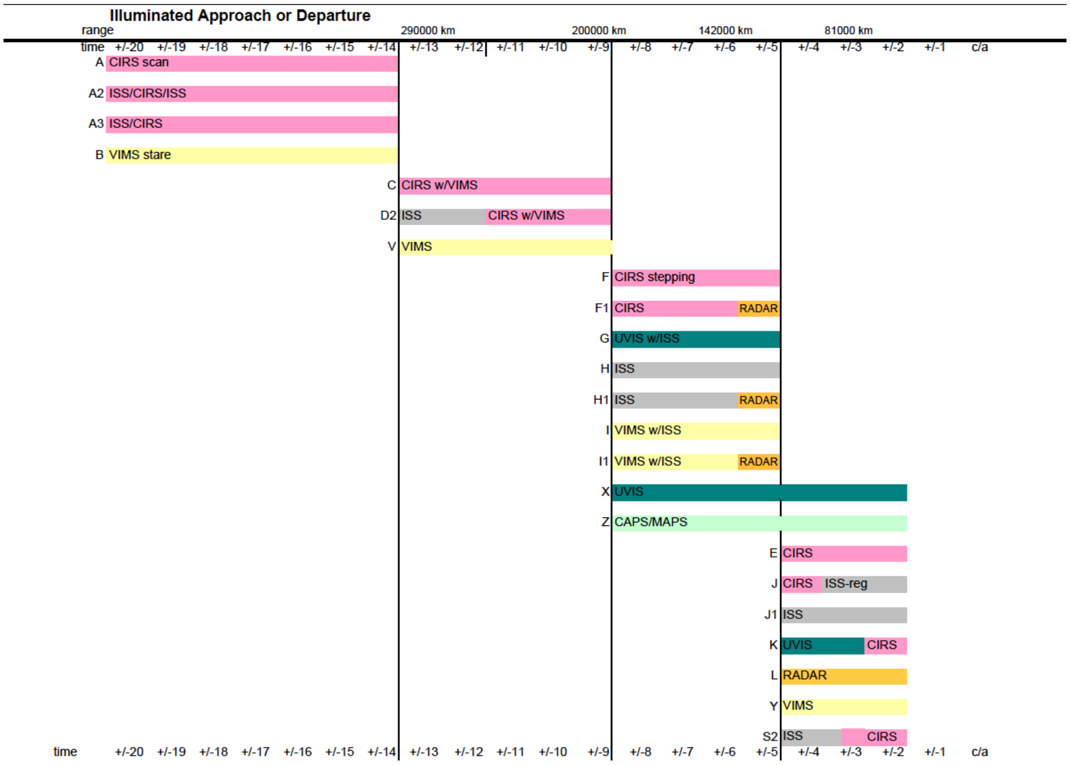
TOST History/Overview

TOST (Titan Orbiter Science Team) was chartered and starting working in the year 2000--just after the selection of Cassini's prime mission trajectory, and roughly halfway through the spacecraft's 7-year cruise to Saturn. TOST started work even though there was no overarching science planning process (or software) yet in place, since it was a given that the twenty four hours before and after each Titan flyby would be dedicated to Titan observations. Consequently, there were several innovations to the mission science planning process that were led by this group, and several idiosyncrasies where they later proved to be the exception.

It was determined that the first task was to decide how to allocate control of the spacecraft pointing between the different instrument teams for each flyby. The general process was always for individual teams to make a science case to justify their instrument being given such a key resource. Early "sharing" opportunities were developed and seized upon, with many surviving until the end of the mission (e.g. INMS and RADAR can share the minutes around closest approach with both being close to their ideal alignments). The ability of a science team to "ride along" with another also became key; for example once ISS was pointed at Titan, then we only needed to negotiate how much time was allocated for staring vs. slewing observations among the 4 Optical Remote Sensing (ORS) instruments (ISS, CIRS, UVIS and VIMS).

The first dozen flybys were worked out one by one with the general philosophy of giving each instrument an opportunity to take a shot at doing their best uncompromized science. The second dozen flybys were also optimized one by one, but with a higher emphasis on sharing opportunities between two or more instruments, with the understanding that the chosen pointing might not be the optimal configuration for either.

At the same time, the TOST leadership started recognizing patterns, particularly on the ORS-dominated approach and departure legs of each flyby, leading to the concept of "templates" (see Fig 1). Physically this was due to the fact that all the flybys occurred at approximately the same speed (6 km/sec), so time from closest approach mapped to distance away from the body. A series of specific options was created to cover explicit time periods outside of the closest approach period. For instance, as can be seen at the top of Fig 1, there are options covering the interval from 14 hours before (or after) closest approach until 20 hours before (or after) closest approach, with different divisions of the timeline between CIRS, ISS, and/or VIMS, the three instruments that were consistently interested in observing during that time. Negotiations sped up considerably as we simply chose between the preexisting templates for each segment of time (e.g. on the approach leg: downlink to -14 hours before closest approach; -14 to -9, -9 to -5, and -5 to -1). Inside of +/- 1 hour of closest approach, templates were not used as that time was always optimized for specific science goals.



Because of Titan's complex nature, multi-disciplinary groups formed around four science "themes": surface characterization, interior structure, atmospheric properties, and magnetospheric interactions. With interest in Titan so high, throughout the entire science team, several Principal Investigators and/or Team Leaders chose to be the Titan representative to TOST rather than designating a representative from their teams, which proved to be managerially challenging. We also had one instrument team where most of the Co-I's were specifically dedicated to Titan, so there was the challenge of considerable numbers of TOST representatives from a single instrument (RADAR). In response, TOST created the "core" TOST group: one speaking representative per instrument and the Titan interdisciplinary scientists. Core TOST was used when nominal negotiations within regular TOST were unable to come to consensus. If the core TOST group was unable to come to consensus, then the decision was bumped up to the Project Scientist. This happened only twice in all of prime mission: T20 (RADAR vs VIMS) and T38 (UVIS vs INMS). In both of those cases, dual plans were created for each flyby until the beginning of detailed sequence production when a final decision was made (maintaining dual timelines created significant extra work and was used only rarely).

The TOST group recognized early on that Titan observations would be tricky. Therefore, unlike other Target Working Teams (TWTs) and Orbit Science Team (OST), instrument teams chose to send sequence implementation experts to Titan integration meetings. Five out of the seven instruments who dominated our "prime" pointing timeline sent implementers to every TOST telecon (CIRS, ISS, INMS, RSS and RADAR).

In addition to the inherent challenges of Cassini Science Planning (e.g. distributed operations), the TOST group faced the additional challenge of limited opportunity. The relative amount of time near Titan (only 45 days in a 4 year prime mission) made opportunities rare and precious, and negotiations highly contentious. Titan science needs also pushed the spacecraft and science planning processes. Examples of off-nominal spacecraft and process considerations are:

- Using thruster control due to Titan's atmosphere: Any closest approach altitude of 1400 km or lower meant that the spacecraft needed to use thrusters rather than reaction models to maintain the desired attitude. Modeling Titan's atmosphere became a standing working group (led by Mission Planning) consisting of atmospheric scientists, instrument specialists, and spacecraft specialists. The spacecraft team had to develop and maintain experts in understanding the attitude control authority and teasing out atmospheric information from the Attitude and Articulation Control System (AACS) and Navigation data
- Tracking hydrazine usage: As the Titan flybys were one of the major hydrazine consumers due to low-altitude Titan flybys, it was critical that this limited fuel resource be modeled and tracked. The spacecraft team did not have the resources, so Mission Planning and TOST took the lead in modeling hydrazine usage. The TOST hydrazine estimation tool was developed so that it could be used early enough in the design process to be effective. It was based on looking at the hydrazine used during previous flybys with similar science observations. It was ultimately the main basis of all trade decisions.
- Ambitious pointing profiles: As inbound/outbound observations were dominated by ORS (NEG_Y to Titan) and closest approach often is not, there were routinely very big turns (greater than 90 degrees) near Titan and often 2 or 3 or 4 of them. Large turns became a concern as the reaction wheels aged, but often it was necessary to accomplish high priority Titan science.
- Dual playbacks of high value data: There was always some risk of data loss in the event of a problem with a Deep Space Net station. Consequently, the need for dual playback of high value science data was clear from the beginning of TOST's work (for example: the critical INMS and AACS data acquired during the initial Titan flyby for making the go/no-go decision for probe release).
- Custom handoffs: as the TOST group formed before the general science planning process was in place, they constructed the pointing profile by choosing the science pointing timeline, with each instrument "handing off" the spacecraft to the next instrument. The next instrument would "pick up" with the previous science pointing attitude, and then, if necessary, turn the spacecraft to the new preferred attitude. This was an efficient use of the spacecraft, and the best choice for science throughput, but it was time consuming in planning. The Science Planning Team introduced the concept of waypoints (each instrument picking up and returning the spacecraft to the same mutually agreed upon safe attitude) as a way to simplify the timeline integration process, at the cost of a less-efficient science timeline. However, TOST chose to put extra effort into continuing to negotiate handoffs in order to keep high science efficiency. The Science Planning process and software had to be augmented to allow for these custom handoffs.
- Unique Operation (Op) Modes: because of TOST's heavy use of RADAR and Radio Science (instruments that require more complex warmup and operations power profiles), we were often a requestor of unique op modes. In particular, turning on Radio Science

for warmup while maintaining the heaters necessary for a transition to thrusters drove several unique op modes.

Ultimately, all 45 targeted flybys in the prime mission were integrated before Saturn Orbit Insertion (SOI). The modifications to the PRIME mission timline were made as we learned better how to use the instruments and as we learned more about Titan in order to prepare for mission extensions.

Process Evolution for the First Extended Mission

The TOST Jumpstart for the first extended mission (XM) (The Equinox Mission phase) was a significant evolution of the TOST process. Because spacecraft performance was affected by atmospheric resistance, resulting in constraints in spacecraft attitude, the final altitude that the spacecraft could flyby was determined by the science being done at closest approach (at least +/- 15 min). Orbit-by-orbit trajectory design was critical . As a result, the closest approach science had to be negotiated very quickly (and early) and then fed fed back to the trajectory design folks so they could release a final trajectory with the Titan flybys optimized for science. The key result was to lower the altitudes for the in-situ instruments as far as possible and raise the altitude for the other instrument so that we could stay on the (more stable) reaction wheels and conserve hydrozine.

Other benefits of the Jumpstart were looking at the whole set of flybys at once allowing for negotiations over the entire set of flybys, so that TOST could allocate the top science priorities first. The Jumpstart was also a more efficient process; rather than asking the Titan scientists to attend weekly meetings in order to determine the activity timeline for every single Titan flyby, a high-level plan was developed far more quickly via several long intense telecons, followed by a two day in-person workshop for key decisions. There were additional telecons afterwards to integrate the inbound and outbound legs (decide on which template to use) and then the standard Science Planning telecons to work out the remaining operational details. Working out the Master Timelines via the Jumpstart allowed a more just-in-time process (no formal change requests for populating CIMS - a big workload saver for TOST scientists and science planners).

During the PRIME mission, the TOST group had focused almost exclusively on the targeted Titan flybys which were a month (or more) apart in time. Subsquently, we had taken no data in a 2 week period where a giant planetwide storm was observed by Earth based scientists. The storm was completely gone by the time Cassini had returned to Titan. The Titan atmospheric scientists worked with Science Planning to implement a campaign to observe Titan six to eight times per month to capture these sorts of events, search for surface changes, and to track seasonal changes in Titan's upper haze layers. The "Titan Meteorological Campaign" (TMC) had to be negotiated with all the other disciplines, as it would, by design, be taking time from Rings, Saturn, and other disciplines' timelines. It was designed to be as least invasive as possible, with TMC observations being scheduled either immediately before or after downlinks (i.e. they were the first or last thing requested in any observation block), and had a fixed duration, data volume, and pointing. The ISS team took the responsibility for developing software that would generate the simple pointing to Titan for the TMC observations and to shepherd them through the sequencing system. The TMCs used the following naming conventions:

1. For cloud observations (lower phase angle) ISS_138TI_M60R2CLD270_PRIME where M60 = phase angle between 30° and 60°, R2 = distance between 1,200,000 and 2,000,000 km, CLD = cloud observation, and 270 = day of year.
2. For haze monitoring observations (higher phase angle) ISS_279TI_M150R3HZ166_PRIME where M150 = phase angle between 120° and 150°, R3 = distance greater than 2,000,000 km, HZ = haze observation, and 166 = day of year.

The TOST group also routinely asked for the entire day before or after the flyby on whichever leg the lighting conditions were favorable for the ORS instruments to track cloud evolution etc. If it was the day after than it was called a “caboose” day and if it was the day before it became and “engine”day. The exceptions were the days after inbound (to Saturn) Titan flybys and before outbound (from Saturn) Titan flybys. As Titan flybys are typically 3 days from Saturn periapsis those days were in high contention with the Saturn and Rings disciplines. In the Prime mission this had been the responsibility of the individual instrument teams to see the opportunity, put in requests and then go to the various discipline meetings and defend the observations. Bringing it under the umbrella of the TOST group allowed the argument to happen once (during segmentation) and saved all the time Titan scientists spent in other discipline meetings to maintain these “extenstions” of the Titan flbys.

The end of XM also brought the most ambitious flybys of the mission. T70 was designated a “super go low” flyby, meant to go as low as was physically possible while maintaining spacecraft safety. The science goal was to attempt to go below the ionosphere in order to detect Titan’s internal/intrinsic magnetic field (if it existed). Significant resources by the spacecraft team were expended to determine what was the limiting factor for a low flyby. The spacecraft team determined that with a minimum torque attitude, the limiting factor was heating of the Stellar Reference Units. This extensive effort allowed Cassini to fly T70 at an altitude of a mere 880km. This did not probe below the ionosphere, but did establish a limiting constraint on Titan’s intrinsic magnetic field

Process Evolution for Second Extended Mission

When the second extended mission (XXM) (The Solstice Mission phase) was approved, Due to funding restrictions the project was required to restructure the planning processes, utilizing longer sequences, fewer overlaps of parallel sequence development processes, discipline focused periapses and fewer meetings, which could enabled significant staff reductions. Each area of the organization was asked to simplify operations, especially in areas where the operations staff could be cut. The most significant developments for TOST:

- The initial proposal of “no dual playbacks” was a major concern for high resolution surface observations, given the recent loss of T60 data that had no dual playback. Consequently, the TOST group along with a subset of instruments (e.g RADAR) pushed back, and got the dual playback reinstated.
- TOST modeled it’s internal simplification efforts after the project wide discipline focused periapsis concept put forth by Science Planning for the overall mission simplification.

For TOST this meant a single body vector +/- 2 hours with templates outside of that, and a continuous Magnetic and Plasma Science (MAPS) survey. It included,
  - Fewer custom handoffs
  - Fewer custom op modes
  - No RADAR and RSS on the same flyby
- Using a second TOST Jumpstart for XXM, we were able to reap all the rewards we had seen in the XM jumpstart.
- Changing from a three stage integration process (Kickoff, Detailed, and Wrapup meetings) to just two (along with the jumpstart) allowed us to drop our meeting frequency from once every two weeks to once per month

While challenges revealed by application of the Reaction-wheel Bias Optimization Tool (RBOT) were significant for other integration groups, the only issue for TOST was redefining our Titan Meteorological Campaign (TMC) requests to be insensitive to the choice of the spacecrafts secondary axis

The Titan Science Planners, while researching the TMC opportunities for the XXM discovered that there were several stretches of time (many days to almost two weeks) where the trajectory of the spacecraft and Titan seemed to glide along together giving us incredible stretches (one of the best was over 14 days long) of observing Titan with good lighting and decent range. These opportunites were called TEA (Titan Exploration at Apoapsis…yes contrived, but they that time the project had PIE - Pre-Integrated Events, and CAKE - Cassini Apoapsis Kronian Exploration…so we really had to have TEA). Over the 6 years of the XXM we integrated a handful of these unique very long Titan observations , which provided excellent opportunities for observing time dependent atmospheric phenoma.

By the end of the mission the TOST philosophy for integration was well established and can be summarized as follows:

- Targeted Titan flybys are by far, the highest priority, and within each flyby, the time at closest approach (+/- 2 hours) is usually substantially higher priority.
  - Titan Interiors Science: RSS gravity flybys are key observations, although RADAR overlapping tracks from different flybys has become important. The super go-low flyby for MAG and RPWS is also key.
  - Titan Surface Science: High resolution surface observations (RADAR and VIMS) are the key observations and are usually part of a dual playback strategy
  - Atmospheres (lower altitude): Solar, Earth, and stellar occultations are the key observations since they are rare and hard to obtain. Since the Solar occultations can be recorded on the spacecraft, they are usually part of a dual playback strategy; Earth occultations, although just as rare, are recorded on the ground. Atmospheric observations near closest approach (like CIRS limb scans) are also of high interest
  - Atmospheres (higher altitude): INMS in situ observations are the key observation, but CAPS (heavy negative ion) observations are a close second.
  - Magnetospheres: The Dusk Quadrant was not well sampled during the prime mission, so the flybys in that quadrant were key for XM and XXM. Also, the

Noon quadrant where the opportunity to observe Titan in the solar wind (if it happens) is rare.

- One leg of the flyby is lit and the other unlit. Usually the lit leg has higher priority

Note:

- Time tended to map int0 range
    - +/- 24 hours from targeted Titan flyby: range=+/- 500,000 km
    - +/- 5 hours from targeted Titan flyby: range=+/- 100,000km
    - +/- 2 hours from targeted Titan flyby: range=+/- 42,000km
- Titan observations outside the time of the targeted flyby fall into 4 categories
    - Good lit viewing opportunities (usually one day away from a targeted flyby)
        - CIRS and ISS takes the lead on many of these. Titan is usually < 1Mkm away. If it is the day after it is usually called a "caboose" and if it is the day before it is usually called an "engine"
    - Filling gaps in the surface coverage not covered in the prime mission
        - ISS takes the lead on these; the observation requests have names like LDHEM (leading hemisphere) etc to indicate which gap they are trying to fill. These opportunities were a driver in selecting a final XXM tour.
    - Cloud tracking requests, usually 10 hours to acquire a series of images to observe shorter-term temporal evolution of individual clouds (if present, of course)
        - ISS takes the lead on these, with observation request names like ISSCLOUD001. In XXM we went after many day long observation campaigns called Titan Exploration at Apoapsis (TEA) when we serindipioutosly had many days of good lit viewing.
    - Titan Meterolgical Campaign
        - Three of the four ORS instrument participated in a coordinated approach and all three have observations at this time (VIMS is the only instrument not participating in XXM). The Titan Monitoring Campaign with its funny naming convention is usually easy to spot M90R3CLD330.

Instrument inputs

CAPS data and observing strategy during Titan encounters

CAPS measurements are made by three electrostatic analyzers, the Ion Mass Spectrometer (IMS), the Ion Beam Spectrometer (IBS) and the ELectron Spectrometer (ELS). These sensors have long (160^o, 150^o and 160^o) but relatively narrow (8.3^o, 5.2^o and 1.4^o) fields of view which are co-aligned. The IMS and ELS sensors' field of view are divided into eight angular pixels. All three sensors are mounted on a rotating platform, allowing an approximately hemispheric scan. The axis of rotation is parallel to the spacecraft Z axis and the full range of actuation is approximately centered on the spacecraft –Y axis. Several instrument modes were changed for observations of Titan's ionosphere.

With the exception of data rates (which correspond to resolution), all these changes were intended for altitudes below 1400 km. Many CAPS commands do not take effect immediately, but at the end of an instrument cycle (256 seconds). Actuator motion depends on the actuator's position at the time of the command. As a result, many of the commands for Titan ionosphere modes were issued at approximately 2000 km altitude (depending on the geometry of the encounter.), so that they would have taken effect before the spacecraft reached 1400 km. Similarly, outbound command to return to non-ionosphere modes may not have taken effect until the spacecraft reached approximately 2000 km.

During Titan encounters, IMS data are primarily useful for determining the plasma properties of Titan's environment, including ion composition, density, flow speed and temperature. The data also allow determinations of non-thermal ion distributions. However, since the ion flow speed is comparable to the ion thermal velocity, the quality of these data is sensitive to spacecraft pointing. This varies considerably from encounter to encounter, and even within a given encounter (e.g. when tracking Titan for remote sensing measurements, the spacecraft's orientation changes by approximately 180^o between the inbound and outbound legs.) While the flow direction is, on average, in the direction of corotation, there is considerable variability. For these reasons, the CAPS team never assembled a list of good and poor pointing periods around Titan encounters. Instead, this must be assessed on a case-by-case basis. The moments calculated by Thomsen et al., 2010, (archived in the PDS) are a useful starting point although users are cautioned to pay attention to the quality flags included with these data.

Within Titan's ionosphere, IMS data are generally not useful. During the TA and TB encounters, very high fluxes were observed at low energies and while looking in the ram direction. These fluxes were sufficiently high to degrade the quality of the data, saturate the time-of-flight measurement and raise concerns for long-term wear on the sensor's detectors. On subsequent encounters, the IMS energy range was limited and energies below 27 eV were not sampled at altitudes below 1400 km. Titan's ionosphere is composed of heavy ions at or near their ram energy (roughly 142 AMU for a ram energy of 27 eV.) Heavy, molecular ions of this sort are fragmented and severely scattered by the ultra-thin carbon foil in the IMS time-of-flight system. As a result, the IMS data from Titan's ionosphere is very poor quality.

In contrast, the IBS sensor was designed to observe ions in narrow beams. This is very well suited to the high Mach flow of Titan's ionosphere when the ram direction is within the CAPS field of view (which is always the case on INMS- and RADAR-prime encounters). Above Titan's ionosphere, as a result of its lower sensitivity and angular response, the IBS data are generally considered less useful than ion data from IMS. Although IBS is not a mass spectrometer, ions in a high Mach flow are observed very close to their ram direction (0.19 eV/AMU at 6 km/s which is typical of Titan encounters.) The narrowness of the peaks in the IBS energy spectra, combined with the sensor's high energy resolution (1.4%) allow determination of ion mass. The IBS energy range is limited compared to many electrostatic analyzers. Given its high resolution and with only 255 energy steps per spectrum, it can sample a factor of 67 range of energies. This energy range can be shifted up or down by command. Away from Titan's ionosphere, this is typically set to 90.5 to 6070 eV. Initially this range was commanded to 1.02 to 68.3 eV, corresponding to masses of 5.4 to 359 AMU at their ram energy, when Cassini's altitude was below 1400 km. Starting with T?, and based on the discovery of very heavy ions, IBS was commanded to 3.03 to 203.7 eV (15.9 to 1072 AMU.)

The ELS sensor's measurements of electrons are generally of good quality and much less sensitive to spacecraft orientation than ion measurements. These measurements cover an energy range from 0.58 to 26,000 eV. In addition, a major, and surprising, discovery from the ELS data was the presence of negatively charged ions in Titan's ionosphere. Although designed to measure electrons, an electrostatic analyzer actually measures any charged particle with the appropriate energy per change. Negative ions were identified by their directionality (narrowly peaking in the ram direction) and from approximately 25 AMU to over 13,800 AMU. Since the energy resolution of ELS is lower than IBS (17% versus 1.4%), the ability to determine mass from ram energy is similarly limited.

Although the CAPS instrument can observe particle fluxes over nearly a hemisphere, covering this full range of actuation requires 204 seconds. In Titan's ionosphere, this angular coverage was not considered necessary, since ions are closely confined to the ram direction in a high Mach flow. In order to improve time resolution, the CAPS range of actuation was reduced to 28^o when the spacecraft was below 1400 km. This resulted in one scan across the ram direction every 52 seconds. This range of actuation was determined on an encounter-by-encounter basis, so that it would be centered on the ram direction. Note that 28^o was an operational limit for the minimum, non-zero range of actuation. In cases where the ram direction would not be observable at closest approach, different strategies were used below 1400 km, selected on an encounter-by-encounter basis. Non-zero actuation assured that the sensors would, in fact, sample the true ram direction. A 100 m/s cross-track neutral winds and/or ion drift produces a 1^o of apparent ram direction. This could seriously affect the quality of data from IBS, given its 1.4^o field of view.

This actuation strategy was not used for the T5 encounter, due to an instrument anomaly which temporarily prevented actuation. Although efforts were made to fix the actuator angle in the ram direction, analysis of the data strongly suggest the pointing was off by at least a few degrees. In addition, the actuator was intentionally fixed in the predicted ram direction on a series of encounters. This allowed 2 second time resolution while accepting uncertainties due to the potential difference between the true and predicted ram directions.

CAPS data rates correspond to resolution, since the full energy/angle spectra are summed over adjacent samples in the lower rate modes. Away from Titan encounters, the instrument typically operated in a survey mode. This mode alternated between a medium resolution (2 or 4 kbps, which is 1/8th or 1/4th of full resolution) and a low resolution, 0.5

kbps mode. On typical Titan encounters, this was increases to a constant, 4 kbps rate at four hours before closest approach. At two hours before closest approach, the instrument was commaned to its 16 kbps (full resolution) data rate. Outbound, the reverse changes were made at two and four hours after closest approach. This pattern was altered on many encounters, based on data allocations and availability. Occasionally, non-survey data were obtained more than ten hours from closest approach. The timing and details of these variations from the typical pattern were determined on a case-by-case basis, including considerations such as spacecraft pointing on the inbound versus outbound legs.

Thomsen, et al., 2010, Survey of ion plasma parameters in Saturn's JGR, 115, A10, DOI 10.1029/2010JA015267

CDA – Mapping the dust environment

The Dust Analyser is sensitive to particles within a large mass range ($5X10^{-18}$ kg to 10^{-12} kg for vd ≈ 20km/sec) and velocity range (1km/sec to 100km/sec), and measures the charge carried by the dust grain, mass, impact velocity, and elemental composition of the impactor. Details of the instrument can be found in Srama, et al., (2004)

Srama, R., et al., 2004. The Cassini Cosmic Dust Analyzer. Space Sci- ence Reviews 114, 465–518.

CIRS - Sensing of tropospheric and stratospheric temperatures and composition.

This includes abundances of the major and minor secies, the hunt for new gaseous species, isotope ratios for major species, and dynamics.
CIRS may also be able to sense the surface near 600 cm-1. Allocation of time for Titan observations was primarily done in the TOST group (Titan Orbiter Science Team), in conjunction with recommendations from the AWG (Atmospheric Working Group).

CIRS can achieve different science goals at different distances from Titan. Typically, CIRS makes the following requests (symmetric about closest approach):

+ 0 to +10 mins HIRES surface mapping (e.g. slew over south pole).

+10 to +45 mins FIRLMBT - radial limb scans with FP1 (focal plane 1) to derive temperatures in the 8--100 mbar region via the N2-N2 collision-induced absorption between 20--100 cm-1.

+45 to +75 mins FIRLMBAER - radial limb scans with FP1 to measure/ characterize particulate and condensate distributions, abundances and properties.

+75 to +135 mins FIRLMBINT - integrate at two altitudes on the limb
with FP1 to search for signals of CO, H2O and new
species.

+2:25 hrs to +5 hrs FIRNADMAP - slow scan north-south or east-west on
the disk to sound tropospheric temperatures at 40--200
mbar, via the N2-N2 absorption,

OR,

slow scans at constant emission angle on the disk,
to retrieve surface temperatures in the presence of
aerosols around 520 cm-1.

+5 to +9 hrs MIRLMBMAP - map 1/4 limb using the FP3 and FP4 arrays,
to infer stratospheric temeratures via the 1304 cm-1
band of CH4. The arrays are placed perpendicular to
the limb at two altitudes, chosen to provide
overlapping coverage of the altitude range 150 to 420
km. The arrays are used in blink (ODD-EVEN)
mode. After mapping both altitudes, the arrays are
stepped 5 degrees in latitudes for the next step.

OR,

MIRLMBINT - as in MIRLMBMAP, except that only a
single latitude is covered, at two over-lapping
altitudes for 2 hrs in each position. To search for
and measure new species in the mid-IR: methyl, benzene
etc

+9 to +13 hrs FIRNADCMP - integrate on the disk at emission angle
approximately 60 degrees with the FP1 detector, in
order to measure spatial abundance distribution of
weak species and search for new species in the far-IR.

+13 to +22 hrs MIDIRTMAP - scan the entire visible disk with the
FP3/FP4 arrays perpendicular to the scan direction
('push-broom'), to measure stratospheric temperatures
via the CH4 v4 band. Used for later dynamical
analysis, for winds, waves etc.

+22 to +48 hrs COMPMAP or TEMPMAP - map a meridian across the planet
either E-W or N-S, using the Fp3/FP4 arrays in two
positions longwise. To search for new species, and/or
monitor temperatures.

INMS - Measurements of mass, composition and number densities

The Cassini INMS investigation measures the mass composition and number densities of neutral species and low-energy ions in key regions of the Saturn system. The primary focus of the INMS investigation is on the composition and structure of Titan's upper atmosphere and its interaction with Saturn's magnetospheric plasma. Of particular interest is the high-altitude region, between 900 and 1000 km, where the methane and nitrogen photochemistry is initiated that leads to the creation of complex hydrocarbons and nitriles that may eventually precipitate onto the moon's surface to form hydrocarbon–nitrile lakes or oceans. The investigation is also focused on the neutral and plasma environments of Saturn's ring system and icy moons and on the identification of neutral species in the plume of Enceladus.

The INMS instrument consists of a closed neutral source and an open ion source, various focusing lenses, an electrostatic quadrupole switching lens, a radio frequency quadrupole mass analyzer, two secondary electron multiplier detectors, and the associated supporting electronics and power supply systems. Waite et al. (2004) provides a full description of INMS.

Waite et al., The Cassini Ion and Neutral Mass Spectromter (INMS) Investigation, 2004, Space Science Reviews, Volume 114, Issue 1-4, pp. 113-231, DOI 10.1007/s11214-004-1408-2

ISS - Mapping Titan's surface features, cloud activity and photometric properties

Over the course of more than 13 years, from April 2004 through September 2017, the Imaging Science Sub-System (ISS) experiment (Porco et al. 2004) on the Cassini spacecraft acquired nearly 45,000 images targeting Saturn's largest moon, Titan: ~30,000 were taken using the Narrow-Angle Camera (NAC), with the remainder taken using the Wide-Angle Camera (WAC). These images were acquired to: map Titan's surface features, monitor tropospheric cloud activity and map Titan's global wind field, and examine the photometric properties of Titan's hazy atmosphere and how it changes over time. Observations were originally planned over the course of Cassini's nominal 4-year mission and eventually extended to cover nearly half of a Titan year. Images of Titan were acquired during nearly all of Cassini's 127 targeted encounters with the satellite, as well as during relatively close (<1,000,000 km), non-targeted encounters and at more distant imaging opportunities throughout Cassini's orbital tour around Saturn including the Titan meteorological campaign (TMC) observations taken primarily during the Cassini Solstice Mission, which ran from July 2010 to September 2017.

ISS observations of Titan were generally taken at ranges from three to four million kilometers from Titan (up to 44 million km during approach) to within 10,000 kilometers on some Titan flybys. At ranges closer than 1,000,000 km, Titan more than filled the field-of-view of the NAC, necessitating mosaic observations. Mosaic observations taken during close targeted TItan encounters typically used the names MONITORNA, GLOBMAP, REGMAP, and HIRES to distinguish observations taken at different distances from Titan: MONITORNA observations were taken 12–14 hours from closest approach (C/A) to Titan, GLOBMAP observations were 5–9 hours from C/A, REGMAP observations were 2–5 hours from C/A, and HIRES observations were within 2 hours of C/A. Images were also taken while "riding along" with observations made by other instruments (e.g., CIRS' MIDIRTMAP observations or UVIS' EUVFUV observations), where ISS did not control pointing. As such, images were occasionally taken when the spacecraft was slewing, resulting in image smear. Also, given the long exposure times used (see below), when relatively close to Titan, images could sometimes be subject to range-to-target smear.

Observation naming convention:
ISS_218TI_GLOBMAP001_PRIME = ISS observation during Rev 218 of TItan named GLOBMAP observation 001 during this encounter with ISS as the PRIME instrument (i.e. controlling spacecraft pointing)

ISS_218TI_MIDIRTMAP001_CIRS = ISS ride-along observation during Rev 218 of TItan named MIDIRTMAP observation 001 during this encounter with CIRS as the prime instrument (i.e. controlling spacecraft pointing and providing the name of the observation).

Starting in the Cassini Equinox Mission, which ran from July 2008 to July 2010, ISS acquired several observations during extended periods before or after an encounter period, that were called cabooses or engines by the Titan Orbital Science Team [TOST], depending on whether they came after or before the targeted flyby period. These observations were typically given names like ISS_147TI_CLOUD001_PRIME. The observation name "CLOUD" was also used for some observations during distant non-targeted encounters in the F-ring and Proximal orbits in the last year of the mission, which were patterned after the engine/caboose observations due to their similar altitudes.

Also starting during the Equinox Mission, ISS acquired distant images of Titan that were designed to monitor cloud activity outside of close encounters, to track seasonal changes in Titan's upper haze layers, and to search for surface changes. These were collectively referred to as the Titan Meteorological Campaign and used the following naming conventions:
For cloud observations (lower phase angle) ISS_138TI_M60R2CLD270_PRIME where M60 = phase angle between 30° and 60°, R2 = distance between 1,200,000 and 2,000,000 km, CLD = cloud observation, and 270 = day of year.
And for haze monitoring observations (higher phase angle) ISS_279TI_M150R3HZ166_PRIME where M150 = phase angle between 120° and 150°, R3 = distance greater than 2,000,000 km, HZ = haze observation, and 166 = day of year.

Phase angle bins for these observations are:

M30 = 0°–30° (used primarily for cloud observations)
M60 = 30°–60° (used primarily for cloud observations)
M90 = 60°–90° (used primarily for cloud observations)
M120 = 90°–120° (used primarily for haze observations)

M150 = 120°–150° (used primarily for haze observations)
M180 = 150°–180° (used primarily for haze observations)

Range bins for these observations are:

R1 is under 1,200,000 km
R2 is 1,200,000 – 2,000,000 km
R3 is over 2,000,000 km

The best ISS filter to image Titan's surface was the CB3 filter, which was an option on both the WAC and NAC (Porco et al. 2004, Table VIII and Fig. 21), typically combined with a clear filter. (Polarizing filters could be combined with the CB3 filter, but generally were not because the number of single-scattered photons from Titan's surface was so low.) The CB3 filter is a narrow-band filter centered at 938 nanometers, within a "methane-window" through Titan's atmosphere, where absorption by atmospheric methane is low, and at the long-wavelength end of the spectrum to which ISS was sensitive – haze opacity decreases at longer wavelengths, compared to visible wavelengths where the surface is almost completely obscured from orbit. The combination of the filter being near the limit of the sensitivity range of the cameras' CCDs and the low surface contrast even in this methane-window meant that long exposure times (typically 18 – 82 seconds) and multiple images were required to build up an adequate signal-to-noise ration (S/N) for surface science. To accommodate this imaging strategy, dwell times for an individual footprint during a mosaic acquired during a Titan encounter ran 8–12 minutes.

Due to the low surface contrast of raw ISS images of Titan surface even using the CB3 filter, image acquisition and image processing strategies were developed to increase the S/N for scientific analysis of surface features (see Fig. 2). Typically, for an individual surface observation or mosaic footprint, 2–3 CB3 images would be acquired and then summed on the ground, after appropriate noise filtering, flat-fielding (due to low image contrast and S/N, flat-field artifacts were more apparent than in typical ISS images of other targets), calibration (see below), and co-registration. The summed CB3 image was then ratioed with an image taken using the MT1 filter during the same observation or mosaic footprint. MT1, a narrow-band filter centered at 619 nanometers within a methane absorption band (Porco et al. 2004, Table VIII and Fig. 21), acted as an ad hoc photometric filter for removing some of the contribution of the stratosphere and upper troposphere from the summed CB3 image. Finally, the resulting image was run through an unsharp mask filter to reduce the effect of photon scattering by Titan's atmosphere. The box size for this unsharp mask was typically 62 kilometers. While this processing strategy is effective for revealing surface and tropospheric cloud features, only relative albedo contrast is preserved within a single observation, and absolute albedo information is lost.

Calibration was performed using CISSCAL, the Cassini ISS Calibration Software Pipeline tool in IDL, developed by the Cassini Imaging Central Laboratory for Operations (CICLOPS). Other image processing steps described above were performed in ISIS2, a suite of planetary image processing and analysis tools developed at the U.S. Geological Survey’s Astrogeology Science Center (https://isis.astrogeology.usgs.gov).

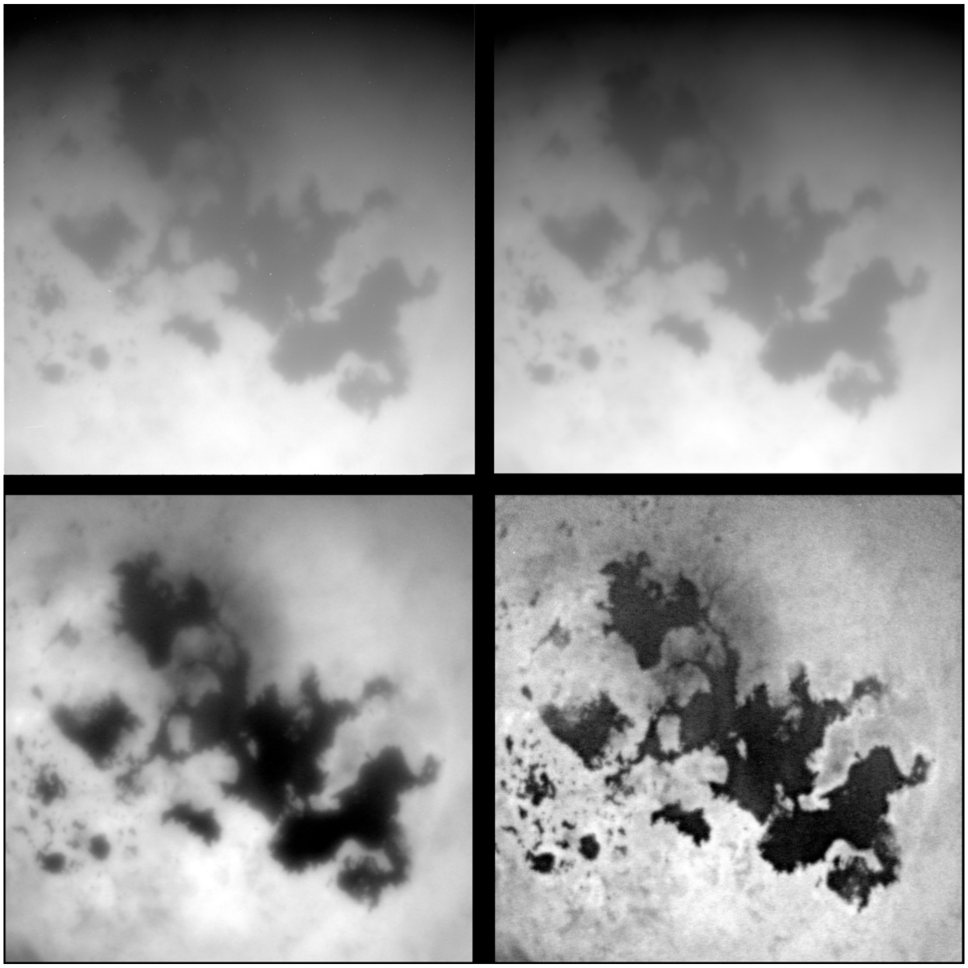


Figure 2: Cassini ISS image of Titan's north polar region showing Kraken, Ligeia, and Punga Maria (from ISS_283TI_MIDIRTMAP001_CIRS) at four stages of image processing:
Upper left: N1878419503_1 after CISSCAL calibration.
Upper right: same footprint after noise filtering, residual flat-fielding, co-registration, and stacking with two other CB3 images from this footprint (N1878419695_1 and N1878419855_1).
Lower left: Stacked CB3 image after ratioing with an MT1 frame (N1878419927_1) taken during the same footprint.
Lower right: Final image after unsharp mask routine, reducing the effect of atmospheric scattering on the final product

Reference:

Porco C.C. et al., Cassini Imaging Science: Instrument Characteristics and Anticipated Science Investigations at Saturn, Space Science Reviews 115, 363-497, 2004.

MAG - Search for intrinsic magnetic field

The Cassini magnetometer (MAG) instrument consists of a fluxgate (FGM) and a vector helium (VHM) magnetometer mounted halfway and at the end of the spacecraft 11-meter boom. Both sensors provided in situ measurements of the three components of the ambient magnetic field with a maximum temporal resolution of 32 and 2 Hz, respectively. FGM and VHM measurements were also used to measure the spacecraft's static and dynamic magnetic fields in order to obtain clean ambient field measurements. VHM data has been unavailable from day 2005-321 due to a failure in the sensor. Cassini MAG measurements have confirmed that Titan's own magnetic field, if any, is not sufficiently strong to generate an intrinsic magnetosphere. As a result, Titan's plasma environment will directly interact with its atmosphere with photoionization, charge exchange and electron impact ionization acting as catalysts of that interaction. In induced magnetospheres such as Titan's the knowledge of the orientation and strength of the background magnetic field the moon sits in is essential to infer the morphology of Titan's induced magnetosphere and the processes of transfer of energy and momentum responsible for the loss of the moon's atmosphere to space.

Because of Titan's location in the confines of Saturn's flapping, rotating magnetospheric disk, the moon is exposed to a magnetic field which varies on different temporal and spatial scales. The characterization of these variabilities allows not only to identify traces of an intrinsic field, but also to assess whether the moon generates an induced magnetic field linked to a global, conducting ocean beneath its surface. In this way, MAG is an invaluable tool to diagnose Titan's interior.

MIMI - Interaction of the local plasma environment with Titan’s upper atmosphere

The MIMI instrument goals at Titan are primarily focused on the interaction of the local plasma environment with Titan’s upper atmosphere and ionosphere. The atmosphere and ionosphere themselves lie below the energy range of sensitivity for the three MIMI sensors (LEMMS, CHEMS, and INCA), but these sensors are well suited to measure the energetic particle (ion and electron) environment, and therefore the energy input into the Titan atmosphere and ionosphere. LEMMS measures the energetic ions and electrons that penetrate the Titan atmosphere and ionosphere, CHEMS measures the ion populations, their composition and charge state, and INCA images the global interaction of the ion environment with Titan, showing locations of particularly intense energetic ion entry down to the Titan exobase. Because INCA is an imager, its best opportunities occurred for approaches and departures for which the co-aligned ORS instruments pointed toward Titan, although at closest approach the Radar/INMS spacecraft attitude was also useful for INCA imaging. Of all the Titan encounters, almost all were inside the Saturn bowshock, with the noteable exception of T96 which occurred in the upstream solar wind during a compression that pushed the Saturn magnetopause and bowshock planetward of both Cassini and Titan.

RADAR - Investigation of Titan’s surface

The Cassini Radar (RADAR) is used to investigate the surface of Saturn's moon Titan by taking four types of observations: imaging, altimetry, backscatter, and radiometry. Radar is a key technique for mapping Titan because the microwave signals are essentially unaffected by Titan’s atmosphere.

In the imaging mode of operation, the RADAR instrument bounces pulses of microwave energy off the surface of Titan from an incidence angle of typically 10-30 degrees : echo contributions from different parts of the surface within the beam footprint are isolated via the echo time (range) and azimuth (Doppler shift) via Synthetic Aperture Radar (SAR) processing, achieving surface resolution from a few kilometers down to ~350m. To achieve a usefully-wide image swath (parallel to the spacecraft groundtrack) the High-Gain Antenna (HGA) is fed by 5 different beams; pulses are sent to the 5 feeds in rapid succession. During the mission, a technique (‘SARtopo’) was developed to estimate terrain height by exploiting the overlap between the 5 SAR beams. Because adequate signal-to-noise is needed to bin the echo by range and Doppler, SAR is only typically performed near Titan close approach (below altitudes of ~5000km, i.e. out to about 15 minutes from c/a), although some longer-range observations are made from higher altitudes (“HiSAR”) using only the central beam (Beam 3) which has a stronger gain, allowing more distant operation. During the mission, half to two-thirds (depending on resolution threshold) of Titan’s surface was imaged, some areas multiple times for change detection or for stereo topography.

Radar altimetry is performed with the HGA aimed at nadir (i.e. vertical) to measure the topographic profile along the groundtrack. Altimetry generally has a greater precision than SARtopo. The measurement is achieved simply by ranging - measuring the echo strength vs time : this can be accomplished at altitudes up to 10,000km. Some low-altitude altimetry was performed, either for thermal management reasons, or to achieve higher signal-to-noise and narrower footprints. This was especially the case for studying the polar lakes and seas – altimetry is a powerful way to constrain surface roughness (detect waves) on scales smaller than the footprint, and in some cases a bottom echo could be detected from the seafloor, allowing the bathymetry to be profiled.

Scatterometry is used to map wide areas of the surface in real-aperture mode (no ranging or Doppler processing), so it can be performed at greater ranges, typically to about 25,000km, or a little over an hour from c/a. The ground resolution is therefore some tens of km. Scatterometry and altimetry use only Beam 3.

Finally, in the radiometry mode, the RADAR operates as a passive instrument, simply recording the microwave energy emanating from the surface of Titan : this is a function of emission angle, surface composition and physical temperature. Radiometry can be performed out to 5 hours from c/a (~100,000km) with Beam 3. Radiometry measurements are also interleaved with the active modes (including all 5 beams during SAR) : high quality radiometer data requires the instrument to be warmed up for several hours prior to start. Essentially global coverage of radiometry and scatterometry was obtained during the mission.

RPWS – Characterizing Titan's upper atmosphere

The RPWS instrument had the following primary science goals during Tian flybys (in no particular order):
1. Establish the spectrum and types of plasma and radio waves associated with Titan and its interaction with Saturn's magnetospheric plasma (and the solar wind).
2. Characterize the escape of thermal plasma from Titan's ionosphere in the downstream wake region.
3. Determine the electron density in the ionosphere of Titan.
4. Determine the spatial and temporal distribution of the electron density and temperature in Titan's ionosphere.
5 Carry out a definitive search for lightning in Titan's atmosphere during the numerous close flybys of Titan.
6. Search for the existence of radio emissions from Titan.

Operationally, the RPWS instrument was usually operated in a higher data rate mode (primarily to obtain 80 kHz WBR data at a high sample rate) during the period around Cassini closest approach to Titan. The exact length of the higher rate period depended on the amount of data volume allocated to RPWS but was usually on the order of 60 minutes. On flybys where the CA altitude was <1500km, the Langmuir Probe (LP) was usually operated in a higher resolution mode (+/-4 volt sweeps) to obtain higher resolution measurements of the ionosphere. For more distant flybys,
the typical +/-32 volt sweeps were usually used for the LP.

RSS - Gravity measurements, atmospheric occultations and bistatic scattering

Gravity Observations
With the Cassini High Gain Antenna (HGA) pointed at Earth, coherent X-band and Ka-band tracking data were acquired around the Titan Closest Approach (C/A) period to determine Titan's gravity field and its tidal variations. The DSN provided the uplink signal, which was then received by the Cassini spacecraft, and retransmitted to the ground. The gravity data are critical for:
1. assessing the presence of a global subsurface ocean by measuring the short-period changes of the gravity field induced by Saturn's tidal field (eccentricity tides);
2. determining the geoid and the presence of large scale gravity anomalies;
3. determine the rheology of the icy crust by correlative analysis with altimetric data.

Flybys: T11, T22, T33, T45, T68, T74, T89, T99, T110 (LGA), T122

Atmospheric Occultation Experiments
During an occultation experiment, Cassini generated and transmitted three sinusoidal signals (S-, X- and Ka-bands) using the ultra stable oscillator (USO) as a common

reference for all three signals. The signals traversed through the atmosphere and were received at ground antennas at the Deep Space Network. A limbtrack maneuver, in which the spacecraft attitude was continually adjusted to ensure that the refracted radio waves reached Earth, was performed.

After the failure of the USO in December 2011, the subsequent experiments were conducted in two-way mode using a highly stable frequency reference provided by uplink from DSN antennas.

The interpretation of the observed effects of refraction by the atmosphere and ionosphere allowed the determination of the vertical electron density structure in the ionosphere and the temperature-pressure profiles and absorption characteristics of the neutral atmosphere.

Flybys: T12, T14, T27, T31, T46, T52, T57, T101, T102, T117, T119

Bistatic Scattering Experiments

During a bistatic experiment, the Cassini HGA antenna was pointed at Titan and transmitted radio waves that penetrated the atmosphere and reached the surface of Titan. The surface then acted much like a mirror, reflecting the radio waves at various angles, depending on the kind of surface encountered. The reflected radio waves that reached Earth were received and recorded at antennas at the Deep Space Network (DSN).

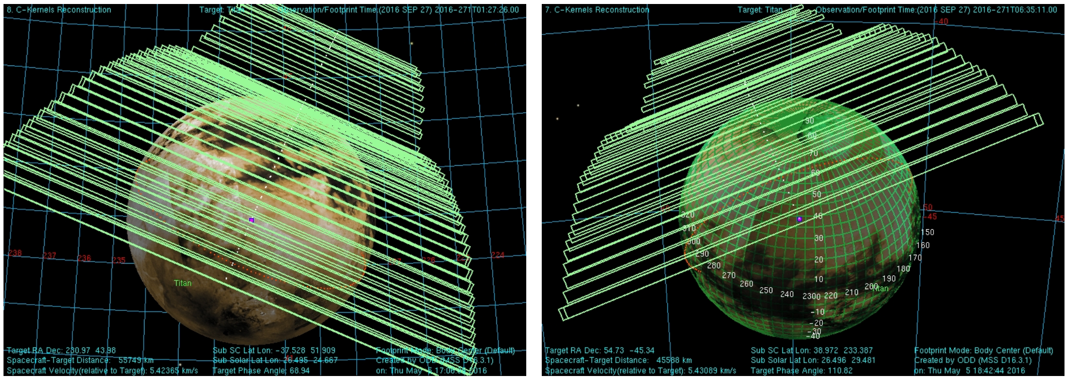
Measurements of the absolute power of the polarized components of mirror-like surface reflections (surface echoes), when detectable, yielded information about surface reflectivity, dielectric constant and implied composition, and roughness.

Flybys: T12, T14, T27, T34, T46, T51, T52, T101, T102, T106, T117, T119, T124

UVIS _ Study of Titan’s atmospheric haze and gas

At the wavelengths covered by UVIS (50 – 190 nm) Titan’s atmospheric haze and gas obscures the surface. UVIS spectra contain information on atmospheric composition (CH4, C2H2, C2H6, C6H6), excited nitrogen (atomic and molecular) in the high atmosphere, and haze. UVIS-driven observations are mainly of two types: solar and stellar occultations and spectral image scans. The latter can be identified by the ‘EUVFUV’ in the request name, because both the EUV and FUV detectors are typically used in these scans. Both detectors are used for stellar occultations but only the EUV detector is able to observe solar occultations. The occultations provide detailed vertical profiles of constituents (down to a limiting altitude determined by opacity along the line of sight), but only at the latitude and time of each observation. The EUVFUV scans usually cover all or a portion of the disk, but provide degraded vertical resolution. The EUVFUV observations taken at a variety of phase angles throughout the mission provide information on the haze scattering phase function. Below is an example of inbound and outbound EUVFUV scans done on the Titan 123 flyby. The apparent length of the UVIS slit on Titan grows as the distance to Titan grows during the observation interval (typically 5 hours).

T123 Inbound and Outbound EUVFUV



8. C-Kernels Reconstruction
Target: Titan
Observation/Footprint Time:(2016 SEP 27) 2016-271T01:27:26.00
Target RA Dec: 230.97 43.98
Spacecraft-Target Distance: 55749 km
Spacecraft Velocity(relative to Target): 5.42365 km/s
Sub SC Lat Lon: -37.528 51.909
Sub Solar Lat Lon: 26.495 24.667
Target Phase Angle: 68.94
Footprint Mode: Body Center (Default)
Created by ODD (MSS D16.3.1)
on: Thu May 5 17:06:[illegible] 2016

7. C-Kernels Reconstruction
Target: Titan
Observation/Footprint Time:(2016 SEP 27) 2016-271T06:35:11.00
Target RA Dec: 54.73 -45.34
Spacecraft-Target Distance: 45588 km
Spacecraft Velocity(relative to Target): 5.43089 km/s
Sub SC Lat Lon: 38.972 233.387
Sub Solar Lat Lon: 26.496 29.481
Target Phase Angle: 110.82
Footprint Mode: Body Center (Default)
Created by ODD (MSS D16.3.1)
on: Thu May 5 18:42:44 2016

Inbound Phase = 69 degrees

Outbound Phase = 111 degrees

VIMS - Analysis of the surface and atmosphere of Titan

The Visual and Infrared Mapping Spectrometer (VIMS) provided information on the surface and atmosphere of Titan. The VIMS instrument took images up to 64x64 pixels and spans the 0.3-5.1 µm wavelength range. It took images of Titan's surface in seven infrared atmospheric windows present in the spectral range between 0.9 and 5.1 microns. There are 5 narrow windows [0.93, 1.06, 1.28, 1.57, 2.02 µm] and two broader windows at 2.7 and 5-µm. The 2.02-µm window is the best compromise between atmospheric scattering (mostly haze), and solar luminosity and detector sensitivity (Signal to Noise ratio). The footprint is at best 1km/pixel when the VIMS instrument is operating at Titan's closest flybys. The VIMS instrument also took spectra of Titan's atmosphere and was able to follow the distribution of clouds during Titan's seasons. Stellar and solar occultation observations provided atmospheric spectra that are independent of any calibration. A detailed description of the VIMS instrument can be found in Brown et al. 2004.

Brown R.H., et al. The Cassini visual and infrared mapping spectrometer (VIMS) investigation Space Science Review, 115 (1-4) (2004), pp. 111-168