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CASSINI’S SOLSTICE MISSION

David Seal
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109-8099
seal@jpl.nasa.gov

Robert Mitchell
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109-8099
robert.t.michell@jpl.nasa.gov

With the recent approval of NASA’s flagship Cassini mission for seven more years of continued operations, dozens more Titan, Enceladus and other icy moon flybys await, as well as many occultations and multiple close passages to Saturn. Seasonal change is the principal scientific theme as Cassini extends its survey of the target-rich system over one full half-season, from just after northern winter solstice at arrival back in 2004, to northern summer solstice at the end of mission in 2017. The new seven-year mission extension requires careful propellant management as well as streamlined operations strategies with smaller spacecraft, sequencing and science teams. Cassini’s never-before-envisioned end of mission scenario also includes nearly two dozen high-inclination orbits which pass between the rings and the planet allowing thrilling and unique science opportunities before entry into Saturn’s atmosphere.

I. INTRODUCTION

The Cassini-Huygens program, a joint mission between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI), completed its Prime Mission (PM) in June of 2008 and its first mission extension, named the Equinox Mission (EM), in September of 2010.

Saturn is arguably the most target-rich environment in the Solar System (see Figure 1), with 53 named moons; an active Saturn atmosphere, magnetosphere, and network of aurorae; a highly dynamic and diverse ring system; a prominent system of rings and ringlets, both dense and diffuse; active water ice geysers spouting from the south polar region of Enceladus; and a very large satellite - Titan - with the only appreciable atmosphere of any moon and more Earth-like features than any other extraterrestrial body in the Solar System. Titan is the only object in the solar system other than Earth possessing an active hydrological cycle with surface liquids, meteorology, and climate change. Nowhere else beyond Earth can one find in one area so many intriguing phenomena with dynamics on the time scale of a human lifetime.

After a highly successful orbit insertion in June of 2004 and Huygens Probe descent to the surface of Titan in January of 2005, Cassini went on to complete a four-year prime tour of Saturn, its rings, satellites, and magnetosphere via 75 orbits around Saturn, 45 close Titan flybys, ten close icy satellite encounters, and dozens of Saturn, rings, and Titan radio and Solar occultations. The Equinox Mission, so named since it included key observations during Saturn’s northern vernal equinox in August of 2009, supplemented Cassini’s prime tour with just over two more years of observations, including 28 additional close Titan flybys, 11 icy satellite encounters, 64 orbits around Saturn, and dozens more radio and Solar occultations.

Figure 1: The Saturnian system.

Cassini has demonstrated a sustained and staggering pace of scientific discovery, with over one thousand independent publications in prominent science journals. This was made possible by highly successful spacecraft operations and maintenance, sequencing, instrument monitoring, and risk management. In particular, the Cassini navigation team has also excelled at the most complex gravity-assist trajectory ever flown, with a challenging schedule of over 250 planned maneuvers to date. Approximately one-third of these were ultimately able to be cancelled without appreciable propellant or science cost.

The understanding of the Saturnian system has been greatly enhanced by the Cassini-Huygens mission. Fundamental discoveries have been made across all disciplines of study at Saturn, and new questions have arisen deserving of more detailed study. Furthermore,
the Saturnian system has already shown signs of seasonal change across its nearly 30-year cycle. Since the Pioneer, Voyager and Cassini missions have all observed the system at nearly the same seasonal period (see Figure 2), further study is crucial to understand temporally dependent processes and prepare for future missions.

Figure 2: Seasonal cycle (top) - Pioneer/Voyager epoch at Saturn (middle) and Cassini epoch (bottom). Note the proximity of the Pioneer and Voyager seasons to that of Cassini, as compared to the full cycle.

All spacecraft subsystems and instruments remain healthy, and substantial margins exist (and had been projected) in both bi- and mono-propellant systems used for orbital maneuvering and attitude control. Lastly, power levels from Cassini’s Radioisotope Thermal Generators (RTGs) allow for continued science operations for many years.

For these reasons, and with the support of the outer planet and decadal survey scientific community, NASA approved a seven-year Solstice Mission (SM) extension, to be conducted from October 2010 through September 2017, and continue scientific investigations in a similar, though slightly reduced pace as the prime and equinox missions. The mission is so named because it carries Cassini through the Saturn north hemispheric summer solstice in May of 2017, when the Sun achieves its maximum northern declination.

II. SOLSTICE MISSION SCIENCE OBJECTIVES

Key science objectives of the Solstice Mission, organized by discipline, are listed as follows.1 Throughout all disciplinary studies, measurements of seasonal and temporal change are a common thread, as Saturn’s system moves from equinox (Sun in the plane of the equator / satellites) to solstice (Sun at its maximum declination [northern] of 27°).

Titan

• Observe Titan’s hundreds of lakes (some are even designated “seas”) as signposts of climate change, and study the cycling of methane and ethane between Titan’s poles.

• Quantitatively test the hypothesis that lakes are connected to an underground methane aquifer system.

• Study meteorological effects of the seasons.

• Observe changes in global circulation in the stratosphere, including polar vortices.

• Determine the presence / absence of an internal magnetic field and/or ocean.

Icy Satellites

• Study temporal variability of Enceladus’ endogenic activity via plume observations, towards understanding of orbital modulation and therefore the plumes’ driving mechanisms, and longer time scale effects to constrain the lifetime of individual vents.

• Probe Enceladus’ interior structure via mapping of its gravitational field.

• Search for intrinsic or induced magnetic field of Enceladus.

• Study composition of gas and dust in Enceladus’ plumes via deep plume passages.

• Map Enceladus’ surface thermal radiation to constrain vent temperatures.

• Investigate possible geological activity on Dione; search for signs of current or recent activity such as plumes or thermal emission.

• Investigate further the possible ring of material orbiting Rhea, and the nature of its internal differentiation.

Rings

• Take advantage of new trajectory geometries and the varying ring opening angle as seen from Earth to study microstructure in both thick and diffuse rings.

• Further constrain ring age via direct measurement of ring mass and incoming meteoroid mass flux.

• Observe seasonal variation of ring spokes.

• Study ring gaps and determine presence and role of cohabitating moonlets.

• Track evolving “propellers” and collisions in the F ring.

• Conduct targeted compositional and high-resolution observations in regions lacking said measurements.

Saturn

• Complete studies of seasonal atmospheric change from ring shadowing (northern to southern).

• Examine changes in Saturn’s internal rotation rate and probe higher-order gravitational harmonics,
towards a better understanding of its internal structure and core mass.

- Determine changes in winds at cloud-top levels.
- Settle issue / debate with atmospheric helium to hydrogen ratio.
- Measure acetylene and ethane to help separate seasonal effects from circulation and upwelling.
- Study seasonal trends in lightning activity.
- Monitor the north polar hexagonal cloud pattern and south pole hot spot (“hurricane”).

**Magnetospheres**

- Assess the nature of the drift in periods between Saturn kilometric radio emission and the deep interior.
- Determine relative contributions of possible sources of plasma in magnetosphere (solar wind, Saturn ionosphere, Titan, rings, icy satellites).
- Examine how Enceladus’ gas production, plume composition and dust-to-gas ratio change seasonally.
- Study the seasonal variability and interplay between the magnetospheric / plasma cycles.
- Examine possible mechanisms that give rise to magnetotail periodicities.
- Resolve key questions of Saturn’s aurorae, including evidence of currents connecting ionosphere and magnetopause.

In addition to these scientific objectives, conceived primarily as continuations of existing objectives whose study was begun during the Prime Mission, Cassini’s end of mission scenario, with 22 orbits passing between the rings and planet, offer never-before-anticipated opportunities to gather groundbreaking science. In many ways, this phase is a completely new mission, much like the Juno mission at Jupiter (which will be taking place at nearly the same time). Science objectives that could be addressed, or significantly improved (from above) in this phase are as follows.

- Improved determination of Saturn’s internal structure, gravity and magnetic fields, and internal rotation rates.
- Measurement of the ring mass, currently uncertain by an order of magnitude.
- In-situ measurements of Saturn’s ionosphere, innermost radiation belts, D ring, and auroral acceleration region (possibly).
- Highest resolution studies of the main rings and atmosphere.

**III. TRAJECTORY OVERVIEW**

The Solstice Mission trajectory is the culmination of two years of development via frequent and iterative interactions between the project, trajectory designers and science community. After careful study, a subset of science objectives were observed to drive the design of different phases. Many activities, such as Enceladus plume passages, require equatorial orbits, whereas others, such as rings or Saturn polar observations, require moderate to high inclination. A variety of mission constraints were also present, such as the propellant available, total mission duration, planetary protection requirements, dust hazard avoidance, and minimum Titan flyby altitudes. Moreover, Titan is the only satellite with sufficient mass to significantly alter the spacecraft trajectory, so each orbit must be designed to return to Titan. Otherwise, the spacecraft remains stuck in one orbit geometry with only a tiny fraction of the propellant required to make significant orbital changes.

The resulting mission spans seven years at Saturn (October 2010 through September 2017) with 54 close Titan flybys, 11 close Enceladus flybys (of which 4 pass through the plumes), six close encounters with other moons, and 155 orbits around Saturn in a wide array of geometries. The final 22 orbits pass between the rings and the planet, some only a few hundred kilometers above the cloud tops, with a final distant Titan flyby acting to push Cassini into Saturn’s atmosphere permanently as its end of mission.

* A single low Titan flyby provides a gravity assist $\Delta V$ of over 800 m/s, over four times the $\Delta V$ available in Cassini’s propellant tanks for the entire Solstice Mission.
trajectory ever flown. Figure 3 illustrates the entire Cassini mission, with the Prime and Equinox Missions at the left half, and the Solstice Mission (again, beginning in fall 2010) at the right half. Each moon icon represents a close encounter with the named body; the Saturnian seasons are illustrated figuratively at the bottom. The view of Saturn from the Sun/Earth is shown to illustrate the varying lighting conditions.

The Solstice Mission begins with a brief low inclination phase (see Figure 4, IN-1), and two encounters are used to set up an extended equatorial orbit phase (EQ-1).

Figure 4: Solstice Mission trajectory, color coded by mission phase. Top: view from Saturn north pole, Sun is up; Middle: equatorial view, Sun at left; Bottom: oblique view.

This phase provides Enceladus flybys early in the SM, near-edge-on rings geometry, high latitude grazing Saturn occultations, and other icy satellite flybys. The second inclined phase (IN-2) provides wide Titan surface coverage, radio and ultraviolet ring and Saturn occultations, rings viewing, and magnetotail passages. The second and final equatorial phase (EQ-2) extends the temporal baseline for Saturn observations (without the rings in the way) and icy satellite encounters, including plume observations at Enceladus. The third inclined phase (IN-3) climbs to the inclination required to set up the final orbits of the mission, as well as providing high phase Titan observations and high latitude radio and ultraviolet Titan occultations.

At the completion of IN-3, one single Titan flyby is used to jump over the entire ring system, from just outside the F ring to between the rings and planet. 22 “proximal orbits” (shown in red in Figure 4; also Figure 5) are completed before a final, more distant Titan flyby lowers the orbit into Saturn’s atmosphere at end of mission.

By following the precedent established by the Galileo spacecraft at Jupiter at the end of its mission, Cassini’s end of mission ensures that the spacecraft will not impact any of Saturn’s satellites at some future time and possibly contaminate a body of potential biological interest. In fact, the entire sequence of proximal orbits, beginning with the final Titan flyby, is entirely ballistic, requiring no further ground intervention or spacecraft capabilities between that flyby and Saturn entry.

The design of the orbits for this mission phase has deliberately put periapsis passages in direct view of Earth in order to optimize the use of Doppler data for gravity analysis of both the rings and Saturn’s interior, as well as to provide a geometry that enables the near end-of-mission occultation experiments. It is also convenient that the final end-of-mission entry into Saturn occurs when communication with Earth is feasible.

Current predictions of propellant margins at end-of-mission show them to be positive but small, so any mission extension beyond September 2017 is not
overly likely, nor is it likely to last beyond a handful of additional week-long orbits.

IV. MISSION AND OPERATIONS CONSTRAINTS

The Cassini Solstice Mission represents a significant departure from the Prime and Equinox missions. This is immediately visible from even a cursory glance at Figure 3; clearly the right half of the chart, i.e. the Solstice phase, displays a moderate reduction in scientific intensity, both in the number of orbits and encounters.

In 2007, as the planning for a second mission extension was begun, it became immediately obvious that the project could not continue operating past the Equinox mission in the same fashion as it had previously. First, despite Cassini’s rapid pace of scientific discovery, it was very unlikely that NASA would continue to fund the project at the same level as the Prime and Equinox missions. With NASA’s impressive suite of upcoming missions such as Dawn, Kepler, Juno, Mars Science Laboratory, and others, and the bulk of Cassini’s primary science objectives having been met to great degree, NASA was appropriately motivated to devote significant funding in other areas. NASA Headquarters (HQ) lavished high praise upon Cassini’s continuing successes, but made overtures that some level of budget reduction would be sought. Therefore, Cassini management concluded (without rancor) that it would behoove the project to develop a proposal at a moderately reduced level that would continue to deliver scientific discoveries befitting a flagship mission. Therefore, the project vigorously undertook the tasks of streamlining its operations processes to allow for a reduction in team sizes, as well as developing a tour of reduced scientific intensity. Levels of 60-70% in both areas, as compared to the Prime and Equinox missions, were sought. Figure 3 bears this out, as the Solstice (right-hand) half of the chart looks to be, on average, 60-70% of the level of the Prime/Equinox half.

This profile was built in to the very design of the trajectory after careful study and many discussions at the highest level of the project. Longer-period orbits were strongly encouraged, with a limited number of shorter-period orbits in a row. Also, the time between targeted encounters was closely monitored to ensure that short transfers, which place a high burden on the navigation and spacecraft teams, as well as requiring significant sequencing effort, were not designed too frequently to be operable by a team at 60-70% total workforce. Fortunately, nearly all science objectives could be fully met under these conditions.

With the Prime and Equinox missions, nearly every day of operations was highly optimized, with close encounters and periapses planned with highly interleaved multi-instrument and often multi-disciplinary science observations. For Solstice, particular focus was given to the highest science objectives, but less optimization and interleaving was to be present away from these time periods. Away from periapses and flybys, Deep Space Network tracking was reduced from the norm of one pass per day to one pass every other day.

In the initial stages of planning the second extension, it was believed that only one or two years was feasible, due to the pace of propellant consumption observed to date (see Figure 6). About 100 m/s of ΔV, or 70-80 kg of bipropellant, was thought to be the required cost of being in orbit at Saturn. And with only 110 kg remaining, the budget seemed to be sufficient only for one to two years of additional operations. Soon after initial planning was begun, however, this conclusion was quickly discounted.5,6

Figure 6: Bipropellant usage (kg) as of the end of the Equinox mission

The propellant costs during the PM and EM phases were found to be dominated by two effects: close periapses at high inclination, and complex and strict geometric targeting to optimize specific scientific measurements (e.g. flying over a particular feature of an icy satellite, as opposed to allowing the encounter targeting to “float” to the least costly trajectory). Relaxing both of these project-imposed constraints - often only slightly - allow for dramatically reduced propellant consumption per unit time and significantly longer potential extensions.

Supplied with a newly understood not-so-stringent budget of approximately 160 m/s, the trajectory designers delivered the Solstice Mission as described in the previous section. And this mission does indeed meet the propellant budget with margin to spare. Figure 7 shows the fuel remaining - both of the bipropellant system, used for large maneuvers, and the monopropellant (hydrazine) system used for small maneuvers and attitude control. By the end of the mission, over 20 m/s of margin is available. (Usable propellant has already been set aside in this analysis.)
During the Prime and Equinox missions, the process used for designing, developing, validating, and executing sequences consisted of one sequence of around five weeks duration in execution, and five sequences in various stages of development, with each development process lasting for 24 weeks. In the Solstice Mission, there will be one sequence of 10 weeks duration in execution and two in development at any given time, with a 22 week development period. The net effect of this, combined with simpler sequences and less frequent satellite encounters, yields an operations process that can be accommodated with a net reduction to 60% engineering workforce. While somewhat less rich in science return, this process will still provide a significant addition to the science results that have been achieved to this point in the mission.

It is also important to note that by project policy, the project’s risk position as it relates to the maintenance and safety of the flight assets is to be unchanged from what it has been up through the Equinox Mission. All necessary spacecraft monitoring, modeling and diagnosis will be continued at the same level of confidence. However, some increased level of risk to the acquisition of science data will be tolerated, at least to the extent that it is consistent with a reduction in the level of staffing to conduct the mission.

Pursuant to this policy, there are two areas in the Project where little if any reduction in workforce was possible: Navigation and Spacecraft Operations. The Navigation Team’s staffing was able to be reduced a small amount because of the reduced tour complexity and generally increased time between satellite encounters, but the navigation functions of orbit determination, maneuver design, and trajectory analysis are still required to the same level of detail and accuracy to ensure that the spacecraft is kept on course with sufficient accuracy to keep propellant consumption within the necessary bounds. For the Spacecraft Operations Team, a slight reduction in staffing was possible because of the reduced complexity of the sequences, but the primary activities associated with keeping a spacecraft of the complexity of the Cassini orbiter operating properly, including the implementation of maneuvers in support of Navigation, were largely unaffected by this. The net result was that the bulk of the workforce reduction required to fit within the 60% allocation for engineering support fell to the sequence design and development teams.

In addition to the reduction in overall staffing level, some internal reorganizations were performed. The sequencing personnel, once divided into two separate teams (one handing over to the other halfway through the implementation process), was combined into one team and training was undertaken to ensure that all team members were versed in the sequencing skills across all phases. The project management was flattened slightly to streamline communications and main-
tain (approximately) the same worker-to-manager ratio, while consolidating some roles and responsibilities.

In addition, formal policies were established to control the growth of optimization and interleaving of science activities, to ensure that the assumptions upon which the budget was approved, teams resized, and the trajectory designed remain valid all the way through to the implementation of the sequences. Trades between science disciplines for time at high priority targets were (and continue to be) vetted at high-level project meetings with representation from all affected parties. Working team sizes are generally smaller, but decision-making is more efficient and there is less optimization per unit time. As Cassini progresses into the Solstice Mission, the project will remain mindful of the processes and constraints in place to determine if further improvements can be made.

V. Conclusions

The Cassini mission has been remarkably successful, having completed its original four-year Prime Mission in orbit at Saturn as well as its 27 month Equinox Mission extension, and now poised to begin its second mission extension with a healthy and fully functional spacecraft and complement of scientific instruments. Scientific discoveries have easily matched, and in all likelihood have exceeded, the expectations at the outset of this endeavor. The prospects for additional exciting discoveries as Cassini enters its seven-year Solstice Mission are excellent. The proposed end-of-mission profile provides for new and unique observational opportunities not available at any prior time in the mission. The prospects for continuing scientific discoveries for Cassini appear to be excellent as the mission continues into its next phase.

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