Chapter 17
Titan in the Cassini–Huygens Extended Mission

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17.1 Titan in the Cassini–Huygens Extended Mission

At the culmination of the Primary Mission Cassini began a 2-year extended orbital phase called the Cassini Equinox Mission. The sun crosses Saturn's equatorial plane on 11 August 2009. With 2 extra years the discoveries and deficiencies in the Primary Mission can be addressed, as well as new opportunities presented by the equinox crossing. This chapter covers the state of knowledge and outstanding questions at the end of the Primary Mission, and outlines the opportunities in the Equinox Mission. Key questions are identified and the strategies by which they will be addressed are discussed. Specific geometries and scientific goals of individual Titan flybys are described. The chapter ends with a brief description of the proposed Cassini Solstice Mission, which may extend spacecraft operation to 2017.

17.1.1 Overview

The Cassini–Huygens extended mission, called the Equinox Mission (EM), began July 1, 2008. There will be 26 flybys of Titan in the 2-year extended mission, numbered T45 to T70. Tables 17.1 and 17.2 give the flyby dates and important geometric data for each of the Titan flybys in the primary and extended mission phases, respectively. The extended mission tour of the Saturnian system was designed to fill in gaps in the Primary Mission (PM), either in terms of scientific investigations or in missing geometric conditions, and to respond to discoveries made in the PM.

The overall cadence of the Cassini equinox mission is driven by a balance of different disciplinary goals. Cassini's orbit inclination at the end of the primary mission is 74.8°. Figure 17.1 shows the inclination profile punctuated by the EM Titan flybys. High inclination orbits for the first ~9 months of the EM enable viewing of stellar occultations for ring science, auroral observations, and polar passes of Enceladus. Good views of Titan's south polar region occur early while the region is still well-illuminated. Titan flybys flip from outbound to inbound node crossings between T51 and T52, changing the local solar time of the flybys from ~10 to 22 h, respectively. This sets up the orbit orientation to satisfy the Titan scientific requirements for encounters in the dusk sector of Saturn's magnetosphere. The ring science requirement to observe the equinox with the spacecraft 15° above Saturn's equatorial plane sets the slow pace from T52 to T62 of returning the spacecraft to an equatorial orbit for more icy satellite flybys and ansa-to-ansa ring occultations. T52, T53 and T54 were designed for high quality occultations of the sun and earth by Titan's atmosphere. Missing from the primary mission, thus deliberately designed into the extended mission tour, were wake passages and dusk encounters, achieved in T63 to T70. The tour is described in detail in Buffington et al. 2008.

One of the prime drivers in designing the extended mission tour was simply to have numerous Titan flybys. The decision early in the project development to eliminate the spacecraft scan platform means that multiple experiments cannot be carried out simultaneously, thus any given Titan flyby must be dedicated to just a few of Cassini's dozen instruments.

Considering the 2-year EM combined with the 4-year primary mission we also have the opportunity to observe seasonal changes. One Saturn year is 29.47 earth years; when Cassini–Huygens arrived at Saturn the season was winter in the northern hemisphere. Within the extended mission the sun crosses Saturn's equatorial plane on August 11, 2009, and the northern hemisphere of Titan will experience the onset of spring. Figure 17.2 shows the "calendar" of Titan

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Table 17.1 Titan flybys in the primary mission. Values are given for closest approach (C/A) to Titan. C/A time is formatted Day-of-year Thours:minutes:seconds. "LST" is Local Solar Time

Flyby	Orbit	Date	C/A Time	Altitude (km)	LST	Lat	Lon (West)	Phase angle
T0	0	3-Jul-04	184T09:29:00	341,500	5.76	−65.1	333.17	67.0
Ta	A	26-Oct-04	300T15:20:33	1,174	11.00	38.8	88.5	90.9
Tb	B	13-Dec-04	348T11:38:13	1,192	10.47	59.1	84.2	101.5
Tc	C	13-Jan-05	014T11:12:00	60,003	10.47	0.1	251.8	92.9
T3	3	15-Feb-05	046T06:54:21	1,579	10.33	29.9	68.9	98.5
T4	5	1-Apr-05	091T19:55:12	2,404	5.27	33.4	118.7	66.4
T5	6	16-Apr-05	106T19:11:46	1,027	5.27	74.0	272.3	127.2
T6	13	22-Aug-05	234T08:53:37	3,660	5.00	−58.5	102.7	43.1
T7	14	7-Sep-05	250T07:50:26	1,075	4.93	−67.0	308.1	84.5
T8	17	28-Oct-05	301T03:58:09	1,353	9.27	1.2	246.1	104.8
T9	19	26-Dec-05	360T18:54:15	10,411	3.00	−0.2	110.4	67.1
T10	20	15-Jan-06	015T11:41:27	2,043	8.47	0.1	250.8	120.5
T11	21	27-Feb-06	058T08:25:19	1,812	1.13	0	107.4	92.5
T12	22	19-Mar-06	078T00:05:57	1,949	6.40	0.1	250.6	148.0
T13	23	30-Apr-06	120T20:53:31	1,856	23.13	0.1	106.3	120.7
T14	24	20-May-06	140T12:18:12	1,879	4.40	0.4	249.9	163.0
T15	25	2-Jul-06	183T09:12:19	1,906	21.20	−0.4	105.5	147.9
T16	26	22-Jul-06	203T00:25:13	950	2.40	85.2	316.2	105.3
T17	28	7-Sep-06	250T20:12:04	1,000	2.27	23	56.74	44.7
T18	29	23-Sep-06	266T18:58:49	960	2.27	71.0	357.0	89.9
T19	30	9-Oct-06	282T17:23:24	980	2.20	60.7	357.5	80.9
T20	31	25-Oct-06	298T15:58:07	1,030	2.13	7.5	44.34	25.3
T21	35	12-Dec-06	346T11:41:31	1,000	2.00	43.9	265.0	123.9
T22	36	28-Dec-06	362T10:05:22	1,297	1.93	40.2	357.6	61.6
T23	37	13-Jan-07	013T08:34:00	1,000	1.93	30.5	357.9	53.1
T24	38	29-Jan-07	029T07:15:55	2,631	1.87	32.8	330.1	72.4
T25	39	22-Feb-07	053T03:10:59	1,000	13.8	30.3	16.25	161.2
T26	40	10-Mar-07	069T01:47:22	981	13.8	31.7	357.9	149.5
T27	41	26-Mar-07	085T00:21:52	1,010	13.73	41.1	358	144.0
T28	42	10-Apr-07	100T22:58:00	991	13.67	50.4	358.1	137.2
T29	43	26-Apr-07	116T21:32:52	981	13.67	59.7	358.4	129.6
T30	44	12-May-07	132T20:08:14	959	13.60	68.9	358.9	121.4
T31	45	28-May-07	148T18:51:27	2,299	13.60	76.8	360	114.3
T32	46	13-Jun-07	164T17:47:57	965	13.53	84.5	0.9	106.9
T33	47	29-Jun-07	180T16:59:46	1,932	13.53	8.1	294.9	95.6
T34	48	19-Jul-07	200T00:39:58	1,332	18.80	1.3	244.7	34.0
T35	49	31-Aug-07	243T06:34:25	3,324	11.53	63.5	110.6	87.0
T36	50	2-Oct-07	275T04:49:50	973	11.47	−59.9	109.0	67.5
T37	52	19-Nov-07	323T00:52:51	999	11.40	−22.1	117.4	51.3
T38	53	5-Dec-07	339T00:07:37	1,298	11.40	−78.9	175.1	69.7
T39	54	20-Dec-07	354T22:56:41	970	11.33	−70.1	176.6	61.3
T40	55	5-Jan-08	005T21:26:24	1,014	11.33	−12.2	130.4	37.1
T41	59	22-Feb-08	053T17:39:08	1,000	11.20	−34.7	151.7	30.1
T42	62	25-Mar-08	085T14:36:12	999	11.13	−27.1	156.4	21.3
T43	67	12-May-08	133T10:09:59	1,001	11.00	17.1	137.2	34.8
T44	69	28-May-08	149T08:33:21	1,400	10.93	12.4	150.1	23.1

flybys, compared to the equivalent earth date. Voyager flybys took place on earth-equivalent dates March 23 and April 3.

The scientific objectives for Titan in both the primary and extended mission phases have been divided informally into disciplines proceeding from Titan's interior out to its exosphere: interior structure, surface science, atmospheric investigations, and study of the interface of Titan's upper atmosphere with Saturn's magnetosphere. This chapter is divided into those four categories. For each we discuss how the new state of knowledge from data acquired in the primary mission drove

Table 17.2 Titan flybys in the Equinox Mission. Values are given for closest approach (C/A) to Titan. "LST" is Local Solar Time

Flyby	Orbit	Date	C/A Time	Altitude (km)	LST	Lat	Lon (West)	Phase angle
T45	78	31-July-08	213T02:13:11	1,614	11.0	−43.31	195.40	48.74
T46	91	3-Nov-08	308T17:35:23	1,100	10.5	−3.51	339.91	170.90
T47	93	19-Nov-08	324T15:56:28	1,023	10.5	−21.56	177.60	28.05
T48	95	5-Dec-08	340T14:25:45	960	10.5	−10.28	178.78	25.01
T49	97	21-Dec-08	356T12:59:52	970	10.4	−43.85	236.81	83.55
T50	102	7-Feb-09	038T08:50:52	960	10.2	−33.67	306.32	135.80
T51	106	27-Mar-09	086T04:43:37	960	10.0	−30.27	234.80	86.56
T52	108	4-Apr-09	094T01:47:48	4,150	22.0	−2.81	176.29	151.50
T53	109	20-Apr-09	110T00:20:46	3,600	22.0	−7.74	177.61	148.40
T54	110	5-May-09	125T22:54:16	3,244	22.0	−13.78	177.78	145.60
T55	111	21-May-09	141T21:26:42	965	22.0	−22.03	177.77	141.30
T56	112	6-June-09	157T20:00:01	965	22.0	−32.10	177.96	134.90
T57	113	22-June-09	173T18:32:36	955	22.0	−42.17	178.12	127.70
T58	114	8-July-09	189T17:04:04	965	22.0	−52.25	178.38	120.20
T59	115	24-July-09	205T15:34:04	955	22.0	−62.31	179.05	112.50
T60	116	9-Aug-09	221T14:03:54	970	21.9	−72.49	179.98	104.40
T61	117	25-Aug-09	237T12:51:39	970	21.8	−19.34	237.12	85.79
T62	119	12-Oct-09	285T08:36:25	1,300	21.7	−61.47	68.81	99.34
T63	122	12-Dec-09	346T01:03:15	4,850	17.0	33.20	114.78	124.20
T64	123	28-Dec-09	362T00:17:00	9,55	17.0	81.77	172.17	85.90
T65	124	12-Jan-10	012T23:10:37	1,073	17.0	−81.92	358.35	95.15
T66	125	28-Jan-10	028T22:28:50	7,490	17.0	−52.75	297.07	69.11
T67	129	5-Apr-10	095T15:50:39	7,462	21.0	0.0	240.35	73.00
T68	131	20-May-10	140T03:24:21	1,400	16.0	−49.09	116.61	112.40
T69	132	5-June-10	156T02:26:28	2,044	16.0	87.29	9.36	87.26
T70	133	21-June-10	172T01:27:18	880	16.0	83.52	171.67	82.43

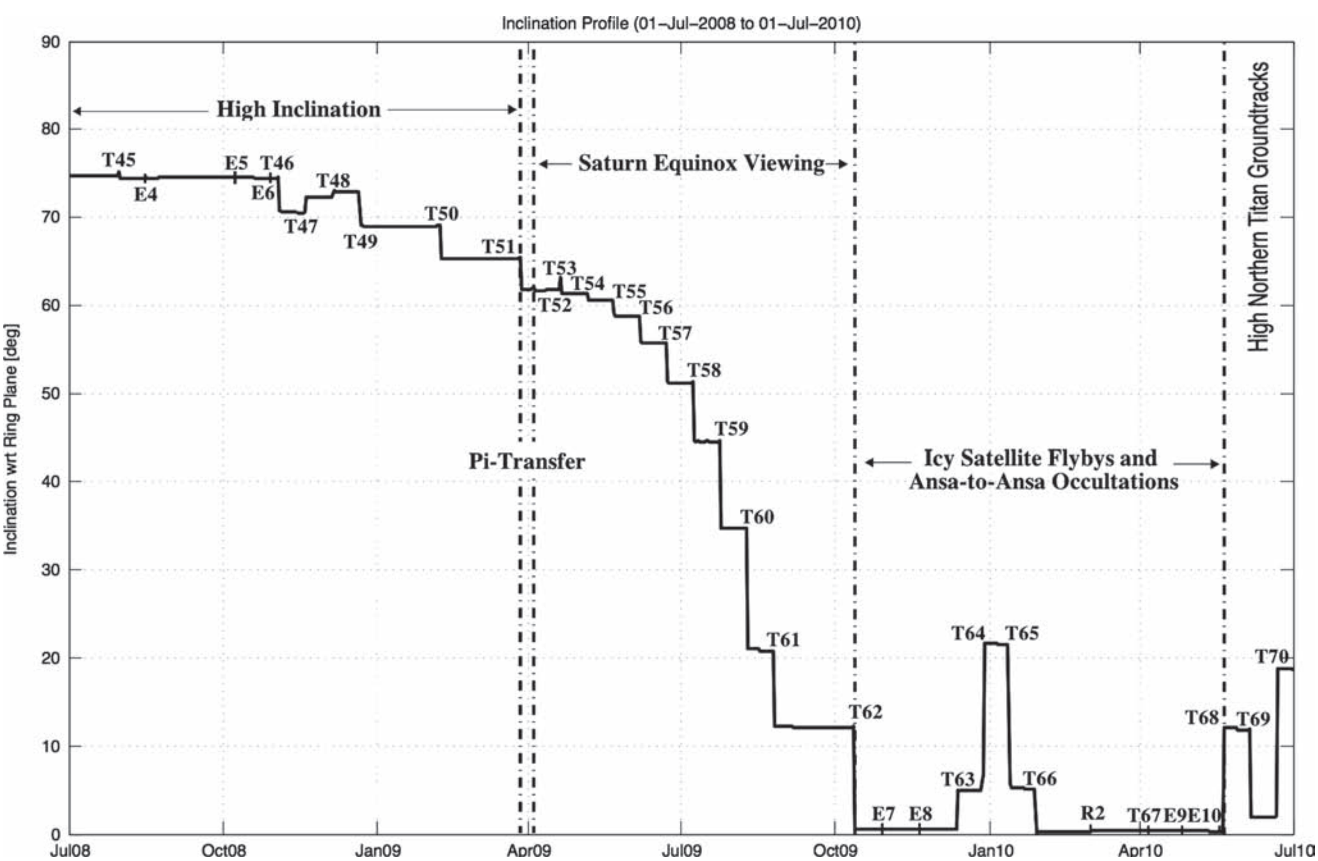

Fig. 17.1 Orbit inclination profile in the EM. Cassini's orbit inclination is 74.8° at the end of the primary mission. Titan flybys are used to shape the inclination profile and to rotate the long axis of Cassini's elliptical orbit around Saturn. This figure was originally published in Buffington et al. 2008.

Prime Mission Titan Activity	Extended Mission Titan Activity	Voyager Flyby Dates	Possible SM

January

M	T	W	T	F	S	S
				1	2	3
4	5	6	7	8	9	10
11 SOI	12	13	14	15 TA	16 TB	17 H
18 T4	19	20 T4&T5	21	22	23	24
25 T6&T7	26	27 T8	28	29 T9	30 T10	31 T11

February

M	T	W	T	F	S	S
1 T12	2 T13	3 T14	4 T15	5 T16	6	7 T17&T18
8 T18&T19	9	10 T21	11 T22&T23	12 T24	13 T25&T26	14 T27&T28
15 T29&T30	16 T31&T32	17 T33	18 T34	19 T35	20 T36	21
22 T37&T38	23 T39&T40	24	25 T41	26 T42	27	28 T43&T44

March

M	T	W	T	F	S	S
1 EOM	2 T45	3	4	5 T46	6 T47	7 T48&T49
8	9 T50	10 T51	11 T52&T53	12 T54&T55	13 T56&T57	14 T58&T59
15 T60&T61	16	17 T62	18	19 T63	20 T64&T65	21 66&Equinox
22	23 T67&V1	24	25 T68&T69	26 T70&T71	27	28
29 T72	30	31 T73				

April

M	T	W	T	F	S	S
			1 T74	2	3 T75&V2	4 T76
5 T77	6	7	8 T78	9	10	11 T79
12	13	14 T80	15 T81&T82	16	17	18 T83
19 T84	20	21 T85	22	23 T86	24 T87	25 T88
26	27	28 T89	29 T90	30		

May

M	T	W	T	F	S	S
					1 T91	2
3 T92&T93	4	5 T94	6 T95	7 T96	8 T97	9
10 T98	11 T99	12 T100	13 T101	14 T102	15 T103	16 T104
17 T105	18 T106	19	20 T107	21 T108	22 T109	23 T110
24	25 T111	26	27 T112	28	29	30 T113
31						

June

M	T	W	T	F	S	S
	1 T114	2	3 T115&T11(	4 T117	5 T118	6
7 T119	8 T120	9 T121	10 T122	11 T123	12	13 T124
14 T125	15	16	17	18 T126	19	20
21 Solstice	22	23	24	25	26	27
28	29	30				

Fig. 17.2 Titan flybys in an earth-equivalent Saturn calendar. After a 6 year mission Cassini observations of Titan cover just the northern winter/southern summer season. Titan flybys are shown on earth-equivalent dates during the primary mission (*light green*) and the EM. (*dark green*). The proposed SM flybys (*yellow*) will go to summer solstice, equivalent to just half of an earth year. Voyager flybys occurred on earth-equivalent dates of March 23 and April 3

the identification of new objectives in the extended mission, the required geometries for the extended mission observations, the flybys that will achieve the new scientific goals, and the anticipated state of knowledge at the end of the extended mission. The final section addresses tasks and geometries remaining to be achieved in the Solstice Mission, a proposed extension of Cassini operation that goes out to 2017.

17.2 Interior Structure

There are only a few ways that Cassini can probe the deep interior of Titan. These are the gravitational field and the figure of Titan, and magnetic fields of internal origin. Results from the PM are covered in Chapter 4. At the end of the primary mission two fundamental questions regarding Titan's interior remain:

- Does Titan have an intrinsic or induced magnetic field?
- Does Titan have an internal liquid layer / ocean?

17.2.1 Internal Magnetic Field

Titan could have an intrinsic magnetic field due to internal dynamo currents or an induced time-varying magnetic field due to currents driven by Saturn's magnetic field: the energy source of a dynamo is located in the interior of the body, while an induced field is generated in response to the penetration of an external time-varying field into the moon's body, provided that its interior contains conducting elements. Observational evidence shows the presence of an induced field, but whether the conduction in Titan's ionosphere has a contribution from the conducting fluid in the interior is unknown (Backes et al. 2005). The first step is to determine whether an intrinsic field exists and what its contribution is, followed by observations that allow separation of an interior induced field from the ionosphere's induced field.

In the primary mission the closest Titan flybys were at an altitude of 950 km. The presence of Titan's ionosphere and the distance and geometries of the close flybys relative to the orientation of Saturn's magnetic field masked any signature of an intrinsic Titan field. Small fields of internal origin would be easiest to detect in spatial regions near Titan that are not reached by field lines of Saturn's magnetic field because of efficient shielding by high electric conductivity in Titan's ionosphere. It was thus a high priority to go lower than 900 km, below Titan's ionosphere, on one of the flybys in the EM. The induced field is produced most effectively when Titan is on the dawn side of Saturn because the corotation plasma carrying Saturn's field impacts Titan on the night side, thus to see the intrinsic field a dusk pass is preferred. Shielded regions occur on the dayside of Titan because photoionization is by far the most important mechanism of ionization, thus this low flyby needed to be a dayside pass in the dusk quadrant of Saturn's magnetosphere where the corotation plasma comes from the same direction as the extreme ultraviolet (EUV) flux from the sun. Figure 17.3 illustrates the desired dropoff in Saturn's B field below 900 km.

Flyby T70 has the desired geometry, is at an altitude of 880 km, and will be flown in an attitude that minimizes torque on the spacecraft. One of the reasons that primary mission flybys did not go lower than 950 km was due to concerns that the pressure of the atmosphere on the spacecraft would introduce a bias in the spacecraft attitude that the spacecraft thrusters could not overcome. This would result in loss of pointing control and if it lasted long enough would put the spacecraft in safe mode. The spacecraft attitude in T70 has been selected to be the most stable available relative to the atmospheric flow. The most important magnetometer and Langmuir probe data are not very sensitive to spacecraft orientation. Unfortunately however Cassini Plasma Spectrometer (CAPS), Magnetospheric Imaging Instrument (MIMI) and Ion and Neutral Mass Spectrometer (INMS) data will not be optimal.

17.2.2 Internal Ocean

To carry out a gravity science flyby the spacecraft High Gain Antenna is pointed to earth. The telecom link is maintained throughout the flyby in order to detect subtle changes in the Doppler shift that can be attributed to Titan's gravity field.

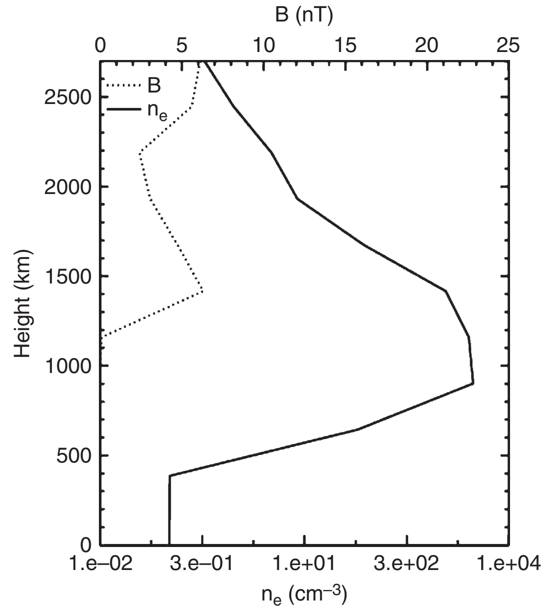

Fig. 17.3 Internal Dynamo or Induced Field. The ideal geometry for detection of an internal magnetic field requires a spacecraft dayside flyby altitude of <900 km, so that Saturn's magnetic field is blocked by Titan's ionosphere. In this plot B is the magnitude of Saturn's magnetic field, decreasing to zero as the number of electrons (n_e) in Titan's ionosphere increases. This figure was originally published by Heiko Backes (2004). Model computations assumed Saturn's plasma inflow along the positive x-axis under the solar conditions corresponding to flyby T34 of Cassini's primary mission. Incident plasma conditions were considered Voyager-like.

The Love number, k_2, is indicative of whether or not there is a layer of liquid in the interior decoupling the surface from the interior, although this result is model-dependent. The original plan in the primary mission to look for the existence of an internal liquid layer called for four flybys to measure the Love number k_2: two equatorial passes – one when Titan was at perikrone and one at apokrone, and two inclined passes – also at perikrone and apokrone. Changes in Titan's figure due to tidal and centrifugal forces would be most different and detectable between these geometries. The appropriate four primary mission flybys (T11, T22, T33 and T38) were allocated to Radio Science (RSS). Later it was found that the Deep Space Network (DSN) viewing conditions on earth for T38 were not adequate and T38 was reassigned to the Visible and Infrared Mapping Spectrometer (VIMS) for surface observations. In the extended mission it was a tour requirement to have a replacement for the T38 flyby. T45 has the required geometry, including the earth / DSN phasing needed. T68 is a backup in the event of problems at the DSN station.

A k_2 value of 0.04 is consistent with no liquid layer, while k_2 between 0.33 and 0.5, indicative of larger tidal deformation, corresponds to the presence of a liquid layer. (The exact value depends on the thickness of the ice crust over the liquid layer.) To be certain we can differentiate between the no-liquid-layer case and an internal ocean at the 2-sigma or 95%

level, the uncertainty in k_2 must be <0.1 (Rappaport et al. 2008). After three flybys in the primary mission the k_2 uncertainty of 0.2 precluded a definitive answer. One challenge to data interpretation was that the spacecraft experienced unanticipated torques due to Titan's atmosphere even at the relatively high 1400 km altitude of the T22 flyby. Another reason it has been so difficult to determine the value of k_2 may be that Titan's interior is not divided neatly into concentric shells, that the mass distribution in the interior is more complex (see Chapter 4). Simulations show that T45, the fourth flyby, will bring the uncertainty in k_2 down to 0.12, thus addressing the goal of determining the existence of a liquid layer (Rappaport et al. 2008).

In the meantime events have overtaken these EM plans. The mismatch of surface features from their predicted locations discovered in overlapping Radar swaths revealed that Titan is not rotating synchronously (Stiles et al. 2008). The discovery by the Radar team that Titan's obliquity is 0.3° and that the spin rate is slightly non-synchronous implies that an internal liquid layer is likely. Such a layer decouples the ice crust from the rest of the planet and thus makes it easier for exchange of angular momentum between the super-rotating atmosphere and the surface to change the observed rotation (Tokano and Neubauer 2005; Lorenz et al. 2008b). While the long-term average rotation is synchronous there are seasonal variations about that rate. Polar precession was also measured (Stiles et al. 2008) although libration was not included in the rotation solution. Data on surface positions after the equinox will be key in constraining libration and confirming model predictions of the coupling of the winds with the surface in response to the seasonal zonal wind changes.

17.3 Surface Science

As Cassini approached Saturn the only known surface feature on Titan was Xanadu (Smith et al. 1996). Now, at the culmination of the primary mission, we know that Titan has geology that rivals the complexity of earth. We now know that Titan has dunes, lakes of liquid ethane and methane, eroded drainage channels, craters, mountains and evidence for cryovolcanism (see Chapters 5 and 6). Maps show features, and features have names, evidence of the progress in exploration that has been made by the Cassini–Huygens mission.

17.3.1 Coverage and Resolution

One of the most important aspects of understanding a body's geologic evolution is surface coverage at an adequate resolution to see processes at work. Only the most general of planetary structures such as continents, basins, polar caps, or large craters can be studied with 10–100 km resolution. Below 10 km it becomes possible to identify regional provinces such as mountains, tectonic ridges, volcanic constructs and medium size craters. To identify geological features such as river channels, dunes, lakes, or cryovolcanic flow with certainty resolution better than 1 km is best. It is important to note that even though a surface feature may be quite large, its correct identification could require high resolution data. For example a channel might be identifiable in moderate resolution images, but to determine whether it is a tectonic rift or has been fluvially eroded requires high resolution. The peril of prematurely interpreting planetary evolution with incomplete surface coverage is well illustrated by the history of Mars exploration.

Three of Cassini's instruments are used to image the surface: Radar, the Imaging Science Subsystem (ISS) and VIMS. The lack of articulation on the Cassini spacecraft means that Radar data must be acquired separately from ISS and VIMS, which are bore sighted with respect to each other but orthogonal to the Radar. By the culmination of the primary mission Radar had achieved 22% coverage of the surface at 500 m resolution, as illustrated in Fig. 17.4a. Figure 17.4b shows the additional 8% surface coverage Radar will achieve by the end of the EM. The hazy atmosphere limits ISS resolution to ~1 km other than under ideal viewing conditions. Figure 17.5a illustrates ISS coverage and resolution at the end of the primary mission. As the sun moves toward the northern hemisphere higher northern latitudes will be imaged. Much additional coverage to be achieved in the EM is focused on filling in gaps, particularly on the trailing side (hemisphere centered on 270W longitude), and latitudes below ~40S before the equinox. It is difficult to get coverage of the leading (hemisphere centered on 90W longitude) and trailing sides of Titan on the asymptotes of ~equatorial flybys (i.e. approach and departure), because within 15° of these longitudes the spacecraft will be on a trajectory that will impact Saturn's rings. Furthermore, to get the closest approach at 90^0 or 270^0 longitude puts the spacecraft on an escape trajectory.

VIMS acquires only sparse high resolution coverage in the PM and EM, partially due to the limited number of flybys with adequate illumination at closest approach. Ideally the spacecraft should be at a phase angle <45° when it is within 50,000 km of the surface. Figure 17.6 shows range vs. phase angle for all the flybys in the EM and how few meet this criteria. It will be a Solstice Mission goal to design a tour with flybys that are at low phase angle near closest approach. Figure 17.7 illustrates the coverage and resolution VIMS will have achieved by the culmination of the PM and EM at better than 10 km resolution. VIMS has mapped about 60% of the surface at better than 20 km resolution.

a

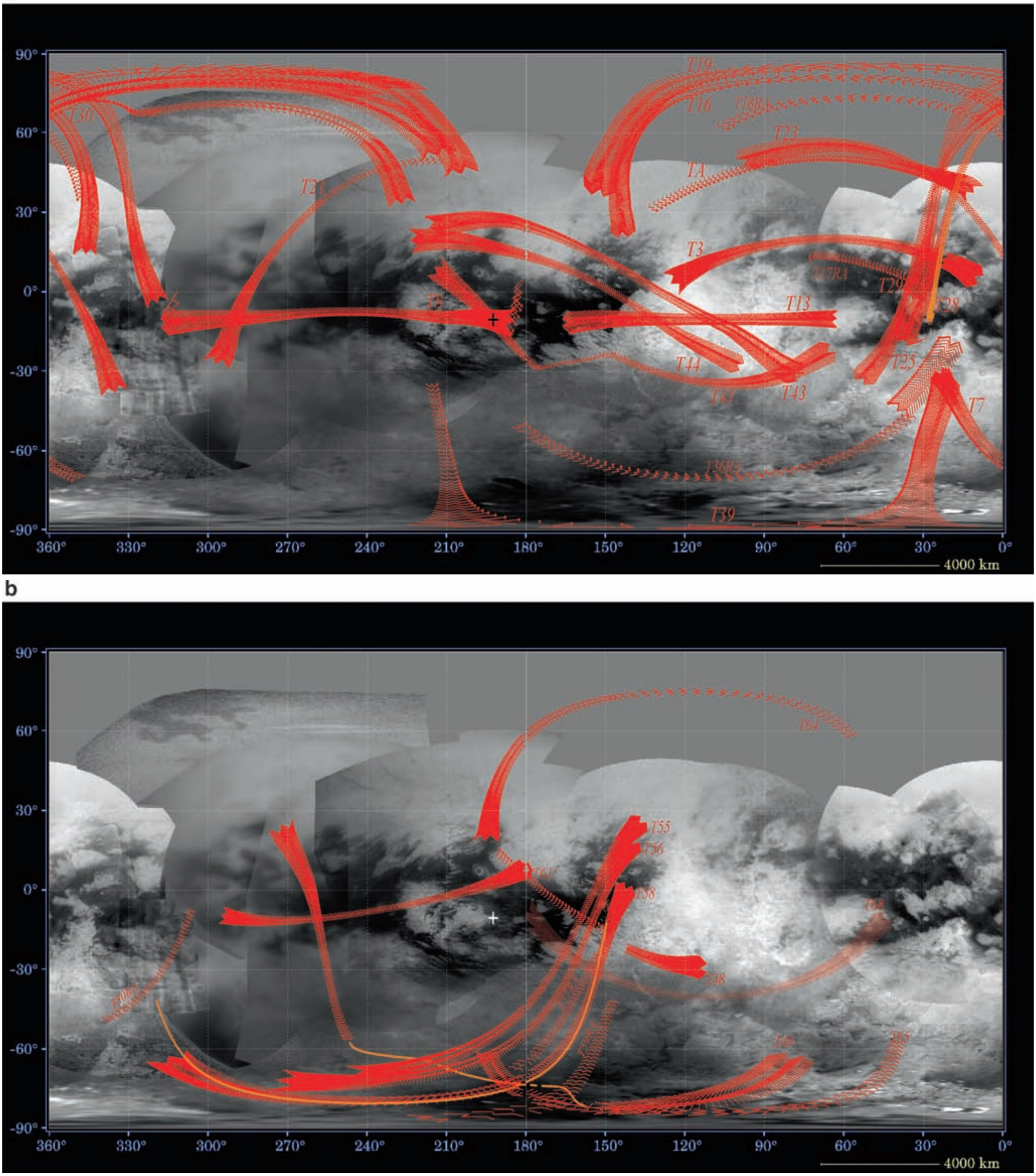

Fig. 17.4 Radar coverage in the PM and the EM. (**a**) High resolution (better than 500 m) Radar coverage in the primary mission was 22% of Titan's surface. The authors thank Yanhua Anderson and Ralph Lorenz for providing this figure. (**b**) Additional EM high resolution Radar coverage is 8% of Titan's surface.

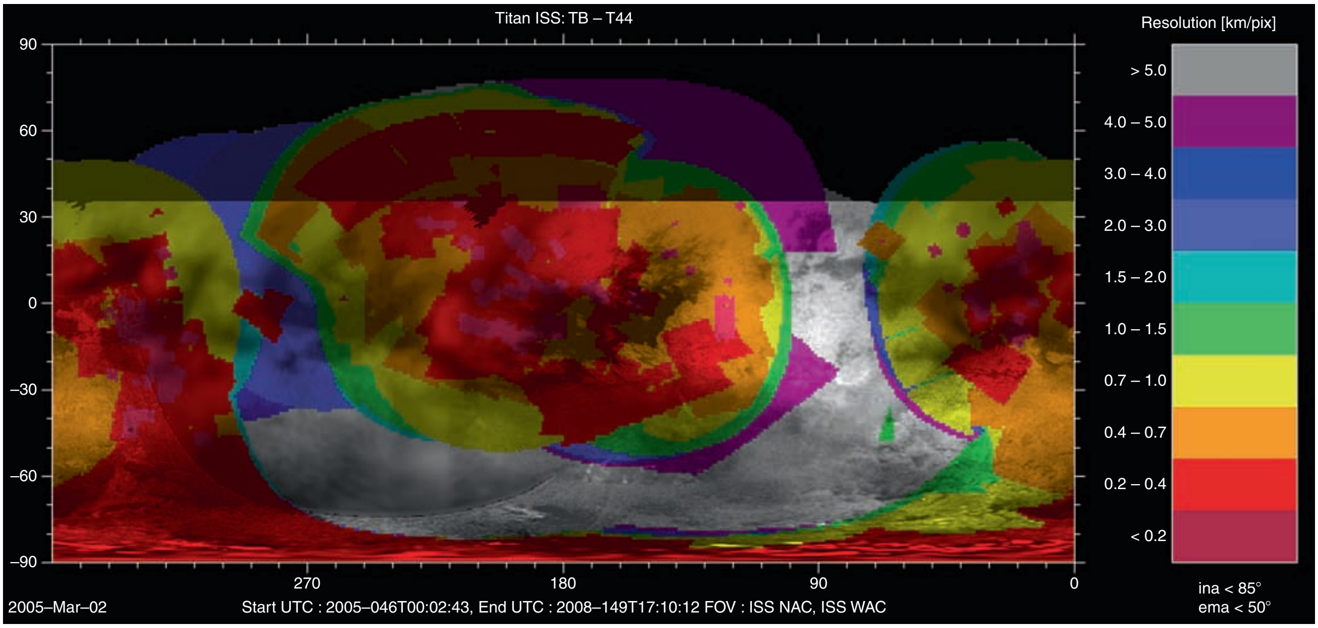

Fig. 17.5 ISS coverage and resolution in the primary mission. Acquiring coverage at leading (90W) and trailing (270W) longitudes and in the southern hemisphere are important goals for the EM, to fill in regions imaged only at low resolution in the PM. More northern hemisphere coverage will be acquired as the subsolar point moves north. Atmospheric haze limits ISS resolution to ~1 km even when the spatial scale is less than 1 km. The authors thank Elizabeth Turtle for providing this figure.

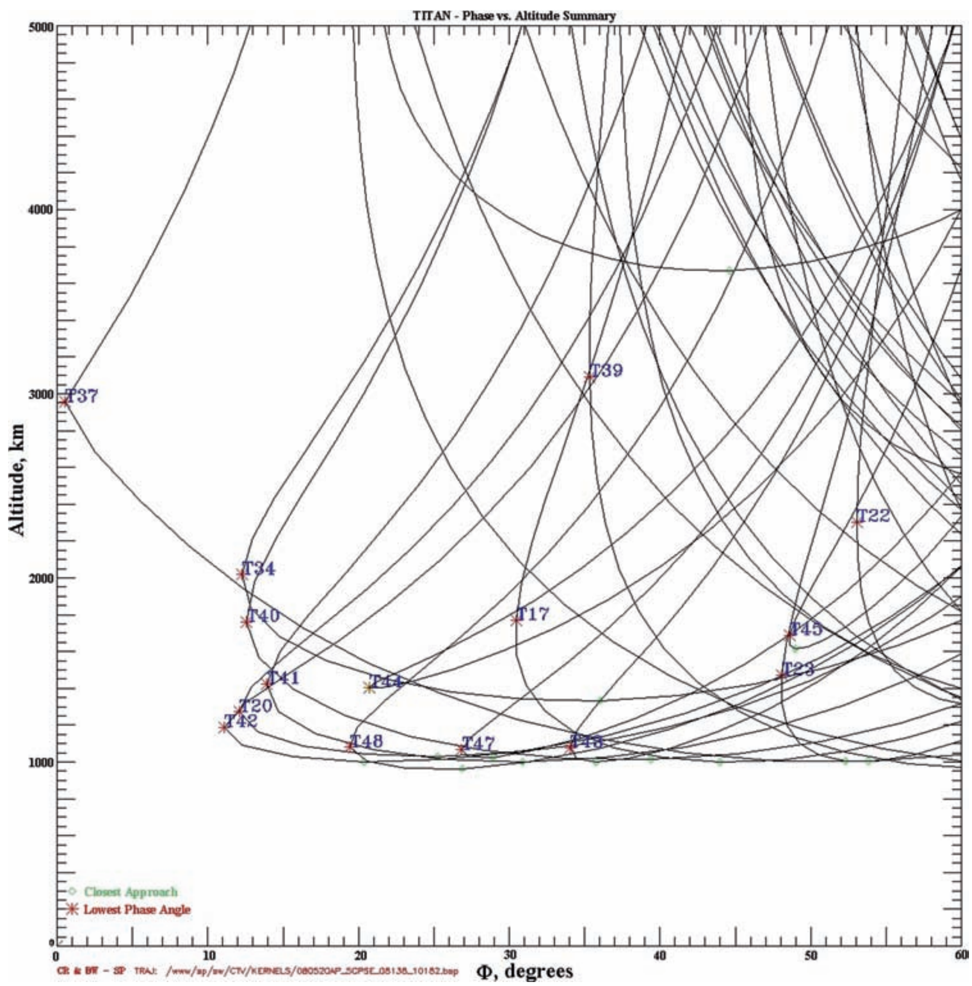

Fig. 17.6 Lighting conditions in the EM for composition measurements by VIMS. Ideal lighting conditions for VIMS are bounded by phase angles less than 45° at altitudes less than 5,000 km. The authors thank Chris Roumeliotis for providing this figure.

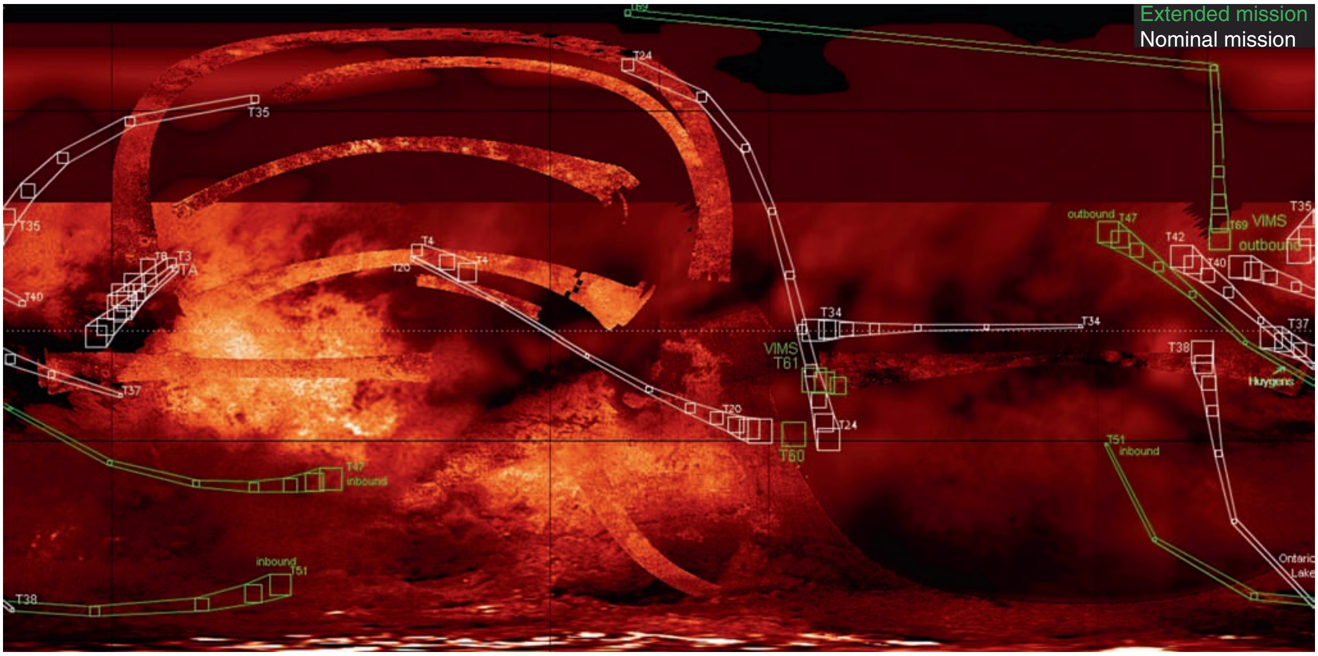

Fig. 17.7 VIMS coverage in the PM and EM at resolution better than 10 km. VIMS collects narrow swaths of data near closest approach, so it takes numerous flybys to build up high resolution coverage. This plot shows swaths collected at 5 km/pixel scale and higher, along with low resolution ISS near-global coverage and radar swaths. The authors thank Stephane Le Mouelic at the University of Nantes for providing this figure.

17.3.2 Targeted Scientific Investigations in the EM

EM scientific goals are directed at understanding processes identified in the PM, described in detail in Chapter 5. Table 17.3 lists specific targets for Titan flybys dedicated to surface scientific observations. In the EM we will continue to fill in coverage of Titan's surface at radar and optical wavelengths in order to:

- Map surface units, topography, stratigraphy – especially areas previously imaged only at low resolution; characterize latitudinal trends; Map surface composition.
- Investigate cryovolcanism; Look for changes that may be evidence of ongoing volcanic activity.
- Study eolian processes, dunes.
- Improve characterization of methane cycle timescales; Monitor seasonal change such as lakes filling and drying up.

17.3.2.1 Surface units

Major surface units identified in the primary mission by Cassini–Huygens are the ~equatorial dune fields (Lorenz et al. 2006; Radebaugh et al. 2008b), the lakes and lakebeds at high southern and northern latitudes (Stofan et al. 2007; Brown et al. 2008, Turtle et al. 2008), mountain chains (Radebaugh et al. 2008a) and relatively high terrain cut by fluvial channels draining into dark plains (Soderblom et al. 2007a; Barnes et al. 2007; Lorenz et al. 2008a). The small number of craters is consistent with a young surface modified by erosional and depositional processes (Porco et al. 2005). Tectonic activity is implied by Titan's young surface and chains of mountains, but a definitive picture of tectonic processes has not emerged from data collected in the PM. In the EM the T50 Radar swath crosses mountains identified in lower resolution VIMS data. Filling gaps in global coverage will complete the inventory of surface units and further the investigation of their latitudinal distribution, which also gives us insight into Titan's meteorology. T66 and T67 fill in major gaps in ISS and VIMS coverage on the trailing hemisphere southern and equatorial regions. Likewise, T55, T56, and T57 Radar swaths cross the southern trailing hemisphere.

17.3.2.2 Surface Composition

The powerful combination of VIMS and Radar data for interpretation of surface units has been amply illustrated (Chapter 6; Brown et al. 2006; Soderblom et al. 2007b). High resolution

Table 17.3 Targets of flybys assigned to surface science investigations

Flyby	Instrument(s)	Target coverage
T47	ISS, VIMS	Global- and regional-scale images of leading hemisphere, including Hotei Arcus, Huygens landing site
T48	Radar	Swath across Xanadu, Tui Regio
T49	Radar	Ontario Lacus (altimetry), SAR before (southern high latitudes) and after
T49	VIMS, ISS	South Xanadu, Hotei Arcus
T50	Radar	Possible mountains
T51	ISS, VIMS	High-resolution imaging of the south-polar region, including Ontario Lacus
T53	ISS, VIMS	Trailing hemisphere at high southern latitudes
T54	ISS, VIMS	High-resolution imaging of trailing hemisphere at high southern latitudes
T55	Radar	Southern hemisphere swath, cross Shangri-La dunes
T56	Radar	Southern hemisphere swath, cross Tortola Facula, then Shangri-La dunes
T57	Radar	Southern hemisphere, western edge of Xanadu
T58	Radar	Western edge of Xanadu, Ontario Lacus (SAR)
T60	Radar	Altimetry swath, Xanadu to south pole
T60	ISS, VIMS	High-resolution, low-phase-angle imaging of western Senkyo
T61	Radar	Near-equatorial swath covers Dilmun, Aderi, and Belet
T61	ISS, VIMS	Western Senkyo at low phase angles
T64	Radar	North polar swath over lakes – stereo and/or seasonal change
T65	Radar	Ontario Lacus (SAR)
T66	ISS, VIMS	Fill trailing hemisphere gap, south midlatitude
T67	ISS, VIMS	Fill trailing hemisphere gap, equatorial region
T69	ISS, VIMS	Best north polar coverage

Radar swaths identifying a specific terrain type (such as the dunes) are correlated with spectral types in the VIMS global data set, enabling global mapping of a variety of surface units (Barnes et al. 2007). The T47 ground track goes over the Huygens landing site at low phase angle. In situ data from the surface from the Huygens probe will be combined with VIMS data from above to develop an atmospheric scattering model. The model will then be applied globally to refine analysis of VIMS data. VIMS spectral data shows the presence of 9 major compositional units (Barnes et al. 2007) and with the improved atmospheric model more are certain to emerge.

Another method for acquiring surface composition data is through the Radio Science Subsystem (RSS) bistatic scattering measurements. The quasi-specular surface echo is observed by bouncing the radio signal from the spacecraft off Titan's surface to the earth. These measurements give the surface dielectric constant and with it constraints on the composition, along with surface roughness, at the location of the reflection. Results to-date are consistent in some of the locations probed with the presence of liquid hydrocarbons (Marouf et al. 2006). This observation will be carried out again on T46, T51 and T52.

17.3.2.3 Cryovolcanism

Titan's young surface age requires some mode of resurfacing to hide ancient craters. Cryovolcanism is a candidate surface modification process and its presence has been suggested by both Radar (Elachi et al. 2005) and VIMS (Sotin et al. 2005) data. The evidence is based largely on surface feature morphology and odd spectral characteristics. Lobate flows around Ganesa Macula are consistent with morphology expected from cryovolcanic activity (Lopes et al. 2007). Hotei Arcus seems to have changed its reflectivity twice over the course of the PM (Nelson et al. 2009) and Tui Regio is bright in the VIMS data in the 5 micron atmospheric spectral window (Barnes et al. 2006). Are spectral and morphological characteristics adequate to declare that cryovolcanism is in fact the responsible process? When did the cryovolcanism occur? Is it extant today? These are questions that will be addressed in the EM. One test is whether a feature appears cryovolcanic in both Radar and Optical Remote Sensing (ORS) data. For example, Tortola Facula was initially thought to be a cryovolcanic feature from VIMS data (Sotin et al. 2005), but Radar data shows nothing to support that interpretation. A Radar swath will cross Tui Regio on T48, one of the areas identified by VIMS as spectrally distinct. Definitive evidence of current cryovolcanism as compared to morphological data indicative of past volcanism could come from detection of changes on the surface. The T56 Radar swath will cross Tortola Facula again, to compare to T43 data. Hotei Arcus is targeted by VIMS and ISS on T47 and T49. Radar radiometry data has the potential to detect thermal anomalies.

17.3.2.4 Dunes

Wind is an important agent for landscape evolution on Titan, evidenced by the wide equatorial expanse of dunes

(Elachi et al. 2005; Lorenz et al. 2006; Barnes et al. 2008). Surface color from the multispectral data of VIMS allows us to extrapolate Radar dune identification to broad regions of Titan (Soderblom et al. 2007b). Questions remain: why does the orientation of the dunes defy expectations from models of low-latitude trade winds? What are the dunes composed of? Dunes are concentrated in the equatorial region – what does that tell us about the long-term meteorology of Titan and the distribution of methane humidity? More high resolution coverage will provide additional insight into dune origins from their morphologies and orientations. Radar swaths on T55 and T56 cross the Shangri-La dunes. The T61 Radar swath crosses the dunes of the Belet sand sea.

17.3.2.5 Lakes and river channels

Dark features with morphologies consistent with lakes were identified during the PM in high northern latitude Radar swaths (Stofan et al. 2007) and at high southern latitudes by ISS (McEwen et al. 2005). These features are quite likely to be lakes of liquid methane and/or ethane however other interpretations are possible. Features with similar morphology but that are Radar-bright are interpreted as dry lake-beds. A transitional class termed “granular” is also identified (Hayes et al. 2008). All three categories are identified so far only at high latitudes (above 55°). Lakes are darker and larger in size above 65N, which may be indicative of the presence of deeper liquid. Detection of seasonal change consistent with lakes evaporating as the season in the north turns to summer would allow us to definitively conclude that the lakes are indeed filled to varying levels with liquid. Surface permeability and the role of a subsurface alkanofer can also be studied by observing the long-term evolution of the lakes. Sparse coverage in the south as illumination wanes may limit our ability to document similar trends, however some evidence of changes in the south polar lakes has been detected (Turtle et al. 2009). Only one lake has been identified with certainty: Ontario Lacus. VIMS spectra of Ontario Lacus in the southern hemisphere show that it is filled with liquid ethane and methane (Brown et al. 2008). Seasonal control of the lakes is a model that has been proposed in order to explain the difference between the number of lakes in the south and north polar regions (Hayes et al. 2008).

In the EM it is urgent to get ISS and VIMS coverage of the south polar region while the surface is still illuminated, before the onset of the long winter night. The largest lake in the southern hemisphere, Ontario Lacus, will be the focus of four flybys. On T49 Radar will collect altimetry data across the lake. ISS and VIMS will image Ontario Lacus on T51. Radar SAR swaths will be collected on T58 and T65. Changes in size of the lake will refine seasonal models of precipitation and evaporation. In the northern hemisphere the Radar swath on T64 will be used to look for changes in the size of the lakes, which will bolster arguments that these are bodies of liquid. ISS will also continue to observe the northern lakes and seas, monitoring them for changes. VIMS will image the northern lakes in daylight for the first time on T69.

River channels are observed at all latitudes, not just in the polar regions (see Chapters 5 and 7). The distribution of channels and lakes suggests two different methane cycles – one in which lakes are filled by rainfall in the polar regions seasonally, and the other operative over a centuries-long timescale, capable of eroding channels but not of filling long-lasting lakes (Lunine and Atreya 2008). Observations of Titan’s surface will continue to yield key insights into Titan’s meteorology.

17.4 Atmospheric Investigations

Titan has a thick nitrogen atmosphere with dynamic meteorology and complex methane-based minor constituent chemistry. In the PM initial Cassini–Huygens results were focused on basic atmospheric structure and composition, then evolved to elucidation of dynamic processes as more data were acquired (see Chapters 7, 10, 12 and 13). Huygens returned in situ data including pressure, temperature, and composition during its descent to the surface (see Chapter 10) on January 14, 2005. Orbiter instruments probe Titan’s atmosphere remotely from the surface up to as high as 3,500 km. Above 950 km in situ instruments on Cassini collect data (described in Section 17.5). Figure 17.8 illustrates the approximate altitudes of Titan’s troposphere, stratosphere, mesosphere, thermosphere and exosphere (see Chapter 10 for a discussion of the uncertainties of these boundaries).

Atmospheric scientific objectives include study of

- Atmospheric properties from the surface to the exosphere
- Composition and chemistry; sources and sinks of minor constituents
- Titan’s weather – temperatures, global winds, precipitation and the methane cycle
- Aerosols – formation/destruction/influence on atmospheric properties

All of these are a function of time and space, so it is only with data acquired in numerous locations over a long time span that we can understand the whole dynamical picture, including seasonal changes as Titan goes through equinox, especially in the polar regions.

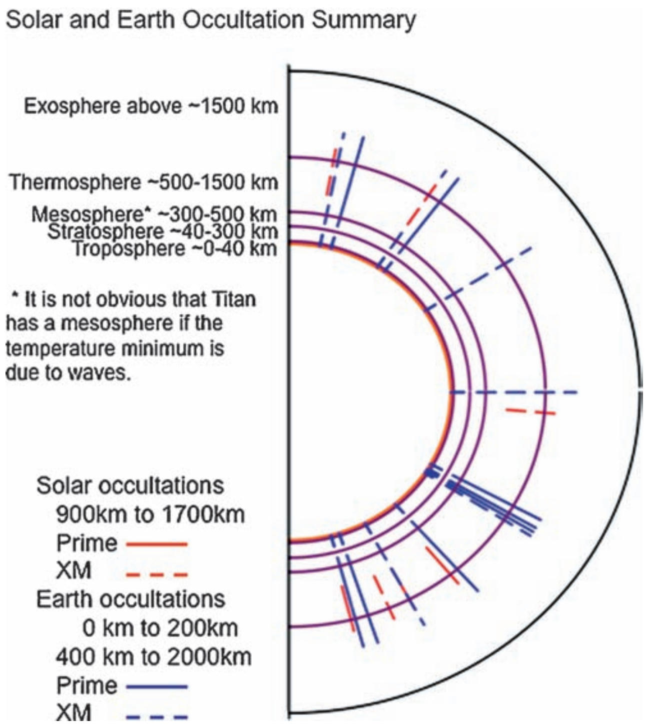

Fig. 17.8 Occultations of the sun and earth by Titan's atmosphere. Solid lines are occultations acquired in the PM, and dashed lines are occultations planned for the EM, listed in Table 17.4. Blue lines are occultations of the earth as seen from the spacecraft. The radio science signal probes from the surface to 200 km, then the ionosphere, from 400 km to 2000 km. Red lines are occultations of the sun by Titan's atmosphere as seen from the spacecraft, that probe from the surface with VIMS or 850 km altitude with UVIS, up to ~1,700 km. Altitudes of atmospheric regions (troposphere, stratosphere, etc.) vary with time and latitude and should not be used as rigorous definitions. Tracks of the sun and earth behind the atmosphere are not radial as depicted here. The authors thank Trina Ray for providing this figure.

17.4.1 Primary Mission Observations

Cassini observes Titan's atmosphere on every Titan flyby typically starting and ending at a range of ~300,000 km. On both the dayside and the nightside ORS instruments carry out scans across the limb and/or body, or point at one location to collect long integration data and monitor clouds. Within 2 h of closest approach the activities have more variety (and may be focused on other scientific discipline investigations such as surface mapping). Atmospheric investigations that may take place in these 4 h around closest approach include high resolution scans of the limb, and/or occultations of the earth, sun or stars. In situ atmospheric observations acquired at the spacecraft closest approach to Titan are discussed in Section 17.5.

The temperature and pressure from the surface up through the stratosphere is probed by the Radio Science Subsystem (RSS) using 3 wavelengths (S, X, and Ka band). The spacecraft sends radio waves to earth at these wavelengths, as the earth is occulted by the atmosphere of Titan. The signal received at the DSN is attenuated by Titan's atmosphere. The RSS measurement is sensitive to the neutral atmosphere from the surface to 200 km altitude, and to the ionosphere from 400 to 2000 km. Four occultations of the earth by Titan's atmosphere were observed during the PM in northern winter at 8 mid- and high-latitude locations: 74S, 69S, 53S, 34S, 33S, 31S, 53N, and 73N.

Cassini's Composite Infrared Spectrometer (CIRS) far infrared spectra are used to map temperatures and derive wind fields from the upper part of the troposphere through the stratosphere, to an altitude of ~400 km (Flasar et al. 2005; Achterberg et al. 2008). CIRS thermal emission spectra in the mid-infrared reveal the composition of the troposphere and stratosphere, including higher order hydrocarbons. Nitriles are enriched at latitudes above 60N, consistent with a confining circumpolar vortex and the downwelling of organic-rich air (Flasar et al. 2005). Temperature structure and composition together are used to derive atmospheric dynamics (e.g. Teanby et al. 2007).

The Ultraviolet Imaging Spectrograph (UVIS) observes ultraviolet light (1) reflected from the aerosols in Titan's atmosphere, (2) emitted from atomic and molecular species, and (3) spectrally absorbed during occultations of the sun and occultations of stars by Titan's atmosphere. Titan's reflectance spectrum is best fit with scattering from a combination of tholins and hydrocarbons (Ajello et al. 2008). At extreme ultraviolet wavelengths (EUV) UVIS detects nitrogen, CH_4 and other hydrocarbons from 850 to 3,500 km altitude with solar occultations. Observations of stellar occultations in the far ultraviolet (FUV) wavelength range determine abundance and vertical structure of aerosols, hydrocarbons, and N_2 through the range of 300 to 1,200 km (Shemansky et al. 2005).

VIMS observations of occultations of the sun by Titan's atmosphere yield the mixing ratio of CO, CH_4, CO_2, HCN and aerosols as a function of altitude. VIMS observations of thermal emission on the nightside of Titan enabled quantitative analysis of the behavior of CO in the atmosphere (Baines et al. 2006). ISS and VIMS mapped clouds in the troposphere (Griffith et al. 2006; Turtle et al. 2008). A cluster of convective clouds was imaged over the south pole in July 2004 (Porco et al. 2005). Mid-latitude clouds, particularly around 40S, have been imaged intermittently. Thin clouds are visible at 60N. VIMS observed a large cloud system in 2006 reaching from the north pole down to 62N (Barnes et al. 2006). ISS and VIMS have also imaged multiple high altitude haze layers in the stratosphere, with the most prominent at ~500 km altitude. Aerosols are re-distributed seasonally from one pole to the other, forming a polar hood. Nightside observations looking for lightning have not detected any (yet).

With these observations PM data have given us a picture of Titan's current meteorology. Most of the year solar forcing leads to a hemisphere-to-hemisphere Hadley cell, possibly with more earth-like symmetric equator-to-pole Hadley cells around equinox (see Chapter 13). Titan has a methane cycle similar to earth's hydrological cycle. The zonal wind field has been mapped and we have a global view of the distribution of minor species. The next step is to look at Titan's longer-term meteorology, seasonal changes, and implications for its climate on >1,000 year timescales.

17.4.2 Equinox Mission Scientific Investigations

In the EM the major scientific questions to be addressed are:

What are sources and sinks of higher order hydrocarbons?

How and when does the polar vortex form? Polar hood?

What is the process of aerosol formation?

What about rainfall? Will Cassini detect a methane rainstorm?

What changes in the clouds and weather take place as the season evolves?

The EM extends the temporal coverage of the primary mission to the beginning of spring. This is a time of change for the atmosphere as the dominant solar heating moves from the southern to the northern hemisphere. As in the primary mission every flyby in the EM begins and ends with remote sensing coverage. VIMS and ISS look for clouds and lightning. Near closest approach CIRS maps the thermal field and composition via limb scans. Occultations of the earth, sun and stars by Titan's atmosphere allow RSS, VIMS, and UVIS to probe the structure and vertical compositional profile of the atmosphere.

17.4.2.1 Atmospheric Structure and Distribution of Hydrocarbons

Occultations of the sun and the earth by Titan's atmosphere in the PM and EM are listed in Table 17.4. Stellar occultations in the PM and EM are listed in Table 17.5. Occultation altitudes and latitudes are illustrated in Figs. 17.8 (solar and earth) and 17.9 (stellar) for the PM and the EM. Occultations that occur at the same latitude at different times will provide data on seasonal change. CIRS high resolution limb scans will be acquired on T53, T54, T62, T66, T67, and T70.

Table 17.4 Occultations of the sun and earth by Titan's atmosphere in the PM and EM. Latitudes refer to sub-raypoint at minimum altitude. In the case of earth occultations and VIMS solar occultations this is at the surface. See Fig. 17.8

Flyby	Type	Ingress latitude	Egress latitude
Primary mission			
T12	Earth	29S	49S
T14	Earth	31S	32S
T27	Earth	72S	54N
T31	Earth	75S	75N
T10	Solar	62S	51S
T26	Solar	76S	Not observed
Equinox mission			
T46	Earth	33N	33S
T52	Earth	57N	0
T57	Earth	79N	Not observed
T53	Solar	60N	3S
T58	Solar	80N	Not observed
T62	Solar	10S	75S

Table 17.5 Occultations of stars by Titan's atmosphere in the PM and EM. The second column identifies the occultation path of the star that is illustrated in Fig. 17.9

Flyby	Occultation number in Fig. 17.9	Star	Latitude at minimum altitude (300 km)	Latitude at maximum altitude (1,200 km)
Tb	1	Alpha Virginis	51.1N	32.6N
Tb	2	Lambda Scorpii	36.0S	35.8S
T7	3	54 Alpha Pegasi	49.5N	50.9N
T13	4	Beta Orionis	17.7S	14.9S
T16	5	Alpha Virginis	71.5S	71.7S
T21	6	Alpha Eridani	35.9S	35.1S
T23	7	Eta Ursae Majoris	2.6S	8.8S
T35	8	Sigma Sagittarii	32.4S	35.0S
T40	9	Alpha Lyrae	54.3N	50.7N
T41	10	31 Eta Canis Majoris	48.2S	36.4S
T41	11	Epsilon Canis Majoris	9.0S	4.2S
T41	12	Epsilon Canis Majoris	28.7S	24.0S
T47	13	Eta Ursae Majoris	0.9N	0.7N
T47	14	Beta Canis Majoris	56.4N	53.6N
T48	15	Epsilon Canis Majoris	18.4N	20.1N
(distant)	16	Alpha Eridani	37.6N	35.0N
T53	17	Alpha Eridani	39.0N	37.8N
T56	18	Eta Ursae Majoris	45.1S	35.6S
T58	19	Eta Ursae Majoris	13.6S	6.1S
T70	20	Alpha Virginis	20.8S	31.0S

17.4.2.2 Clouds and Haze

In the EM we begin a distant Titan monitoring campaign that will continue throughout the rest of the Cassini mission. Low resolution data are sufficient to detect and locate clouds and large-scale haze structures. These observations provide isolated

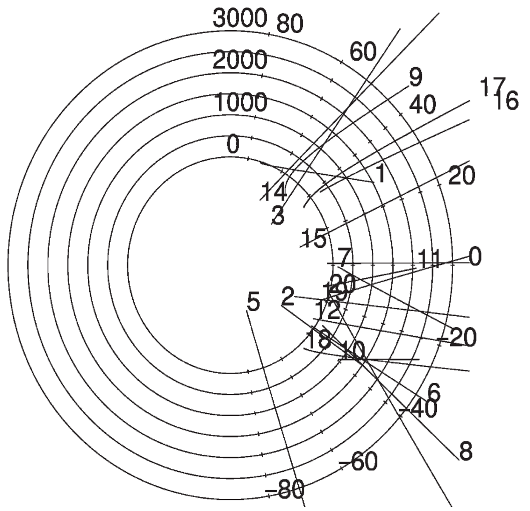

Fig. 17.9 Occultations of stars by Titan's atmosphere. Both PM and EM occultations of stars by Titan's atmosphere are shown, labeled with the number cross-referenced to Table 17.5. Altitudes are shown from 0 to 3,000 km and latitudes are labeled from +80 to −80. Occultations are rarely radial, as can be seen by the slanted track as various altitudes are crossed. The number labeling each occultation track is shown at the beginning of the track, thus differentiating between the ingress and the egress of the star, going behind or coming out from behind Titan's atmosphere, respectively. The authors thank Robert West for providing this figure.

snapshots, and are intended to improve our understanding of how often there are clouds on Titan, how quickly they appear and dissipate, where they're appearing as the seasons change, how fast and in what direction the winds blow, and also how the haze evolves with the season. These distant observations will be much more frequent than Titan flybys and will be more likely to detect sporadic cloud appearances. Ground based and Cassini observations have shown clouds changing over hours and days. Will we see a change in altitude of detached haze layer as the season changes? It was 150 km lower during Voyager observations (Rages and Pollack 1983; Porco et al. 2005). As discussed in Chapter 14, the nominal mission took place in a period of relatively slow change. The Hubble Space Telescope record of the late 1990s however shows that changes in the haze will be more rapid in the years following equinox, as the pole-to-pole Hadley circulation reverses (Lorenz et al 2004). The evolution of the UV-dark north polar hood will be observed – the Hubble record showed that the south polar hood decayed rapidly after the southern summer solstice.

17.4.2.3 Atmospheric Dynamics

Zonal winds are inferred from the temperature fields observed by CIRS (see Chapter 13). Changes in the winter polar vortex will be observed in the EM. Subsidence in the winter enhances the concentration of organics. At what point does this process begin to reverse? What is the time scale for the atmosphere to go from a single pole-to-pole Hadley cell to two hemispheric Hadley cells back to a single pole-to-pole (reversed in direction) Hadley cell? Global Circulation Models have been developed (Tokano 2008), and will be tested against Cassini data.

17.5 Titan's Thermosphere and Ionosphere, and the Interaction of Titan's Upper Atmosphere with Saturn's Magnetosphere

Titan has a weak magnetic field induced as a result of Saturn's magnetospheric plasma and energetic particles interacting directly with Titan's upper atmosphere and ionosphere. Exceptions can occur when Titan's orbit is near local solar noon where under conditions of strong solar wind dynamic pressure Titan's atmosphere can interact directly with the solar wind or Saturn's magnetosheath. Since at Titan's orbit at 20 Rs the magnetic field of Saturn is relatively weak and the gyroradii of the interaction of the magnetospheric ions can be of the order of the radius of Titan (depending on ion mass and plasma flow speed), a very asymmetric interaction is created where ions flow into Titan at Titan longitudes on the Saturn facing flank and away from Titan on the interaction flank away from Saturn. The interaction results in energy deposition in Titan's upper atmosphere from magnetospheric plasma and energetic ions that depend on Titan's longitude and Titan's position in its orbit. The orbital position is especially important in defining the energetic ion input due to the asymmetry with respect to solar local time that exists in Saturn's current sheet. For a more complete illustration of this interaction see Fig. 17.10.

Although the heating of the thermosphere is predominantly due to solar extreme ultraviolet and x-ray radiation, the magnetospheric interaction provides an appreciable, and not yet well-determined amount of energy to the upper atmosphere. Furthermore, molecular hydrogen, methane, and molecular nitrogen escape from the upper atmosphere. Jean's escape dominates the loss of molecular hydrogen from the atmosphere whereas molecular nitrogen and methane are primarily lost by the heating of the upper atmosphere from the magnetospheric interaction (via sputtering processes, and if ionized by ion pickup). See Chapters 15 and 16 for further discussion and references. The complex interaction geometries and the dimensionality of the parameter space that must be sampled require a large number of flybys under varying positions and conditions in order to fully characterize the interaction (see Figs. 17.11 and 17.12).

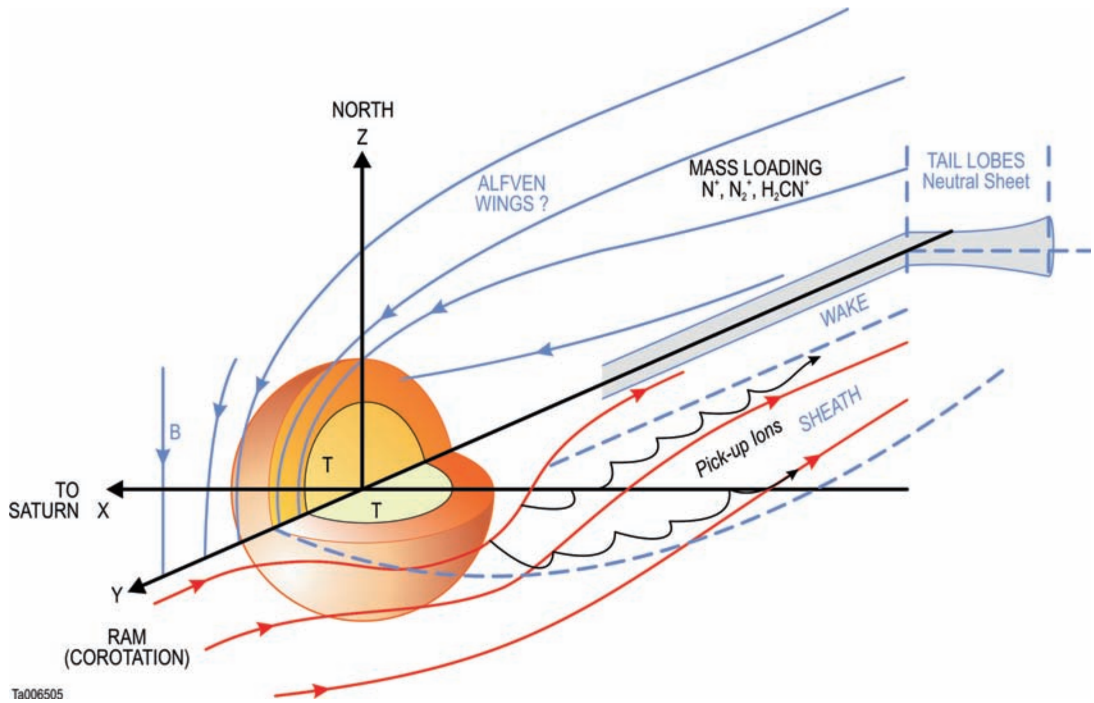

Fig. 17.10 This figure illustrates in three dimensions the interaction of Titan with Saturn's magnetosphere. The effects of the large gyroradius of the interacting ions, as compared to the size of Titan, are illustrated by the cycloidal motion of the particles. The gyroradius is schematic and can range from several Titan radii to relatively small sizes depending on ion mass and the flow speed of the underlying plasma. The rotation of Titan is in the opposite direction of ram since Saturn's spin rate is much faster than Titan's rotation.

17.5.1 Primary Mission Achievements

The basic upper atmosphere structure (see Chapter 10) and magnetospheric interaction have been characterized in the primary mission. The deposition of energy in the upper atmosphere and the resulting escape of the atmosphere (Chapter 16) have been characterized in several geometries and under a sparce set of conditions, including at least one instance of Titan being encountered by Cassini while Titan was in Saturn's magnetosheath (T32).

Four very interesting results emerge from the data available from the primary mission that require further investigation: (1) the discovery of the chemical complexity of the upper atmosphere – organic poly-aromatic compounds and associated ions having measurable densities with masses exceeding 300 Da, and most surprisingly negative ions with masses that exceed 10,000 Daltons – larger than an insulin molecule (see Chapter 8), (2) the large influx of energetic ions that deposits energy deep within Titan's atmosphere, (3) the large influx of oxygen-rich plasma from Saturn's magnetosphere, and (4) the unexpected orientation of the induced magnetic field produced by the interaction of Titan with Saturn's magnetosphere. All of these processes can produce significant effects on the chemistry and composition of the atmosphere – the significance of which is determined by the amount of energy and oxygen that is input. This input varies considerably temporally and spatially. Due to the comparable scale lengths of the ions and the radius of Titan the spatial variation is quite complicated so the EM must explore all longitudes of the interaction region at all positions of Titan within its orbit – a tall bill to fill.

17.5.2 EM Major Scientific Goals

The four important findings from the PM, described in the previous paragraph, will be the focus of EM investigations. The best spacecraft orientation for sampling the upper atmosphere has INMS pointed in the ram direction. At closest approach this can be achieved with either Radar or ORS pointed at Titan, however this compatible geometry only lasts for a few minutes. "Full" flybys leave INMS pointed in the ram direction throughout the +/−15 min around closest approach. "Half" flybys orient the INMS in the ram direction either on approach or departure. Typical altitudes at closest approach range from 950 to 1,400 km. Figure 17.13 illustrates the parameter space covered in local time, latitude, and sector of Saturn's magnetosphere on each of the INMS flybys in the PM and EM.

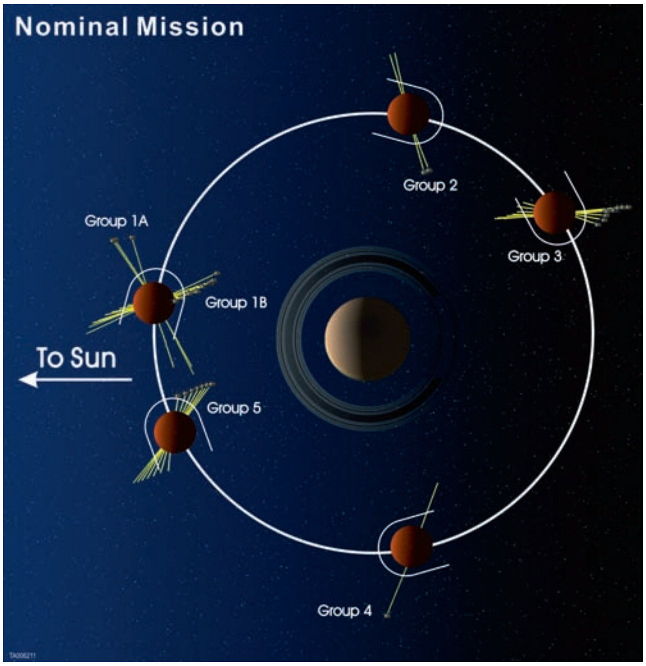

Fig. 17.11 Titan's interaction with Saturn's magnetosphere and the solar wind during Cassini's Primary Mission. This figure illustrates Cassini flybys of Titan for passes with closest approach altitudes below 1,500 km during the Primary (Nominal) Mission tour. Due to geometric constraints governed by orbital mechanics, these flybys fall into distinct groups. The average position of the groups is depicted by Titan, where the actual position of Titan during each flyby is within approximately +/– 3° in Saturn longitude (inside the radius of the Titan images depicted as the group average). Groups 1A, 1B and 5 are on Saturn's dayside, and experience the highest level of solar wind interaction. Groups 2, 3 and 4 are on the dawn, night and dusk side respectively. The yellow lines show the trajectory of Cassini for each of the flybys, with the gray dots showing the outbound leg. The white arc around Titan represents the bow shock of the interaction between Saturn's magnetosphere and Titan's atmosphere. The authors thank Greg Fletcher for providing this figure. Group 1A – Ta, Tb and T8. Group 1B – T35, T36, T37, T38, T39, T40, T41, T42, T43 and T44. Group 2 – T5 and T7. Group 3 – T16, T17, T18, T19, T20, T21, T22, T23 and T24. Group 4 – T34. Group 5 – T25, T26, T27, T28, T29, T30, T31, and T32.

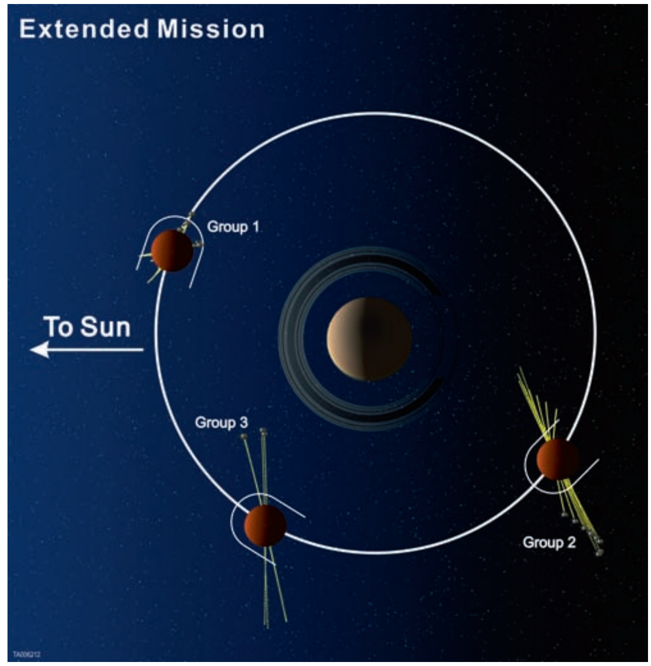

Fig. 17.12 Titan's interaction with Saturn's magnetosphere and the solar wind during Cassini's Equinox Mission. This figure illustrates Cassini flybys of Titan for passes with closest approach altitudes below 1,500 km during the Equinox Mission. Due to geometric constraints governed by orbital mechanics, these flybys fall into distinct groups. The average position of the groups is depicted by Titan, where the actual position of Titan during each flyby is within approximately +/– 3° in Saturn longitude (inside the radius of the Titan images depicted as the group average). Groups 1 and 3 are on Saturn's dayside, and experience the highest level of solar wind interaction. Group 2 is on the night/dusk side. The yellow lines show the trajectory of Cassini for each of the flybys, with the gray dots showing the outbound leg. The white arc around Titan represents the bow shock of the interaction between Saturn's magnetosphere and Titan's atmosphere. The authors thank Greg Fletcher for providing this figure. Group 1 – T45, T46, T46, T47, T48, T49, T50 and T51. Group 2 – T52, T53, T54, T55, T56, T57, T58, T59, T60, T61, T62 and T67. Group 3 – T63, T64, T65, T66, T67, T68, T69, T70.

17.5.2.1 Complex Organic Formation in Titan's Upper Atmosphere

EM goals are to (a) disentangle effects of solar, magnetospheric and wave forcing on trace constituents; (b) study upper atmosphere chemistry, tholin formation; and (c) investigate complex ion composition. CAPS and INMS will have evaluated the latitude and altitude dependence of the complex ion and neutral formation process by the end of the EM. There will also be one opportunity to view seasonal variation at northern high latitudes. A first order understanding of the contribution of energetic ion precipitation to the macromolecule formation process is also anticipated.

Planned INMS and CAPS flybys

(a) Full flybys: T48, T50, T57, T59
(b) Half flybys: T51, T64, T65
(c) Coverage for several minutes at closest approach: T38, T44, T47, T49, T55, T56, T60, T61

17.5.2.2 Energetic Ion Precipitation

The key objective for the EM is to understand effects associated with the position of Titan within the current sheet and how the Saturn solar local time of the orbit affects the process. MIMI will characterize the energetic ion and electron environment of Titan to first order, and conduct correlative investigations of the energetic particle input to the upper

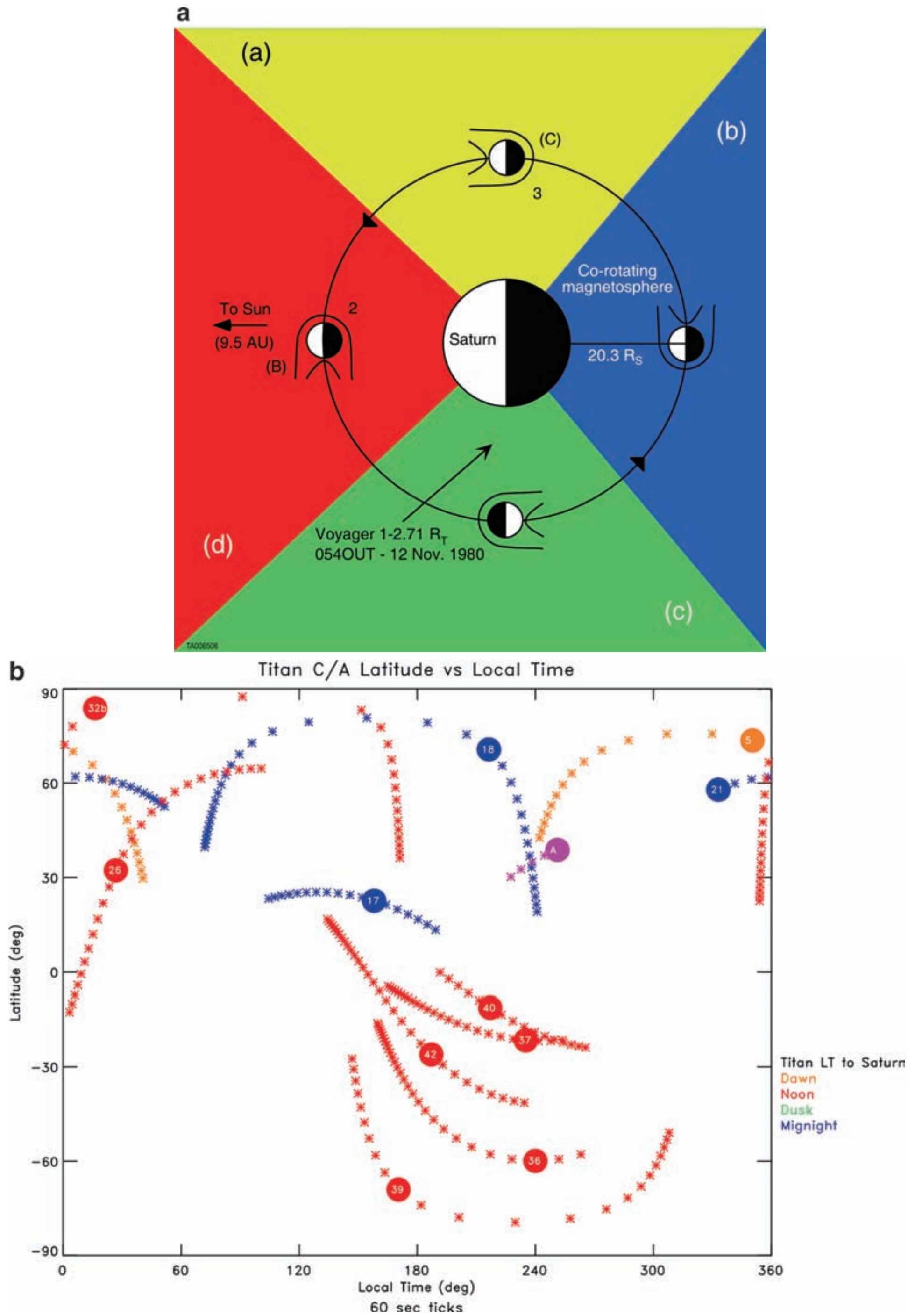

Fig. 17.13 Coverage of all sectors of the magnetosphere, latitude and local time are plotted for each INMS flyby. The authors thank Greg Fletcher for providing these figures. (**a**) Sectors of Saturn's magnetosphere referenced in 17.13b and 17.13c. (**b**) Primary mission INMS flybys' locations in Titan latitude vs. local time.

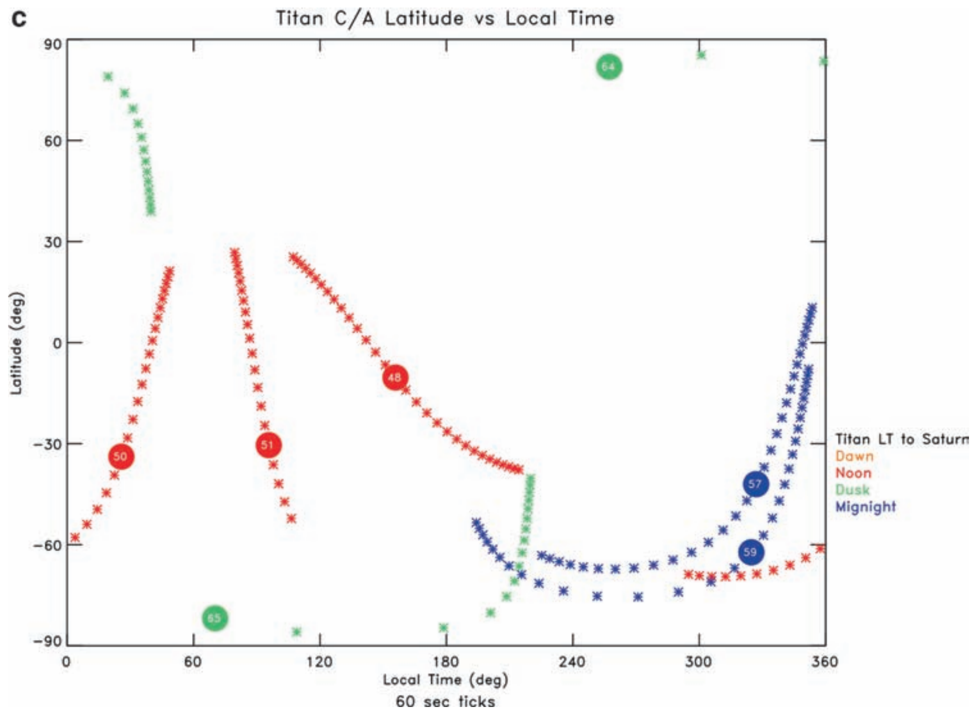

Fig. 17.13 (**c**) Extended mission INMS flybys' locations in Titan latitude vs. local time.

atmosphere and ionosphere with INMS measurements of the atmospheric chemistry and ionosphere, radio occultation data which probes the ionosphere, and CAPS measurements of the heavy negative-ion population in the upper atmosphere with a particular focus on the secondary ionospheric peak below 1,000 km altitude, and its dependence on the intensity of energetic ions and electrons. We also expect to complete our investigation of the outer reaches of Titan's exosphere, since the creation of energetic neutral atoms through charge exchange with the exospheric neutrals is a more sensitive probe of those neutrals than any other technique on the Cassini spacecraft.

Planned Magnetosphere and Plasma Science (MAPS) flybys:

T63 – dedicated to CAPS for wake passage

T65 – close downstream encounter at dusk

T68 – close downstream encounter at dusk

T70 – "Go Low" flyby for MAG to investigate induced magnetic field

17.5.2.3 Oxygen Plasma Injection into Atmosphere

In the EM we want to (a) understand effects associated with the Saturn solar local time of the orbit, and (b) sample different magnetospheric ram angles at closest approach to Titan. CAPS will assess the input of ram oxygen-rich plasmas into the nose of the interaction region and correlate this with the INMS ion and neutral composition. Planned MAPS flybys are the same as listed above.

17.5.2.4 Geometry of the Induced Magnetic Field

MAG will obtain a more accurate upper limit on Titan's weak intrinsic magnetic field as compared to the Voyager 1 magnetometer measurements (Neubauer et al. 1984) and, if there is indeed an intrinsic field, investigate its origin. With an unprecedented closest approach altitude of 880 km, we shall try to answer these questions with data from Cassini's T70 flyby. Once the intrinsic permanent field is measured, we will be able to measure any extra contribution resulting from the magnetic induction linked to the presence of conducting elements in Titan's crust and interior. Unfortunately the geometry of the Cassini encounters during the extended mission is not ideal for these studies, but hopefully flybys in the early morning sector of Saturn's magnetosphere will help answer this question.

MAG will also constrain the region downstream from Titan where its plasma escapes as a consequence of its interaction with Saturn's magnetosphere. Flybys like T9 (Barnes et al. 2007 and others within the T9 special issue of GRL, volume 34 2007) provided us with a picture of the extent of Titan's magnetotail and the way in which charged particles from Titan escape along the draped magnetic field lines, but more detailed magnetic field and plasma observations are needed beyond three Titan radii downstream from the moon. During the EM, the T63 flyby will give us the opportunity to do that. The study of Titan's flow side induced magnetosphere and the pressure balance between the magnetic barrier and the collisional ionosphere will tell us about how easily the external field from Saturn penetrates Titan's atmosphere and gives origin to an induced field with a very asymmetric geometry.

To investigate the geometry of the induced magnetic field in the EM the approach is likewise to (a) understand effects associated with the Saturn solar local time of the orbit and (b) sample different magnetospheric ram angles at closest approach to Titan. Planned MAPs flybys are the same as listed above.

17.6 The Solstice Mission

The Cassini spacecraft will have a substantial amount of fuel at the end of the EM. Planetary protection requires the disposal of the spacecraft at the end of its mission to prevent any contamination of Enceladus and/or Titan. In between the end of the EM and the end-of-mission (EOM) disposal of the spacecraft, the Project has proposed an extended scientific phase termed the "Cassini Solstice Mission". The Solstice Mission (SM) will extend from the end of the EM in July 2010 through the Saturn solstice on May 23, 2017, and then enter into an end-of-life Juno-like set of high inclination proximal orbits culminating with the spacecraft entering into Saturn's atmosphere.

The advantages of observing Titan through half of its year, illustrated in Fig. 17.14, are significant for understanding the yearly meteorological cycle, as discussed in Chapter 14. Weather and winds change seasonally in response to changes in insolation. The methane cycle can be monitored both in the atmosphere, and as evidenced by changes in liquid level in the lakes. Furthermore, doubling the length of time over which Cassini observes Titan increases the probability of identifying changes due to other geologic processes, e.g. aeolian modification, fluvial erosion, or cryovolcanism. Higher order hydrocarbon distribution in Titan's atmosphere is known to change seasonally as evidenced by overall brightness changes in the atmosphere and polar hood, and the Cassini Solstice Mission will be able to observe this process.

There are 56 Titan flybys in the 7-year SM, as shown in Fig. 17.2. There will be more opportunities to continue to fill in surface coverage at high resolution and to react to discoveries made in the PM and EM. The SM also provides the chance to achieve trajectory geometries that eluded the PM and EM, the prime example of which is low phase angle illumination at closest approach. Overall the EM tour does not provide good illumination for VIMS and ISS. Most flybys are "dark", with high phase angles at closest approach. This situation is remedied in the proposed SM.

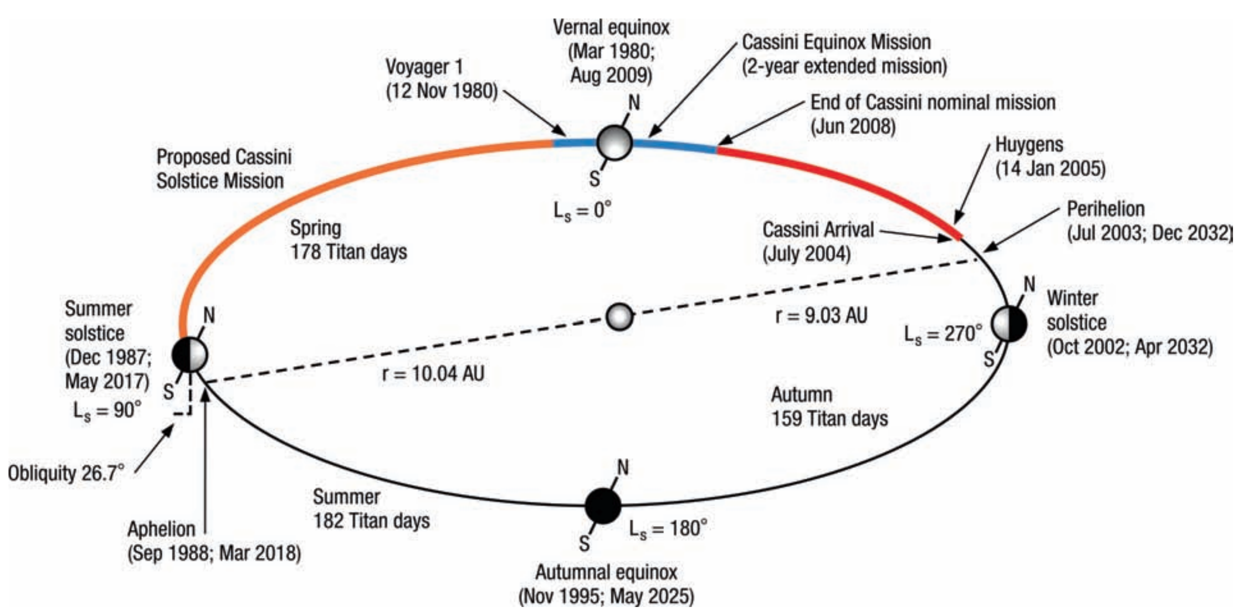

Fig. 17.14 Solstice mission. A Saturn year is 29.47 earth years. The entire primary, equinox, and solstice phases of the Cassini mission cover just half of a Saturn/Titan year. The authors thank Ralph Lorenz for providing this figure.

Specific SM Titan scientific objectives are to:

- Observe seasonal changes in the methane/hydrocarbon cycle of lakes, clouds, aerosols, and their seasonal transport.
- Observe seasonal changes in the high latitude atmosphere (specifically the temperature structure and formation and breakup of the winter polar vortex).
- Characterize changes in surface temperature.
- Observe Titan's plasma interaction as it goes from south to north of Saturn's solar-wind-warped magnetodisk from one solstice to the next.
- Determine inner and crustal structure; liquid mantle, crustal mass distribution, rotational state of the surface with time, investigate icy shell topography and viscosity.
- Further characterize the types, composition, distribution, and ages of surface units and materials, most notably lakes (i.e. filled vs. dry, depth; liquid vs. solid, composition; polar vs lake basin origin).
- Resolve current inconsistencies in atmospheric density measurements in which different techniques have yielded different results. Accurate density data are critical for any future Titan mission that uses the atmosphere for aerobraking or aerocapture.

Interior Structure. The mismatch of surface features in Radar data has been attributed to nonsynchronous rotation, arguing for the presence of an interior liquid layer (allowing slippage of the crust) and for seasonal variation in zonal winds. The nonsynchroneity during the nominal mission acted in the opposite sense to the polar precession, yielding a net drift in apparent longitude that is quite small. However if the Tokano and Neubauer (2005) zonal wind model is correct, during the EM the drift will become rather rapid as these two effects will add together as shown in Chapter 4. Such an acceleration would be convincing support of both seasonal changes in atmospheric angular momentum and of a thin ice crust decoupled from the interior. The additional data acquired during the EM may also allow higher-order changes in rotation state (such as libration) to be detected.

Surface Science. The polar regions are particularly interesting as they are the sites likely to change the most. Titan investigators have requested that the SM tour design include at least two polar excursions (preferably three) with as many Titan flybys as possible.

Atmospheric Investigations. Occultations of the earth, sun and stars by Titan's atmosphere, distributed in latitude but heavily weighted to the high latitudes, will elucidate changes in temperature, haze, and trace constituents in the atmosphere. CIRS will continue to map winds and hydrocarbon transport as the season progresses. A brand new observation will take place to resolve the ongoing discrepancy between INMS and AACS determinations of the atmospheric density at 950 km altitude, which currently differ by a factor of three. One of the SM flybys will be assigned to the navigation team and will be flown to an altitude of 950 km with Cassini's HGA pointed to earth to maintain radio contact through the time that the spacecraft is in the atmosphere. The navigation team will measure the effect on the trajectory that results from atmospheric drag on the spacecraft, enabling a third derivation of density.

Thermosphere/Magnetosphere interaction. In the SM MAPS measurements will benefit from a good mix of Titan flybys relative to Saturn's magnetic field, including several dayside (upstream) dusk flybys, and to be near dawn at solstice. Another mid-tail crossing and another low altitude flyby like T70 for MAG at dawn (vs. dusk) would be very useful to continue to refine internal and induced field measurements.

In addition to achieving basic Titan scientific goals, an over-arching consideration for all SM decisions will be to leave a legacy of data that are important for planning the next Titan mission. Table 17.6 shows the tentative plan for the

Table 17.6 Titan flybys in the Solstice Mission. Prime instruments and major science emphasis have been selected for the hours around closest approach

Flyby	Altitude (km)	Prime instruments	Science emphasis
T71	1,005	CAPS, INMS, RADAR	Mid southern latitude dawn side pass
T72	8,124	CIRS, VIMS, ISS	New surface territory, highest southern latitude
T73	7,921	CAPS, CIRS	Composition, aerosols, thermal map
T74	3,640	CAPS	Upstream pass
T75	9,996	CAPS	Wake crossing
T76	1,862	CIRS, VIMS	Belet sand sea
T77	1,383	RADAR	Xanadu
T78	5,941	CIRS, VIMS, UVIS, CAPS	Composition, aerosols, southern vortex, wake crossing
T79	3,763	CAPS	Excellent upstream pass
T80	29,331	ISS	Mid / high southern trailing hemisphere
T81	31,172	ISS	High southern leading hemisphere and Ontario Lacus on terminator
T82	3,844	CIRS	Composition, aerosols, thermal map

Table 17.6 (continued)

Flyby	Altitude (km)	Prime instruments	Science emphasis
T83	990	INMS, RADAR	Northern lakes change detection
T84	990	RADAR, INMS	Global shape
T85	990	CIRS, VIMS	Northern lakes
T86	990	CIRS, INMS	Northern lakes
T87	990	INMS, NAV	Atmospheric density
T88	1,164	CIRS, VIMS	Temperature at equator
T89	1,500	RSS, CAPS	Gravity field, flank encounter
T90	1,302	CIRS, VIMS	Tui Regio, Xanadu
T91	990	RADAR, CAPS	Global shape, altimetry, stereo of small northern lakes
T92	990	RADAR, INMS, VIMS	Stereo (with T91)
T93	990	ISS, VIMS	High northern leading latitudes, Ontario Lacus outbound
T94	990	VIMS, ISS, CIRS	High northern lakes composition
T95	990	ISS, RADAR, INMS	High northern lakes coverage
T96	990	ISS, VIMS, CIRS	High northern lakes, western Xanadu
T97	3,087	VIMS, CIRS	Dunes
T98	2,500	RADAR	Ontario Lacus change detection
T99	1,612	RSS, CAPS	Gravity field
T100	990	CIRS, VIMS, INMS	Atmospheric structure
T101	2,515	RSS	Occultation at high latitude for polar vortex, bistatic for surface properties
T102	3,288	RSS	Occultation at high latitude for polar vortex, bistatic for surface properties
T103	4,810	UVIS	Solar occultation at high latitude for polar vortex, stellar occ near equator
T104	990	INMS, RADAR, ISS	Southern edge of Kraken Mare
T105	990	VIMS, CIRS	Kraken Mare composition
T106	990	RSS	Bistatic for Kraken Mare properties
T107	990	INMS, NAV	Atmospheric density
T108	990	RADAR, INMS	Southern edge of Ligela
T109	1,200	VIMS, CIRS	Punga Mare, Sinlap
T110	2,270	VIMS, CIRS	Northern lakes composition
T111	2,722	VIMS, CIRS	Xanadu
T112	10,964	CIRS	Composition, aerosols, thermal map
T113	1,036	MAG	Intrinsic magnetic field
T114	11,907	ISS, CIRS	Hotei, Xanadu
T115	3,830	CIRS	Composition, aerosols, thermal map
T116	990	UVIS, VIMS	Solar occultation
T117	990	RSS	Occultation for seasonal variation
T118	990	UVIS, INMS	Atmospheric density
T119	990	Not assigned	
T120	990	CIRS, RADAR, INMS	Small southern lakes, global shape
T121	990	VIMS, RADAR	Tui Regio, Hotei
T122	1,679	RSS	Gravity field
T123	1,766	VIMS, CIRS	Hotei
T124	1,585	RSS	Bistatic for northern lake properties
T125	3,197	ISS, VIMS, CIRS	Hotei
T126	990	INMS, RADAR	Northern lakes change detection

Titan flybys in the SM. Developing a model of temporal changes in the structure of the atmosphere will be key to designing and flying future aerial craft such as balloons. The SM will allow us to quantify the lifetime of lakes for future missions that may send probes to land on or in the lakes.

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