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

Richard French, Cassini Radio Science Team Leader
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Optimized tour for occultations, gravity, bistatic observations
Test of General Relativity during Cassini’s 2002 Superior Conjunction

B. Bertotti¹, L. Iess², P. Tortora³,

¹ Università di Pavia, Italy
² Università di Roma “la Sapienza”, Italy
³ Università di Bologna, Italy
“Moonlighting Satellite Vindicates Einstein”

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

RMS range rate residuals:
$2 \times 10^{-3} \text{ mm/s @ 300 s}$

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

$\gamma_{\text{Viking}} = 1 \times 10^{3}$

\[ \gamma = \gamma_{\text{space curvature}} g_{ij} \text{ per unit rest mass} \]

\[ \gamma = 1 \text{ for GR} \]

PPN – Parameterized post-Newtonian formalism

The parameter \((1 + \gamma)/2\) vs. year of experiment.

Cassini result.
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 \( \gamma \)

• GAIA and BepiColombo should reach a level of accuracy of \( 2 \times 10^{-6} \)
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)

Occultation Sequence: revs 7 to 14
\[ 20 \leq B \leq 24^\circ \]

(Rev 44) 2005 MAY 3,
-23.6, 21.9, 5

180° Transfer Sequence: revs 44, 46
\[ B \sim 15^\circ \]

(Rev 63) 2007 JUN 11,
-14.4, 18.4, 5.3

High Inc Sequence Orbits 56 to 67
(Rev 63) 2008 APR 1,
-9.6, 63.8, 6.5
The Coherent (Direct) & Scattered Signals
Direct (Coherent) & Scattered signals

Observed Signal Spectrum

Coherent

Scattered

RSS

Cassini

Observables
Periodic microstructure in the rings
Thomson et al. 2007, GRL 34, L24203
Saturn’s Maxwell Ringlet
Standing wave discovered in RSS ring occultations
Generation of standing wave: Co-addition of leading/trailing prograde density waves
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

“Virtual” Earth

“Actual” Earth

Refracted Ray Path

“Apparent” Line of Sight

Geometric Line of Sight

Saturn or Titan

Adapted from D. Wait 05/07/04
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)

Descent:
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]

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
Detecting radio reflections from Titan’s Northern Seas
Titan Tides and Rotation

- Organic-rich atmosphere and surface
- De-coupled icy shell
- Global subsurface ocean
- High-pressure ice
- Hydrous silicate core
Albedo map with gravity flybys

- **T11**
  - $h_{C/A} = 1600 \text{ km}$
  - $Lat_{C/A} = 9^\circ$
  - $Lon_{C/A} = 128^\circ$

- **T22**
  - $h_{C/A} = 1297 \text{ km}$
  - $Lat_{C/A} = 41^\circ$
  - $Lon_{C/A} = 338^\circ$

- **T33**
  - $h_{C/A} = 1932 \text{ km}$
  - $Lat_{C/A} = 8^\circ$
  - $Lon_{C/A} = 297^\circ$

- **T45**
  - $h_{C/A} = 1613 \text{ km}$
  - $Lat_{C/A} = 44^\circ$
  - $Lon_{C/A} = 197^\circ$

- **T68**
  - $h_{C/A} = 1397 \text{ km}$
  - $Lat_{C/A} = -49^\circ$
  - $Lon_{C/A} = 119^\circ$

- **T74**
  - $h_{C/A} = 3650 \text{ km}$
  - $Lat_{C/A} = 1^\circ$
  - $Lon_{C/A} = 245^\circ$

- **T89**
  - $h_{C/A} = 1978 \text{ km}$
  - $Lat_{C/A} = 21^\circ$
  - $Lon_{C/A} = 157^\circ$

- **T99**
  - $h_{C/A} = 1500 \text{ km}$
  - $Lat_{C/A} = -31^\circ$
  - $Lon_{C/A} = 179^\circ$
Cassini gravity field measurements of Titan reveal liquid ocean
## Icy Satellites Gravity Science

<table>
<thead>
<tr>
<th>Saturn icy satellite</th>
<th>Estimated GM (km³/s²)</th>
<th>$J_2$ (x10⁶)</th>
<th>$C_{21}$ (x10⁶)</th>
<th>$S_{21}$ (x10⁶)</th>
<th>$C_{22}$ (x10⁶)</th>
<th>$S_{22}$ (x10⁶)</th>
<th>$J_2/C_{22}$</th>
<th>$J_3$ (x10⁶)</th>
</tr>
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<tbody>
<tr>
<td>Phoebe</td>
<td>0.5517 ± 0.0007</td>
<td>–</td>
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<tr>
<td>Iapetus</td>
<td>120.2064 ± 0.0631</td>
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<tr>
<td>Hyperion</td>
<td>0.375 ± 0.003</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>Dione</td>
<td>73.11646 ± 0.00050</td>
<td>1453.6 ± 16.2</td>
<td>–</td>
<td>–</td>
<td>363.1 ± 2.0</td>
<td>-17.0 ± 1.9</td>
<td>4.00 ± 0.06</td>
<td>–</td>
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<tr>
<td>Rhea</td>
<td>153.9416 ± 0.0049</td>
<td>946.0 ± 13.9</td>
<td>-19.9 ± 11.0</td>
<td>23.5 ± 21.3</td>
<td>242.1 ± 4.0</td>
<td>-15.3 ± 5.0</td>
<td>3.91 ± 0.10</td>
<td>–</td>
</tr>
<tr>
<td>Enceladus</td>
<td>7.2096 ± 0.0067</td>
<td>5435.2 ± 34.9</td>
<td>9.2 ± 11.6</td>
<td>39.8 ± 22.4</td>
<td>1549.8 ± 15.6</td>
<td>22.6 ± 7.4</td>
<td>3.51 ± 0.05</td>
<td>-115.3 ± 22.9</td>
</tr>
</tbody>
</table>
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 (+J₃), (less 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!
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° 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.