The Cassini/Huygens Mission to Saturn

The Cassini/Huygens mission to Saturn is a joint endeavor by NASA, the European Space Agency, and the Italian Space Agency to conduct an extensive investigation of Saturn, its atmosphere, rings, satellites, and magnetosphere. The spacecraft was launched in October, 1997, and has completed six years of its almost seven year journey to Saturn with essentially flawless performance. On July 1, 2004, it will arrive at Saturn and begin a four year orbital mission, releasing the Huygens probe in December, 2004 to enter the atmosphere of Titan, Saturn's largest moon. This paper provides an overview of the mission but focuses primarily on the activities over the past year in preparation for Saturn arrival and beginning the scientific observations to be made in orbit. Details are provided on the completion, validation, and uplink of new on-board flight software, development and testing of the sequences to be used for orbit insertion and relay of the data stream from the Huygens probe as it descends through the atmosphere of Titan, and design and preparation of the science sequences to be performed by the orbiter. The past year has been a very productive one for the Cassini/Huygens team and, although much remains to be done before arrival, the work is on schedule, the team is highly motivated and performing well, and an exciting and productive mission is assured.
Abstract
The Cassini/Huygens mission to Saturn is a joint endeavor by NASA, the European Space Agency, and the Italian Space Agency to conduct an extensive investigation of Saturn, its atmosphere, rings, satellites, and magnetosphere. The spacecraft was launched in October, 1997, and has completed six years of its almost seven year journey to Saturn with nearly flawless performance. On July 1, 2004, it will arrive at Saturn and begin a four-year orbital mission, releasing the Huygens probe in December 2004 to enter the atmosphere of Titan, Saturn's largest moon, in January 2005. This paper provides an overview of the mission but focuses primarily on the activities over the past year in preparation for Saturn arrival and beginning the scientific observations to be made in orbit. Details are provided on the completion, validation, and uplink of new on-board flight software, development and testing of the sequences to be used for orbit insertion and relay of the data stream from the Huygens probe as it descends through the atmosphere of Titan, and design and preparation of the science sequences to be performed by the orbiter. The past year has been a very productive one for the Cassini/Huygens team and, although much remains to be done before arrival, the work is on schedule, the team is highly motivated and performing well, and is looking forward to an exciting and productive mission.

Introduction
The past year has been another very productive one for the Cassini Program in its ongoing tasks of flying the spacecraft to Saturn and preparations for executing both the orbiter and probe science missions once at Saturn. The spacecraft continues to perform well, although there have been two hardware anomalies. One is a bearing in one of the reaction wheels, and the other is the Ka-band translator (KaT) required for supporting a two-way coherent Ka-band signal. Details on these problems and the implications to the mission are given later in the text. Complete software reloads for the Command and Data Subsystem (CDS) and Attitude Control Subsystem (ACS) were performed following the conclusion of coding and testing. This new flight software provides all capabilities necessary to execute the orbital science phase of
the mission as well as support the unique "critical mode" sequences that will perform Saturn Orbit Insertion (SOI) and Huygens probe relay. The development of the science sequences that will perform the observations in the tour continued on schedule. The sequence integration process, which produces observation timelines free of conflict among the various investigations, is on track for completion in January 2004. The sequence implementation process, which develops the sequences to a level of detail that allows resolution of all spacecraft operational limitations and constraints, will be completed in January 2005. The remaining sequencing effort, which is the development of all the detailed command parameters and resolution of any residual problems found in the integration and implementation tasks, is planned to be completed on a just-in-time basis during tour operations. A detailed tour operations simulation verification and validation effort was successfully completed with the objective of finding any holes or weak parts in the ground system tools and processes that are planned to support tour operations. No showstoppers were found, but some areas were identified where fixes and modifications to processes and tools are planned to make the overall process more efficient and reliable. Overall ground system development has continued on schedule and is nearing completion.

Figure 1 shows the Cassini flight path from launch to Saturn encounter, with markers for Cassini's
position today, as well as for the two IAF conferences. Straight-line distance to Saturn is about 130,000,000 km and shrinking rapidly. It is now less than three months to when the approach science phase starts in late December, less than nine months to SOI, and a little over a year to the probe mission. The pace and the excitement level are picking up quickly for the Cassini Team.

Navigation Status
All spacecraft navigation activities for the Program continue to perform normally. The approximately annual trajectory correction maneuver (TCM) required for propulsion system maintenance was performed on April 1. This was a 0.5 m/sec, 5 second burn of the main engine. For navigation purposes, this maneuver, TCM-19, could have been designed so that no further maneuvers were required prior to TCM-20 on approach to Phoebe. However, two additional maneuvers are being planned for increased operations reliability later in the mission. TCM-19a is scheduled for September 10, and will be the first use of the Reaction Control Subsystem (RCS) for performing a trajectory correction maneuver since well before the new CDS and ACS flight software was loaded on the spacecraft last spring. There are no plans to use the RCS for propulsive maneuvers, other than this test, between now and the start of the tour after orbit insertion, so this planned exercise of the system is designed to minimize surprises at what will already be a very busy time in the mission. TCM-19b is scheduled for October 1, and will exercise an energy based SOI burn termination algorithm and burn attitude steering algorithm which otherwise would constitute first time events at SOI. The combined effects of TCM-19, 19a, and 19b are designed to set up the trajectory for TCM-20, the Phoebe encounter ten days later, and then the ring plane crossing and SOI three weeks after Phoebe.

Communications During the Orbit Insertion Burn
It is always desirable to have communications from the spacecraft during key mission events in order to understand spacecraft performance and analyze any anomalous performance that may occur. The propulsion system use during Saturn Orbit Insertion certainly qualifies as one of these events. However, the geometry during the burn places the high-gain antenna axis off Earth-line by about 45 deg at burn start, decreasing to about 25 deg at end of burn, well beyond the angle where any communication would be possible. Pre-launch design options to provide communications during the burn focused primarily on another antenna, medium gain and steerable, but for reasons of cost and mass, this option was not implemented and the decision was made to do the burn “in the blind”. A major part of the rationale behind this decision was that, with a round-trip light time of nearly three hours, no real-time interaction would be possible with the spacecraft during
the approximately one and-a-half hour burn, and the spacecraft would have to be capable of handling any anomalies autonomously. The resulting timeline design for this mission phase had the spacecraft turn off Earth line a little over one hour prior to burn start to put the spacecraft in a safe attitude for protection from dust during the ring plane crossing. Following the ring plane crossing, the spacecraft turned to the burn attitude, performed the approximately 1.5 hr burn, and then returned to Earth point, for a total time of about three hours in the blind. However, since that design decision was made, anomalies during critical events on other missions have raised the priorities on having visibility during critical events. The Cassini team was asked to investigate options to provide some degree of visibility just prior to SOI as well as during the burn itself. One troublesome feature of the baseline design was that in the event of a mission catastrophic failure during the blind period that led to no further contact with the spacecraft, it would not be possible to determine whether the failure was caused by an environmental failure, i.e., the ring plane crossing, or by a spacecraft failure related to the long burn.

Three options were developed that provided varying degrees of insight during this period. One was to simply perform the burn with the HGA Earth pointed. Such a non-optimal burn direction would use significantly more propellant but would provide telemetry starting shortly prior to and during most of the burn. No signal would be available for a period of about 28 minutes part way through the burn because the B ring occults Earth. Even in this configuration, visibility would be less than it might appear because of the 64 sec telemetry pickup rate from many of the subsystems. So anomalies leading to a relatively quick catastrophic failure would only be seen in telemetry with fortuitous timing relative to the telemetry pickup schedule. However, one-way Doppler would be available continuously beginning shortly prior to burn start, except for the 28 min outage, which would be a very good indicator of burn performance. Another impact with this option is that the longer burn time required reduces the time available after the burn is complete to collect unique science data, unique because this is the only time in the mission that the spacecraft will be this close to the rings and to Saturn.

A second option was to switch from the HGA to one of the two low-gain antennas, the one co-aligned with the HGA boresight. The LGA performance at these off-Earth angles cannot provide telemetry, even at the lowest telemetry rates, and also cannot reliably provide normal carrier-only acquisition. However, by using a special Radio Science receiver designed to do open loop tracking, i.e., no closed loop phase tracking, a carrier signal can be acquired with margin throughout the burn, except for two periods of occultation by the A and B
rings with a total duration of 53 minutes. This option has no impact on propellant usage or science observing time. The burn attitude and duration in this case is identical to that of the baseline option.

The third option considered was to turn the HGA to Earth-point for a brief period after the ring plane crossing, and prior to the burn initiation. The burn would be in the optimal attitude, but delayed due to the time spent getting to Earth-point, at attitude, and then to the burn attitude. This option would not provide any visibility during the burn, but would allow a differentiation between an environmentally induced failure, i.e., the ring plane crossing, and a burn induced failure, by providing an indication of a safe ring plane passage or not. This option actually reduces propellant usage because it more nearly centers the burn on periapsis than the nominal case, but has the drawbacks of complicating the overall sequence, reduces the time available for autonomous fault recovery, and reduces science observing time.

After consultation with and approval from NASA Headquarters, the decision was made to proceed with the second option – use the LGA and the Radio Science receiver. This provides considerable visibility overall with few penalties. Figure 2 shows a pictorial timeline of events surrounding SOI. Starting from the left, Cassini approaches from below the ring plane, passes through ascending, performs the SOI burn

![Diagram](image-url)
Over about half of the arc length above the ring plane, reorients to Earth point briefly, then executes a science acquisition sequence over approximately the second half of the arc, before reorienting to a safe attitude for the descending ring plane crossing. Following this, both engineering and science data are returned to Earth, and the spacecraft begins its long awaited tour of the Saturnian system.

**Gravitational Wave and Solar Conjunction Experiments**
Cassini prime science objectives during cruise include three gravitational wave search opportunities which occur when the spacecraft is in opposition, and two solar conjunction experiments which are scheduled when the spacecraft is in conjunction. During the past year, one of each of these investigations was completed. Both experiments rely heavily on Cassini's 2-way Ka-band frequency capability which, although only supported by DSS-25 at the DSN's Goldstone facility, and hence only slightly more than one-third of the time during the experiment, nevertheless adds considerably to the sensitivity of the measurements made. The December, '02 Gravitational Wave experiment was very successful. Data analysis is underway, and while no results are available yet, data acquisition went well, with both X-band and Ka-band data capture running at the 95% level. The Ka-band translator (KaT) on the spacecraft has been somewhat erratic in its operation since its first use, but operating strategies, including power cycling and leaving it powered on during extended periods of non-use had largely mitigated the problem. However, during the solar conjunction experiment in June, '03, the KaT was never successfully operated in an effective data collection mode. Analyses and diagnostic efforts are underway, but the prognosis for further use of the instrument is not favorable. Useful data were collected throughout the conjunction period, but were limited to X-band data and Ka-band data coherent with the X-band uplink. No two-way Ka-band data was acquired.

**Reaction Wheel Performance**
For a spacecraft as complex as Cassini, it has been remarkably trouble-free over its six years in flight to date. However, one subsystem that has caused some anxiety is the reaction wheels. The Cassini spacecraft carries four reaction wheels for attitude control, three for prime use and a fourth that can be articulated to replace any one of the three prime wheels. The Reaction Control Subsystem (RCS) is also used for attitude control, using the small thrusters and hydrazine. For the RCS, the primary consumable is hydrazine. For the wheels, the consumable is mechanical wear, generally measured by total wheel revolutions for each unit. Project practice to date has been to use the RCS system in periods of time where the primary activity is maintaining a fixed, or nearly fixed, attitude such as maintaining Earth point, and other
activities requiring minimal turning, and hence limited hydrazine use. Keeping the HGA on Earth point uses about one gram of hydrazine per day. For activities that require considerable slewing of the spacecraft, such as antenna and instrument calibrations, where hydrazine usage could reach levels approaching one kilogram per day, the wheels have been used. The wheels are also used for the Gravitational Wave and Solar Conjunction experiments because these activities require the pointing accuracy and stability that only the wheels can provide.

Beginning in the fall of '02, wheel number 3 began to exhibit signs of occasional increased friction in the bearings. The increased torque requirement to drive the wheel was easily within the capability of the drive motor, and the attitude control capability was unaffected, but it was a cause for concern and careful monitoring. With passing time and events requiring use of the wheels, such as GWE #2 in December, '02 and the new flight software checkout in the spring of '03, telemetry showed that the instances of increased friction and vibration were worsening. Figure 3 shows one example of increased drag and the effects of vibration. Some degree of friction is normal, and varies with wheel speed, but the increased levels shown in the figure indicate clear anomalous performance.

Figure 3
Bearing experts were consulted and the unanimous opinion was that wheel 3 was experiencing a phenomenon known as cage instability. This is caused by a nonuniform dispersal of lubricants within the bearing which causes the cage that holds the balls in place between the races to vibrate against the balls, creating hot spots and wear. No information was found that would give any basis for a prediction of the remaining useful life of wheel #3.

The decision about whether to continue using wheel 3 until it failed and then bring on wheel 4, or to swap to wheel 4 now and preserve the remaining life in wheel 3 was made in favor of the second option. By keeping a still functioning wheel 3, the capability to respond to a failure in either of wheels 1 and 2 could be maintained by bringing wheel 3 back into use at such a time, and moving the articulating wheel to replace another failed wheel. However, confidence is high that the set of wheels 1, 2, and 4 will continue to perform well. Wheel 3 has a different history than the other three, and while it was fully flight qualified, its performance isn't necessarily an indication of the performance of the other wheels.

In July, '03, wheel 4 was brought online in its stowed, original position which was aligned with wheel 1. An attitude control exercise was performed using the set 4, 2, 3 to validate the functionality of wheel 4, which had been run up several times previously in flight, but never actually brought into the attitude control loop. Then wheel 4 was articulated into the position to replace wheel 3 and another exercise was performed to calibrate accurately its exact alignment. A final exercise validated the attitude control capability of wheel set 1, 2, 4, and the plan is to continue with this set for the remainder of the mission. Efforts are under way to evaluate the feasibility of mixed mode operations, a combination of thrusters and two wheels, as a contingency mode should this become necessary later in the mission. While this remains to be confirmed, the idea behind this mode of operation is that two wheels plus thrusters should require less hydrazine usage than pure thruster operation.

**CDS and AACS Flight**

The flight software available at launch for the Command and Data Subsystem (CDS) and Attitude Control Subsystem (ACS) by design did not contain all the capabilities necessary to conduct SOI, probe relay, and the tour phase of the mission. The plan from the outset had been to complete this development during the nearly seven years of flight to Saturn. The first inflight uplink of new software was done in the summer of '00, four years before SOI, to give some inflight experience and burn-in, with time to influence the continuing development as appropriate. In particular, this upload first brought online the validated capability to operate on reaction wheels and
provided several capabilities required for operating in the Saturn tour that were exercised during the Jupiter encounter the following December. The next and planned-to-be final flight software load was sent to the spacecraft and checked out in March and April of '03. This final load supports the special sequences that will operate in “critical mode” on the spacecraft for SOI and probe relay, including all planned fault response capabilities, as well as all needed capabilities for the tour. In addition to extensive ground testing on the spacecraft test bed, a substantial inflight checkout was performed as well. By the time of SOI on July 1, 2004, over one year of inflight operations will have been accumulated on this software. Performance to date has been excellent.

Science Planning
Planning and preparation for the science observations that will be made on approach to Saturn, as well as for the four years of the tour, constitutes a large part of the Cassini Team’s workload. The requirement to do this planning well in advance of performing the observations is driven by the fact that the Cassini spacecraft carries twelve complex and sophisticated instruments, all of which are fixed to the spacecraft bus, and many of which have very different pointing requirements to perform their measurements. In addition, there are numerous constraints driven by other instruments during any given instrument’s observing time to protect their own optics and thermal environment. The process for developing the science observation plan has been developed and in place since May, ’01. The step referred to as integration, in which observing timelines are developed with all observation conflicts among the different investigations resolved, is scheduled for completion in January, ’04. The next step in the process, referred to as implementation, further develops the sequence to the point that all pointing profiles are defined and all constraint violations are resolved, and the data management plan is fully developed. Data management includes the allocation of memory space on the solid state recorder, development of the plan for data playback over the planned DSN passes, and the strategy for data carryover from one pass to the next as required. Except for the fields and particles instruments and some Radio Science activities, data acquisition and data playback cannot be performed simultaneously. Other required support activities, such as engineering subsystem calibrations and navigation, are also included in the implementation product. Implementation for the entire tour is scheduled for completion in January, ’05. After completion, these products go “on the-shelf” until shortly prior to their execution. There is an opportunity for limited observation modifications followed by a period where the final detailed instrument operating commands are generated and the entire sequence is prepared for uplink and execution. The
The science planning process is progressing well and is on schedule.

**Orbit Insertion and Probe Relay Sequence Development**
The sequences that will operate on the spacecraft during the burn for Saturn orbit insertion and during the relay of data to the orbiter from the probe during its descent in Titan's atmosphere are run in what is called "critical mode". In this mode, some of the fault protection responses are disabled to insure that the sequence will run to completion. For all other times in the mission except for launch and an SOI sequence in-flight test, the spacecraft is run in a mode where a fault will halt the executing sequence, put the spacecraft in a safe state, and await further instructions from the ground. This is done to insure that the spacecraft cannot damage itself by continuing to operate in a condition where something has gone wrong. But in the case of SOI and probe relay, failure to run the sequence to completion would have catastrophic consequences to the mission. Note that the probe release from the orbiter is not run in "critical mode" because an aborted probe release can be performed at a later time, up to a point, with minimal consequences.

Development and testing of the two critical sequences has been underway for about two years. At this point, both sequences have completed designs, requirements on flight software are implemented and on-board, and testing has been quite extensive. Further testing will be conducted, and additional reviews will be held, because of the critical nature of these sequences and the dependence of mission success on their proper execution. However, with these sequences in nearly final form with nine months to go to SOI and over a year to probe relay, the Program's risk position is a good one.

**Conclusion**
The past year has been a good one for the Cassini Program. All development activities have continued on schedule, as has the tour science planning. The spacecraft continues to perform very well, although the apparent failure of the KaT will have an impact on the Radio Science investigations and the degraded performance of reaction wheel #3 has used a degree of redundancy. The team is well trained and prepared for orbit insertion, the Huygens probe mission, and the beginning of tour operations. Overall things look very promising for a highly successful and rewarding mission.

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