

TOST History – Integrated Sequence Planning

by Instrument Team Representatives

Formation and Initial Process (Prime Mission (PM))

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 TOST later proved to be the exception.

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 this key resource. Early on, teams developed methods for "sharing" pointing, with many of these methods surviving until the end of the mission (e.g. INMS and RADAR could 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 instrument's spacecraft pointing also became key; for example, once ISS was pointed at Titan, then because the other three Optical Remote Sensing (ORS) instruments were riders on the ISS pointing, TOST only had to negotiate how much time was allocated for staring vs. slewing observations.

The first dozen Titan flybys were worked out one-by-one with the general philosophy of giving each instrument team an opportunity to take a shot at doing their best science uncompromised by the needs of any other instrument. 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 Figure 1). Physically this was due to the fact that all the flybys were at a similar speed during the closest approach period. For instance, as can be seen at the top of Figure 1, there were 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 were reduced by 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.

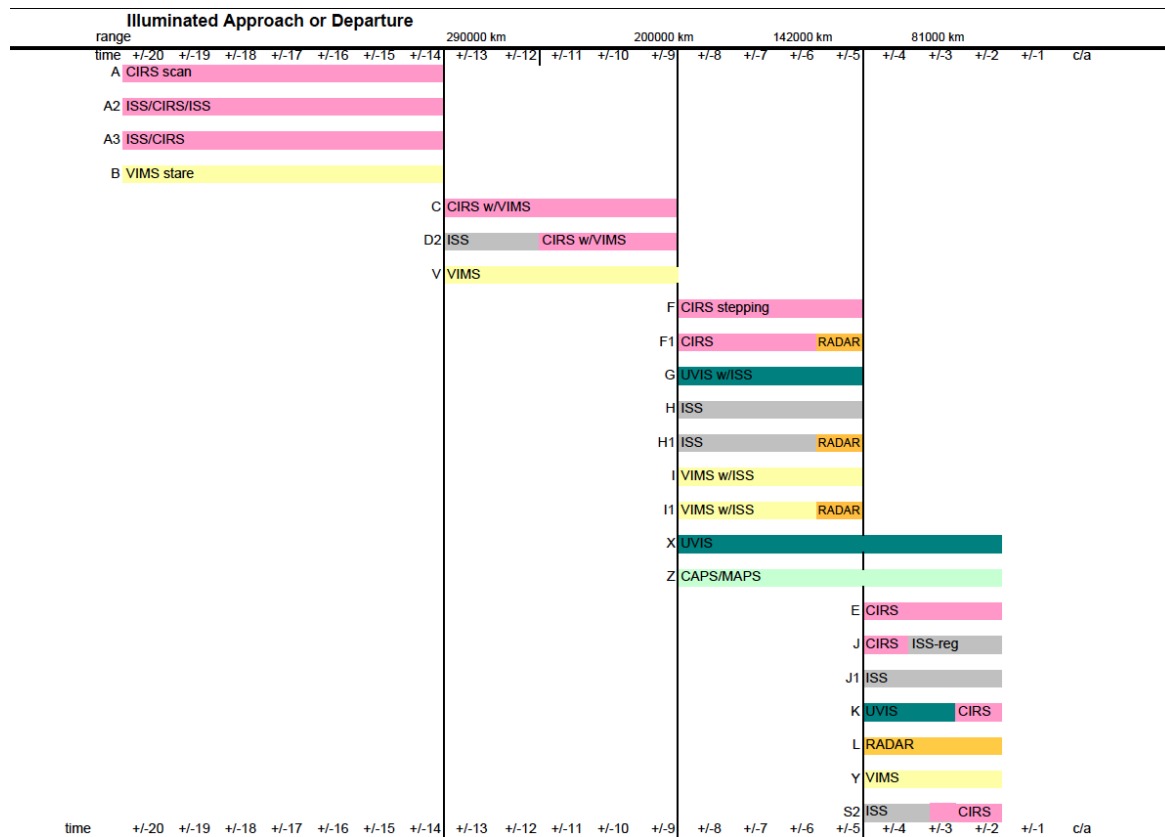


Figure 1. Scheduling Options for ORS Instruments

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 (RADAR) where most of the Co-I’s were specifically dedicated to Titan, so there was the challenge of considerable numbers of TOST representatives from that single instrument. 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 the 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: the T20 (RADAR vs VIMS) and T38 (UVIS vs INMS) flybys. 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 for this length of time was a significant increase in effort and was therefore used only rarely.

The TOST group recognized early on that Titan observations would be especially tricky to convert from science intent to actual implemented observation. Therefore, unlike other working groups, many instrument teams chose to send sequence implementation experts to Titan integration meetings so that the implementers understood the science intent, and could identify and avoid “unimplementable” observations. Five out of the seven instruments who dominated the “prime” pointing timeline sent implementers to every TOST telecon (CIRS, ISS, INMS, RSS and RADAR).

The additional resources allocated to the Titan integration have borne fruit in that almost half of all prime mission publications were Titan related (about double that of any other discipline).

In addition to the inherent challenges of Cassini Science Planning (e.g. distributed operations), the TOST group (and the icy satellite working group (SOST)) faced the additional challenge of limited observational opportunity. The relative amount of time near Titan (only 45 days in the 4 year prime mission) made opportunities rare and precious. Consequently, negotiations between instruments were highly contentious. Titan science requirements also pushed the spacecraft and science planning processes. This is illustrated by a short list of Titan-driven off-nominal spacecraft and process considerations:

- 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 wheels to maintain the desired attitude, so understanding the structure of Titan's upper atmosphere was an operational concern. Modeling Titan's atmosphere and incorporating the latest atmospheric data within the model 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 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 resource be modeled and tracked. The spacecraft team did not initially 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 in evaluating if the observation's science benefit was worth the hydrazine "cost". The tool was based on looking at the hydrazine used during previous flybys with similar science observations. It was ultimately the basis of all science versus hydrazine trade decisions.
- Ambitious pointing profiles: As inbound/outbound observations were dominated by ORS instruments (orienting NEG_Y to Titan) and closest approach often was not (RADAR using NEG_Z to Titan, RSS using NEG_Z to Earth), there were routinely very large turns (greater than 90 degrees) near Titan and often up to four such turns within a few hours. Large turns became a concern as the reaction wheels aged, but often these turns were 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 DSN station, as data could be overwritten once it was played back. Consequently, the need for dual playback of high value science data was clear from the beginning of TOST's work, where the initial motivation was to ensure the safe return of the critical INMS and AACS data obtained during the TA flyby for making the go/no-go decision for probe release. Dual playbacks became a common TOST strategy.
- Custom handoffs: As the TOST group formed before the general science planning process was in place, TOST initially constructed the pointing profile for each flyby 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 a 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, since changes in an instrument's observation design could impact the next instrument's designs as well. 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. TOST chose to put extra effort into continuing to negotiate handoffs in order to keep high science efficiency in cases when the waypoint strategy would have resulted in a great loss of science opportunity. The Science Planning process and software had to be augmented to allow for these custom handoffs.

- Unique Op Modes: Because of TOST's heavy use of RADAR and Radio Science (instruments that required more complex warmup and operations power profiles), we often requested unique "op" modes (operations modes). In particular, turning on Radio Science for warmup while maintaining the heaters necessary for a transition to thrusters drove the development of several unique op modes.

Ultimately, all 45 targeted flybys in the prime mission were integrated before Saturn Orbit Insertion (SOI). As we learned better how to use the instruments, and learned more about Titan, we made modifications to the prime mission timeline. An example of a key modification was:

- ISS challenges due to rapidly changing incidence angle made the closest approach time less valuable to them than the time from 10,000 to 50,000 km away, so VIMS usually took the lead for developing observations for ORS instruments within 2 hours of C/A. Both ISS and VIMS wanted long dwell times at Titan, and consequently worked well together. This incidence angle challenge also forced the ISS team to come up with an observing scheme of using many short exposures summed together. Had the Cassini spacecraft not been so stable, that scheme would have been needed by the other ORS instruments

Process Evolution for Extended Mission (XM)

The TOST Jumpstart for Extended Mission (XM) was a significant evolution of the TOST process. The change in process was driven by the non-intuitive interaction between the type of science desired at closest approach (typically, at closest approach +/- 15 minutes) for each Titan flyby, and the trajectory design for the mission. The spacecraft's altitude at closest approach was determined by the spacecraft's attitude (or orientation), which was chosen to enable the science selected for closest approach. In-situ instruments wanted to go as deep as possible into Titan's atmosphere, but the remote science instruments preferred to stay at higher altitude so that pointing could be managed by the more stable reaction wheels, rather than the thruster control needed to counteract Titan's atmospheric forces. Since the geometry of each flyby was different in terms of phase angle, position relative to Saturn, and the like, instruments often needed specific flyby design to meet their science goals. The only way to meet science desires in some of these cases was to change the spacecraft trajectory, but the trajectory was designed years in advance as a multi-year path that could not be easily changed. Consequently, the closest approach science had to be negotiated very quickly (and early) and then fed back to the trajectory design group so they could release a final trajectory with the Titan flybys optimized for science. The key result was to lower the desired altitudes for the in-situ instruments as far as possible and raise them for the other instruments to be able to stay on the (more stable for pointing) reaction wheels.

The Jumpstart offered other benefits. Titan scientists could look at and negotiate the whole set of XM flybys at once; this allowed TOST to allocate time during closest approach to ensure that top science priorities were addressed. The Jumpstart was also a highly 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 timelines for each flyby's inbound and outbound legs and then the standard Science Planning telecons to work out the remaining operational details. Working out the Master Timelines via the Jumpstart allowed for a more just-in-time process. Unlike other target working teams, TOST did not need to issue formal change requests for populating the Cassini Information Management System (CIMS) observation database - 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. Subsequently there was no Titan data during a two week

period in which a giant storm on Titan was observed by Earth based scientists. The storm was completely gone by the time of Cassini's next targeted Titan flyby. In order to avoid this kind of missed opportunity, Titan atmospheric scientists and Science Planning worked out how to implement a campaign of looking at Titan six to eight times per month to capture storm events, search for surface changes, and 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 observation time away from Rings, Saturn, and other disciplines' timelines. It was designed to be as noninvasive to these other disciplines' timelines as possible: TMC observations were scheduled either immediately before or after data downlinks to Earth (minimizing the time spent turning to Titan), and had a fixed duration, data volume, and pointing to ease planning. The ISS team created software that would generate the simple pointing to Titan for the TMC observations, and also shepherd the observations through the sequencing system. The TMCs used the following naming conventions:

Cloud observations (lower phase angle)

For example, 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.

Haze monitoring observations (higher phase angle)

For example, 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:

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:

R1: < 1,200,000 km
R2: 1,200,000 – 2,000,000 km
R3: > 2,000,000 km

TOST also routinely asked to add an additional day to each XM Titan segment, increasing their duration from two to three days. The extra day was used by the ORS instruments to track cloud evolution and other changes. If the spacecraft approached Titan's lit side, then the extra day was scheduled at the start of the segment (an "engine" day); if Titan's day side was only visible after the flyby, then the extra day was tacked onto the end (a "caboose" day). During the Prime mission, this kind of Titan monitoring opportunities were the responsibility of the individual instrument teams. They needed to be aware of the scheduling opportunity, put in observation requests, and then attend the various non-Titan discipline meetings to support including the observations in the proposed timeline. Bringing caboose and engine days under the scheduling umbrella of the TOST group allowed the argument over scientific merit to happen once (during segmentation, when all of the disciplines negotiated for time), saving considerable time for the Titan scientists. (A side note: many of these engine/caboose requests were granted except when they would interfere with Saturn or Rings observations near Saturn periapsis. As Titan flybys

typically occurred three days before or after Saturn periapsis, TOST could not schedule a caboose day while inbound to Saturn, or an engine day while outbound from Saturn.)

The end of XM also brought the most ambitious Titan flyby of the mission. T70 was designated a “super go low” flyby, meant to go as deeply into Titan’s atmosphere as was physically possible while maintaining spacecraft safety. The science goal was to attempt to go below Titan’s ionosphere in order to detect Titan’s internal/intrinsic magnetic field (if it existed). After concentrated and detailed analysis the spacecraft team found that with a minimum torque attitude, the limiting factor for a low flyby was the heating of the Stellar Reference Units. This analysis allowed Cassini to fly T70 at an altitude of a mere 880km. The spacecraft didn’t quite get below the ionosphere, but this flyby allowed the team to place an upper limit on Titan’s intrinsic magnetic field that revealed the field to be very small at best.

Since every science team was learning how to better use their instrument, this resulted in improved performance and increased scientific yield.

Process Evolution for “Extended Extended” Mission (XXM)

In order to continue into the seven year long so-called Solstice Mission phase, the project went through a major cut in funds and a restructuring of the planning processes to enable significant staff reductions. Each area of the organization was asked to simplify operations, especially in areas where the operations staff could be cut. This led to significant changes in TOST planning:

- The initial proposal of “no dual playbacks during XXM” was a major concern for high resolution surface observations, given that the Titan science community was still smarting from the loss of T60 data (a segment that had no dual playback). Consequently, the TOST group and a subset of instruments most invested in dual playbacks (e.g RADAR) pushed back, and got dual playback capability during XXM reinstated.
- TOST simplified its segment planning. The most significant changes included these rules and guidelines:
 - Only one body vector would be designated as the “prime” pointing vector during the period within +/- 2 hours of closest approach. Outside of that interval, templates were used rather than customizing science.
 - MAPS operated in continuous survey mode.
 - Fewer custom handoffs
 - No RADAR and RSS observations would be allowed on the same flyby. This decision greatly simplified power management, leading to fewer custom “op modes”
- Using a second TOST Jumpstart for XXM, TOST reaped all the rewards that were gained 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 the other discipline teams were challenged by the rules and guidelines, the only issue for TOST was redefining 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 opportunities were called TEA (Titan Exploration at Apoapsis) – by then the project had PIE - Pre-Integrated Events and CAKE - Cassini Apoapsis Kronian Exploration...TEA was needed. Over the 6 years of the XXM a few of these unique very long Titan observations were integrated, providing the basis for study of atmospheric circulation (and movies).

Science team were still coming up with better ideas for operating their instrument which turned into some great performance improvements: for example,

- Bathymetry for RADAR
- Dust observations by CDA when Cassini was occultated by Titan and its atmosphere

At the end of the mission TOST's integration philosophy for TOST could be encapsulate as:

- Targeted Titan flybys are by far, our 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 but 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:
 - +/- 24 hours from targeted Titan flyby: range= \pm 500,000 km
 - +/- 5 hours from targeted Titan flyby: range= \pm 100,000km
 - +/- 2 hours from targeted Titan flyby: range= \pm 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 many day long observation campaigns were executed called Titan Exploration at Apoapsis (TEA) when serendipitously there was many days of good lit viewing.
 - Titan Meteorological 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.

Individual Instrument Approaches

CAPS: Data and Observing Strategy During Titan Encounters

CAPS measurements were made by three electrostatic analyzers, the Ion Mass Spectrometer (IMS), the Ion Beam Spectrometer (IBS) and the Electron Spectrometer (ELS). These sensors had long (160° , 150° and 160°) but relatively narrow (8.3° , 5.2° and 1.4°) fields of view which were co-aligned. The IMS and ELS sensors' field of view were divided into eight angular pixels. All three sensors were mounted on a rotating platform, allowing the instrument to scan out up to approximately an hemisphere. The axis of rotation was parallel to the spacecraft Z axis and the full range of actuation was 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 did 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 were 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 varied considerably from encounter to encounter, and even within a given encounter (e.g. when tracking Titan for remote sensing measurements, the spacecraft's orientation changed by approximately 180° 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 of 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 was 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. 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 charge. 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 could observe particle fluxes over nearly a hemisphere, covering this full range of actuation required 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° 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° 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 produced a 1 degree of apparent ram direction. This could seriously affect the quality of data from IBS, given its 1.4° 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 (including T55 and T59). This allowed for two second time resolution while accepting uncertainties due to the potential difference between the true and predicted ram directions.

As stated above, 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 increased to a constant rate of 4 kbps at four hours before closest approach. At two hours before closest approach, the instrument was commanded 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.

CDA: No Response

CIRS: Sensing of Tropospheric and Stratospheric Temperatures and Composition.

This includes abundances of the major and minor species, the hunt for new gaseous species, isotope ratios for major species, and Atmospheric dynamics.

The greatest atmospheric depth to which CIRS can penetrate occurs at 600 cm-1. Possibly reaching the surface,. Allocation of time for CIRS Titan observations was primarily done in the TOST group (Titan Orbiter Science Team), in conjunction with recommendations from Cassini's Atmospheric Working Group (AWG).

CIRS achieved different science goals at different distances from Titan, which corresponded to different times relative to closest approach. Typically, CIRS made a similar list of requests for each flyby (note: as distance is symmetric about closest approach, the requests were also symmetric, e.g. the observations from closest approach + 0 minutes to closest approach + 10 minutes would also be requested for the interval -10 minutes to 0 minutes). More details about these observations can be found in the CIRS decoder ring document.

Types of observations are:

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

+10 to +45 mins: Far Infrared Limb Temperature (FIRLMBT) - radial limb scans with the focal plane 1 (FP1) field of view 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: FIRLMBBAER - 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 ¼ of the limb using the focal plane 3 and 4 (FP3 and FP4) arrays, to infer stratospheric temperatures via the 1304 cm⁻¹ band of CH₄. The arrays were oriented perpendicular to the limb at two altitudes, chosen to provide overlapping coverage of the altitude range 150 to 420 km. The arrays were used in blink (ODD-EVEN) mode. After mapping both altitudes, the arrays were stepped five degrees in latitude for the next step.

OR

MIRLMBINT - as in MIRLMBMAP, except that only a single latitude is covered, at two overlapping altitudes for 2 hours 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 (a technique also referred to as 'push-broom'), to measure stratospheric temperatures via the CH₄ v₄ band. Used for later dynamical analysis, for winds, waves, etc.

+22 to +48 hrs: Composition Map (COMPMAP) or Temperature Map (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: Measuring the Mass Composition and Number Densities of Neutral Species and Low-energy Ions

The Cassini INMS investigation measured 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 consisted 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.

ISS: Mapping Surface features and the Global Wind Field, Monitor Tropospheric Cloud Activity and Studing the Photometric Properties and Time Dependence of Titan's Hazy Atmosphere

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 (monitor using narrow angle), GLOBMAP (global map), REGMAP (regional map), and HIRES (high resolution) 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 ratio (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, two to three 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>).

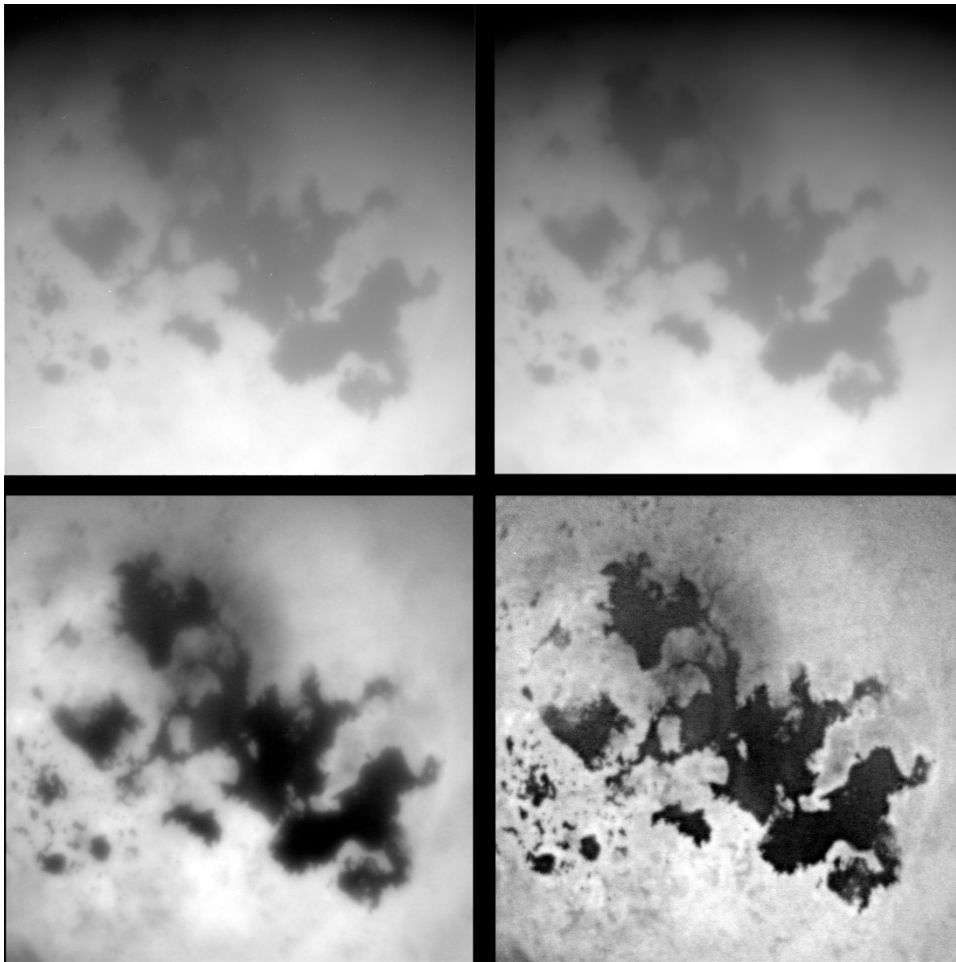


Figure 3: Cassini ISS image of Titan's north polar region showing Kraken, Ligeia, and Punga Maria (from ISS_283TI_MIDIRTMAP001_CIRS) at four stages of image processing: Upper left: N1878419503_1 after CISSCAL calibration. Upper right: same footprint after noise filtering, residual flat-fielding, co-registration, 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: Providing In Situ Measurements of the Three Components of the Ambient Magnetic Field

The Cassini magnetometer (MAG) instrument consisted 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. There is no VHM data from day 2005-321 onward 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 in which the moon sits 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 us 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 help diagnose the nature of Titan's interior.

MIMI: Studying the Interaction of the Local Plasma Environment with Titan's upper Atmosphere and Ionosphere.

The goals of the MIMI instrument at Titan primarily focused on studying 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 (Low-Energy Magnetospheric Measurement System (LEMMS), Charge-Energy-Mass Spectrometer (CHEMS), and Ion and Neutral Camera (INCA)), but these sensors were well suited to measure the energetic particle (ion and electron) environment, and therefore the energy input into the Titan atmosphere and ionosphere. LEMMS measured the energetic ions and electrons that penetrate the Titan atmosphere and ionosphere; CHEMS measured the ion populations, their composition, and charge state; and INCA imaged the global interaction of the ion environment with Titan, showing locations of particularly intense energetic ion entry down to the Titan exobase. Because INCA was an imager, its best opportunities occurred during approaches and departures when the co-aligned ORS instruments pointed toward Titan, although at closest approach the spacecraft attitude used by the Radar and INMS instruments in tandem was also useful for INCA imaging. Of all the Titan encounters, almost all were inside the Saturn bowshock, with the notable 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 Investigated Titan's Surface with Imaging, Altimetry, Backscatter, and Radiometry

The Cassini Radar (RADAR) was used to investigate the surface of Saturn's moon Titan by taking four types of observations: imaging, altimetry, backscatter, and radiometry. Radar was 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 bounced 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 were isolated using 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) was fed by five different beams; pulses were sent to the five feeds in rapid succession. During the mission, a technique (“SARtopo”) was developed to estimate terrain height by exploiting the overlap between the five SAR beams. Because adequate signal-to-noise is needed to bin the echo by range and Doppler, SAR was only typically performed near Titan closest approach (below altitudes of ~5000km, i.e. within about 15 minutes from c/a). Some longer-range observations were 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 were observed multiple times to enable change detection or stereo topography.

Radar altimetry was performed with the HGA aimed at nadir (i.e. vertical) to measure the topographic profile along the groundtrack. Altimetry generally had greater precision than SARtopo. The measurement was achieved simply by ranging (measuring the echo strength vs time), a technique that could 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. Low altitude altimetry was especially useful for studying the polar lakes and seas – altimetry was a powerful way to constrain surface roughness (e.g. to 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 was used to map wide areas of the surface in real-aperture mode with no need of ranging or Doppler processing. Consequently, it could be performed at greater ranges, typically to about 25,000km (a little over an hour from c/a). The ground resolution was therefore some tens of kilometers.

Scatterometry and altimetry used only Beam 3.

Finally, in the radiometry mode, RADAR operated as a passive instrument, simply recording the microwave energy emanating from the surface of Titan as a function of emission angle, surface composition and physical temperature. Radiometry could be performed out to five hours from c/a (~100,000km range) with Beam 3. Radiometry measurements were also interleaved with the active modes (including all five beams during SAR) : high quality radiometer data required the instrument to be warmed up for several hours prior to start, which caused some operational constraints due to power needs.

Essentially global coverage of Titan using radiometry and scatterometry was obtained during the mission.

RPWS: Studing the Spectrum and Types of Plasma and Radio Waves and the Electron Density in the Ionosphere

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's closest approach (CA) 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: Measuring Titan's Gravity Field and Carrying Out Atmospheric Occultation Experiments

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) determining the rheology of the icy crust by correlative analysis with altimetric data.

Flybys with gravity observations: T11, T22, T33, T45, T68, T74, T89, T99, T110 (using the Low Gain Antenna (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 (DSN). The spacecraft attitude was continually adjusted to ensure that the refracted radio waves reached Earth, a technique called a limbtrack maneuver.

After the failure of the USO in December 2011, subsequent occultation 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 with atmospheric occultation experiments: 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 moon's surface. 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 with bistatic scattering experiments: T12, T14, T27, T34, T46, T51, T52, T101, T102, T106, T117, T119, T124

UVIS: Carrying out Solar and Stellar Observations of Atmospheric Hazes and Gases

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 'EUUVFUV' 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 was able to observe solar occultations. The occultations provided 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 EUUVFUV scans usually cover all or a portion of the disk, but provide degraded vertical resolution. The EUUVFUV observations taken at a variety of phase angles throughout the mission provided information on the haze scattering phase function. Below in Fig. 3 is an example of inbound and outbound EUUVFUV 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 EUUVFUV

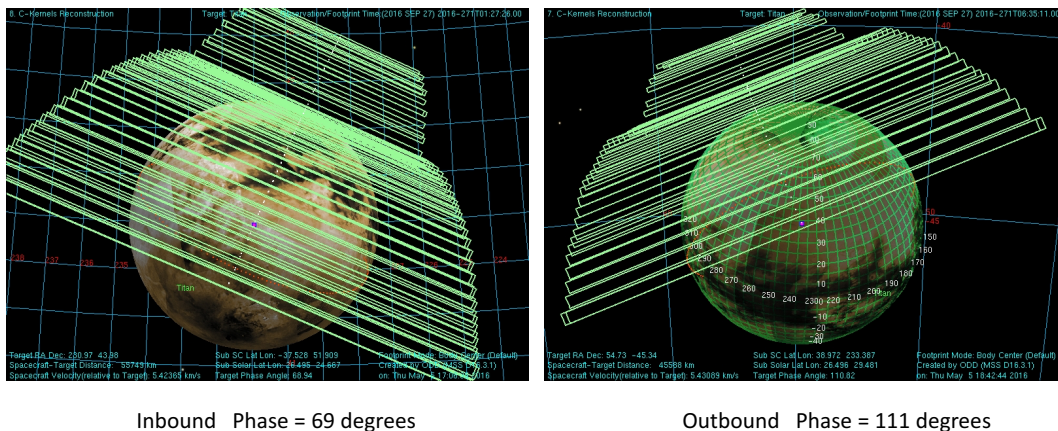


Figure 3. UVIS Titan Scans

VIMS; Imaging 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 spanned 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 five 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 was the best compromise between atmospheric scattering (mostly haze), and solar luminosity and detector sensitivity (Signal to Noise ratio). The footprint was at best 1km/pixel when the VIMS instrument was 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

TOST Representation over Time

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