Adding "Missed" Science to Cassini's Ops Plan

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The phenomenal success of the Cassini Mission at Saturn is largely due to flagship instruments, in a target rich environment, for a long period of time, executing almost error free complex mission operations. A smooth transition from cruise operations through the prime science mission and extended science (Equinox) mission culminating in the currently executing Solstice mission has folded in necessary procedural alterations due to improved understanding of the spacecraft, instruments, uplink and planning systems as well as additional science objectives. These have come with the maturation of the mission along with management of workforce reductions. One important set of operational changes has been initiated due to scientific findings highlighting "missed" science opportunities. This is the case for the Titan Meteorology Campaigns and Saturn Storm Watch Campaigns. These observations involve long term monitoring of the atmospheres of Titan and Saturn while the spacecraft and science teams are focused on other high priority targets of opportunity (like Enceladus). Our objective in this paper is to emphasize how a non-invasive strategy to get additional remarkable science was conceived and implemented in a mission with an already well defined operational plan. To illustrate this we will detail Titan Meteorology Campaign and Saturn Storm Watch Campaign integration and implementation strategies as well as the scientific goals and achievements of both.

Nomenclature

CSM	=	Cassini Solstice Mission
IDS	=	Interdisciplinary Scientist
MAPS	=	Magnetospheric and Plasma Science
OST	=	Orbital Science Team
PSG	=	Project Science Group
RBOT	=	Reaction Wheel Assembly Bias Optimization Tool
RSS	=	Radio Science Subsystem
SOST	=	Satellites Orbital Science Team
TEA	=	Titan Exploration at Apoapses
TMC	=	Titan Meteorology Campaign
TOST	=	Titan Orbital Science Team
TWT	=	Target Working Team

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I. The Mission, Spacecraft, Instruments and Operations

The Cassini-Huygens mission to Saturn is a collaborative effort of NASA, ESA, and the Italian Space Agency. The spacecraft launched on October 15, 1997 on a Titan IV-B/Centaur launch vehicle. After seven years, 3.2 billion kilometers (2 billion miles), and 4 gravity-assist flybys of other planets, it entered orbit on July 1, 2004[1]. The Cassini Orbiter also carried along the Huygens probe, destined to measure Titan's atmosphere *in situ* and land on Titan's surface. The probe was deployed on December 25, 2004. Three weeks later, on January 14, 2005, it entered Titan's atmosphere and landed on the surface 2 hours later. The probe was equipped with six instruments to study Titan, Saturn's largest moon and returned spectacular results[2]. The spacecraft studied the planet, its rings, and its magnetosphere over the course of 76 varied orbits in the prime mission. To study Saturn's satellites, the spacecraft made targeted flybys of Phoebe, Hyperion, Dione, Rhea, and Iapetus, along with 3 flybys of Enceladus, and 45 of Titan. In summary, the Cassini prime mission was the most complicated gravity assist tour ever flown[3].

Cassini completed its initial four-year mission to explore the Saturn System in June 2008 and the first extended mission, called the Cassini Equinox Mission, in September 2010. Now, the healthy spacecraft is making exciting new discoveries in a second extended mission called the Cassini Solstice Mission (CSM). The mission's extension, which goes through September 2017, is named for the Saturnian summer solstice occurring in May 2017. The northern summer solstice marks the beginning of summer in the northern hemisphere and winter in the southern hemisphere. Since Cassini arrived at Saturn just after the planet's northern winter solstice, the extension will allow for the first study of a complete seasonal period. Among the most important targets of the mission are the moons Titan and Enceladus, as well as some of Saturn's other icy moons. Towards the end of the mission, Cassini will make closer studies of the planet and its rings. Current planning continues for the F ring and proximal orbits leading to end of mission. F ring orbits extend till April 23, 2017 followed by proximal orbits ending on Sept 15, 2017. Finally the spacecraft will be on a ballistic impact trajectory followed by atmospheric entry (and end of mission) on Sept 15, 2017.

The Cassini spacecraft communicates with Earth largely through one high gain antenna but also carries two low gain antennas. Three radioisotope thermoelectric generators (RTG) provide power. Cassini's 12 science instruments are grouped into three categories: Optical Remote Sensing, Fields/Particles/Waves, and Microwave Remote Sensing. The Optical Remote Sensing suite is comprised of a visible wavelength imaging camera (Imaging Science Subsystem, or ISS), an ultraviolet imaging spectrometer (UVIS), and infrared instruments (Cassini Infrared Spectrometer, or CIRS, and Visible and Infrared Mapping Spectrometer, or VIMS). The Fields/Particles/Waves suite is comprised of a magnetometer (MAG), cosmic dust analyzer (CDA), radio and plasma wave system (RPWS), ion and neutral mass spectrometer (INMS), plasma spectrometer (Cassini Plasma Spectrometer, or CAPS), and a magnetospheric imaging instrument (MIMI).The Microwave Remote Sensing suite is comprised of RADAR and the Radio Science Instrument (RSS), both of which use the high-gain antenna as an instrument. Figure 1 identifies the science instruments on the Cassini spacecraft. Cassini's instruments have returned a daily stream of data from Saturn's system since arriving at Saturn in 2004 (The CAPS was turned off in 2011). The Cassini mission requires operations on a global scale, and in multiple time zones. In the final spacecraft configuration, the instruments were all mounted to the body of the spacecraft instead of a scan platform, which posed the single greatest challenge to operation complexity. The entire spacecraft must be rotated for any one instrument to point at a desired target, and the entire spacecraft must be rotated to point the high-gain antenna to earth to downlink the collected data. However, the optical remote sensing instruments are roughly co-aligned so they can often collect data collaboratively. On a typical Titan flyby the spacecraft collects science data for 30-40 hours by pointing the spacecraft at a variety of targets. One instrument at a time controls the pointing of the spacecraft (prime), and other instruments (riders) may "ride along" and collect data at the same time if the selected orientation is useful to them. There are some operational restrictions to riding along;

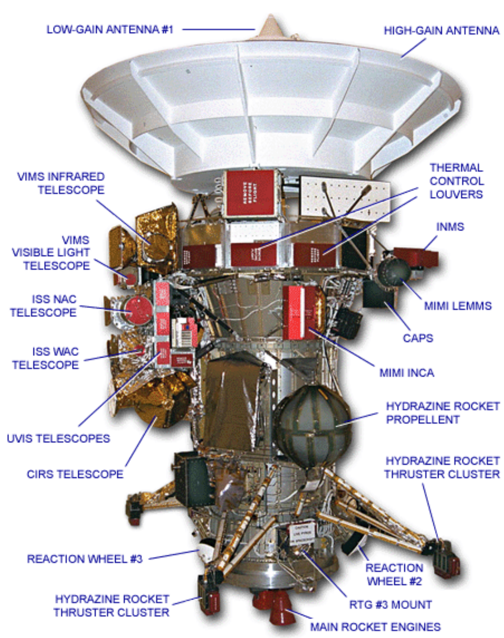

Figure 1: The Cassini Spacecraft

for instance, the two Microwave Remote Sensing instruments (RADAR and Radio Science) are both major power consumers and cannot be operated simultaneously. After the Jupiter flyby during Cassini cruise, a “waypoint” strategy was adopted wherein the spacecraft attitude at the start and end of observations was determined by the science planners before the instrument teams planned their observations. The waypoint attitudes were chosen to leave the spacecraft at a safe attitude between observations. Waypoints include, but are not limited to, the center of the Earth and locations in the Saturn system. Each sequence contains approximately one waypoint per day. Groups of science observations must start and end at the same waypoint. All science observations are bracketed between turns to and from that waypoint, lasting 20-30 minutes. The spacecraft turns its high-gain antenna to the Earth once a day to downlink data. These downlink passes can also be used to uplink new commands and execute manoeuvers.

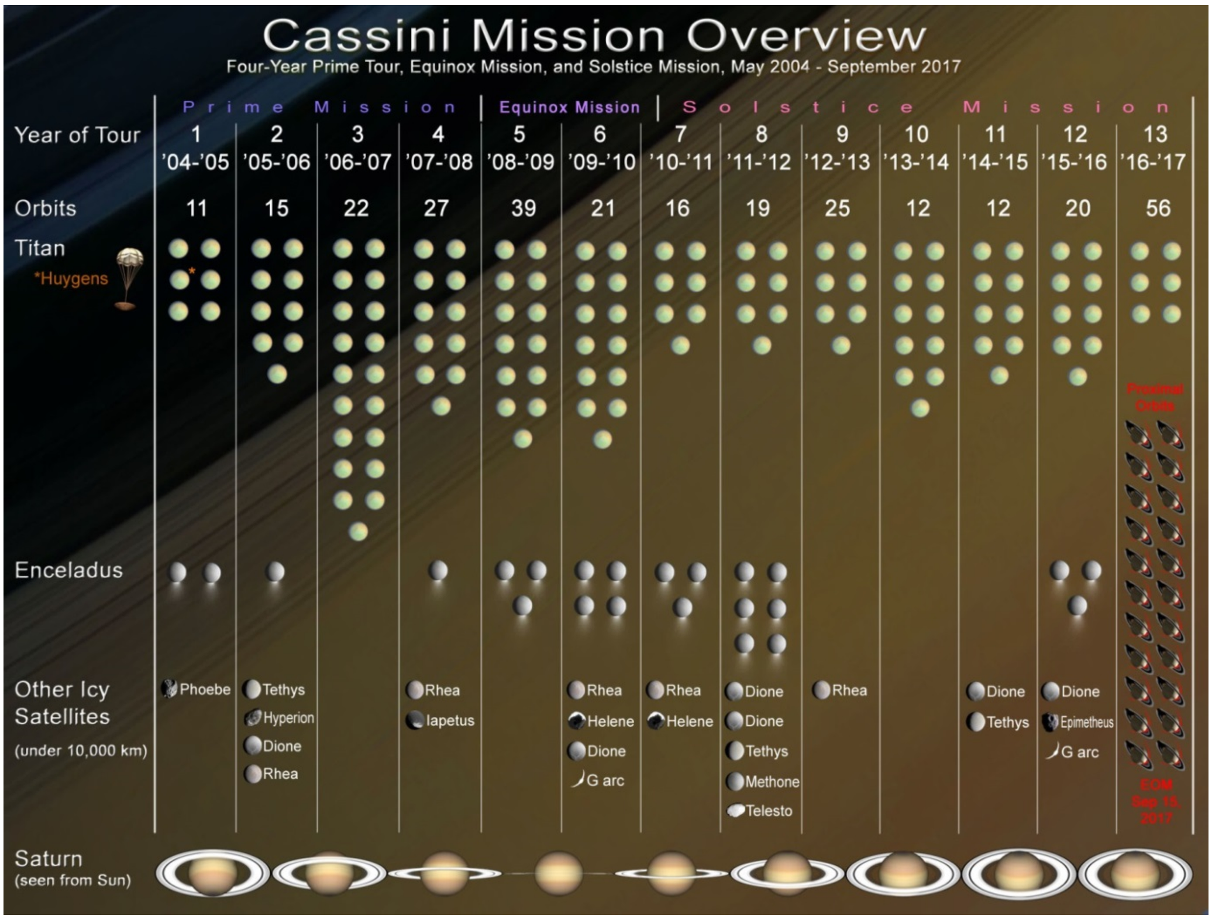

Figure 2: Cassini Mission Overview. A yearly summary of the number of orbits and flybys for the entire mission from 2004 through 2017. Figure courtesy David Seal, NASA/JPL

II. How Cassini Plans Science in Solstice Mission

The chosen trajectory for the Cassini Solstice Mission (CSM) contained a wealth of competing multi-disciplinary science opportunities (see Fig. 2). Making the most of these opportunities presented challenges in allocating observing time to different disciplines and instruments, and in preserving the precise timing required for individual observations when there can be a gap of years from initial high level planning to execution. Fairly allocating observing time among the disciplines required intense advance planning, complicated by needing consensus among the various disciplines. To accommodate all of these concerns, the science planning process was segmented along science discipline lines[4].

After the release of the final trajectory, Science Planning divided the entire trajectory into smaller segments that were assigned to a science discipline working group. There are six discipline working groups, made up of science planning engineers, scientists from instrument teams, and interdisciplinary scientists. Each working group focuses on a different aspect of Cassini science: the Titan Orbiter Science Team (TOST) concentrates on Titan observations, the Satellite Orbiter Science Team (SOST) on observations of all other satellites, and the Saturn and Rings Target Working Teams (TWTs) are responsible for Saturn and the ring system, respectively. The Magnetosphere and Plasma Science (MAPS) TWT focuses on Saturn's magnetosphere, while the Cross Discipline TWT considers all science objectives during apoapse periods. Each TWT or OST's segments include opportunities especially of interest to that TWT or OST. For example, TOST segments generally run from a day before each Titan encounter closest approach to a day after.

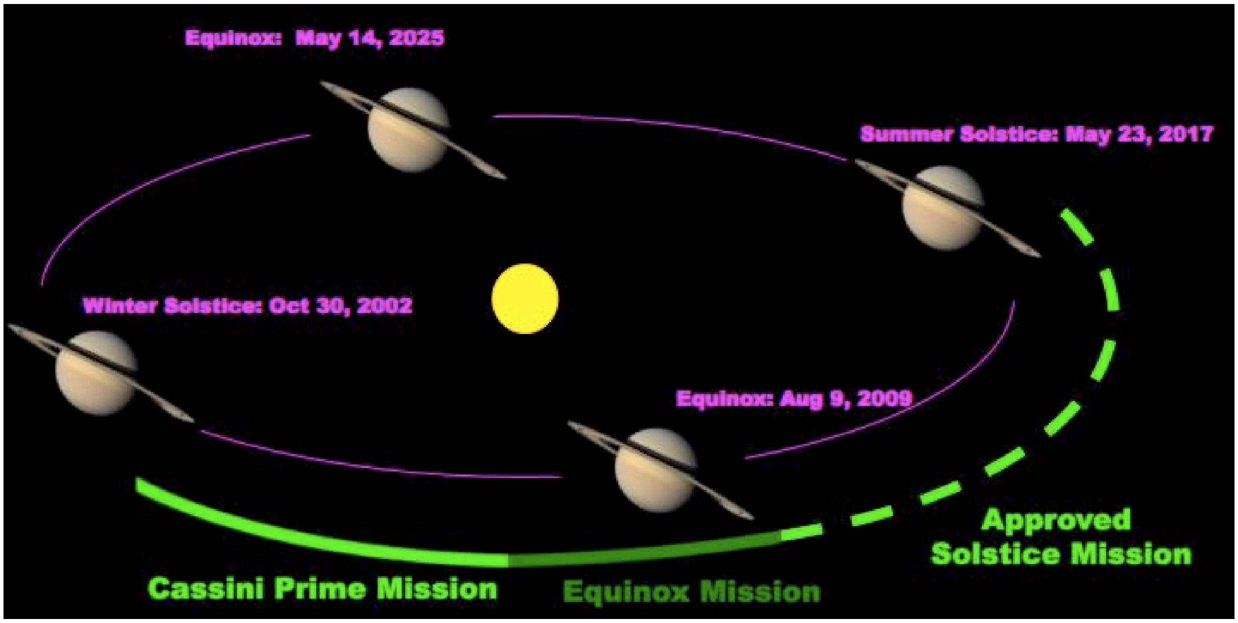

Figure 3. Phases of the Cassini Mission. The Cassini Prime Mission ran from just after winter solstice to just before Equinox. The Equinox Mission was centered on Equinox; the Solstice Mission will last until Saturn's summer solstice.

The science observations contained in each discipline segment was considered against one more metric. CSM funding levels is significantly lower than prime and extended mission funding. Consequently, all CSM science is driven by a carefully honed set of prioritized science objectives. To establish these objectives, each discipline working group identified their top priority science objectives for the CSM. These objectives either *i)* addressed the goal of observing seasonal change in the Saturnian system, understanding underlying processes, and preparing for future missions, or *ii*) were new questions that arose out of prime and extended mission science (e.g. determining the composition and distribution of Titan's newly discovered lakes). The Project Scientist then constructed a matrix of CSM science objectives, and slotted them as Priority 1, 2, or 3. Each discipline working group ensured that any observations planned for the CSM meet the Priority 1 objectives and as many Priority 2 and 3 objectives of the CSM as is possible within the observation time allotted to that discipline. Each working group was responsible for developing fully integrated timelines of the science that will be accomplished during their segments. Fully integrated segments are delivered to the Science Planning Team, which combines the segments into 10 week sequences that are uplinked to the spacecraft at the end of the implementation process. Each discipline developed its own method of getting from raw unintegrated segments to detailed designs ready to be included in a sequence. We are now almost into the fifth year of solstice mission planning and operations and have been very successful. The Cassini project is now finalizing the F-ring and proximal orbits trajectory. Proximal orbits span from 2017-113 (April 23) to 2017-258 (Sept. 15) with 22 orbits over a 6.5 day period at the end of which the spacecraft on ballistic impact trajectory will impact on 15 Sept. 2017[1.]

The "creation" of discipline working groups resulted in each segment focusing on their preferred target (e.g. the Saturn segments focused on Saturn) and so there were naturally instances of "missed" science opportunities for other "out of discipline" targets. It was therefore important to find a way to add some of those "out of discipline" observations without impacting the discipline science being planned. Two successful approaches to this issue are the

Titan Meteorology Campaigns (TMC) and Saturn storm watch campaigns, both of which will be described below. There is also major impact to the science observation placement and design due to the adherence to RBOT, a way to protect the reaction wheels on Cassini to ensure the continuous success of the mission.

III. RBOT (RWA Bias Optimization Tool)

Cassini-Huygens is a three axis stabilized spacecraft using three electrically-powered reaction wheels (also called momentum wheels) for routine control of the spacecraft's orientation. They provide a means to trade angular momentum back and forth between spacecraft and wheels. At launch three wheels were mounted near the bottom of the spacecraft, mutually perpendicular to each other. The fourth reaction wheel was a spare that could be articulated into a position in order to take over from any one of the others in case of failure. In 2001–02, reaction wheel #3 exhibited signs of bearing cage instability[6]. As a result, reaction wheel #4 was articulated to align with reaction wheel #3. Beginning in July 2003, Cassini has been controlled using wheel #1, #2, and #4. The fact that there was no spare wheel added to the importance of efforts to protect the wheels. The operational aspects of the mission impose a number of requirements on the reaction wheels[6]. The reaction wheels must provide sufficient torque for various attitude maneuvering tasks subject to maximum wheel speed and torque limitation. Near zero wheel rates must be minimized to prevent large attitude error build up that could trigger an autonomous fault protection response (transition to thruster control). The reaction wheels must have sufficient margin to absorb the momentum build up due to small environmental torques such as solar radiation torque and RTG torque. Finally, in order to avoid excessive friction loading on the reaction wheel ball bearings (especially an issue when they are operated at low spin rate) and thus preserve RWA health, the operations of the wheel must be performed in such a way to minimize the time the wheels spent inside a low rpm limit. The need to protect the reaction wheels lead to the birth of RBOT[6,8] and the RBOT process, by which AACS (Attitude and Articulation Control System) generates RWA rate bias commands for the Cassini spacecraft. RBOT's algorithm optimizes wheel speeds to minimize low RPM dwell time, RPM over-speeds, zero crossings, and total revolutions. If a science observation resulted in an "unhealthy" RWA state, the scientists would be asked to redesign the observation to make it "RBOT friendly". In some cases, observations could be removed entirely from the sequence if they could not be redesigned to be compatible with RBOT rules. This was frustrating to the science teams, and a great deal of additional work for the flight team. In response, AACS developed basic rules that science teams could use when developing their pointing designs which could help produce "RBOT-friendly" designs[8]. These conditions are absolutely necessary for health and safety of the spacecraft. However these have further increased the number of "missed" scientific opportunities. One constraint that was put into place as the solstice mission started was the so-called "two out of three" rule[7] : "*no more than two of the following three items shall be included in any segment: i. Downlink rolls (e.g. rolls about z) and other science pointing activities where Neg-Z to Earth angle is less than 15 degrees, ii. Rolls about one of either the spacecraft x or y axes-typically this will be an x-axis roll for calibration of the MAG instrument, iii. Pointing changes for other science (e.g., ORS) activities that share a common pointing*." The rule was meant to apply to segments in the apoapses (outside 20Rs); by making these parts of Cassini's orbit less work-intensive for the AACS team, more time could be dedicated to devising RBOT strategies for segments in the periapsis region (usually the region of higher priority science), giving those segments more planning flexibility. This constraint has been followed diligently. Though overall the RBOT process has been a boon for Cassini science,

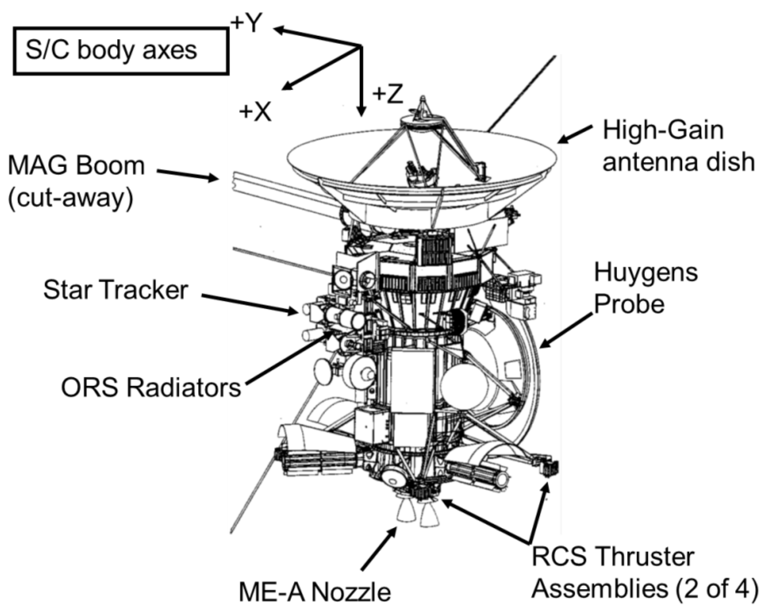

Figure 4: Cassini Spacecraft showing the direction of the three axes

it impacted planning for Titan long-range observations. The rest of this paper describes how the Titan science teams have learned to work with the RBOT process. We will see in the next sections how TMC planning depends on RBOT safe turns.

IV. Science Planning with emphasis to Titan

In the solstice mission Titan science was to be planned only during the TOST segment during and around the planned flybys. A TOST segment generally runs from a day before each Titan encounter closest approach to a day after. The CSM TOST planning used a successful "jumpstart" process prior to the delivery of the trajectory[7]. The jumpstart process was driven by three main objectives: the desire to balance Titan science across all flybys, the desire to increase Titan science by influencing the flyby altitudes in the Cassini Solstice mission and also to find an efficient way to use the Titan scientists' time. However as time progressed it was realized there were several instances of "missed science" due to the fact that Titan science observations were only being scheduled in the TOST segments. TOST leads and scientists realized, that in order to get a real picture of Titan's changing appearance as the seasons moved towards northern summer, it was necessary to capture "snapshots" which would be planned outside the realm of TOST segments and spread across other disciplines' segments.

V. Missing Science gave birth to Titan Metereology Campaigns (TMC)

Even after years spent in orbit around Saturn and dozens of flybys of Titan, the Titan science community needed to find a process which would ensure Titan observations at regular intervals. Several different science campaigns required this support.

Changes in weather patterns have accompanied Titan's seasons. In 2004-2005 large convective methane cloud systems were common around Titan's South Pole[9,10] including one observation of possible surface flooding[9], which appeared to have given way to cloud outbursts at lower latitudes[11,13]. Cassini observed Titan on April 26, 2008 and then only at Northern latitudes, missing a huge low latitude tropical cloud outbreak on April 14 2008 seen by ground based observers[11] (Figure 5) These low latitude clouds became less common in time, and clouds were seen further north as the northern vernal equinox approached. In 2009 clouds at high-north latitudes had become more common and extensive although they still differed in morphology from the south-polar clouds seen early in the Cassini mission[13]. Mid-latitude clouds tended to be smaller and have elongate morphologies. Also VIMS had observed a large north-polar ethane cloud[12] that seemed to be deteriorating. The overarching objective was to determine how the distribution and behavior of clouds change as northern spring begins. In order to monitor the change of cloud systems it was necessary to have frequent observations. Cloud appearances are sporadic and not necessarily related to a Titan flyby. In order to monitor Titan with the change of season, Titan needed to be observed all the time, not just in Titan segment during the Titan flyby. Low resolution is sufficient to detect and locate clouds and large-scale haze structure.

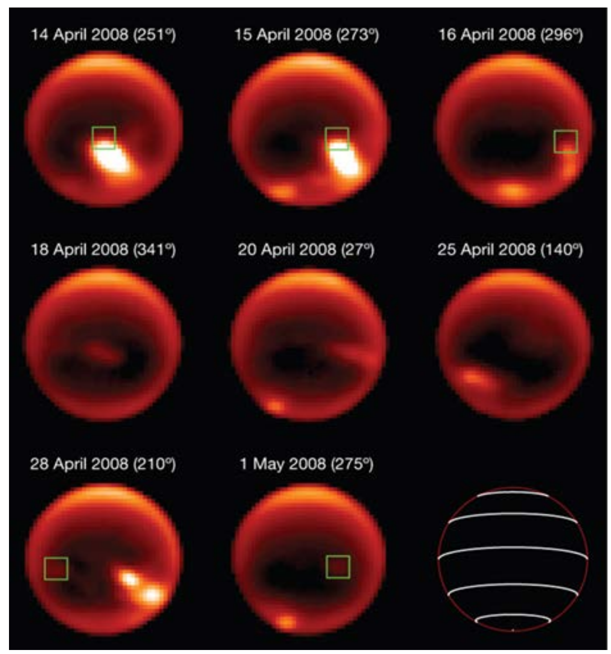

Figure 5: Images of Titan showing a huge low latitude cloud outbreak April 2008 Clouds were first detected on 13 April 2008. Images from 28 April 2008 and 1 June 2008 show a faint cloud persisting over the same location as the north westernmost extent of the initial large cloud from 14 April 2008 (15° S, 250° W; green box), perhaps indicating that the initial cloud outburst may have been localized here (Schaller, et al[10])

Titan has a massive atmosphere laden with layers of photochemical haze. Images of Titan from Voyagers 1 and 2 revealed a hemispheric contrast and a nearly global 'detached' (forming a distinct local maximum) haze layer near 350 km altitude at latitudes outside of the polar vortex[14,15]. The persistent detached haze layer observed by Cassini was found to be at an altitude of over 500 km[19,17] which was higher than the Voyager observations by over 150km. This needed to be investigated further with Titan haze observations at regular intervals.

During the Voyager encounter in 1980 (Titan northern spring equinox), a dark polar collar or hood was seen at high northern latitudes,.[14,15], and the situation was reversed two seasons later when Titan was observed by Hubble Space Telescope (HST)[16] in 1994-1995. The arrival of Cassini in the Saturnian system afforded a new perspective on Titan. Assuming the seasonal cycle repeats, the northern spring equinox seen by Voyager 1 was to be observable by Cassini's extended mission in 2009-2012. It was anticipated that the UV-dark polar hood would switch hemispheres early in northern spring. Indeed, several features reminiscent of the Voyager appearance were already observable in data from Cassini's first encounters (TA and TB) in 2004 October and December[19.] There was no south polar hood visible in 2004 and a detached haze layer was observable against the blackness of space at all latitudes and appears to merge with a complex of haze material standing high above the north polar region[18].

These investigations and more necessitated the Titan Meteorology Campaign (TMC) in order to not have to rely only on data from (roughly) monthly Titan flybys. For such observations we needed a more "regular" observation scenario. For such observations low resolution is sufficient to detect and locate clouds and large scale haze structures. Distant flybys would be sufficient for this purpose.

Finally in September 2008 (within Cassini extended mission), a distant Titan monitoring campaign began which promises to continue throughout the rest of the mission. These observations provide isolated snapshots and are intended to improve our understanding of how often there are clouds on Titan, how quickly they appear and dissipate, where they are appearing as the seasons change, how fast and in what direction the winds blow and also how the haze evolves with the seasons. There have been hundreds of these short observations requested; this is an ongoing process. These requests are not more than once a day and usually a few every week. The goal is to get as many as possible integrated into the final observation plan. These observations have been instrumental in addressing Titan science goals. Planning and implementing them is the focus of the next section.

VI. Initial Requirements and Implementation of TMC

Preliminary Titan internal meetings were held to agree on the least intrusive strategy for TMCs, to be put forth to the science planners and the Cassini project in early 2008. Scientists initially proposed specifications for TMC observations of a range < 9 million km (pixel scale ~ 50 km), phase angle < 90 degrees for cloud observations and > 90 degrees for haze observation. The time with the ORS instruments pointed to Titan would be approximately 30 minutes, with the desired data volume to be negotiated for each instance. ISS would be the prime instrument with the CIRS and UVIS teams riding along. "Prime" is the instrument whose commands control the spacecraft pointing. Once all the primes have been decided, "Rider" observations are placed into the database. These are observations that run simultaneously with the prime observation and collect data without control over the pointing of the spacecraft. Two methods of implementing TMCs were suggested:

(1) OpNav Strategy: Optical navigation (OpNav) is the use of pictures of target bodies in spacecraft orbit determination (OD) (see Section I).

Opnavs start at a waypoint or a downlink and end at a downlink or a different waypoint. The opnav team also implements its own turns. A typical opnav request will start from a waypoint, slew to a satellite, take a picture, then slew to the next target and so on. It then slews from the last target to the downlink attitude. The pictures are then transmitted to the Earth. If the request does not end at a downlink, the pictures are transmitted the next time the spacecraft is at a downlink attitude. The Titan team proposed a strategy similar to the OpNavs as the least intrusive method for implementing TMCs. Just before or after a downlink, science planning would do a waypoint turn to Titan and a 15 minute ISS prime observation and then SP would do a waypoint turn to target. The observations would have to be next to the downlinks. This would achieve the waypoint orientation for that day of the segment, a significant savings of time and effort. However, if an OpNav was already in place, OpNav would turn to Titan followed by a 15 minute ISS observation and an SP turn to target. TMC observations would be put on the other side of down link.

(2) Standalone observation : The other option would be a standalone observation which could be moved anywhere in the day of the segment. This would be more flexible for the scientists, but could prove more disruptive to the planning process.

To do a study of the time required for each proposed option, the range and phase of every downlink in the Extended Mission was calculated to see if it met Titan Monitoring Campaign requirements. Turn times were calculated for turns from Earth and Titan and Titan to Saturn. The time was calculated for both options with an additional 15 minutes margin added in the event of a longer-than-usual turn. It was no surprise that the standalone observation strategy (plus time for an additional waypoint turn) was always larger than the OpNav strategy. However, option 1 was not entertained, due to its greater work load for Cassini science planners. The choice was the second option modified to streamline the process. Each TMC was set to begin at 40 minutes after the downlink. This process is still being used.

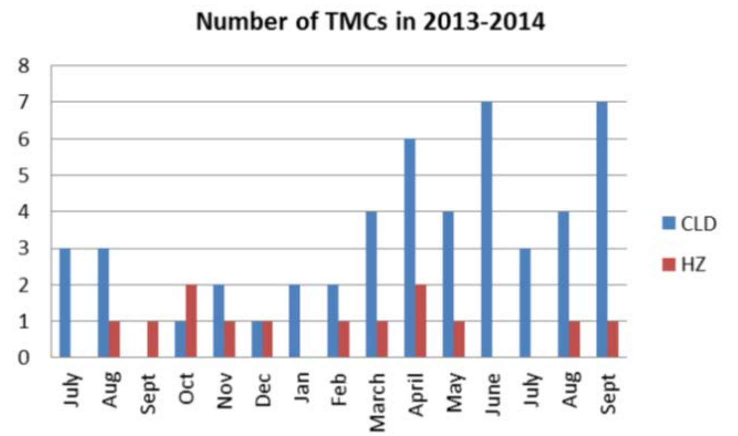

Figure 6: Number of "Cloud" and "Haze" observing planned TMCs between July 2013 and September 2014, the number varies every month.

VII. Current Status of TMCs.

Many Titan TMC are requested. These are short requests about 30 minutes on Titan on roughly 50% of time during the apoapsis time frame outside +/- 18 Rs (hence handled by XD) and are also integrated by other disciplines. Ideally 6-8/month are required. Agreed-upon observing requests are recorded in the Cassini Information Management System (CIMS). This is the starting point for planning observations. Discussed below is the step by step progression of the TMC implementation.

Started in XM: The observations are split into 3 range bins: <1Mkm (R1); 1 to 2 Mkm (R2); > 2Mkm (R3). R1 requires a mosaic 1X2 aligned along the North/South poles. The start and return waypoints are assumed to be –Y to Saturn and –X to Sun. Observations with phase angle < 90 degrees are cloud observations, observations with any other angle is for haze observations. ISS is the prime instrument with the VIMS, CIRS and UVIS teams riding along. The entire allocated data volume was decided to be ~75Mb (10 Mb for VIMS; 18 Mb for CIRS; 35 Mb for ISS; 4.5 Mb for UVIS). The end result was about 300 requests entered into CIMS across all of XM for consideration by the TWT leads.

Revised for Solstice Mission: The Titan group met with implementers and identified areas for easing their work load. The TMC were made independent of secondary so that all RBOT changes could easily be accommodated. Efforts were made for them to start at the RBOT friendly waypoints identified. Margin was added for unexpected changes in secondary. The fixed duration and data volume aspects were maintained. Integration leads requested blocks that were multiples of an hour. The observations continued to be split into the same range bins. However R1 required a 2X2 mosaic so that the observations were independent of the secondary. R1 increased in duration by 35 minutes to get the additional 2 footprints. The observations were split into phase bins (for example <30, 30-60, 60-90) and prioritized for lower phase and closer range. The UVIS team chose to drop out of the campaign. The data volume was changed to ~65Mb for R2 and R3 and ~ 125 Mb for R1. Additional time margin was needed for implementers because the RBOT secondaries were not known during CIMS entries. Observations were made multiples of an hour with R2 and R3 being 90 minutes long and R1 observations being 2 hours long.

Revised for RBOT constraints: The RBOT protective restrictions impact the integration of TMCs due to the "two out of three" rule (see Section III). In practice, for the majority of apoapse time this means choosing one type of roll--either downlink rolls or a MAG calibration roll--and pointing at or near Saturn. The majority of Cassini observations away from periapse periods are of Saturn or objects close to Saturn (for example the rings or inner satellites), which comfortably keeps the spacecraft pointed within a single 30 degree cone. Titan, however, is often more than 30 degrees away from Saturn as seen from Cassini; any potential TMCs occurring during this geometry are removed from further consideration. Figure 7 shows how the two of three rule significantly reduces the possible TMC candidates.

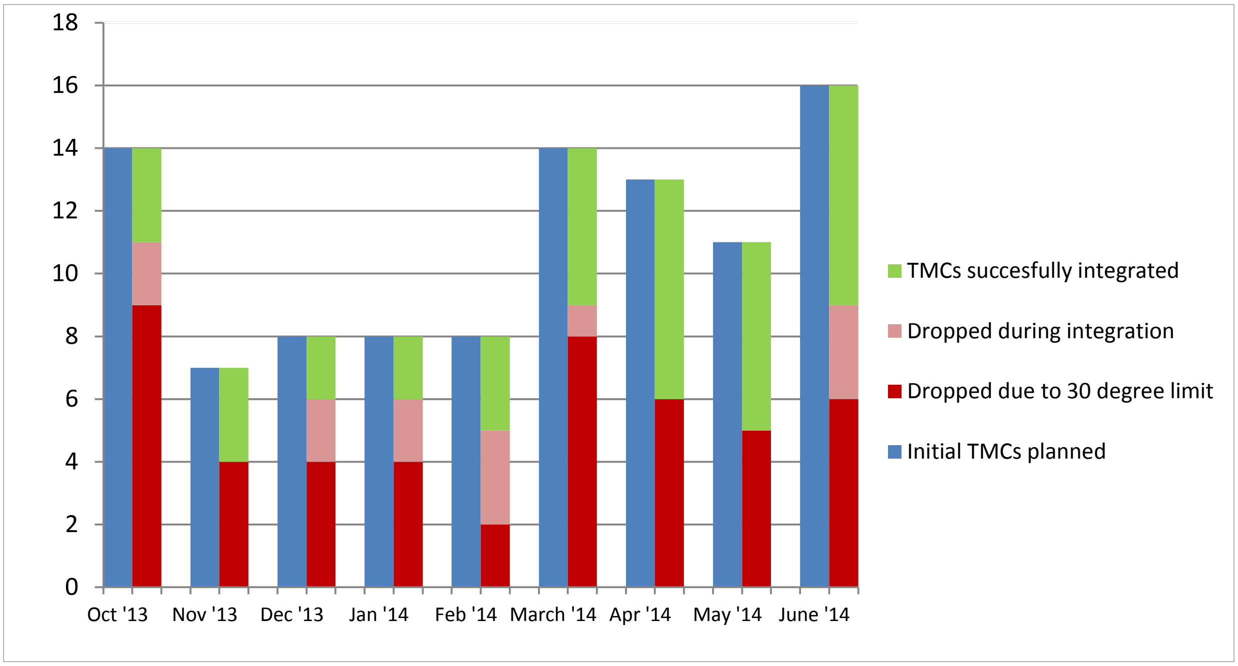

Figure 7: shows the number of TMCs which met the geometric constraints and were subsequently dropped due to RBOT and other integration constraints ending with on many cases TMCs lesser than the required number of 6-8/month

In several sequences the orbit geometry of where Cassini is relative to Saturn and Titan means that a large fraction of the proposed TMC observations are rejected from the integration process due to the 30 degree cone restriction. The AACS team agreed to explore the possibility of relaxing this constraint for the TMC observations because the RBOT rules applied across the entire mission have led to a significant reduction in the workload for the AACS team. As a test case, we are planning TMCs with Saturn-Titan angle >=50 degrees for the S85 (running from August 1 – October 6, 2014) and S86 (running from October 6 – December 17 2014) sequences. If the results of RBOT are encouraging, more TMCs could be added to the process.

Limited number of TMC candidates added back: During periods when there are downlink rolls the 2 of 3 rule may also be satisfied if an observation is adjacent to the downlink and the required spacecraft orientation keeps the -Z to Earth angle at 15 degrees or less which means if using the optical instruments the desired target is 75 to 105 degrees away from the Earth. Adding back any TMC opportunities during these geometries increased the number of TMC candidates.

Addition of UV3 images to cloud observations: Geometric and RBOT constraints seriously reduced TMC haze observations. Specifically, in 2011 it was observed that 10 months passed at a critical part of Titan's seasonal cycle without any UV3 images using the preferred UV3 filter, which is the best for detecting the detached haze, at a critical part of the Titan seasonal cycle. This was mitigated by adding a "haze segment"—observations using the UV3 filter, which is the best for detecting the detached haze--to all the TMC cloud observations. We also needed to add data volume to cover the additional filter

Importance of TMCs during conjunction periods: During conjunction, when Saturn cannot be seen from ground based telescopes, Cassini is the only way to observe Titan for a 3 month period. The TMCs planned during those conjunction time periods—roughly once per Earth year-- were given higher priority because Cassini would be the sole observer of Titan. The TWT leads are requested to give importance to TMCs over other scientific observation during these times.

IX. Science Goals met by TMCS

Monitoring Titan's Seasonal Weather Pattern

A major goal of TMCs is monitoring Titan methane cloud pattern changes, which has been very successful thus far. The first major low latitude cloud event was observed at ~~247° W in April 2008 by ground based observers [11] followed by an observation at ~320°W in September 2010, by Cassini's Imaging Science Subsystem (ISS). In both cases, cloud activity was observed at low latitudes over several weeks[11,13]. ISS observations in October 2010 of a region east of the cloud outburst revealed differences in surface brightness along the southern boundary of an extensive dune field. Some of the bright terrain bordering it was darkened by >10% while adjacent areas remained unchanged. However, in many areas the change has been short-lived: Only some of the darkened area persisted through 29 October, and even more territory had reverted by 15 January 2011. Although there is evidence that liquids have flowed on the surface at Titan's equator in the past, to date, liquids had only been confirmed on the surface at polar latitudes, and the vast expanses of dunes that dominate Titan's equatorial regions required a predominantly arid climate. Cassini's Imaging Science Subsystem detected, with the help of a TMC a large low-latitude cloud system early in Titan's northern spring followed by extensive surface changes (spanning more than 500,000 square kilometers) in the wake of this storm. The changes are most consistent with widespread methane rainfall reaching the surface, which suggests that the dry channels observed at Titan's low latitudes are carved by seasonal precipitation [21]. Cassini and Earth-based observers continue to monitor Titan frequently (typically at least a few times per month). However, clouds have been rare since the 2010 outburst[22], suggesting that enough methane was removed from the atmosphere and the lapse rate sufficiently stabilized to decrease cloud activity. A similar, although shorter, lapse followed the 2004 south-polar storm[10,13]. As a result, clouds may not pick up until the onset of convection at mid northern latitudes anticipated in late northern spring, although most models had predicted that this increase would occur well before 2013[22]. Continuous monitoring of the Titan cloud system by the continuous TMC campaigns should have answers to this important question.

Monitoring Titan's Haze

Titan has a massive atmosphere laden with layers of photochemical haze. The persistent detached haze layer was found to be at an altitude of over 500 km which was off the Voyager results (see section V). More recent Cassini TMC observations have shown a dramatic change in the vertical structure of this haze, with a persistent 'detached' layer dropping in altitude from over 500 km to only 380 km between 2007 and 2010[17]. The temporal change is found to be due to an altitude drop in the gap in the haze. The width of the gap increases with time. The evolution and width of the gap is what is found to be important for seasonal models of haze evolution. These measurements connect the Cassini observations with those made by Voyager almost one seasonal cycle earlier. These observations also lend insight into properties of Titan's extensive haze. Discovery of the altitude of the detached haze as seen in Cassini images in 2004 prompted prediction of seasonal variations in the altitude of the detached haze[19,23]. TMC data provide new detail on the time and rate at which the phenomenon occurs. A striking feature is that the change occurs most rapidly quite close to equinox, providing strong support for the idea that a seasonal dynamical or coupled dynamical/photochemical/microphysical process is responsible.

Titan Polar Hood changes

TMC data has been instrumental in uncovering the following changes in the Titan polar hood. Northern spring equinox on Titan occurred on August 11, 2009. In March of 2012 ISS saw the first evidence for the formation of a polar hood in the atmosphere above Titan's South pole[17]. Views of the limb showed an optical thickening primarily at about 360 km altitude across a few degrees of latitude centered on the pole. Two or more distinct layers were seen, both near the pole and at other latitudes. The highest of these, near 360 km altitude, hosts the embryonic polar hood. On June 27, 2012 ISS observed the pole from high latitude[18]. These images show a distinct and unusual cloudy patch, elongated and not centered on the pole and with an elevated perimeter. The morphology and color indicate an unfamiliar (for Titan) composition and dynamical regime. The interior of the feature consists of concentrations of cloud/haze organized on spatial scales of tens of kilometers. Its morphology is reminiscent of the open cellular convection sometimes seen in the atmospheric boundary layer over Earth's oceans. During the observation of Titan, this feature completed a little over one rotation around the pole, providing direct evidence for a polar vortex rotating at a rate roughly consistent with angular-momentum-conserving flow for air displaced from the equator[17,18].

Other Observations

Observations from VIMS and ISS show localized but extensive surface brightening in the wake of the September 2010 cloudburst observed by a TMC[24]. Four separate areas on Titan, all at similar latitude, showed similar changes. A general pattern to the time-sequence of surface changes is observed. After the cloudburst the areas darkened for months followed by brightening for a year before reverting to the original spectrum. Scientists concur on the process driving the brightening but the chemical composition of the solid layer remains unknown. Evaporative cooling of wetted terrain may play a role in the generation of the layer, or it may result from a physical grain-sorting process

X. Titan Exploration at Apoapses (TEA)

Another dedicated long range Titan observation campaign are the TEAs (dedicated Titan Exploration observations at Apoapsis). These observations, which take place over periods of days to weeks, occur 1-2 times a year at ranges of ~1MKm with low to moderate phase. The TEA campaign started in the Solstice mission with the first observation being in June 2011. The goal is to get ~2 TEA opportunities per year (i.e. individual TEA observations in multiple observation periods in two XD apoapse a year). The CIRS instrument is the prime instrument with ISS and VIMS riding along. The primary science driver for the TEA's is to observe the onset and evolution of methane clouds on Titan using ISS and VIMS. The secondary science driver is to detect trace constituents and isotopic ratios from long CIRS integrations. Since ISS and VIMS have square arrays, it is CIRS that determines the secondary orientation. A north/south alignment gives pole to pole latitude coverage. An east/west orientation yields spectra over a wide range of emission angles. New stratospheric species are most easily observed at high emission angle due to a longer slant path through Titan's stratosphere. We expect the TEAs to play a major role in studies of seasonal change on Titan using CIRS data. In August 2009 Titan passed through northern spring equinox, and the southern hemisphere passed into fall. Since then, the moon's atmosphere has been closely watched for evidence of the expected seasonal reversal of stratospheric circulation, with increased northern insolation leading to upwelling, and consequent down welling at southern high latitudes. If the southern winter mirrors the northern winter, this circulation will be traced by increases in short-lived gas species advected downwards from the upper atmosphere to the stratosphere.

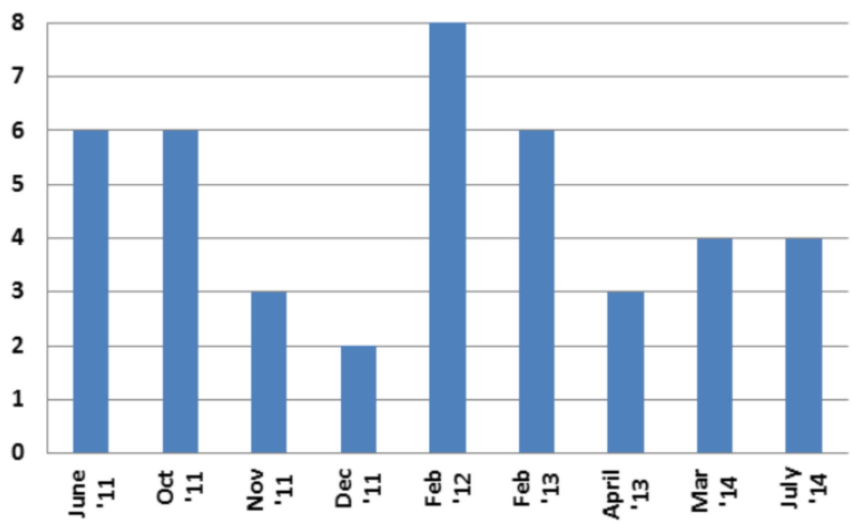

Figure 8: Number of days of planned and executed TEA from 2011-2014

TEA results have confirmed that seasonal change is well underway on Titan[20]. The 2011 TEA observations showed dramatic change between June (no HC3N in the south) and October (clear HC3N in the South). The 2012

TEAs show no HC3N observed at equator with North and South poles having comparable amounts of HC3N. In 2013 CIRS detected large enhancements in C6H6 and HC3N over Titan's South Pole. Prior to 2010, all these molecules were seen in the north, but not in the south. Now, post-equinox we see a buildup in the south. TEAs are also used to calibrate earth based far-IR measurements of Titan. We have a dedicated TEA in July 2014 to use CIRS' far-IR focal plane to calibrate Earth-based Titan observations from Herschel. Figure 8 shows the number of days of dedicated TEA campaigns in the last three years.

XI. Saturn Storm Watch

As a result of Cassini's downsizing after the Prime & Equinox Missions as mentioned in Section II, the Saturn working group decided to consolidate most of its efforts to observe Saturn in detail to a multi-week period about every 6 months apart (called a CAKE = Cassini Apoapsis for Kronian Exploration). This left a gap in observations that hampered their ability to see the birth and evolution of storm systems that seemingly pop up at random times. Often the amateur community would observe such storms more routinely and Cassini would not be able to quickly adapt designs to observing said storms

A solution to this was the introduction of the Storm Watch campaign. By these Saturn is observed in a non-intrusive manner every time Cassini returns to a Saturn-centric waypoint. These are not prime observations and so do not involve any pointing changes. Also minimal data volume is required. Storm Watch Campaigns started on 12 October 2010. At this point images were being added to the end of ISS SATELLORB observations. SATELLORB observations are designed specifically for small satellite astrometry. They can be done at any time, although times away from periapse periods are better. During a single observation images are taken of as many satellites as possible. The seventh and eighth SATELLORB with storm watch images at the end were taken on 4 & 5 December 2010 respectively. The Great Storm detection was in one of the images taken on December 5th in the eighth storm watch image set. Till April 2011 storm watch triggers were added to ISS SATELLORB observations only. After that storm watch triggers were requested to be added to pretty much every suitable ISS observation.This eventually evolved into adding riders for storm watch purposes instead of adding triggers at the end of the prime observation design. The first of these dedicated riders was on 13 Jul 2011. Beyond this till date the STORM WATCH riders only happen on observations in XD and MAG segments. Saturn Storm Watch campaigns are similar to the TMCs in that both of them were developed with the realization of missed science opportunities. Both of these were smoothly planned into the existing integration plan non-invasively.

The mechanics for these observations would be to flag every time Cassini returns to a safe spacecraft attitude where the cameras are pointed towards Saturn. Typically, there are two minutes of turn margin built into spacecraft turns. During this two minute window, ISS inserts a rider which observes Saturn with 5 WAC filters (ISS) for 4.4 Mb VIMS takes a 16x16 mrad^2 and over its entire spectral range using only 2 Mb. The small amount of data volume used makes it rare that there are issues with inserting these observations.

From Saturn Storm Watch images scientists learned that Saturn's atmosphere is primed like an earthquake fault ready to go off. In December 2010 (Great Storm observation mentioned above), a giant planet-encircling storm, the likes of which happen every 20-30 years, erupted as a single localized event in Saturn's northern hemisphere. Fortuitously, there was a Storm Watch observation on the exact day of the storm's birth. Over the next years, we have had observations that allowed the monitoring of the storms evolution until such time when it could be intensively studied during the Saturn CAKEs. The Saturn atmospheric scientists eagerly wait for other Saturn surprises.

XII. Integrating TMCs and Saturn Storm Watch Campaigns

When integration begins for a particular period of time TMC requests already exist in the observation database. They are placed just after every downlink provided certain geometrical requirements are also satisfied. Storm Watch campaign requests do not exist in the database at the start of integration. TMCs are short, 1.5-2 hours long, with relatively small data volume requirements so the primary constraint on the number of this type of observation that can be included in the final integrated plan is actually compatibility with the pointing required for all the other types of observations included. In order to extend the life of the spacecraft's reaction wheels constraints usually referred to as the "two of three rule" (see Section III) were placed on the combination of multi-axis rolls and other science activities during times away from periapse period. In practice for the majority of apoapse time this means one type of roll, either downlink rolls or a MAG calibration roll, and pointing at or near Saturn. The majority of Cassini observations away from periapse periods are of Saturn or objects close to Saturn (for example the rings or inner satellites) which comfortably keeps the spacecraft pointed within a single 30 degree cone. Titan however is often more than 30 degrees away from Saturn as seen from Cassini. Usually this means that TMCs cannot be integrated when the Titan-Saturn separation is more than 30 degrees (ongoing mitigation efforts are described in section VII). Sometimes the Titan-Saturn separation has to be significantly less than this for example if there is an observation of a satellite, say Rhea, that is 20 degrees away from Saturn off the right ansa and Titan is 20 degrees away from Saturn off the left ansa then the spacecraft pointing would not be restricted to a 30 degrees cone since these two pointings are 40 degrees apart. For this example, approximately speaking, a TMC could only be integrated if Titan was within up to 10 degrees from Saturn off the left ansa or 20 degrees from Saturn off the right ansa (not up to 30 degrees away from Rhea since there will also be multiple observations of Saturn, the rings etc , which means that Saturn will nearly always have to fall within the 30 degree cone as well). During periods when there are downlink rolls the two of three rule may also be satisfied if an observation is adjacent to the downlink and the required spacecraft orientation keeps the -Z to Earth angle at 15 degrees or less that is if using the optical instruments the desired target is 75 to 105 degrees away from the Earth (details in section VII). During integration there are multiple, often conflicting, desires that have to be considered. Often this means that conflicting requirements that cannot be simultaneously satisfied for example either rolling downlinks or a MAG calibration roll but not both and one has to be selected at the expense of the other. In practice requirements are prioritized for instance MAG calibration rolls are more important than having rolling downlinks and usually Saturn must fall within the 30 degree cone allowed for pointing. One of the first things done during integration is to calculate the Titan-Saturn and Titan-Earth angles for every TMC request as well as the relative position of Titan with reference to Saturn, off the left/right ansa north/south. These angles slightly influence the choice of whether the downlinks will be rolling or non-rolling. Within the limitations of the two of three rule as many TMC requests as possible are then integrated until a desired number per month value is achieved. Often it isn't possible to achieve this target due to the two of three rule and individual TMC requests are given a lower priority than being able to observe Saturn.

Storm Watch campaign observations are not considered during the main part of integration, choosing prime the observations that will control the spacecraft pointing. Once all the primes have been decided rider observations are placed into the database. As discussed in Section I, these are observations that are simultaneous with the prime observation and just collect data, they have no control over the pointing of the spacecraft. At this point storm watch observations are placed as riders on the last two minutes of suitable prime observations. A suitable prime observation is one where the waypoint for that period points the optical boresight at the center of Saturn. Every period of time has a waypoint, this is a fixed orientation of the spacecraft, at which every observation has to start and end. A waypoint with the optical boresight pointed at the center of Saturn is common. Every turn of the spacecraft has time, called pad, added to the calculated duration. When within 1,000,000 km of a target, that pad has to be at least 2 minutes. To facilitate storm watch observations teams were requested to always use pads of at least 2 minutes when the waypoint was Saturn. The pads are there to allow for turns taking longer than calculated. It was estimated that turns would only extend into the pad ~10% of the time and experience has shown that that figure is roughly correct. This means that for periods when the waypoint is Saturn ~90% of all observations spend the last two minutes staring at Saturn. Once all the primes have been integrated the time ordered listing is examined for all periods when the waypoint is Saturn. This is done only for XD and MAG TWT segments as discussed in the previous section. The aim is to fit the disk of Saturn in a single WAC and this only happens at ranges >~30 Rs. So there are no storm watches in the periapse segments. Storm watch rider observations are then placed on the last two minutes of prime observation with a Saturn waypoint. The number of storm watch riders in a single observation period (end of one downlink to the start of the next) is limited to no more than 2-3 and the separation between them is kept to no less than ~6 hrs. Efforts are made to plan one every 24 hrs. This means that in the end only about 1/3 - 1/2 of eligible prime observations actually have an associated storm watch rider. Figure 9 shows a typical XD segment with 4 planned TMC observations and several Saturn Storm Watch candidates.

SP_203SA_WAYPTTURN102_PRIME	2014-102T14:35:00	000T00:40:00	2014-102T15:15:00	NAC to Saturn
NEW WAYPOINT	**2014-102T15:15**		**2014-104T12:55**	**NAC to Saturn**
ISS_203RI_PROPRETRG003_PRIME	2014-102T15:15:00	000T01:00:00	2014-102T16:15:00	NAC to Rings
CIRS_203RI_COMPLIT001_PRIME	2014-102T16:15:00	000T07:00:00	2014-102T23:15:00	CIRS_FP1 to Rings
CIRS_203RI_COMPLIT002_PRIME	2014-102T23:15:00	000T07:00:00	2014-103T06:15:00	CIRS_FP1 to Rings
VIMS_203SU_SOLARPORT001_PRIME	2014-103T06:15:00	000T03:40:00	2014-103T09:55:00	UVIS_SOL_OFF to Sun
ISS_203RF_FMOVIE001_PRIME	2014-103T09:55:00	000T16:00:00	2014-104T01:55:00	NAC to Rings
SP_203SA_WAYPTTURN108_PRIME	2014-108T14:00:00	000T00:30:00	2014-108T14:30:00	NAC to Saturn
NEW WAYPOINT	**2014-108T14:30**		**2014-109T15:00**	**NAC to Saturn**
ISS_203OT_SATELLORB002_PRIME	2014-108T14:30:00	000T00:40:00	2014-108T15:10:00	NAC to Satellites
CIRS_203SA_MIRMAP001_PRIME	2014-108T15:10:00	000T12:00:00	2014-109T03:10:00	CIRS_FP3 to Saturn
SP_204SA_WAYPTTURN117_PRIME	2014-117T18:16:00	000T00:40:00	2014-117T18:56:00	NAC to Saturn
NEW WAYPOINT	**2014-117T18:56**			**NAC to Saturn**
ISS_204TI_M90R3CLD117_PRIME	2014-117T18:56:00	000T01:30:00	2014-117T20:26:00	NAC to Saturn
ISS_204OT_SATELLORB001_PRIME	2014-117T20:26:00	000T01:00:00	2014-117T21:26:00	NAC to Satellites
CIRS_204SA_COMPSIT001_PRIME	2014-117T21:26:00	000T23:00:00	2014-118T20:26:00	CIRS_FP3 to Saturn
SP_204SA_WAYPTTURN119_PRIME	2014-119T18:01:00	000T00:49:00	2014-119T18:50:00	NAC to Saturn
NEW WAYPOINT	**2014-119T18:50**			**NAC to Saturn**
ISS_204TI_M90R3CLD119_PRIME	2014-119T18:50:00	000T01:30:00	2014-119T20:20:00	NAC to Titan
MIMI_204SU_AURPTG004_PRIME	2014-119T20:20:00	000T10:20:00	2014-120T06:40:00	NEG_Y to Saturn
SP_204SA_WAYPTTURN123_PRIME	2014-123T18:01:00	000T00:40:00	2014-123T18:41:00	NAC to Saturn
NEW WAYPOINT	**2014-123T18:41**		**2014-125T11:26**	**NAC to Saturn**
ISS_204OT_SATELLORB004_PRIME	2014-123T20:11:00	000T01:00:00	2014-123T21:11:00	NAC to Satellites
MAG_204SU_CALROLL001_PRIME	2014-123T21:11:00	001T01:19:00	2014-124T22:30:00	NEG_X to Earth (0.0,0.0,-30.0 deg. offset)
ISS_204TI_M60R3CLD125_PRIME	2014-124T22:30:00	000T01:30:00	2014-125T00:00:00	NAC to Titan
SP_204SA_WAYPTTURN127_PRIME	2014-127T11:16:00	000T00:30:00	2014-127T11:46:00	NAC to Saturn
NEW WAYPOINT	**2014-127T11:46**		**2014-129T11:41**	**NAC to Saturn**
ISS_204TI_M60R2CLD127_PRIME	2014-127T11:46:00	000T01:30:00	2014-127T13:16:00	NAC to Titan
ISS_204OT_SATELLORB006_PRIME	2014-127T13:16:00	000T01:00:00	2014-127T14:16:00	NAC to Satellites
VIMS_204ST_STARCAL002_PRIME	2014-127T14:16:00	000T01:00:00	2014-127T15:16:00	VIMS_IR to 177.19/-26.75
	2014-127T15:16:00	000T06:44:00	2014-127T22:00:00	NAC to Saturn
ISS_204RI_ARCORBIT001_PRIME	2014-127T22:00:00	000T18:00:00	2014-128T16:00:00	NAC to Rings
VIMS_204RI_APOMOSAIC001_PRIME	2014-128T16:00:00	000T08:00:00	2014-129T00:00:00	VIMS_IR to Rings
SP_204SA_WAYPTTURN129_PRIME	2014-129T11:01:00	000T00:40:00	2014-129T11:41:00	NAC to Saturn
NEW WAYPOINT	**2014-129T11:41**		**2014-132T11:01**	**NAC to Saturn**
UVIS_204SA_AURSLEW001_PRIME	2014-129T11:41:00	001T05:40:00	2014-130T17:21:00	UVIS_FUV to Saturn
NAV_204SK_OPNAV301_PRIME	2014-130T17:21:00	000T01:30:00	2014-130T18:51:00	NAC to Satellites
ISS_204RI_RDCOLSCNM001_PRIME	2014-130T18:51:00	000T05:00:00	2014-130T23:51:00	NAC to Rings
SP_204SA_WAYPTTURN131_PRIME	2014-131T11:01:00	000T00:40:00	2014-131T11:41:00	NAC to Saturn
UVIS_204IC_ALPVIR001_PRIME	2014-131T11:41:00	000T03:00:00	2014-131T14:41:00	UVIS_FUV to 201.298/-11.161
UVIS_204TE_ICYLON001_PRIME	2014-131T14:41:00	000T07:00:00	2014-131T21:41:00	UVIS_FUV to Tethys (0.286,0.0,0.0 deg. offset)
UVIS_204EN_ICYLON001_PRIME	2014-131T21:41:00	000T02:00:00	2014-131T23:41:00	UVIS_FUV to Enceladus (0.286,0.0,0.0 deg. offset)

Figure 9: A list of observations in a typical cross discipline segment which shows 4 planned TMC observations on days 117, 119, 125 and 127 (to understand naming convention as an example TMC on day 117 is ISS_204TI_M90R3CLD117_PRIME) Also there are storm watch campaigns planned at the end of all the observations shaded in yellow.

XIII. Conclusions

The Titan Meteorological Campaigns have proved to be very successful and are now one of the most important vessels for Cassini Titan science. These campaigns will continue as planned through the proximal orbits till end of mission to monitor Titan climate changes and for other science goals. Both TMCs and Saturn storm watch campaigns have been instrumental in bringing forth phenomenal scientific results which would have been "missed" with regular science operations. The nonintrusive and successful way of how both these observations entered regular Cassini mission plans should show the path to future missions as well.

XIV. Acknowledgments

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