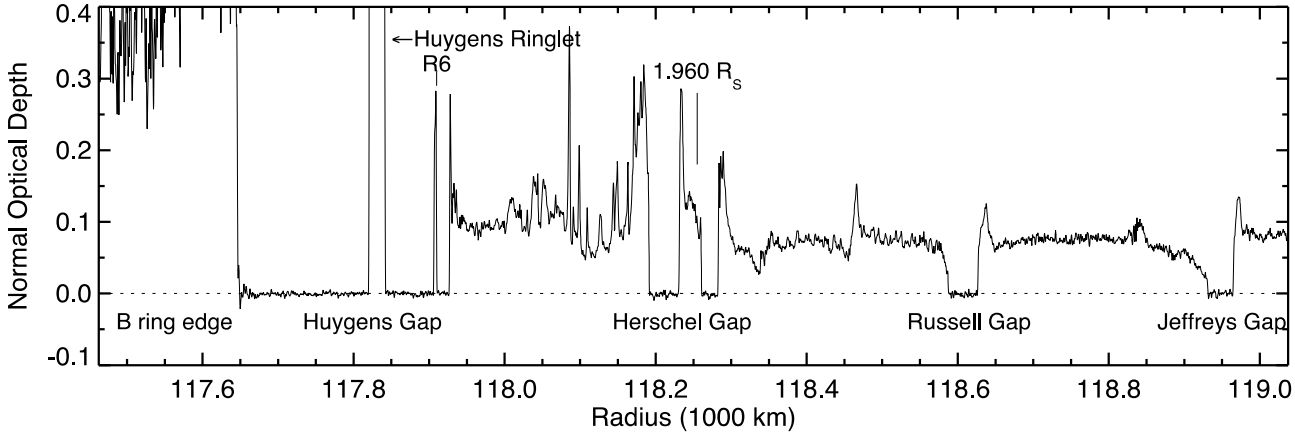
Periodic microstructure in the rings

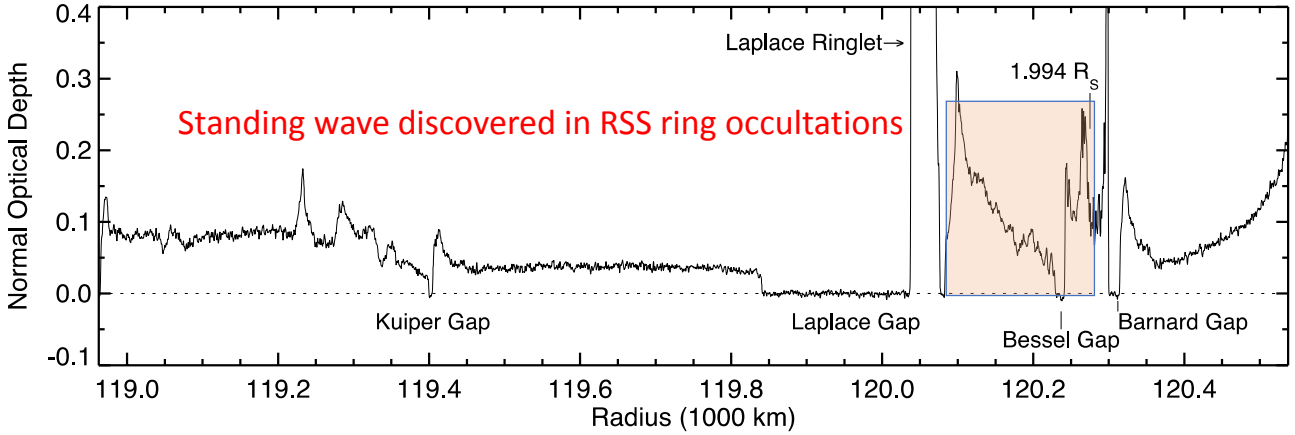
Thomson et al. 2007, GRL 34, L24203



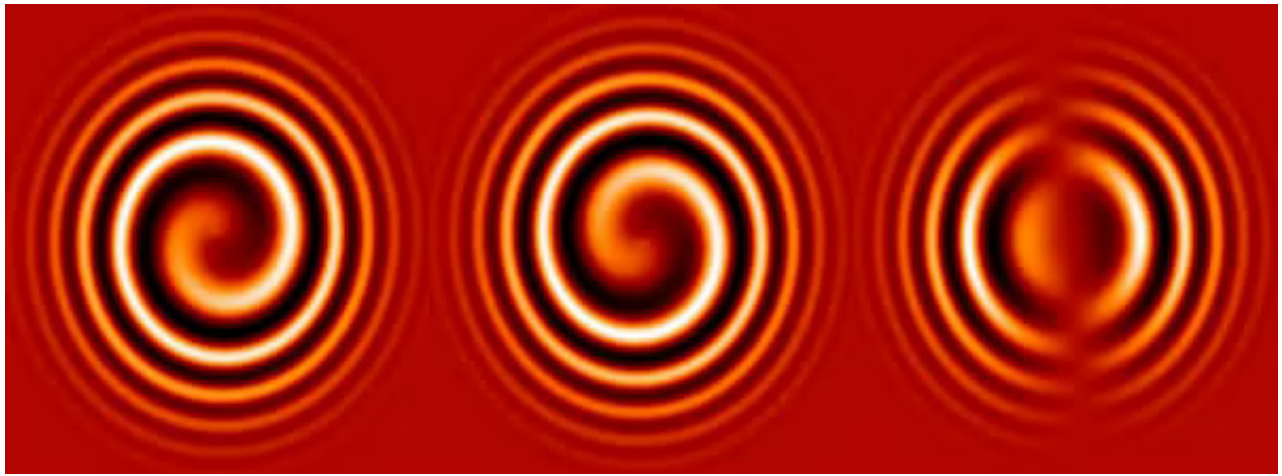

Colombo Gap
Maxwell Gap
D Ring
C Ring
74,500 km
92,000 km
Titan Ringlet
Maxwell Ringlet
Normal Optial Depth
2.0
1.5
1.0
0.5
0.0
70
75
80
85
90
95
Radius (1000 km)

Cassini Division



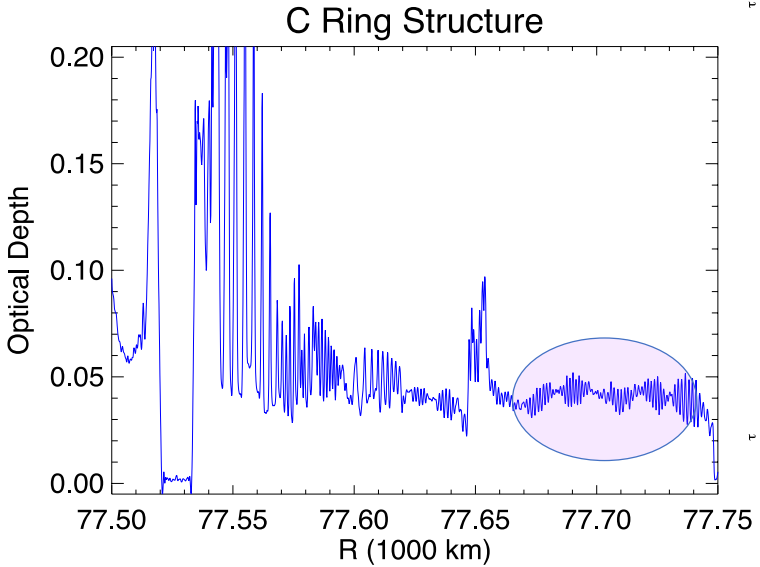


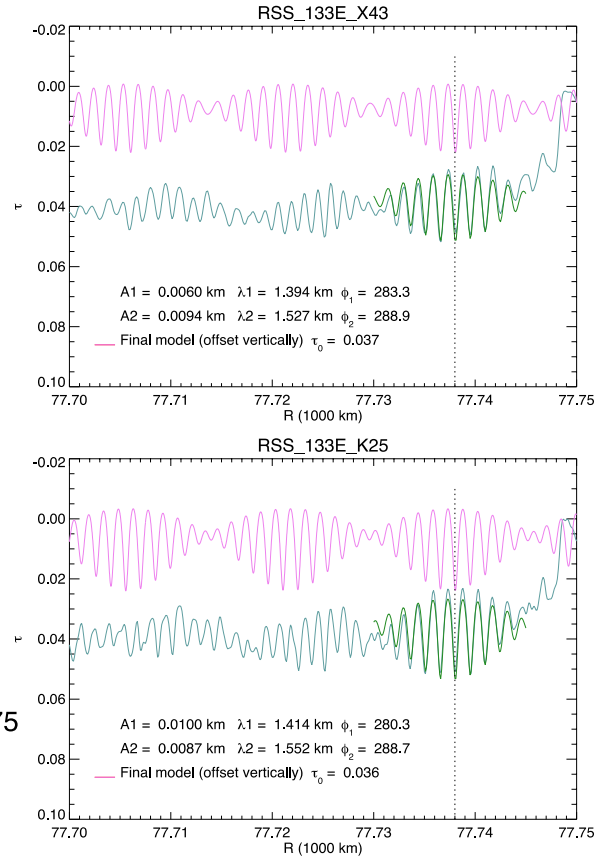
Generation of standing wave: Co-addition of leading/trailing prograde density waves



Leading Trailing Standing

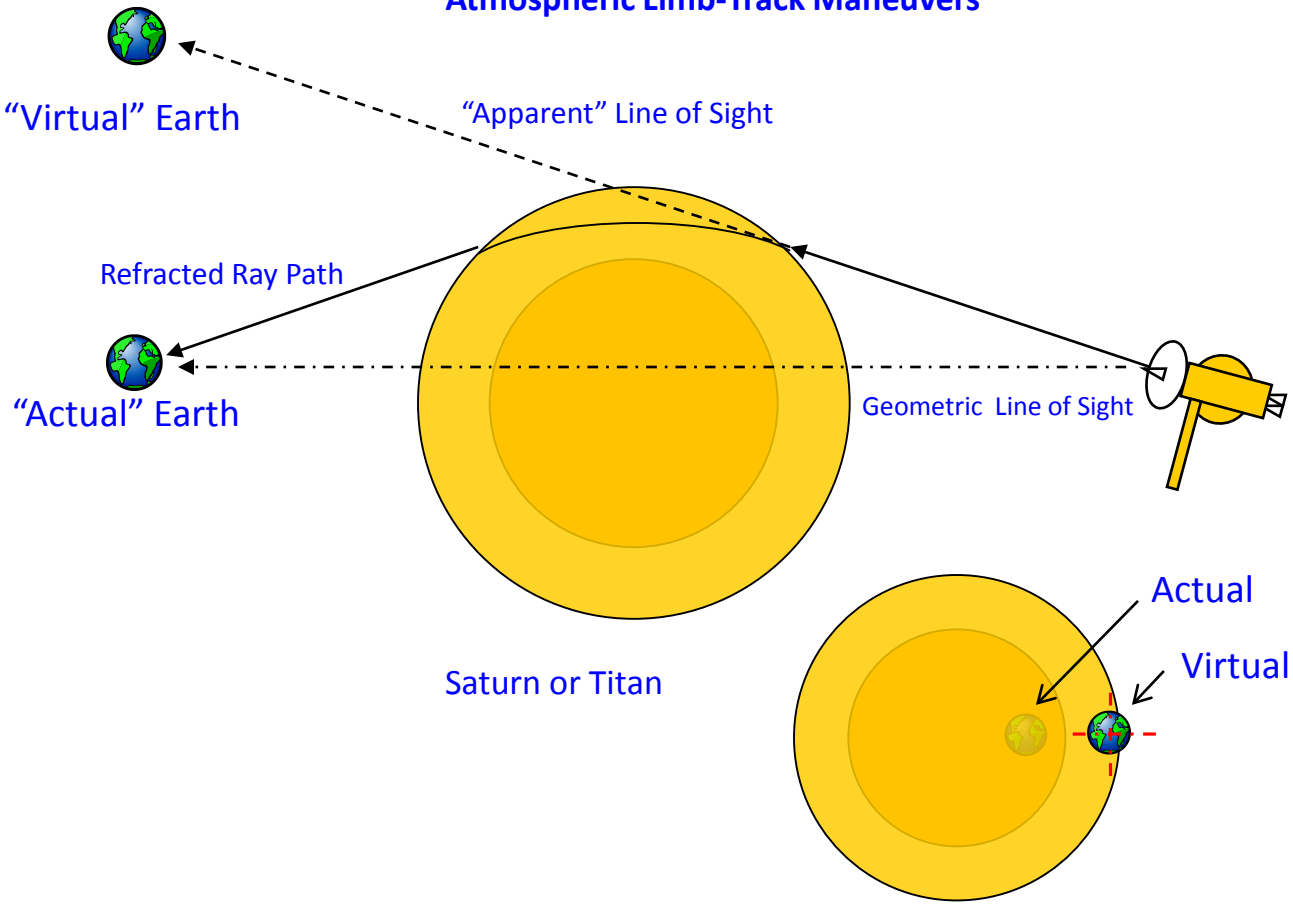
Evidence for two ancient impacts in the 1300's that tilted Saturn's rings



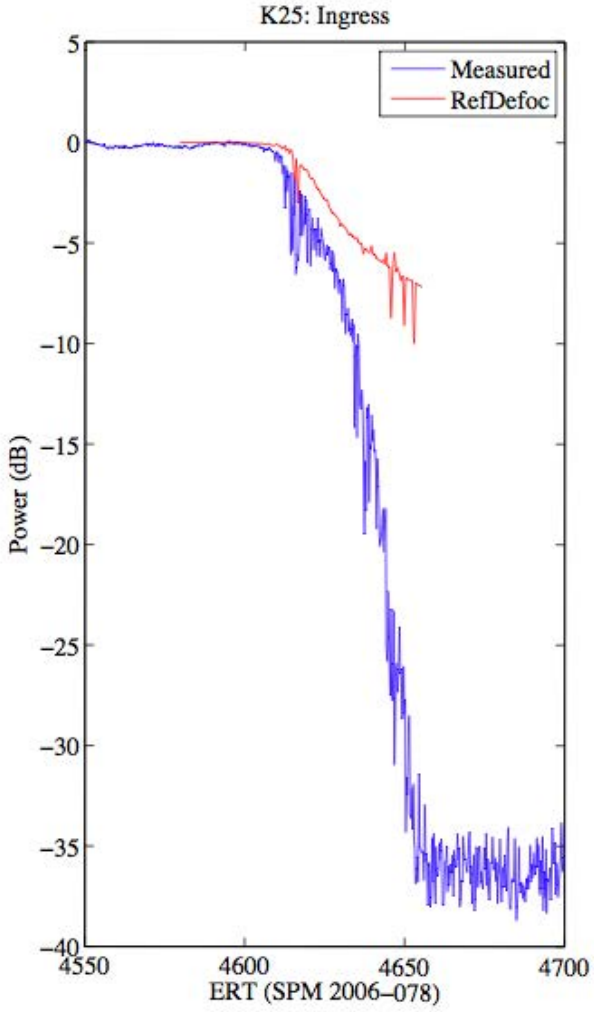


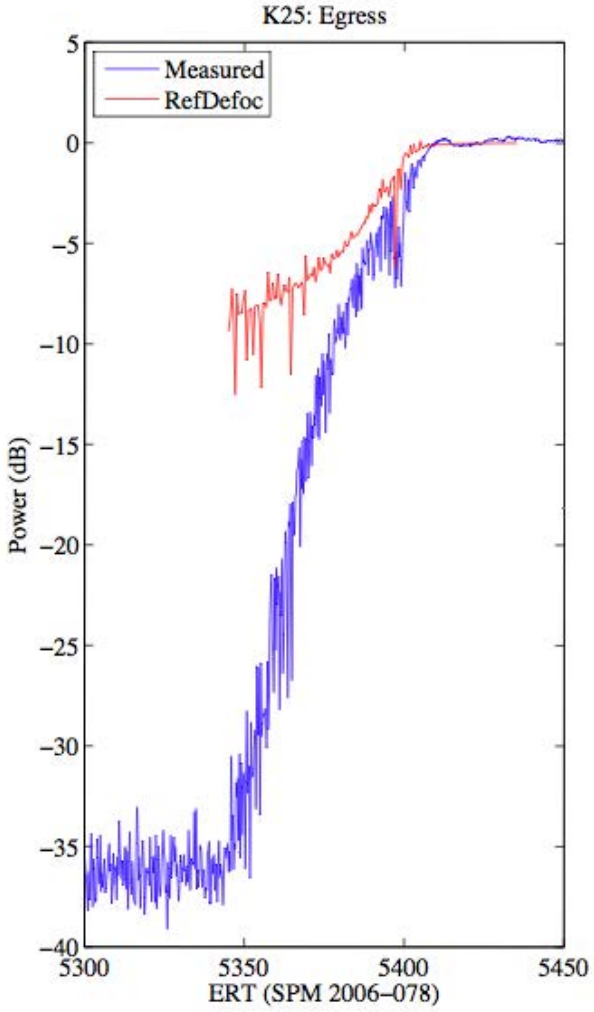
Saturn's C ring, nearly edge on (Marouf et al. 2011)

Atmospheric Limb-Track Maneuvers



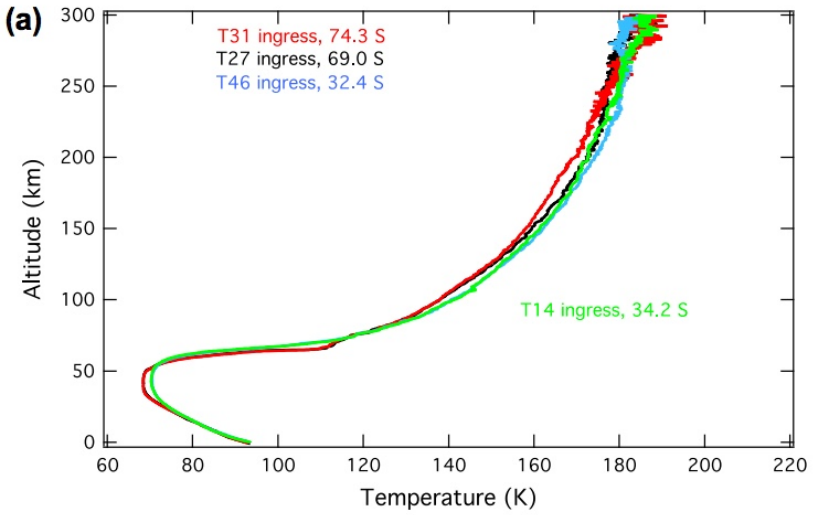
Adapted from D. Wait 05/07/04

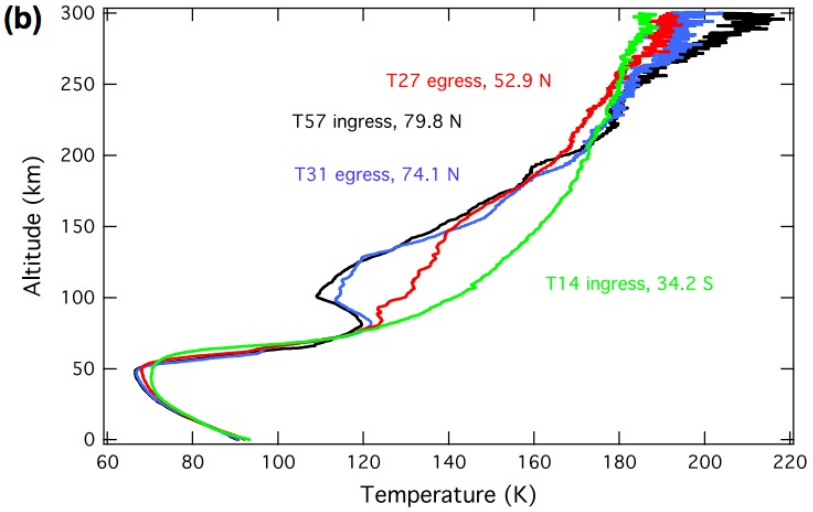

K25: Ingress
Measured
RefDefoc
Power (dB)
5
0
−5
−10
−15
−20
−25
−30
−35
−40
4550
4600
4650
4700
ERT (SPM 2006–078)


K25: Egress
Measured
RefDefoc
Power (dB)
5
0
−5
−10
−15
−20
−25
−30
−35
−40
5300
5350
5400
5450
ERT (SPM 2006–078)

Strong seasonal cooling
In Titan's stratosphere

From Cassini radio occultations

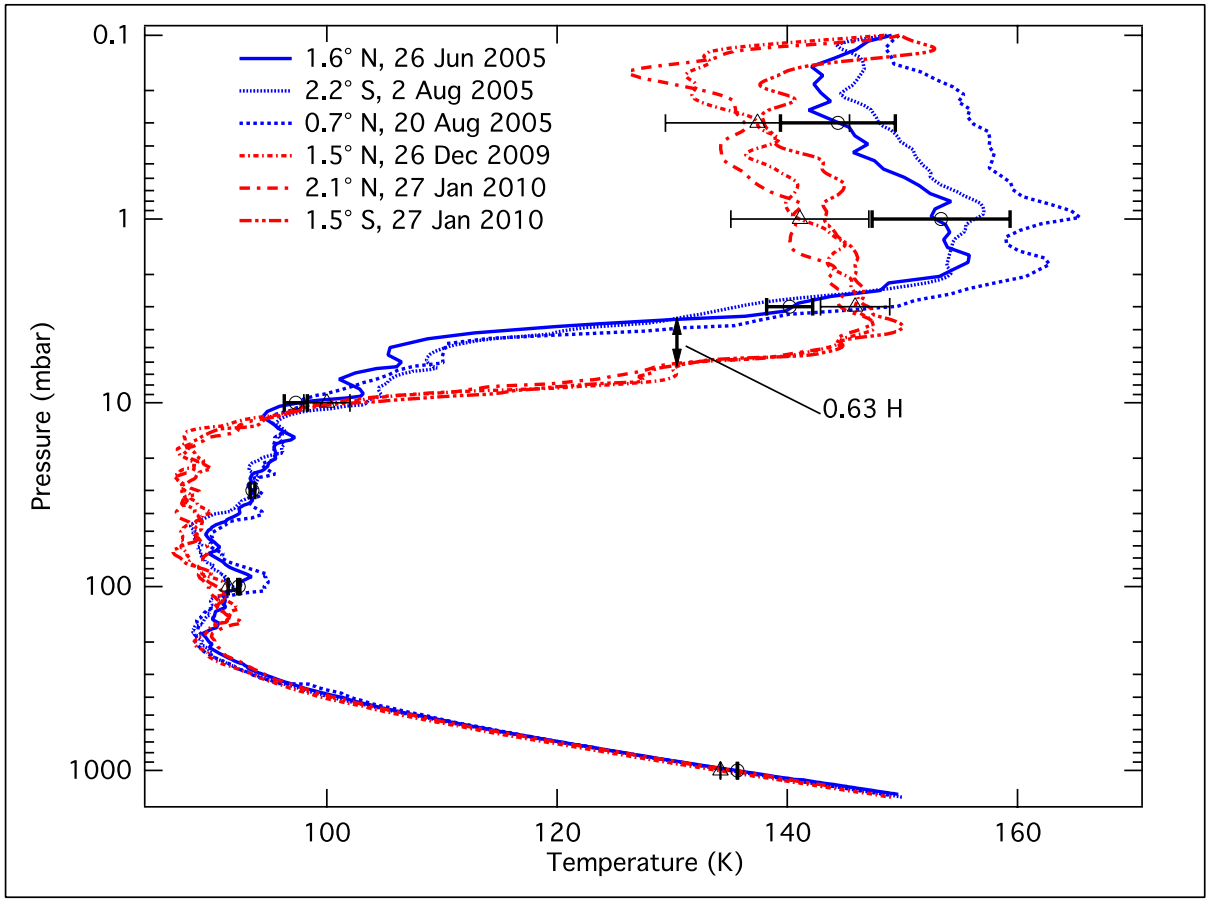


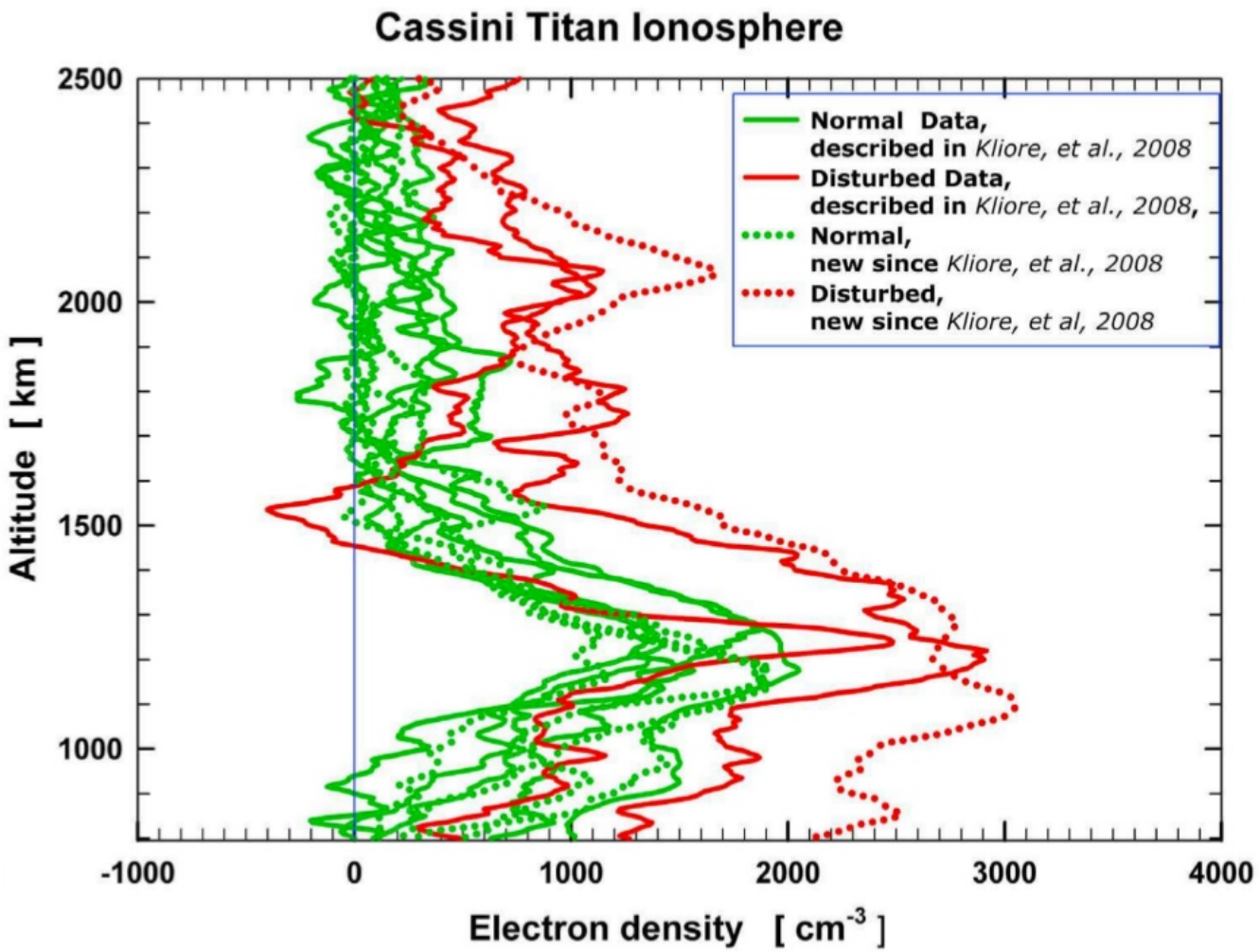


Schinder et al. 2012
Icarus 221, 1020-1031

Cassini Radio Occultation Soundings: Saturn's Equator

(Schinder *et al.* 2011)




Cassini Titan Ionosphere
Normal Data,
described in Kliore, et al., 2008
Disturbed Data,
described in Kliore, et al., 2008,
Normal,
new since Kliore, et al., 2008
Disturbed,
new since Kliore, et al, 2008
Altitude [km]
2500
2000
1500
1000
-1000
0
1000
2000
3000
4000
Electron density [cm-3]

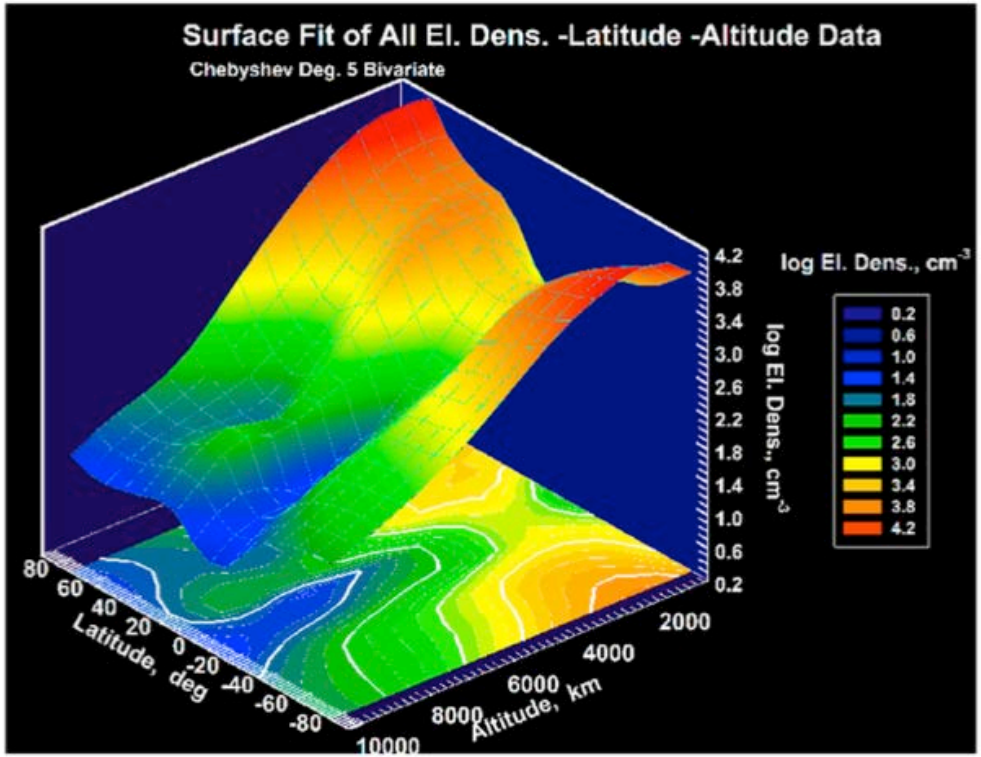
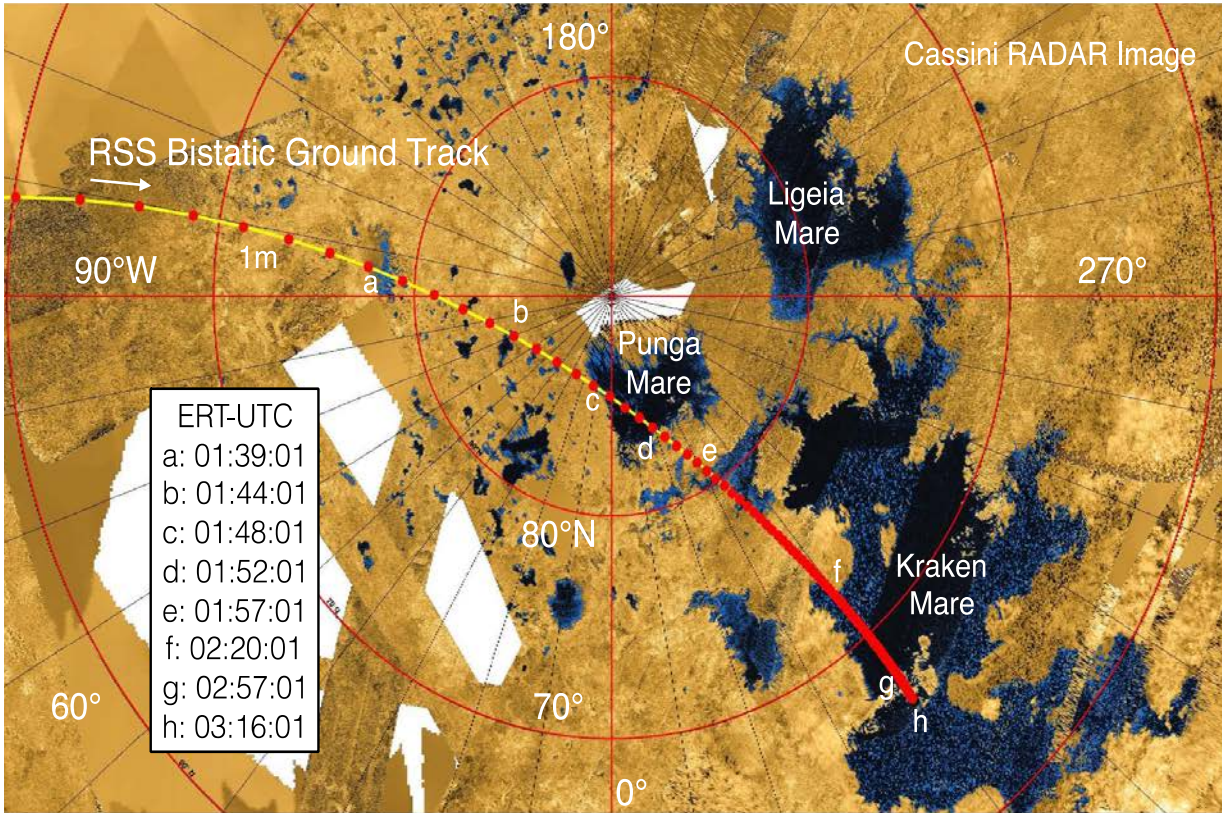
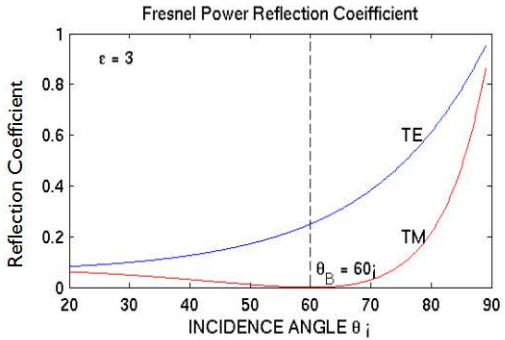


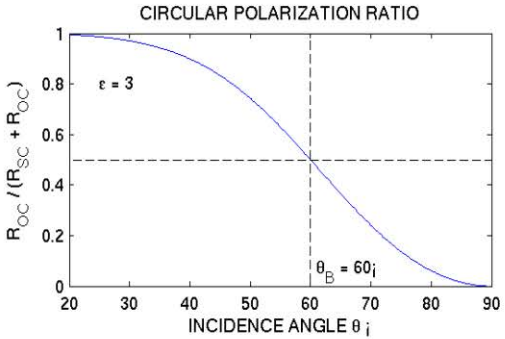
Figure 2. Surface plot of $\log_{10}$ electron density versus altitude and latitude derived from all Cassini RSS Saturn occultation data (approximately 60,000 data points). The upper plot is a 3-D representation of electron density, and the lower graphic is the corresponding contour plot.

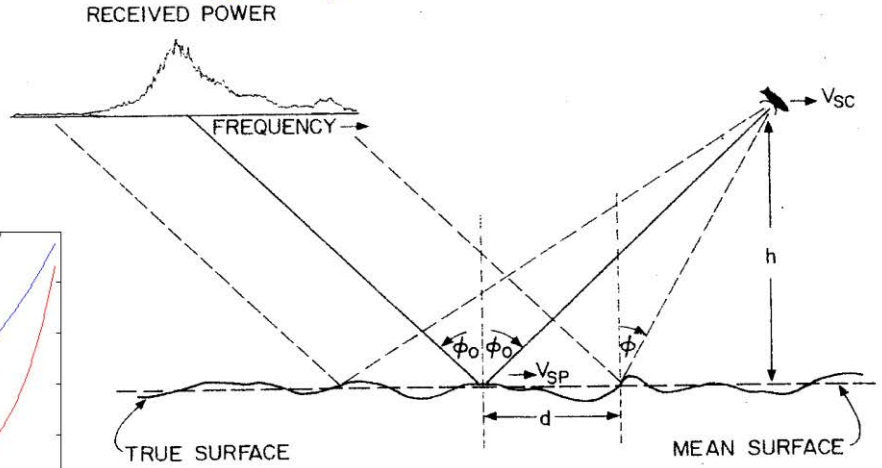
Probing the composition of Titan's seas



Bistatic Scattering: Objectives







From Simpson *et al*. 1977

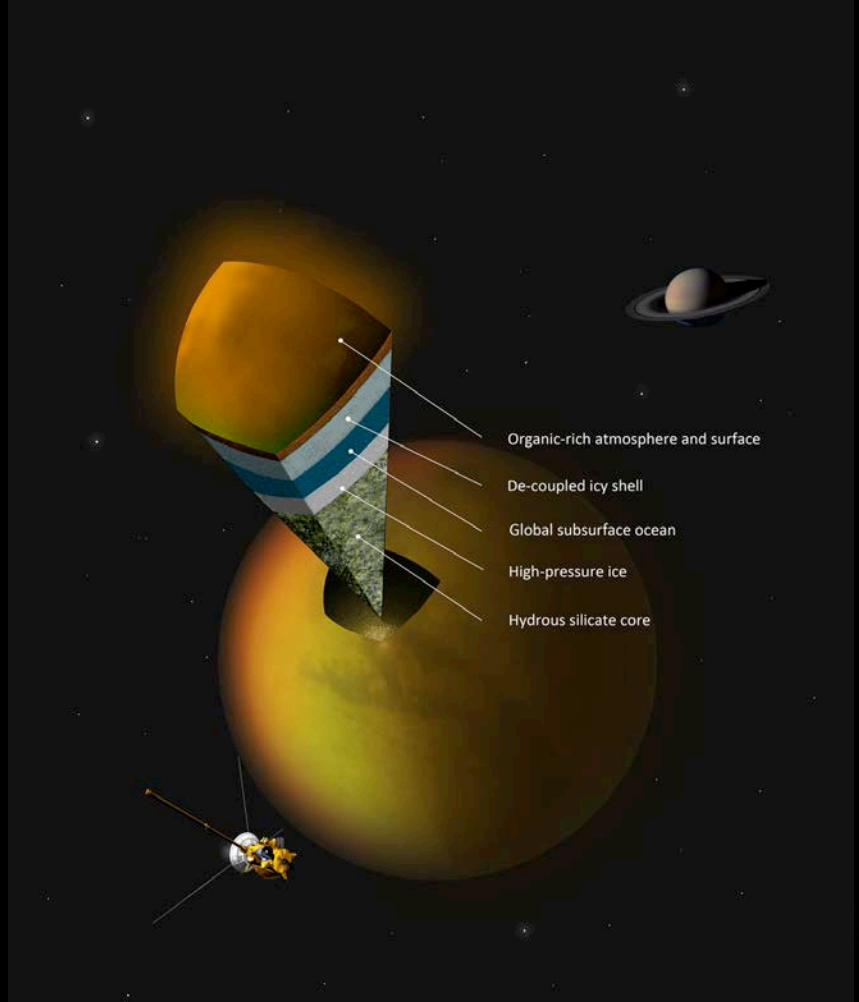
Surface Roughness (Waves if Liquid Surface)

Surface Dielectric Constant

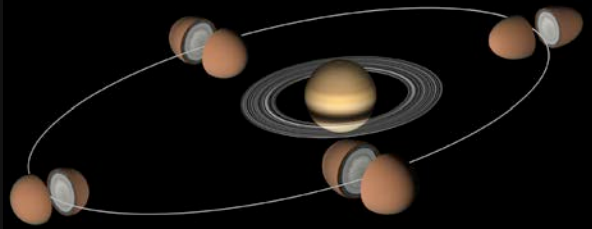
EAM: Cassini RSS

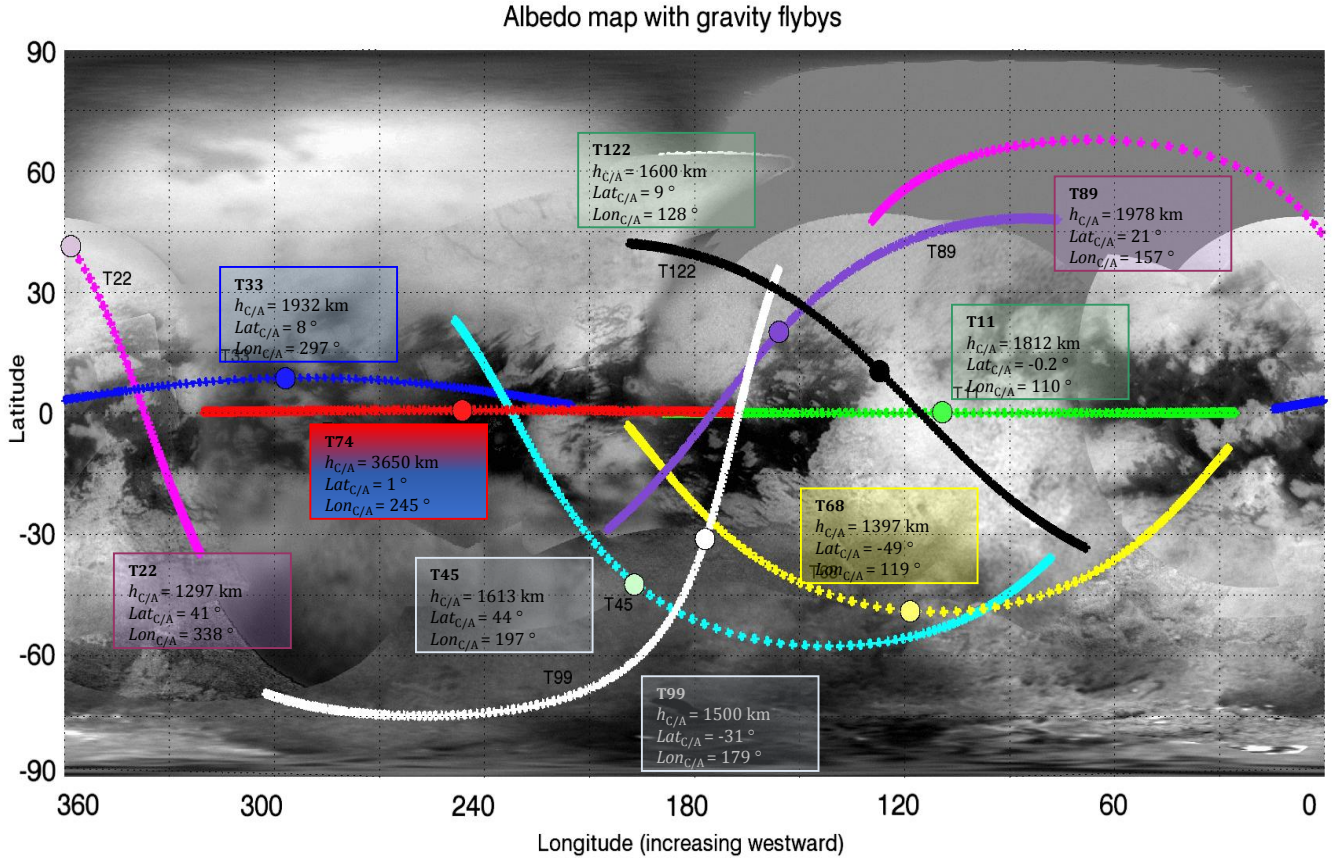
Detecting radio reflections from Titan’s Northern Seas

Detecting reflections from Titan’s Northern Seas

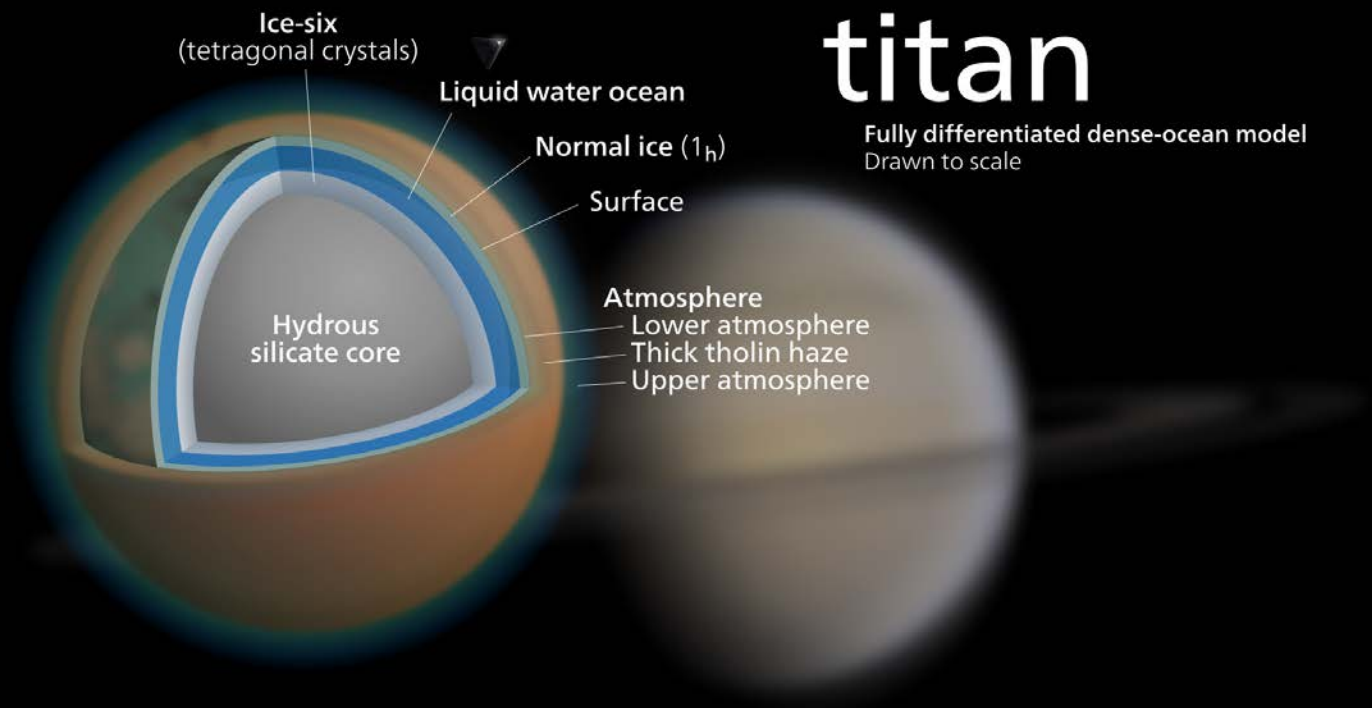


Titan Tides and Rotation




Albedo map with gravity flybys
90
60
30
0
-30
-60
-90
Latitude
360
300
240
180
120
60
0
Longitude (increasing westward)
T22
T33
$h_{C/A}$ = 1932 km
$Lat_{C/A}$ = 8 °
$Lon_{C/A}$ = 297 °
T74
$h_{C/A}$ = 3650 km
$Lat_{C/A}$ = 1 °
$Lon_{C/A}$ = 245 °
T22
$h_{C/A}$ = 1297 km
$Lat_{C/A}$ = 41 °
$Lon_{C/A}$ = 338 °
T45
$h_{C/A}$ = 1613 km
$Lat_{C/A}$ = 44 °
$Lon_{C/A}$ = 197 °
T99
$h_{C/A}$ = 1500 km
$Lat_{C/A}$ = -31 °
$Lon_{C/A}$ = 179 °
T122
$h_{C/A}$ = 1600 km
$Lat_{C/A}$ = 9 °
$Lon_{C/A}$ = 128 °
T89
$h_{C/A}$ = 1978 km
$Lat_{C/A}$ = 21 °
$Lon_{C/A}$ = 157 °
T11
$h_{C/A}$ = 1812 km
$Lat_{C/A}$ = -0.2 °
$Lon_{C/A}$ = 110 °
T68
$h_{C/A}$ = 1397 km
$Lat_{C/A}$ = -49 °
$Lon_{C/A}$ = 119 °

Cassini gravity field measurements of Titan reveal liquid ocean



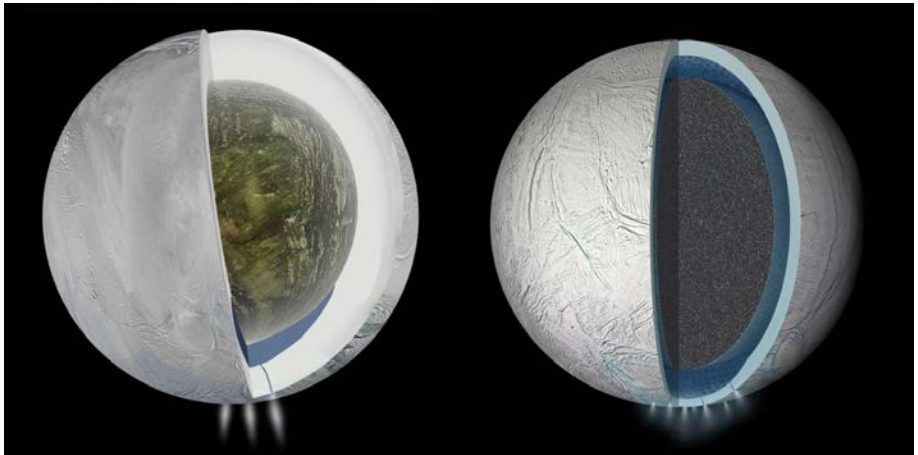
Icy Satellites Gravity Science

Saturn icy satellite	Estimated GM (km^3/s^s)	J_2 ($x10^6$)	C_{21} ($x10^6$)	S_{21} ($x10^6$)	C_{22} ($x10^6$)	S_{22} ($x10^6$)	J_2/C_{22}	J_3 ($x10^6$)
Phoebe	0.5517 ± 0.0007	–	–	–	–	–	–	–
Iapetus	120.2064 ± 0.0631	–	–	–	–	–	–	–
Hyperion	0.375 ± 0.003	–	–	–	–	–	–	–
Dione	73.11646 ± 0.00050	1453.6 ± 16.2	–	–	363.1 ± 2.0	-17.0 ± 1.9	4.00 ± 0.06	–
Rhea	153.9416 ± 0.0049	946.0 ± 13.9	-19.9 ± 11.0	23.5 ± 21.3	242.1 ± 4.0	-15.3 ± 5.0	3.91 ± 0.10	–
Enceladus	7.2096 ± 0.0067	5435.2 ± 34.9	9.2 ± 11.6	39.8 ± 22.4	1549.8 ± 15.6	22.6 ± 7.4	3.51 ± 0.05	**-115.3 ± 22.9**

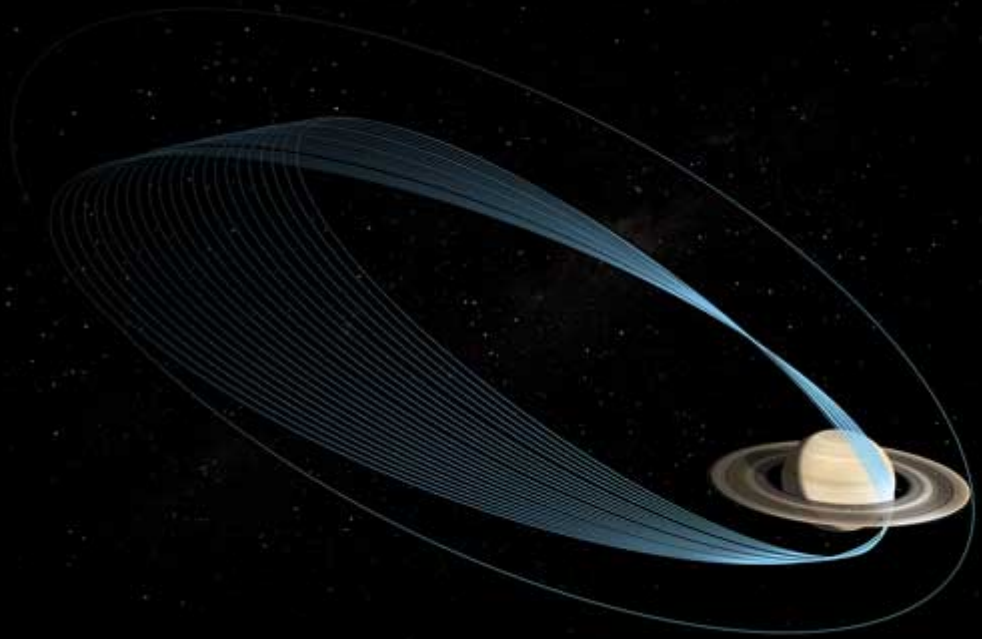
Not in hydrostatic equilibrium (10/3)

Enceladus – what we know from Cassini

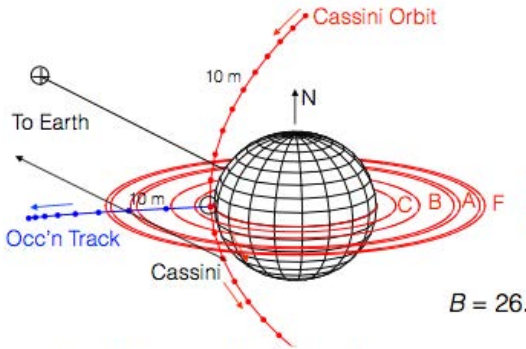
- Cassini carried out gravity measurements of Enceladus in 2010-2012 during **three close flybys**: E9 (Apr ‘10), E12 (Nov. ‘10) and E19 (May ‘12)
- Analysis of Radio Tracking (Doppler) data **provided the first estimation of the full degree-2 gravity field (+J_3)**, (*Iess et al., 2014*), giving evidence of a **subsurface ocean under the icy crust, near the South pole**
- More recently, the analysis of Cassini images provided a measurement of a **large physical libration of Enceladus**, direct evidence of a **global ocean under the icy crust** (Thomas et al. 2016)



The Grand Finale! The first plunge began on April 23, 2016

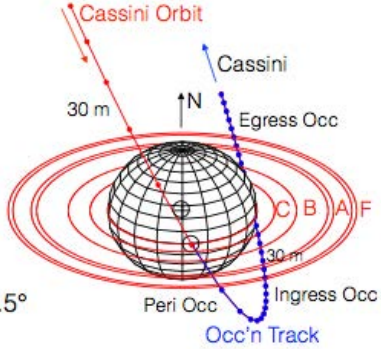


Ring occultations during the Grand Finale – up close and personal!

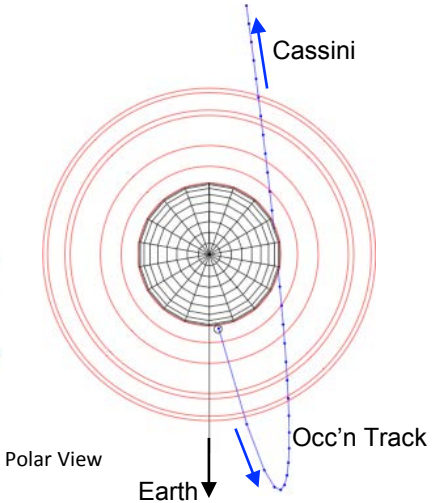


Close (Periapse) Ring Occultation
Side View

$B = 26.5°$

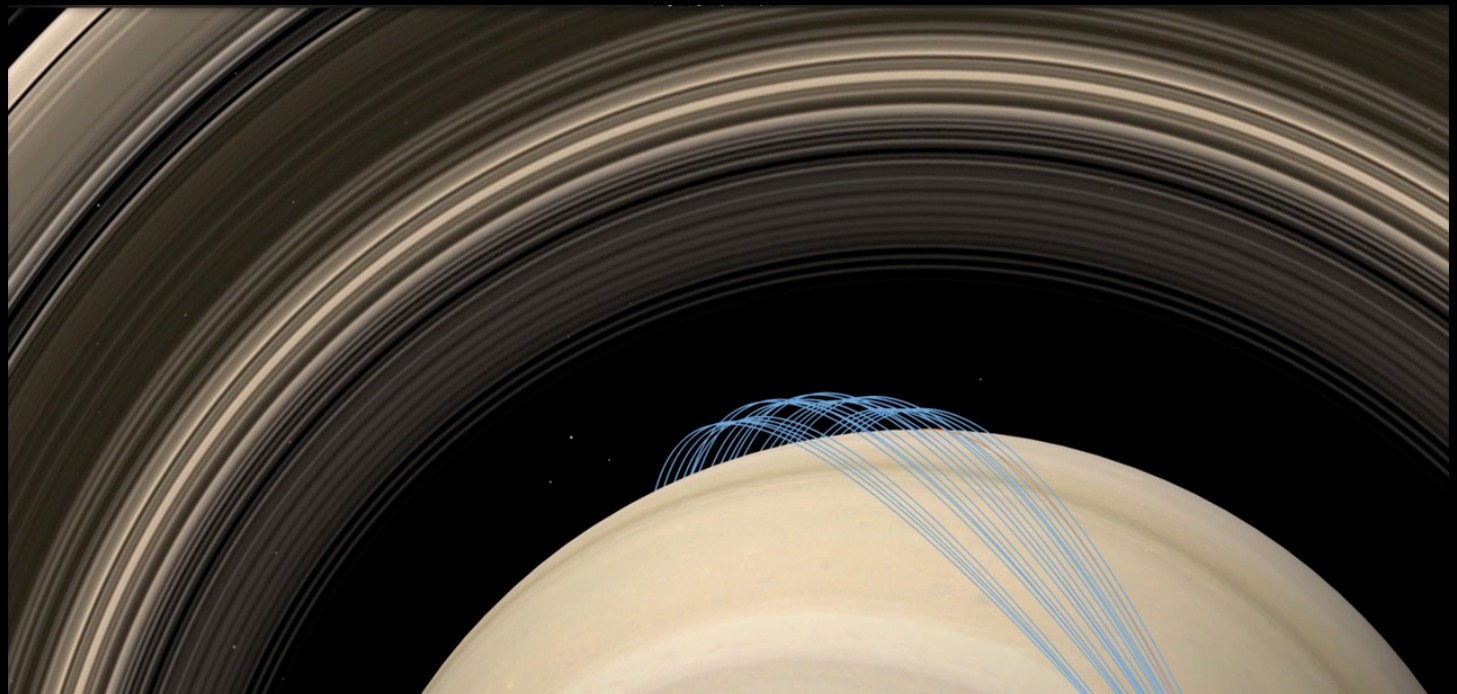


Distant Ring Occultations
View from the Earth



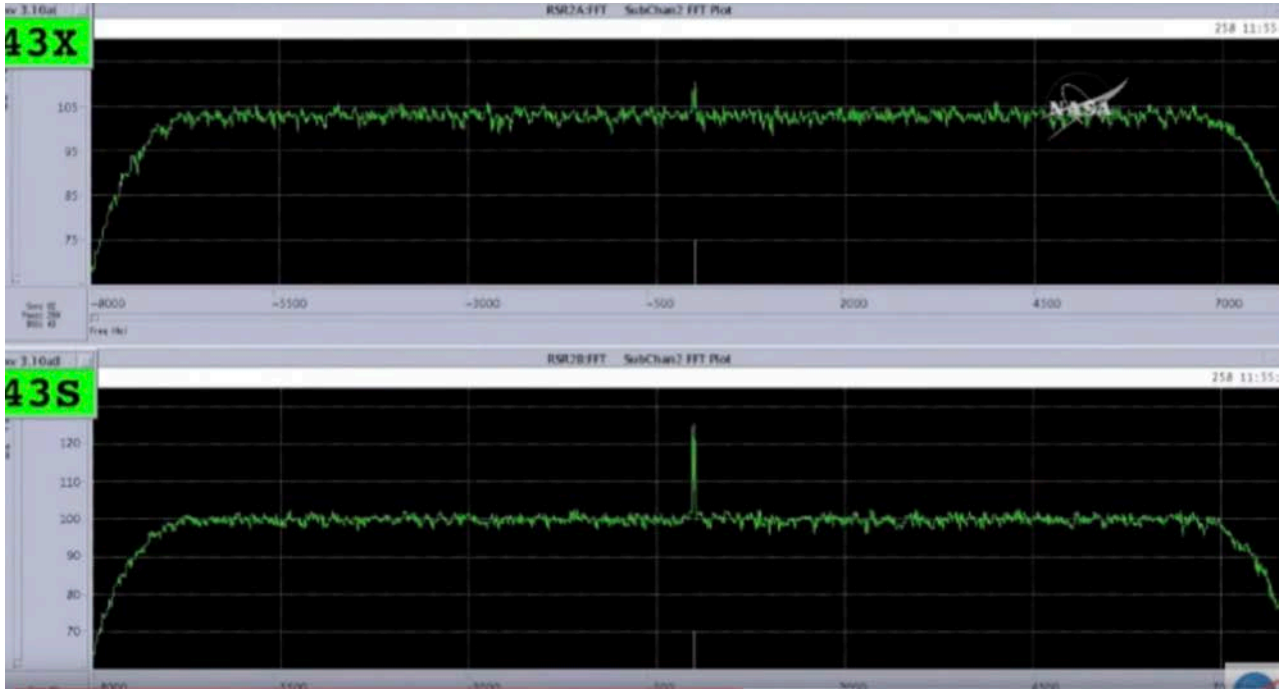
Polar View

Saturn gravity during Grand Finale:
Depth of winds and differential rotation
Mass of Saturn's rings
Comparison with Jupiter



The RSS Operations Team at T119

Cassini's final wave home….



Background material

Radio Science Operations

- The most operationally complex and challenging Radio Science experiments ever conducted
  - Multiple frequency bands
  - Complicated configuration
  - Demanding ground pointing requirements – in particular, at Ka-band
  - Real-time intervention
  - Long duration – extending for over 30 hours late in the mission
  - Ground coverage by several antennas over multiple DSN complexes
- All 70-m and 34-m DSN antennas were utilized to support RS experiments
  - ESA's Malargue and New Norcia antennas were utilized during the last phase of the mission
- In total, there were 1095 radio science events including all science experiments, engineering activities and diagnostic tracks, and these were covered by 1691 individual ground tracks
- ~ 9 TB of Radio Science engineering and science open- and closed-loop data were collected during Tour
- The Radio Science Instrument (both spacecraft and ground) performed above and beyond expectations

Ionospheric Results from RSS

Saturn:

- 65 vertical dawn/dusk ionospheric electron density profiles
- latitude range from the equator to about 72^{o} latitude.
- The mean peak electron densities a few times 10^{5} cm^{-3} and in general increased with latitude.
- This is believed to be the result of rapid recombination of H^{+} with neutral molecules (e. g. methane, water), as well as possible increases in ionization rates.
- The mean altitude of the density peak is around 2200 km, also increasing with latitude.
- In situ measurements during the proximate orbits allowed a comparison with direct measurements and it it showed very good agreement.

Titan:

- 24 vertical electron density profiles
- The “normal” mean electron density peak was found to be 1-2x10^{3} cm^{-3}.
- Sometimes was over 3x10^{3} cm^{-3}attributed to electron precipitation.
- The altitude of the peak density was around 1200 km.
- Unexpected large secondary electron peak was observed to be present on a few occasions near 500 km, which is likely due to intermittent ion precipitation.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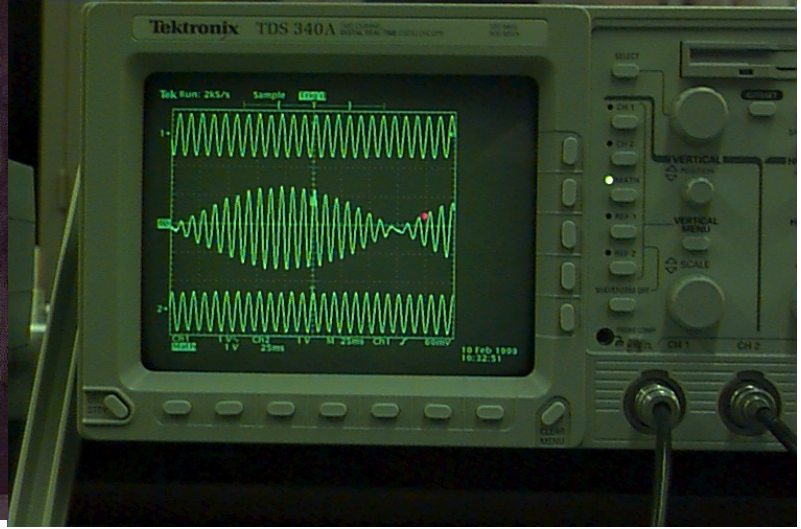
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