Preliminary Results From Titan's Gravity Flybys

Gravity measurements, combined with topography and rotation measurements, are the main sources of constraints on the internal structure of Titan. Due to competition with other science goals the opportunities for gravitational measurements were limited. Titan's main deviations from spherical symmetry are caused by centrifugal and tidal forces, associated respectively with the rotation about its spin axis and the gradient of Saturn's gravity. During the Cassini mission 10 Titan flybys were committed to gravitational measurements. Table1 tabulates characteristics of the flybys. The flyby ID is shown in column 1. The color codes identifying each flyby in the table are used also in Fig. 1 and 2. Column 2 indicates the epoch of closest approach (C/A). The gravity signal is stronger for lower pericentre altitudes (column 3) while Doppler noise due to interplanetary plasma turbulence decrease for larger Sun-Earth-Probe angles (SEP, column 4). T110 was carried out using Cassini's Low Gain Antenna (LGA), as the attitude was set by the needs of other instruments.

Table 1. Main characteristics of Titan's gravity flybys

Flyby	C/A Date	Altitude	SEP
T11	27-FEB-2006 08:25:18 ET	1812 km	150°
T22	28-DEC-2006 10:05:21 ET	1297 km	131°
T33	29-JUN-2007 17:00:51 ET	1933 km	46°
T45	31-JUL-2008 02:14:16 ET	1614 km	30°
T68	20-MAY-2010 03:25:26 ET	1397 km	120°
T74	18-FEB-2011 16:05:17 ET	3651 km	131°
T89	17-FEB-2013 01:57:42 ET	1978 km	106°
T99	06-MAR-2014 16:27:53 ET	1500 km	111°
T110	16-MAR-2015 14:30:55 ET	2274 km	109°
T122	10-AUG-2016 08:32:00 ET	1698 km	113°

In order to obtain the optimal gravity measurements, the goal would be to obtain even global sampling of Titan's gravity; however orbital limitations and competition with other goals prevented this. Figure 1 shows ground tracks achieved within the limited observational opportunities and emphasizes the scarcity of high latitudinal sampling.

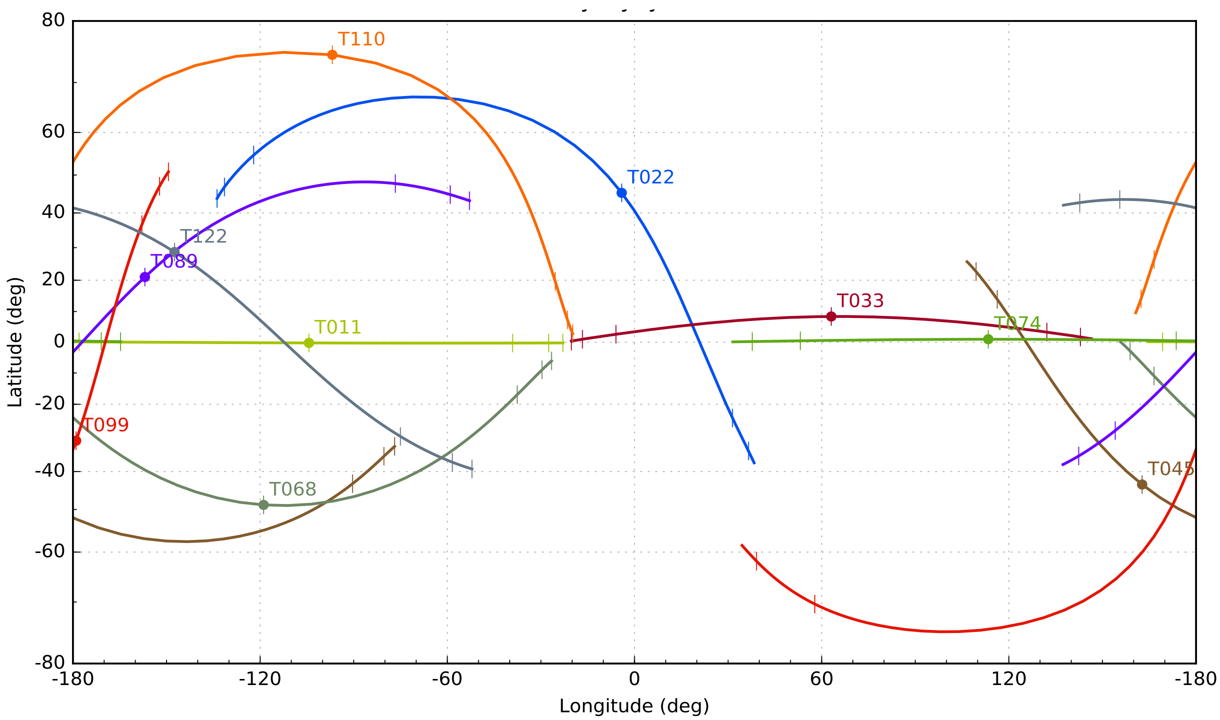

Figure 1. Ground tracks of the 10 Titan gravity flybys showing uneven sampling of the moon's gravity. Each track corresponds to a time window of 3 hours centred at C/A, with tick marks for 30 minutes intervals. Lack of coverage on high latitude regions produce larger uncertainties in the reconstructed geoid on that regions.

The non-negligible eccentricity of Titan's orbit causes a variation with time of the quadrupole tidal field [proportional to $1/r^3$ (*r*, distance between Titan and the Saturn barycenter)]. These short-term variations change the satellite's physical shape and gravity. Titan's linear response to the periodic tidal field entails a corresponding periodic change in its own quadrupole potential. The ratio between the perturbed and the perturbing potentials is known as the $k2$ Love number. It is an indication of the mass redistribution inside the body in response to the forcing potential. $k2$ reaches its theoretical upper limit of 3/2 for an incompressible liquid body, whereas for a perfectly rigid body, $k2 = 0$. If Titan has a global subsurface ocean, then $k2$ must differ substantially from zero.

Figure 2 shows the distribution of the mean anomalies among the 10 flybys. With Titan's orbital eccentricity being about one half that of our moon at 0.0288, this leads to the ratio of the tidal field at apoapse relative to that at periapse being about 84%, allowing for considerable response.

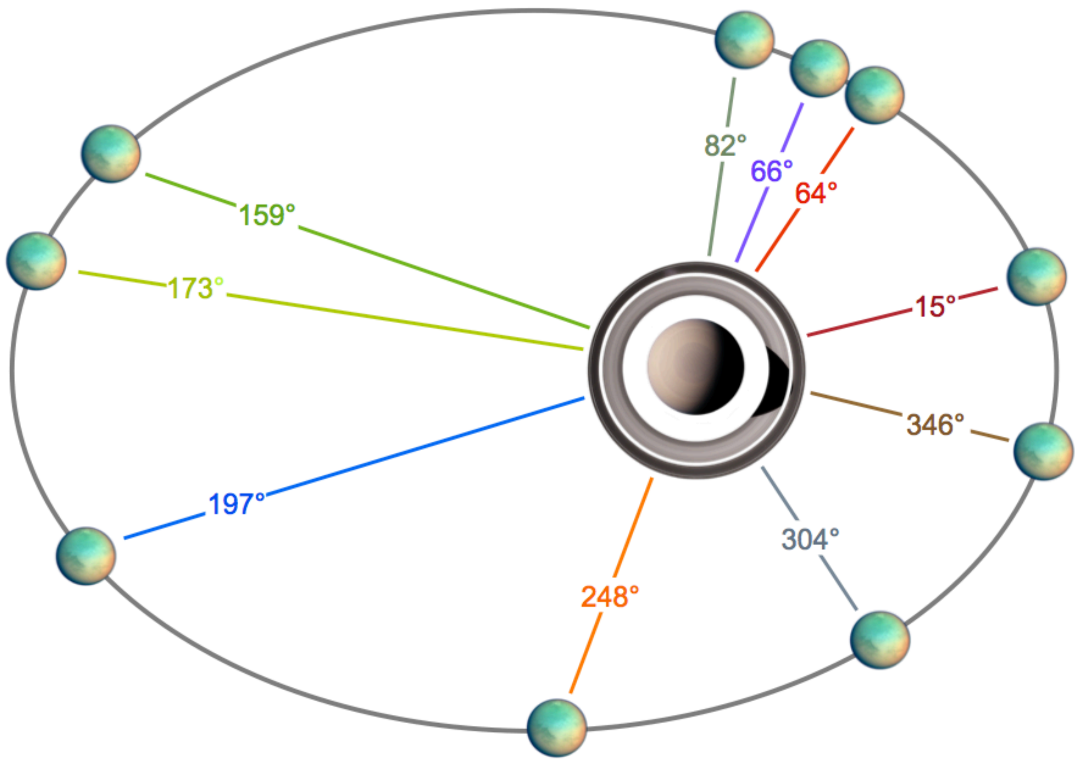

Figure 2. Distribution of Titan mean anomalies of the 10 gravity flybys at the time of closest approach.

Measuring Titan's gravity field at different mean anomalies allows a better determination of eccentricity tides (Love number k_2). If the tidal bulge has no phase lag, the tidal variation of the quadrupole gravity coefficients J2 and C22 peaks at pericentre (M=0°) and apocentre (M=180°).

Table 2 provides estimated spherical harmonics coefficients for the un-normalized Titan gravity field (degree and order 4). Eccentricity tides are also included in the model and described by the degree 2 Love number k_2 (last row). Solution from Iess, L., *et al.* "The tides of Titan." Science 337.6093 (2012): 457-459. (Table 1 and S3). DOI: 10.1126/science.1219631

Table 2. Estimated spherical harmonics coefficients

Solution SOL1b from Iess (2012)
VALUE ±1σ (×10+06)

J2	34.227±	0.477
C21	0.125 ±	0.111
S21	0.816 ±	0.351
C22	10.263±	0.069
S22	0.111 ±	0.055
J3	-1.635 ±	0.838
C31	0.681 ±	0.207
S31	-0.073 ±	0.475
C32	0.150 ±	0.125
S32	0.104 ±	0.114
C33	-0.221 ±	0.016
S33	-0.232 ±	0.016
J4	2.043 ±	0.759
C41	0.175 ±	0.203
S41	0.033 ±	0.250
C42	0.059 ±	0.080
S42	0.093 ±	0.058
C43	0.026 ±	0.015
S43	0.008 ±	0.020
C44	-0.007 ±	0.002
S44	-0.014 ±	0.002
k2	0.670 ±	0.090

Iess, L., et al. "The tides of Titan." Science 337.6093 (2012): 457-459.
(Table 1 and S3)

Estimated gravity anomalies (upper panel) and related formal uncertainties (lower panel) from the analysis of the first 6 Titan gravity flybys are presented in Figure 3 . The anomalies are computed in mGal over the reference gravity of the ellipsoid defined by the estimated monopole and quadrupole coefficients (GM, J_2 and C_{22}), and the rotational state of Titan. Based on the solution SOL1.b from Iess, L., *et al.* "The tides of Titan." Science 337.6093 (2012): 457-459. DOI: 10.1126/science.1219631

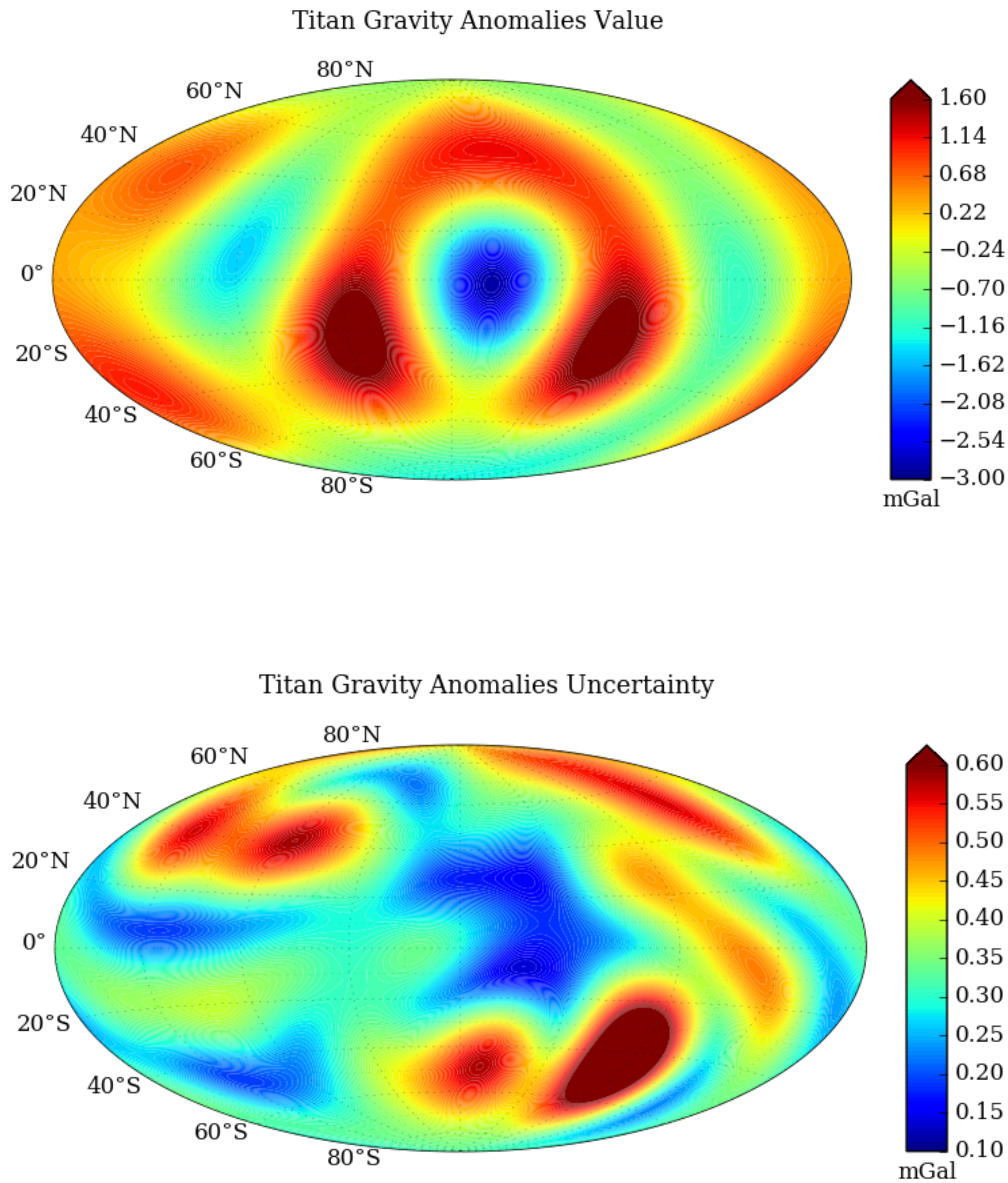

Figure 3. Estimated gravity anomalies (upper panel) and related formal uncertainties (lower panel) from the analysis of the first 6 Titan gravity flybys (t11-T74 (4X4)

Abstract of paper L.Iess et al. "The tides of Titan" (2012):

"We have detected in Cassini spacecraft data the signature of the periodic tidal stresses within Titan, driven by the eccentricity (e = 0.028) of its 16-day orbit around Saturn. Precise measurements of the acceleration of Cassini during six close flybys between 2006 and 2011 have revealed that Titan responds to the variable tidal field exerted by Saturn with periodic changes of its quadrupole gravity, at about 4% of the static value. Two independent determinations of the corresponding degree-2 Love number yield k2 = 0.589 T 0.150 and k2 = 0.637 T 0.224 (2-sigma).