Cassini-Huygens Engineering Operations at Saturn

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On 30th June 2004 the Cassini spacecraft fired its main engine to maneuver into orbit around Saturn. This paper describes the engineering operations that have contributed to the unprecedented scientific success of the Cassini and Huygens missions, and how engineering operations are planned and implemented in concert with the required sequence of science observations. Frequent Orbit Trim Maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Considerable effort has been invested in detailed planning of the complete set of science observations associated with this Tour, so a robust OTM strategy is necessary to protect this investment by ensuring the spacecraft keeps to the planned trajectory. The paper will describe the OTM strategy, the Inertial Vector Propagator capability, and how this system is used to maintain the Tour and pointing accuracies needed for science operations. During such a long mission, careful propulsion subsystem management is necessary; the paper will describe the monopropellant and bipropellant fuel-side re-pressurization operations used to maintain the main engines in their optimal operating envelope, and to keep the monopropellant thrust at the level required to control the spacecraft during Titan flybys. Attached to Cassini during cruise and early Saturn tour was the Huygens Probe, awaiting delivery to Titan. During an in-flight end-to-end communications test with the probe during the cruise to Saturn, a serious anomaly was discovered in the Huygens receiver. The recovery effort resulted in major changes to the Cassini trajectory, flight software, test program, and mission operations. Cassini released Huygens on 25th December 2004 UTC, setting up the correct entry conditions for the probe's arrival during Cassini's third flyby of Titan. As a result of the major engineering effort to recover the Huygens mission, on arrival at Titan on 14th January 2005, the probe studied the composition of the atmosphere, conducted unprecedented science observations, and the science data was returned successfully. The paper describes the Cassini flight system implementation of the revised Huygens mission. Cassini-Huygens is a cooperative project of the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and Agenzia Spaziale Italiana (ASI) to study Saturn, its rings, moons, icy satellites and magnetosphere. The Jet Propulsion Laboratory, a division of the California Institute of Technology in Pasadena, manages the Cassini-Huygens mission for NASA's Science Mission Directorate. JPL designed, developed and assembled the Cassini orbiter.

I. Introduction

On 30th June 2004 the Cassini spacecraft fired its main engine to maneuver into orbit around Saturn. This paper describes the engineering operations that have contributed to the unprecedented scientific success of the Cassini and Huygens missions, and how engineering operations are planned and implemented in concert with the required sequence of science observations.

A. Cassini Spacecraft

Cassini-Huygens was launched 15th October 1997, on a Titan 4 rocket from Cape Canaveral, Florida. Cassini-Huygens is a joint endeavor of NASA, the European Space Agency (ESA) and the Italian Space Agency (ASI). Cassini's mission is to orbit the ringed planet and study the Saturnian system in detail over a four-year period, using its suite of sophisticated instruments. Huygens is a robotic atmospheric probe with a mission to conduct in-situ studies of Titan's atmosphere and surface. At launch, the Cassini-Huygens spacecraft weighed 5574 kg, made up of

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the Cassini Orbiter, the Huygens Probe, launch vehicle adapter and propellants. The Cassini Orbiter subsystems are comprised of Attitude and Articulation Control Subsystem (AACS), Command and Data Subsystem (CDS), Power and Pyrotechnics Subsystem (PPS), Propulsion Module Subsystem (PMS) and Radio Frequency Subsystem (RFS). All critical hardware required for the Probe Relay Mission is fully redundant. At the time of publication, the spacecraft weighs 2709 kg (to be updated), after using up a large portion of the propellants and ejecting the Huygens Probe.

The AACS maintains three-axis attitude control of the spacecraft, and provides pointing control of the main propulsion engines. The CDS stores and processes data from all of the subsystems, sensors and science instruments, and also provides commands to the subsystems and instruments. Commands can either be issued from the ground or through on-board fault protection software that places the spacecraft in a safe, stable state to receive diagnostic and recovery commands, following any on-board equipment failure. The flight software also responds automatically to faults requiring immediate action. The CDS subsystem consists of two Engineering Flight Computers (EFC), two Solid State Recorders (SSR), and 8 Remote Engineering Units (REUs), which gather engineering telemetry from each subsystem and the orbiter instruments.

The PPS provides regulated 30 Volts DC electrical power, derived from the three Radioisotope Thermoelectric Generators (RTGs). This subsystem also initiates pyrotechnic devices used throughout the spacecraft for one-time events such as separating the Huygens Probe from the Cassini orbiter, and isolating parts of the PMS.

The PMS provides thrust for spacecraft maneuvers and attitude control. There are two identical main engines for redundancy, and 16 monopropellant hydrazine thrusters (8 primary and 8 backup) arranged in four separate clusters of four. The thrusters are used for attitude control and for small velocity change maneuvers.

The RFS provides communication functions for the spacecraft, it produces an X-band carrier at 8.4 Ghz, modulates it with data received from CDS, amplifies the X-band carrier power to produce 20W from the Traveling Wave Tube Amplifiers (TWTA), and delivers it to the antenna. More detailed descriptions of the spacecraft and instrument capabilities can be found in Refs 1 and 2.

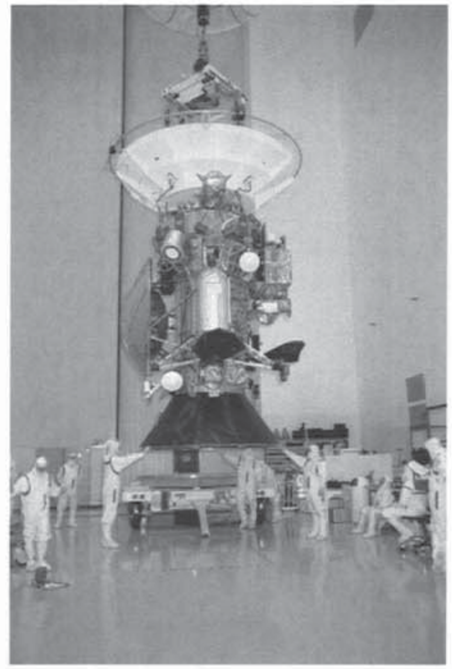

Figure 1. The Cassini-Huygens Spacecraft During Integration

B. The Huygens Probe

The Huygens probe measures 2.7 meters across and is built to withstand the harsh environmental conditions on entering Titan's atmosphere, and to support the science instruments that will operate during Huygens' descent and surface investigations.

The Front Shield is a 2.7m diameter 60° half-cone consisting of tiles of AQ-60 ablative material mounted on a CFRP structure. The Front Shield decelerated the probe from its 6km/s entry velocity to Mach 1.5 in the atmosphere of Titan, reaching temperatures of ~1900°C. The Back Cover is a stiffened aluminum shell with thermal protection consisting of Prosial; a spray-on suspension of silica spheres in elastomer.

The probe's Descent Control Subsystem (DCSS) consists of a 2.59m pilot parachute, deployment mortar, and associated triggering mechanisms, a 8.3m main parachute, and a smaller 3.03m stabilizing parachute. The stabilizing parachute is necessary as the main chute is not suitable for mission descent times of less than 2.5 hours.

The Separation Subsystem (SEPS) provides the electrical and mechanical attachment of the probe to the Cassini orbiter and the means of separation with the required accuracy and stability. Each of the three SEPS fittings has a pyronut for probe separation and incorporates rod-cutters for Front Shield and Back Cover release. The Spin/Eject Device performs the separation from the orbiter; it comprises three steel springs, axial rollers and track necessary to impart the correct separation velocity, spin rate, and stability to the probe as it is released from the orbiter. The umbilical separation mechanism consists of three 19-pin connectors and provided the electrical and data connection between the probe and orbiter during Cassini's long journey to Saturn.

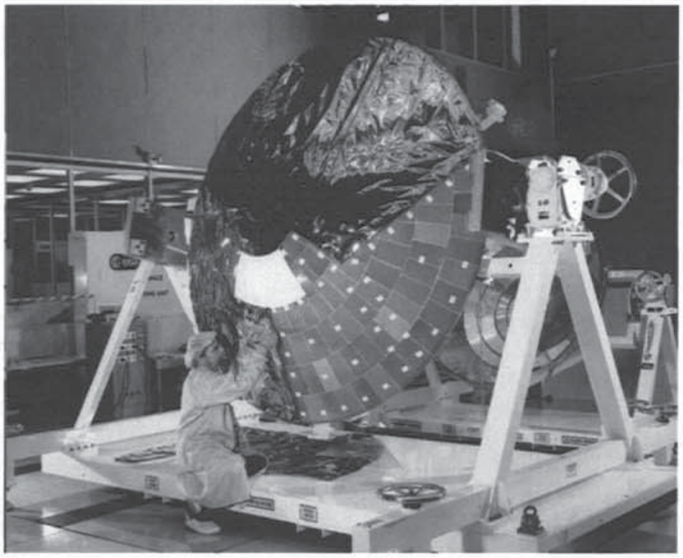

Figure 2. The Huygens Probe during integration

The Probe Support Avionics (PSA) remained attached to Cassini. The redundant PSAs received the probe's S-Band signal via the orbiter's HGA, processed and delivered the data to the orbiter. The Huygens probe payload consisted of six scientific instruments. A comprehensive description of the Huygens probe design is given in Ref. 1.

C. Engineering Operations

As well as the science observations that are the *raison d'etre* of the Cassini-Huygens mission, there are many stand-alone engineering operations that are essential to the success of the mission and the optimal use of spacecraft resources. These engineering operations must be organized in such a way as to have minimal impact on science data gathering, and where appropriate dovetail seamlessly with the existing science plan to result in a coherent set of operations that result in completion of the mission goals with minimum risk.

Orbit trim maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Optical navigation images are taken to provide additional data to the navigation team and enhance the orbit determination solutions obtained by radiometric data. Inertial Reference Unit (IRU) calibrations are performed, with full turns or taking advantage of optical navigation turns. The main engine cover is deployed and stowed in response to dust hazards, and the risk to the Stellar Reference Units (SRU), which are exposed to dust hazards during critical ring plane crossings, must be managed, and the SRUs must be periodically calibrated. Star identification must be suspended during the periods when a bright body, such as Saturn or its rings, appears in the field of view of the SRU. Reaction Wheel Assembly (RWA) biasing must take place to prevent saturation of the wheels' momentum management capability. RWA friction tests are performed periodically to assess wheel performance, and the backup RWA is exercised to ensure even distribution of the lubricant in the wheel casing. Pyrotechnic firing operations are occasionally needed by the propulsion module subsystem (PMS), and the Engine Gimbal Actuators (EGAs) are exercised to ensure continuing correct pointing capability of the Main Engine Assemblies (MEAs) during maneuvers. The Attitude and Articulation Control Subsystem (AACS) must have on-board parameters such as spacecraft mass and thruster magnitudes updated periodically to keep the engineering values recorded in the flight software commensurate with physics. The spacecraft Command Loss Timer (CLT) and other System Fault Protection parameters must be periodically adjusted for prevailing mission conditions, and in response to the needs of specific spacecraft operations; subsystem specific fault protection maintenance is also necessary.

Operating a robotic spacecraft in a complex alien environment presents a number of challenges for the engineering team. The Cassini Mission Operations System is composed of the combination of personnel, procedures, hardware, ground software, and networks needed to implement the operations phase of the mission. It is required to address a large number of objectives, constraints, and mission characteristics, primarily driven by the science requirements as interpreted by the Cassini science teams. Some of the mission constraints are typical of deep space robotic missions, some were common to orbiter missions, and others were unique to Cassini itself.

The distance between the engineering team and the Saturn orbiting spacecraft varies from 1.2 to nearly 1.6 billion kilometers, meaning real time control is precluded by the inherent speed-of-light communications time delays. For Cassini during the Saturn Tour, the one way communication time delay varies between 67 and 90 minutes.

Cassini has no instrument scan platform. A scan platform for remote sensing instruments potentially simplifies operations as optical remote sensing instruments can be oriented independently of fields and particles instruments when performing observations. With no scan platform, science observations take longer as the whole spacecraft has to be accelerated to a given rate, must coast for a while at the achieved rate, and then reduce the turn rate to zero at the desired observation attitude. There is also competition between the different science teams and the different investigators in determining which instrument is observing at any given time, and therefore who specifies the pointing of the spacecraft. Target motion compensation is also more difficult without a scan platform, as the whole spacecraft must be turned to match the target motion. All remote sensing data must be recorded for later transmission because the high gain antenna cannot stay pointed at Earth while the optical remote sensing instruments are in use.

Competition for the spacecraft resources required the science timeline to be established years in advance, to allow time for the science discussions, trade studies, resource negotiations, horse-trading and agreements on a conflict-free science plan to be made.

Cassini operational mode definitions, or opmodes, represent a predefined set of allowable spacecraft configurations that ensure the flight system is operated within specified power margins. Opmodes constrain the power consumption of the spacecraft, not the telemetry rate or attitude, and define the maximum power consumption allowed for each instrument and subsystem. With a few exceptions, the spacecraft is always operated within the power envelope of the specified opmode. Predefined command blocks termed opmode transitions are used to command the spacecraft configuration from one opmode to another. There are four categories of opmode; Downlink Fields Particles & Waves (DFPW), Optical Remote Sensing (ORS), Radar, and Radio Science Subsystem (RSS). During downlink DSN passes the spacecraft can be in any DFPW or RSS Opmode; however the X-band Traveling Wave Tube Amplifier (TWTA) is required to be in standby for the ORS and Radar modes. There are three opmodes in which the spacecraft Reaction Control Subsystem (RCS) can be used; these are used for low Titan flybys, below ~1300km - where there are high atmospheric disturbance torques that may exceed the control authority of the reaction wheels - or for Titan flybys that require turn rates and accelerations faster than the reaction wheels can provide. DFPW opmodes are the normal background state of the spacecraft. The spacecraft is in a DFPW opmode as the initial and final condition of every sequence. Orbit Trim Maneuver (OTM) prime and backup passes, engineering maintenance, and RWA friction tests are performed in DFPW opmodes. ORS, Radar, and RSS opmodes are used for science observation periods. Details of opmode design are given in Ref. 10.

D. Tasks & Processes

Tasks undertaken by the spacecraft team include:

1. Operations Planning

Subsystem experts provide required engineering inputs to the planning process, advise on the effects of planned activities on the operational state of the spacecraft, track consumables usage, check the planned activities against flight system constraints, provide predictions of spacecraft operational performance for planned events, and perform trade studies, if necessary, on the effects of different implementations for spacecraft operations. The team identifies and resolves engineering concerns for the mission phases under development, reviews the mission phase activities to ensure that all required spacecraft engineering activities are implemented, and acceptable from an engineering perspective. It also verifies that the integrated engineering activities satisfy spacecraft operational requirements.

2. Sequencing support

Systems engineers coordinate the efforts of the subsystems in providing detailed command level inputs for required engineering activities, perform constraint checking of command sequences, ensure adequate DSN coverage, and make adjustments for conflicting events. Constraint checking includes ensuring adequate link margins, pointing profile simulation, sun & bright body avoidance for star tracker pointing, the correct power & thermal margins, predictions of fault protection activity, and adherence to flight rules.

3. Test Implementation

This includes management of the Cassini Integrated Test Laboratory, planning and support of spacecraft ground testing, flight and ground software testing, verification & validation, and review and assessment of test and simulation results.

4. Flight Operations Implementation

Uplink of the necessary command sequences, monitoring of all on-board activities, verification that activities occurred as predicted, assessment of anomalous or unexpected results or fault protection responses, verifying health & safety of the engineering subsystems and the ground system supporting spacecraft monitoring.

5. Spacecraft data analysis

Assessments of the state of the spacecraft and the health & safety of the subsystem components are made. The results of engineering calibration and maneuver activities, trend analysis, and unexpected results, are reported.

6. Uplink development

Assessment of changing mission conditions or changes to the operational environment, sequence change requests, support for and involvement in the generation of operational scenarios and operational readiness tests.

7. Flight and ground software development & maintenance:

Development and maintenance of AACS & CDS flight software and the associated fault protection that was deferred from pre-launch development. Development of ground software to support the changing ground operational environment; includes writing software requirements, preparing development plans and schedules, writing code, testing, verification & validation, and delivery of new software versions.

E. Tools

The Kinematic Predictor Tool (KPT) is used to generate commands for attitude changes, inertial vector construction, spacecraft momentum management and the suspension of star identification (Star ID). The tool models AACS flight software components used in attitude estimation and control, reports flight rule violations, models RCS residual delta-V, and models geometries between target bodies and the spacecraft. KPT enables these AACS attributes to be simulated at a few hundred times real-time, so spacecraft command sequences can be simulated and attitude states validated for compliance with mission and flight rules.

The Inertial Vector Propagation (IVP) Tool generates commands that describe the positions of boresights with respect to the spacecraft coordinate system, and that describe the trajectories over time of target bodies. The software can create a fixed, time-invariant vector; a seven-term conic; and a Chebyshev polynomial from zero to twelfth order. The tool enforces compatibility with on-board constraints on possible vector names, and on the number of vectors on-board the spacecraft at any time. Default body vectors are present in the flight software at initialization - the x, y and z spacecraft axes, the negative x, y and z spacecraft axes, and the -X axis low gain antenna. These on-board vectors are duplicated by the tool at initialization, and it will also always produce a safe-spacecraft-vector to Sun, a Sun to Earth vector, and a set of Sun to J2000 coordinate axes. All of these default inertial vectors are long lasting conic vectors that cover a particular time period. Several vector segments can cover the same inertial object over any requested time period as needed. The tool outputs all the IVP commands required for a given command sequence. The activity parameters that are generated have associated error statistics. The user can see a timeline of body and inertial vectors that show how the vectors are sequenced into the flight software, how long they are resident in the flight software, and the total number of vectors active at any time.

The Reaction Wheel Bias Optimization Tool (RBOT) selects the optimal wheel bias to use for any given sequence segment; it is fully described in Ref 11.

II. Orbit Trim Maneuvers

Frequent Orbit Trim Maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Considerable effort has been invested in detailed planning of the complete set of science observations associated with this Tour, so a robust OTM strategy is necessary to protect this investment by ensuring the spacecraft keeps to the planned trajectory. This requires meticulous maneuver planning and a robust system for ensuring that maneuvers can be implemented as planned, with short development times from availability of the final orbit determination solution through uplink.

One hundred sixty Orbit Trim Maneuvers (OTMs) have been planned between Cassini Saturn Orbit Insertion and the original end of mission, planned for July 2008. Each OTM, depending on the size of the burn, is either implemented on the bipropellant main engine or on the smaller, monopropellant reaction control subsystem thrusters. Keeping the spacecraft on the designed trajectory has been achieved using three maneuvers between each targeted encounter of Titan or an icy satellite. The cleanup maneuver is scheduled three days after the previous flyby, and corrects for most of the error resulting from the previous flyby; it generally has a high statistical component. The near apoapsis maneuver adjusts the trajectory for the next targeted encounter, and generally has a high deterministic component. The approach targeting maneuver is scheduled three days before the next Titan or icy satellite flyby and cleans up any errors resulting from the apoapsis maneuver. The Cassini Saturn Tour includes many 16 day orbits, during which maneuvers must be implemented approximately every 5 days, at any hour of the day – in fact they usually occur at the most inconvenient times. As well as the need to stay on the planned Tour, OTMs also serve to ensure trajectory accuracy requirements for target-relative pointing prediction, reconstruction, and control are met.

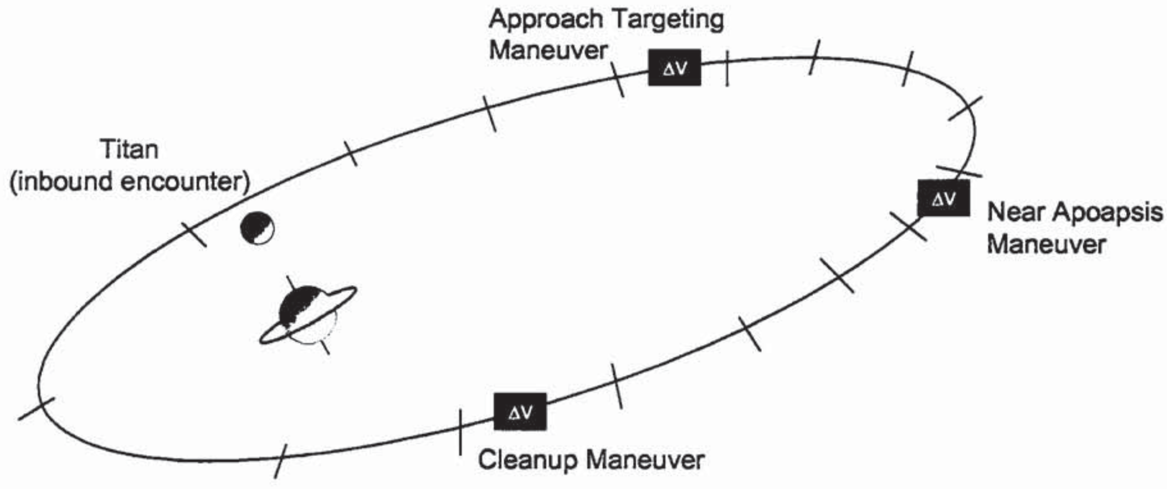

Figure 3. Nomenclature for Cassini Maneuvers, for an inbound Titan Encounter.

In order to facilitate prompt, accurate production of maneuver sequences from orbit determination solutions, a dedicated software tool was developed. The tool consists of Perl scripts that link and sequence the execution of other software used in the maneuver design process; navigation team maneuver design tools, AACS maneuver implementation tools, and software that generates spacecraft sequences. It generates the maneuver parameters and all related uplink and verification products in about 30 minutes from receiving an orbit determination solution.

Each maneuver takes place during a nine hour Deep Space Network (DSN) pass. A backup pass is also scheduled in case the maneuver is not executed during the prime window. Engineering operations that support the maneuver, such as placing the spacecraft in the correct power mode and thermal configuration, are placed in the spacecraft background sequence to execute at the beginning and end of the primary and backup OTM windows.

Following reception of the final orbit determination solution from the navigation team, the maneuver parameters are calculated and the uplink products generated. The uplink products are validated against Cassini flight rules with a series of automated checks. At the beginning of the primary OTM pass, the maneuver uplink lead verifies the health and safety of the spacecraft and uplinks the maneuver. The maneuver is executed during the same DSN pass as the uplink, and monitored in real time by the spacecraft team. The spacecraft does not perform a single turn from Earth pointing to the burn attitude; it is turned in two stages to avoid violating thermal requirements. The first turn is performed using reaction wheels and is about the spacecraft Z-axis (a roll turn), during which the spacecraft remains Earth pointed. The second is about the Y-axis (a yaw turn) and is performed on thrusters; during this turn the spacecraft moves off Earth pointing and telemetry is lost. The roll and yaw turns align the spacecraft pre-aim thrust vector with the delta V vector required for the burn. Following the burn, the same yaw turn is performed in the opposite direction to return the spacecraft to Earth pointing, and the same roll turn is performed in the opposite direction to return to the initial spacecraft secondary axis attitude. The engineering data from the off-Earth portion of the burn is recorded and played back at the end of the pass, along with any science data gathered before and after the maneuver.

In the unlikely event that the maneuver cannot be executed during the prime pass, for example if the DSN station was unable to uplink the maneuver sequence because of a station hardware failure, a backup maneuver can be prepared for execution during the backup pass. It has never been necessary to use a backup OTM pass.

III. Propulsion Subsystem Management

Cassini Reaction Control Subsystem (RCS) has sixteen 1-Newton monopropellant thrusters, divided into two redundant branches, and a Monopropellant Tank Assembly (MTA) consisting of a single 0.36m radius spherical tank. The tank contains an elastomeric diaphragm with monopropellant hydrazine on the thruster side, and pressurized gas on the other, for expulsion of bubble-free hydrazine to supply the thrusters in zero-g. Cassini RCS is used periodically for attitude control, to implement low delta-V maneuvers, and for reaction wheel momentum management.

The MTA is connected to the Recharge Tank Assembly (RTA) via two closed pyrotechnic valves. The recharge tank contains high pressure helium. Firing either of the pyro valves will un-isolate the recharge tank, and the pressure in the MTA and helium tank will equalize, thus recharging the monopropellant tank to provide fuel at higher pressures. Pressure in the RTA and MTA can be monitored by pressure transducer values in telemetry.

A. The need for Recharge

Titan atmospheric density estimates were made by the Cassini Ion and Neutral Mass Spectrometer (INMS), and the Ultraviolet Imaging Spectrograph (UVIS) using data from Titan flybys; and by the Huygens Atmospheric Structure Instrument (HASI) team using data from the Huygens probe descent into Titan's atmosphere. The AACS team also performed a series of Titan atmospheric density reconstructions from the attitude control subsystem performance data obtained during Titan flybys. These measurements suggested that the atmosphere may vary with latitude as well as altitude, and may not be symmetrical over the northern and southern hemispheres. This caused concern that the atmospheric density may be higher than expected for some of the planned flybys, which are to be as low as 950km, and the RCS may in some cases have insufficient control authority to overcome the atmospheric disturbance torques induced. In such a case, there would be a possibility that the spacecraft would lose pointing control, with a consequent loss of science data and the spacecraft entering Safe mode.

Recharge is necessary primarily to provide more control authority from the thrusters, as well as maintaining operation within the flight envelope. The maximum disturbance torques on the spacecraft are expected to occur during low Titan flybys, when the spacecraft will experience the free molecular flow regime in the moon's upper atmosphere. Under these conditions, the minimum safe altitude for the spacecraft is derived from the maximum density the spacecraft can fly through while maintaining the science pointing profile required and overcome the atmospheric disturbance torques.

The date of the earliest possible Monopropellant Tank Assembly recharge was determined from the maximum allowable operating pressure of the hydrazine thrusters. The date when this pressure would represent a ceiling to possible post-recharge pressures is dependant on the rate of hydrazine consumption during future mission events. Hydrazine consumption is modeled from the spacecraft characteristics, the mission profile, and the planned sequence of turns and maneuvers; in this case consumption was dominated by the T7 and T8 flyby hydrazine usage, which is large, deterministic, and well known.

The first Cassini 950km flyby will be the Titan-16 encounter, planned on 22 July 2006. This will be followed by the 1000km Titan 17 encounter on 7 September 2006. If the MTA recharge were not to occur, it would still just be possible to fly T16 at 950km without the spacecraft tumbling, but the subsequent T17 closest approach would have to be raised from 1000km to 1030km. For the rest of the Cassini Saturn Tour, all planned low altitude Titan flybys would have to increase in altitude by approximately 30 km, although there will be no appreciable increase (or even a slight decrease) in the delta-V needed to complete the prime mission. The changes needed to the geometry of Titan flybys would cause a substantial science re-planning effort, as detailed science operations for the Tour are already established for 950km Titan flybys.

B. Pyrovalve Operation & Ageing

MTA recharge is implemented by firing one of two pyrovalves to connect the RTA helium tank to the MTA hydrazine tank. The normally closed pyrovalve assembly controls the flow path until commanded to operate. Each of the valves in question has a single NASA Standard Initiator (NSI), which can be electrically initiated by a sequence of telecommands. The gas output of the pyrotechnic cartridge provides the linear motion of the valve's internal piston, and this piston in turn displaces the shear nipples normally keeping the high pressure helium in check, thus allowing flow to commence.

The NASA Standard Initiators used in the pyrovalves are an Apollo era design with a high reliability. Historically, more than 100,000 NSIs of this type have been fired on spacecraft missions in the past, and there have been no known failures. However, since the specified storage life is 10 years, and the Cassini NSIs were manufactured in 1992, the thermal and radiation environments of the NSIs in question were carefully reexamined and reviewed. Although no cause for extraordinary concern was found, contingency procedures to fire the redundant valve, and to fire the prime and redundant valve using different commanding techniques, were prepared.

C. MTA Recharge Operations

MTA Recharge was successfully completed on 10th April 2006. The single pyro valve PV40 was fired successfully. There was a nominal drop in pressure upstream of the pyro valve, from 2350 psia to 385 psia (+/- 17 psia) and a pressure increase in the Monopropellant Tank Assembly from 253 psia to 404 psia (+/- 2 psia). The post-firing pressures were well within the expected ranges, and the final hydrazine tank pressure was exactly as predicted. As predicted, there were significant thermal transients in the helium recharge tank, with temperatures dropping from initial conditions of 25 degC to a low of -2 degC, followed by gradual recovery. The hydrazine tank temperature only increased by about 3 degC due to adiabatic compression; this initially led to the hydrazine pressure being 406 psia but this transient condition ceased after about 30 minutes.

IV. The Huygens Probe

Attached to Cassini during cruise and early Saturn tour was the Huygens Probe, awaiting delivery to Titan. During an in-flight end-to-end communications test with the probe during the cruise to Saturn, a serious anomaly was discovered in the Huygens receiver. The recovery effort resulted in major changes to the Cassini trajectory, flight software, test program, and mission operations. Cassini released Huygens on 25th December 2004 UTC, setting up the correct entry conditions for the probe's arrival during Cassini's third flyby of Titan. As a result of the major engineering effort to recover the Huygens mission, on arrival at Titan on 14th January 2005, the probe studied the composition of the atmosphere, conducted unprecedented science observations, and the science data was returned successfully. The paper describes the Cassini flight system implementation of the revised Huygens mission.

A high priority mission objective for Cassini was to target and deploy the Huygens probe for Titan entry, and to subsequently receive the data the probe transmitted and relay it to Earth. The original mission design was such that Huygens transmitted science and engineering data via two redundant hardware chains with a six second delay between the signals. Probe Chain A and Chain B signals were to be received at Cassini via the High Gain Antenna (HGA). The Receiver Front End (RFE) diplexer was to split the signal, the signals were amplified by LNAs, and the amplified signals directed to the Probe Support Avionics (PSA) receivers. The PSA receivers were to decode the data and format the probe science and engineering data into probe Super packets and PSA housekeeping Packets, which were to be sent to the PSA Bus Interface Units (BIUs). These data were collected from the BIUs by the Orbiter Command and Data Subsystem (CDS), and subsequently stored on Solid State Recorders (SSRs) for relay.

D. Probe Relay Tests

A series of tests conducted in February 2000 confirmed the existence of a serious flaw in the PSA. The problem was inappropriately selected parameters coded into the RFE firmware and would have rendered the probe's data unrecognizable due to the effects of Doppler shift in the probe data signal arriving at Cassini. The vast majority of Huygens science data would have been lost if the problem had remained undetected and uncorrected.

The test design required Deep Space Network (DSN) ground stations to broadcast test data to Cassini that simulated the signal from Huygens to Cassini during the probe descent. When the test results were analyzed and the flaw discovered, in March 2000 additional testing was performed to confirm and characterize the problem. A European Space Agency (ESA) investigation team completed its work at the end of October 2000, and ESA subsequently convened an independent Enquiry Board, which reported its findings in December 2000.

With the problem fully characterized, the Huygens Recovery Task Force (HRTF) - a joint ESA/NASA team - was established in early 2001, to analyze the failure and to propose and evaluate possible recovery actions. The HRTF developed a redesigned probe mission to allow the Huygens probe relay to be performed while the Cassini orbiter flew by at a higher altitude than originally designed, thus reducing the Doppler effect on the probe signal. This trajectory modification maintained the tour science opportunities following Probe Relay. Increasing the altitude of Cassini during the Titan flyby and Probe Relay allowed for a reduction in the Doppler effect on the radio link and provided a more robust contact that potentially enabled all of the Huygens science data to be collected.

The early portion of the mission trajectory was redesigned to allow release at the third Titan flyby, Tc Instead of releasing the probe during November 2004 at the first Titan flyby. This allowed delivery of the Probe fifty days later than in the original mission and allowed the orbiter to rejoin the original tour at T3. Cassini's early portion of tour was subsequently redesigned to meet this requirement, by delivering the probe at the Tc flyby on 14th January 2005. Significantly, the planned engineering events leading up to the probe relay mission also had to be modified to fit the new timeline.

Additional engineering activities were required on both the probe and orbiter to support the redesigned Huygens mission. Orbiter flight software modifications were implemented to support the frequency tracking mode selection in the PSAs. Probe flight software changes were implemented to allow pre-heating of the probe before entry into Titan's atmosphere in order to thermally stabilize the frequency output by the Ultra Stable Oscillators. These changes required extensive ground testing and verification, and in-flight demonstration involving both the probe and orbiter.

Huygens was designed and built using the best data available on the composition of Titan's atmosphere. Data consisted primarily of the Voyager Titan flyby data and stellar occultation data from which atmospheric models could be derived. It was recognized that Titan's atmospheric structure at the time of the Huygens mission could deviate significantly from that which the probe was designed for, so the mission profile was checked by the collection and analysis of Titan atmospheric data from Cassini after early flybys. Data from the T0 untargeted flyby on July 1st, 2004, and the targeted Ta flyby on October 26th 2004 was used to validate the planned Huygens entry conditions.

E. Impact on Mission Operations

Such profound changes in the planned Cassini-Huygens mission required detailed re-assessment of the scheduled operational activities for the period from the completion of Saturn Orbit Insertion (SOI) on 1 July 2004 until the final receipt of the Huygens data at the Huygens Probe Operations Centre (HPOC) on 15 January 2005.

In order to ensure coordinated implementation of the Huygens recovery mission by the ESA and JPL teams, a Huygens Implementation Team (HIT) was formed, charged with refining and implementing the recovery effort. The HIT produced the Huygens Mission Operations Plan (MOP) [8], a joint ESA-NASA document which described all of the operational activities necessary to implement the Huygens mission. It was the plan that coordinated activities for both sides of the Cassini-Huygens interface, providing a clear and concise roadmap for implementation of the probe mission. The MOP addressed operational activities for both the Huygens probe and the Cassini orbiter, the engineering and management responsibilities, the operational and decision making processes, operational interfaces, and the detailed inputs and outputs for each planned activity. Where necessary, the MOP referred to established detailed procedures such as the Huygens Flight Operations Plan and Cassini Spacecraft Office standard procedures.

The MOP allowed operational detail of the mission to be available and accessible to both ESA and JPL team members. It ensured dialogue, review and scrutiny of operational products among all parties involved. The MOP forced the development of joint schedules and operations plans to eliminate any programmatic misalignment between the agencies. Detailed schedules for operational deliverables were specified down to the level of targeting coordinates and command files. The MOP divided the operations leading up to the probe mission into five phases.

One of the HRTF mission redesign recommendations was that the orbiter continually command the PSAs to a base frequency rather than searching for a signal at the expected Doppler frequency. Fortunately, there was a built-in test equipment mode (BITE Mode) available to the PSAs that enabled this. This test mode frequency was close enough to the redesigned probe mission frequency, but this test mode needed re-enforcement every ~10 seconds in case the PSAs periodically dropped lock. One of the orbiter Automatic Temperature Control (ATC) algorithms was modified to issue 2 BITE Mode commands to the PSAs every 12 seconds, otherwise 3734 separate BITE mode commands would have had to be issued to the PSAs during the 6 hours 46 minute period while the PSAs were powered on.

F. Final Checkout & Depassivation Phase

The final Checkout & Depassivation phase began on 14th September 2004 and ended on 16th December 2004. The major events in this phase were the Probe Checkout F15 and a test of the probe's Mission Timer Unit, Probe Battery Depassivation 1, The Final Probe Checkout, Probe Battery Depassivation 2, the Titan-A encounter, the Titan- b Approach Maneuver, and the Titan-b Encounter.

Checkout F15 took place on 14 September 2004, and was conceptually a rehearsal of the Final Checkout, duplicating F16 in many respects. The engineering data from the probe was used to assess the health of the probe system, and after confirming the probe's excellent health the decisions were made to use the transmitter Ultra-Stable Oscillator (TUSO) for the probe mission, and to load the MTU via CDMU A. Given the probe's good health there was high confidence that the mission could proceed at the primary mission opportunity at Tc.

Battery Depassivation 1 took place on 19 September 04. During battery depassivation, a 55W (2A x 28V per BDR) load is applied to each probe LiSO2 battery section for a few minutes to break the passivation layer on the battery electrodes. The purpose of depassivation is to remove the thin chemical passivating layer that forms within the lithium battery cells, on the surface of their electrodes, when no current flows. This layer, which builds up naturally over time, enabled the cells to retain their charge during the long Cassini cruise phase but could have been problematic for operations during the Probe mission if left in place.

Depassivation can be achieved by discharging each battery against a sufficiently high load for a short period of time. In practice, it first required the Probe and its instruments to be powered on using the Cassini bus, via its Solid State Power Switches (SSPSs), to establish a sufficiently high load on the Probe's bus. Each of the Probe's five power sections was then configured to connect the associated battery to the bus for a period of 5 minutes.

The procedure was in practice somewhat more complex because the Battery Discharge Regulator (BDR) within each power section was built to handle only one type of power source at any given time (i.e. a Probe battery or a Cassini SSPS). It therefore included commands to disconnect the associated SSPS before connecting the battery and visa-versa, as well as a set of commands that were loaded into the Pre-T0 Mission Timeline Table (MTT) to ensure that in the event of a Cassini Safing no battery would remain connected to the Probe's power bus – a situation that would result in a battery being completely discharged.

Depassivation 1 provided the opportunity to assess the battery health four months before the probe mission. Depassivation 1 was not part of the original mission, and was introduced after ground testing of flight spare batteries indicated that there was enough energy to support two battery depassivation activities. Early depassivation was advantageous as it allowed potential problems with the probe batteries and power subsystem to be discovered early in the mission timeline, but fortunately the operation showed the probe to be in perfect health.

The Titan-A flyby took place on 26th October 2004 at 15:30; inbound to Saturn with a 1200 km closest approach velocity of 6.1 km/sec. Science observations that took place around Ta were hoped to provide information to verify the existing Titan atmosphere models, to validate the probe entry conditions. The Cassini Ion and Neutral Mass Spectrometer (INMS) measured the composition of the atmosphere within +/- 10 min of closest approach. This gave the total density in the altitude range >1200 km, and the composition.

The probe Final Checkout, termed F16, took place on 23 November 2004. This further checkout data was used to confirm the health of the probe and the decision to proceed with the primary mission opportunity at Tc.

Battery Depassivation 2 took place on 5th December 2004, and was identical to the first depassivation. The purpose of the second depassivation was to remove any passivation layer that had built up on the battery electrodes since the first depassivation.

The Tb approach maneuver took place on 10 December 2004 to set up the correct conditions for the Tb flyby on 13th December, the maneuver was nominal.

G. Probe Targeting & Separation Phase

The Targeting and Separation phase ran from 16th December 2004 to the separation of the probe on 25 December 2004. The major events in this phase were the Probe Targeting Maneuver (PTM), the uplink of the Probe Relay Critical Sequence, the PTM Cleanup Maneuver, the configuration of the probe for separation, and Probe Separation itself.

The ~12m/s Probe targeting maneuver was executed on December 17, 2004 and placed the spacecraft on an impacting trajectory with Titan. A small cleanup maneuver of 0.138m/s was executed on 23 December.

Final commands to the Probe were sent on 22 December to complete preparations for release. The Huygens mission required the Probe to be powered-up before its entry into Titan's atmosphere; this was achieved via the probe's Mission Timer Unit, (MTU), which used redundant countdown registers to track the time from initial register loading to required power-on. During the ~20 day coast phase, between Cassini separation and Titan entry, the MTU was powered from three of the five batteries via power lines that are separate from the main Probe bus. The MTU was loaded when on battery power, in order to avoid an unnecessary voltage transient that may result from switching over from orbiter power.

Separation of the Probe from the Orbiter occurred on December 25, 2004. The Probe Spin/Eject Device (SED) separated the Probe with a relative speed of ~0.3 m/s. The Probe axis was pointed to achieve a zero-angle-of-attack entry and such that the velocity increment provided by the SED springs provides the final targeting to the entry aim point.

The last two maneuvers of the Orbiter before Probe entry provided the final orbiter targeting to the required aim point to achieve the radio relay link geometry. The first of these was the Orbiter Deflection Maneuver (ODM), which was executed three days after separation. This large main engine maneuver of ~24 m/s targeted the Orbiter for the planned flyby of Titan at an altitude of 60,000 km and timed the Orbiter's closest approach to occur just over two hours after Probe entry. The relative position of the Orbiter with respect to Titan during probe entry and descent was designed to provide a view toward the Probe for approximately four and a half hours after entry. The Orbiter HGA was planned to be pointed toward the predicted Probe landing site to capture the Probe telemetry during descent and for approximately 2 hours after Probe touchdown.

The spin-stabilized Probe was be targeted for a southern latitude landing site on the day side of Titan. In order to meet the probe dynamic entry conditions, minimize trajectory dispersion and thus enhance data relay link performance, the Probe entry angle into the atmosphere was planned to be -65° + 3° (99%). The term "entry" generally referred to the arrival of the Probe at the interface altitude of 1270 km, which defined the interface point for Probe targeting requirements.

Separation of the Probe from the Orbiter was not to jeopardize the functional or structural integrity of either spacecraft, and was to give the Probe the required post-separation trajectory and attitude, within allowable uncertainties, to achieve Titan entry. In order to accomplish this, the pre-separation position vector, velocity vector, and attitude must be such that, after the dynamics of separation have been applied, the Probe is left with the proper velocity to reach the aim point, and the proper attitude for zero angle of attack at atmospheric entry. The pre-separation attitude was achieved by rotating the combined spacecraft to an attitude which left the Probe at the desired post-separation attitude.

The Cassini AACS subsystem provided an estimate of the spacecraft attitude and turning rates with respect to the J2000 coordinate system. In Celestial-Inertial mode, the Stellar Reference Unit (SRU) and an on-board star catalog determined the spacecraft attitude in the J2000 reference frame. Attitude estimates were propagated by an Inertial Reference Unit (IRU) between SRU measurement updates.

The Reaction Control System (RCS) was used to control the combined spacecraft attitude before the separation event. Following the turn to the Probe separation attitude, a settling time was used to allow the spacecraft to attain a quiescent state with very low body rates on all axes. The firing of the thrusters was inhibited for 10 seconds immediately before Probe separation, and re-enabled 60 seconds after. During the period without thruster firings to control the attitude, the Orbiter tumbles in response to the separation impulse. Five minutes after the separation event the AACS was switched to detumble mode. The RCS thrusters were re-enabled and the spacecraft rates reduced to low, commandable threshold values. When the Orbiter rates were within the prescribed threshold limits, the AACS reentered Celestial-Inertial mode and a turn to the probe release attitude was initiated.

Post-separation imaging of the Probe was be used to improve the knowledge of its ephemeris, entry conditions at Titan, and ultimately the descent trajectory.

Failure to separate the probe from the orbiter at the planned time would have resulted in significant impact to both the Huygens and Cassini missions. If the cause of the failure was determined to be a relatively simple one, such as a hardware failure that can be corrected in a matter of days, the recovery would have been relatively clear. However, if the cause of the failure was due to more complex issues, such as higher than expected uncertainties in the probe targeting, there would have been a much larger impact.

A delay in probe separation long enough to jeopardize the Tc probe delivery would result in implementing one of the planned contingency missions, where the Saturn Tour would be modified yet again to create delivery opportunities in February and June 2005. Falling back to any contingency mission would have caused the orbiter to deviate from the nominal tour and thus lose planned science observations and increase the use of propellant.

H. Coast and Probe Relay Phase

Following separation, the separation delta-V telemetry was played back from the spacecraft and used by the navigation team to refine the post separation trajectories of the probe and orbiter. Imaging of the probe took place in order to assist in the post-mission probe descent trajectory reconstruction; it also provided further assurance that the separation event was nominal. The Probe Support Avionics (PSAs) were turned on for a short period in order to check the survival of the PSAs after the pyro shock event of separation. An Orbiter Deflection Maneuver (ODM) was performed to set up the correct conditions for a Titan C flyby consistent with the requirements of the probe mission.

A two day period was defined within which observations of Iapetus were to be made during the fortuitous viewing conditions that occurred during the Rev B apoapse of the redesigned early tour. The observations took place over the 2005 New Year 's Eve period.

ODM clean-up maneuver was implemented to reduce errors relative to the nominal probe-relay pointing. Critical Sequence activation took place on 6th January 2005 - once the Critical Sequence was activated, the orbiter could complete the probe relay mission without ground intervention, even in the event of equipment failure on board.

The probe relay mission took place on 14th January 2005, with the probe reaching the interface altitude of 1270km above the surface of Titan at 2005.014T09:05:56 SCET. On approach to Titan, the last downlink before Probe relay was over the Madrid DSN station (DSS 63). Following the playback of all data remaining on the solid state recorders, the Cassini orbiter turned nearly 180 degrees to point the HGA at the predicted Probe landing point. To prevent any interference with reception of the Probe data, no transmissions from the orbiter are allowed during Probe relay at any frequency; transmissions from the orbiter HGA at X-band were turned off by the Probe mission sequence shortly after the orbiter turned away from Earth. The orbiter pointed to the predicted landing site until that site was below the physical Titan horizon with respect to the orbiter. At that time, the orbiter stopped collecting probe data and began the turn back to Earth. 3h39m22s of probe mission data was collected. Results of the Huygens probe mission are summarized in Ref 9.

V. Conclusion

Cassini is a complex mission, kept on track by meticulous attention to engineering detail. Our approach to operational complexity is progressive automation of ground processes to the extent possible. Automation of ground processes has improved the efficiency and accuracy of operations. Developing tools and processes for the optimal selection of momentum bias has ensured efficient use of reaction wheel consumables.

The spacecraft is in excellent health and we look forward to implementing the remainder of the Saturn Tour and an extended mission.

Acknowledgments

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Cassini-Huygens Engineering Operations at Saturn

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On 30th June 2004 the Cassini spacecraft fired its main engine to maneuver into orbit around Saturn. This paper describes the engineering operations that have contributed to the unprecedented scientific success of the Cassini and Huygens missions, and how engineering operations are planned and implemented in concert with the required sequence of science observations. Frequent Orbit Trim Maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Considerable effort has been invested in detailed planning of the complete set of science observations associated with this Tour, so a robust OTM strategy is necessary to protect this investment by ensuring the spacecraft keeps to the planned trajectory. The paper will describe the OTM strategy, the Inertial Vector Propagator capability, and how this system is used to maintain the Tour and pointing accuracies needed for science operations. During such a long mission, careful propulsion subsystem management is necessary; the paper will describe the monopropellant and bipropellant fuel-side re-pressurization operations used to maintain the main engines in their optimal operating envelope, and to keep the monopropellant thrust at the level required to control the spacecraft during Titan flybys. Attached to Cassini during cruise and early Saturn tour was the Huygens Probe, awaiting delivery to Titan. During an in-flight end-to-end communications test with the probe during the cruise to Saturn, a serious anomaly was discovered in the Huygens receiver. The recovery effort resulted in major changes to the Cassini trajectory, flight software, test program, and mission operations. Cassini released Huygens on 25th December 2004 UTC, setting up the correct entry conditions for the probe's arrival during Cassini's third flyby of Titan. As a result of the major engineering effort to recover the Huygens mission, on arrival at Titan on 14th January 2005, the probe studied the composition of the atmosphere, conducted unprecedented science observations, and the science data was returned successfully. The paper describes the Cassini flight system implementation of the revised Huygens mission. Cassini-Huygens is a cooperative project of the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and Agenzia Spaziale Italiana (ASI) to study Saturn, its rings, moons, icy satellites and magnetosphere. The Jet Propulsion Laboratory, a division of the California Institute of Technology in Pasadena, manages the Cassini-Huygens mission for NASA's Science Mission Directorate. JPL designed, developed and assembled the Cassini orbiter.

I. Introduction

On 30th June 2004 the Cassini spacecraft fired its main engine to maneuver into orbit around Saturn. This paper describes the engineering operations that have contributed to the unprecedented scientific success of the Cassini and Huygens missions, and how engineering operations are planned and implemented in concert with the required sequence of science observations.

A. Cassini Spacecraft

Cassini-Huygens was launched 15th October 1997, on a Titan 4 rocket from Cape Canaveral, Florida. Cassini-Huygens is a joint endeavor of NASA, the European Space Agency (ESA) and the Italian Space Agency (ASI). Cassini's mission is to orbit the ringed planet and study the Saturnian system in detail over a four-year period, using its suite of sophisticated instruments. Huygens is a robotic atmospheric probe with a mission to conduct in-situ studies of Titan's atmosphere and surface. At launch, the Cassini-Huygens spacecraft weighed 5574 kg, made up of

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the Cassini Orbiter, the Huygens Probe, launch vehicle adapter and propellants. The Cassini Orbiter subsystems are comprised of Attitude and Articulation Control Subsystem (AACS), Command and Data Subsystem (CDS), Power and Pyrotechnics Subsystem (PPS), Propulsion Module Subsystem (PMS) and Radio Frequency Subsystem (RFS). All critical hardware required for the Probe Relay Mission is fully redundant. At the time of publication, the spacecraft weighs 2709 kg (to be updated), after using up a large portion of the propellants and ejecting the Huygens Probe.

The AACS maintains three-axis attitude control of the spacecraft, and provides pointing control of the main propulsion engines. The CDS stores and processes data from all of the subsystems, sensors and science instruments, and also provides commands to the subsystems and instruments. Commands can either be issued from the ground or through on-board fault protection software that places the spacecraft in a safe, stable state to receive diagnostic and recovery commands, following any on-board equipment failure. The flight software also responds automatically to faults requiring immediate action. The CDS subsystem consists of two Engineering Flight Computers (EFC), two Solid State Recorders (SSR), and 8 Remote Engineering Units (REUs), which gather engineering telemetry from each subsystem and the orbiter instruments.

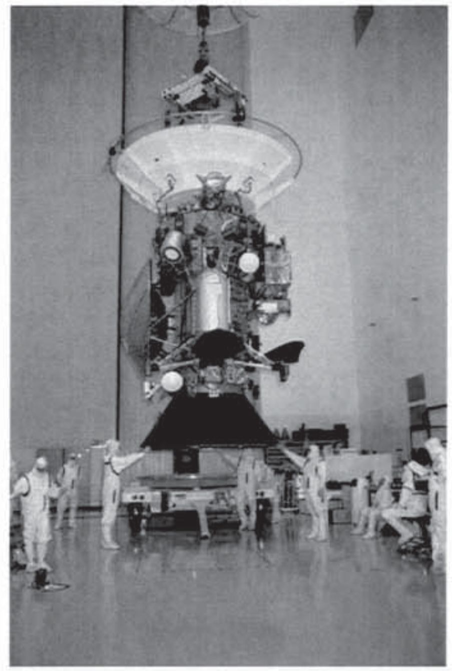

Figure 1. The Cassini-Huygens Spacecraft During Integration

The PPS provides regulated 30 Volts DC electrical power, derived from the three Radioisotope Thermoelectric Generators (RTGs). This subsystem also initiates pyrotechnic devices used throughout the spacecraft for one-time events such as separating the Huygens Probe from the Cassini orbiter, and isolating parts of the PMS.

The PMS provides thrust for spacecraft maneuvers and attitude control. There are two identical main engines for redundancy, and 16 monopropellant hydrazine thrusters (8 primary and 8 backup) arranged in four separate clusters of four. The thrusters are used for attitude control and for small velocity change maneuvers.

The RFS provides communication functions for the spacecraft, it produces an X-band carrier at 8.4 Ghz, modulates it with data received from CDS, amplifies the X-band carrier power to produce 20W from the Traveling Wave Tube Amplifiers (TWTA), and delivers it to the antenna. More detailed descriptions of the spacecraft and instrument capabilities can be found in Refs 1 and 2.

B. The Huygens Probe

The Huygens probe measures 2.7 meters across and is built to withstand the harsh environmental conditions on entering Titan's atmosphere, and to support the science instruments that will operate during Huygens' descent and surface investigations.

The Front Shield is a 2.7m diameter 60° half-cone consisting of tiles of AQ-60 ablative material mounted on a CFRP structure. The Front Shield decelerated the probe from its 6km/s entry velocity to Mach 1.5 in the atmosphere of Titan, reaching temperatures of ~1900°C. The Back Cover is a stiffened aluminum shell with thermal protection consisting of Prosial; a spray-on suspension of silica spheres in elastomer.

The probe's Descent Control Subsystem (DCSS) consists of a 2.59m pilot parachute, deployment mortar, and associated triggering mechanisms, a 8.3m main parachute, and a smaller 3.03m stabilizing parachute. The stabilizing parachute is necessary as the main chute is not suitable for mission descent times of less than 2.5 hours.

The Separation Subsystem (SEPS) provides the electrical and mechanical attachment of the probe to the Cassini orbiter and the means of separation with the required accuracy and stability. Each of the three SEPS fittings has a pyronut for probe separation and incorporates rod-cutters for Front Shield and Back Cover release. The Spin/Eject Device performs the separation from the orbiter; it comprises three steel springs, axial rollers and track necessary to impart the correct separation velocity, spin rate, and stability to the probe as it is released from the orbiter. The umbilical separation mechanism consists of three 19-pin connectors and provided the electrical and data connection between the probe and orbiter during Cassini's long journey to Saturn.

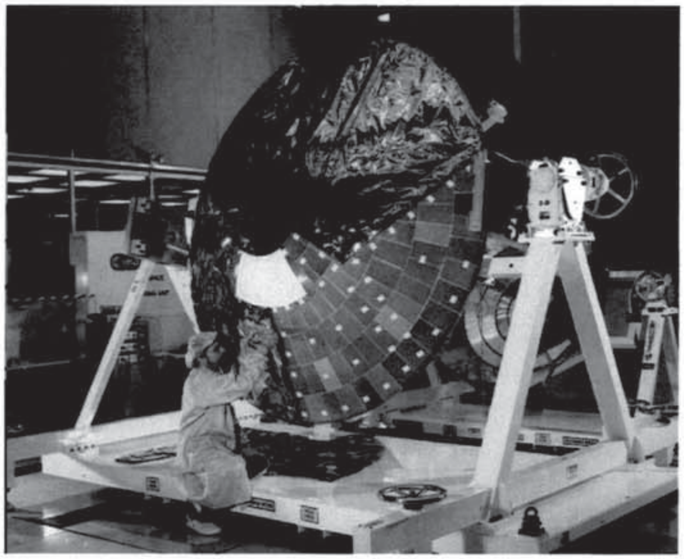

Figure 2. The Huygens Probe during integration

The Probe Support Avionics (PSA) remained attached to Cassini. The redundant PSAs received the probe's S-Band signal via the orbiter's HGA, processed and delivered the data to the orbiter. The Huygens probe payload consisted of six scientific instruments. A comprehensive description of the Huygens probe design is given in Ref. 1.

C. Engineering Operations

As well as the science observations that are the *raison d'etre* of the Cassini-Huygens mission, there are many stand-alone engineering operations that are essential to the success of the mission and the optimal use of spacecraft resources. These engineering operations must be organized in such a way as to have minimal impact on science data gathering, and where appropriate dovetail seamlessly with the existing science plan to result in a coherent set of operations that result in completion of the mission goals with minimum risk.

Orbit trim maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Optical navigation images are taken to provide additional data to the navigation team and enhance the orbit determination solutions obtained by radiometric data. Inertial Reference Unit (IRU) calibrations are performed, with full turns or taking advantage of optical navigation turns. The main engine cover is deployed and stowed in response to dust hazards, and the risk to the Stellar Reference Units (SRU), which are exposed to dust hazards during critical ring plane crossings, must be managed, and the SRUs must be periodically calibrated. Star identification must be suspended during the periods when a bright body, such as Saturn or its rings, appears in the field of view of the SRU. Reaction Wheel Assembly (RWA) biasing must take place to prevent saturation of the wheels' momentum management capability. RWA friction tests are performed periodically to assess wheel performance, and the backup RWA is exercised to ensure even distribution of the lubricant in the wheel casing. Pyrotechnic firing operations are occasionally needed by the propulsion module subsystem (PMS), and the Engine Gimbal Actuators (EGAs) are exercised to ensure continuing correct pointing capability of the Main Engine Assemblies (MEAs) during maneuvers. The Attitude and Articulation Control Subsystem (AACS) must have on-board parameters such as spacecraft mass and thruster magnitudes updated periodically to keep the engineering values recorded in the flight software commensurate with physics. The spacecraft Command Loss Timer (CLT) and other System Fault Protection parameters must be periodically adjusted for prevailing mission conditions, and in response to the needs of specific spacecraft operations; subsystem specific fault protection maintenance is also necessary.

Operating a robotic spacecraft in a complex alien environment presents a number of challenges for the engineering team. The Cassini Mission Operations System is composed of the combination of personnel, procedures, hardware, ground software, and networks needed to implement the operations phase of the mission. It is required to address a large number of objectives, constraints, and mission characteristics, primarily driven by the science requirements as interpreted by the Cassini science teams. Some of the mission constraints are typical of deep space robotic missions, some were common to orbiter missions, and others were unique to Cassini itself.

The distance between the engineering team and the Saturn orbiting spacecraft varies from 1.2 to nearly 1.6 billion kilometers, meaning real time control is precluded by the inherent speed-of-light communications time delays. For Cassini during the Saturn Tour, the one way communication time delay varies between 67 and 90 minutes.

Cassini has no instrument scan platform. A scan platform for remote sensing instruments potentially simplifies operations as optical remote sensing instruments can be oriented independently of fields and particles instruments when performing observations. With no scan platform, science observations take longer as the whole spacecraft has to be accelerated to a given rate, must coast for a while at the achieved rate, and then reduce the turn rate to zero at the desired observation attitude. There is also competition between the different science teams and the different investigators in determining which instrument is observing at any given time, and therefore who specifies the pointing of the spacecraft. Target motion compensation is also more difficult without a scan platform, as the whole spacecraft must be turned to match the target motion. All remote sensing data must be recorded for later transmission because the high gain antenna cannot stay pointed at Earth while the optical remote sensing instruments are in use.

Competition for the spacecraft resources required the science timeline to be established years in advance, to allow time for the science discussions, trade studies, resource negotiations, horse-trading and agreements on a conflict-free science plan to be made.

Cassini operational mode definitions, or opmodes, represent a predefined set of allowable spacecraft configurations that ensure the flight system is operated within specified power margins. Opmodes constrain the power consumption of the spacecraft, not the telemetry rate or attitude, and define the maximum power consumption allowed for each instrument and subsystem. With a few exceptions, the spacecraft is always operated within the power envelope of the specified opmode. Predefined command blocks termed opmode transitions are used to command the spacecraft configuration from one opmode to another. There are four categories of opmode; Downlink Fields Particles & Waves (DFPW), Optical Remote Sensing (ORS), Radar, and Radio Science Subsystem (RSS). During downlink DSN passes the spacecraft can be in any DFPW or RSS Opmode; however the X-band Traveling Wave Tube Amplifier (TWTA) is required to be in standby for the ORS and Radar modes. There are three opmodes in which the spacecraft Reaction Control Subsystem (RCS) can be used; these are used for low Titan flybys, below ~1300km - where there are high atmospheric disturbance torques that may exceed the control authority of the reaction wheels - or for Titan flybys that require turn rates and accelerations faster than the reaction wheels can provide. DFPW opmodes are the normal background state of the spacecraft. The spacecraft is in a DFPW opmode as the initial and final condition of every sequence. Orbit Trim Maneuver (OTM) prime and backup passes, engineering maintenance, and RWA friction tests are performed in DFPW opmodes. ORS, Radar, and RSS opmodes are used for science observation periods. Details of opmode design are given in Ref. 10.

D. Tasks & Processes

Tasks undertaken by the spacecraft team include:

1. Operations Planning

Subsystem experts provide required engineering inputs to the planning process, advise on the effects of planned activities on the operational state of the spacecraft, track consumables usage, check the planned activities against flight system constraints, provide predictions of spacecraft operational performance for planned events, and perform trade studies, if necessary, on the effects of different implementations for spacecraft operations. The team identifies and resolves engineering concerns for the mission phases under development, reviews the mission phase activities to ensure that all required spacecraft engineering activities are implemented, and acceptable from an engineering perspective. It also verifies that the integrated engineering activities satisfy spacecraft operational requirements.

2. Sequencing support

Systems engineers coordinate the efforts of the subsystems in providing detailed command level inputs for required engineering activities, perform constraint checking of command sequences, ensure adequate DSN coverage, and make adjustments for conflicting events. Constraint checking includes ensuring adequate link margins, pointing profile simulation, sun & bright body avoidance for star tracker pointing, the correct power & thermal margins, predictions of fault protection activity, and adherence to flight rules.

3. Test Implementation

This includes management of the Cassini Integrated Test Laboratory, planning and support of spacecraft ground testing, flight and ground software testing, verification & validation, and review and assessment of test and simulation results.

4. Flight Operations Implementation

Uplink of the necessary command sequences, monitoring of all on-board activities, verification that activities occurred as predicted, assessment of anomalous or unexpected results or fault protection responses, verifying health & safety of the engineering subsystems and the ground system supporting spacecraft monitoring.

5. Spacecraft data analysis

Assessments of the state of the spacecraft and the health & safety of the subsystem components are made. The results of engineering calibration and maneuver activities, trend analysis, and unexpected results, are reported.

6. Uplink development

Assessment of changing mission conditions or changes to the operational environment, sequence change requests, support for and involvement in the generation of operational scenarios and operational readiness tests.

7. Flight and ground software development & maintenance:

Development and maintenance of AACS & CDS flight software and the associated fault protection that was deferred from pre-launch development. Development of ground software to support the changing ground operational environment; includes writing software requirements, preparing development plans and schedules, writing code, testing, verification & validation, and delivery of new software versions.

E. Tools

The Kinematic Predictor Tool (KPT) is used to generate commands for attitude changes, inertial vector construction, spacecraft momentum management and the suspension of star identification (Star ID). The tool models AACS flight software components used in attitude estimation and control, reports flight rule violations, models RCS residual delta-V, and models geometries between target bodies and the spacecraft. KPT enables these AACS attributes to be simulated at a few hundred times real-time, so spacecraft command sequences can be simulated and attitude states validated for compliance with mission and flight rules.

The Inertial Vector Propagation (IVP) Tool generates commands that describe the positions of boresights with respect to the spacecraft coordinate system, and that describe the trajectories over time of target bodies. The software can create a fixed, time-invariant vector; a seven-term conic; and a Chebyshev polynomial from zero to twelfth order. The tool enforces compatibility with on-board constraints on possible vector names, and on the number of vectors on-board the spacecraft at any time. Default body vectors are present in the flight software at initialization - the x, y and z spacecraft axes, the negative x, y and z spacecraft axes, and the -X axis low gain antenna. These on-board vectors are duplicated by the tool at initialization, and it will also always produce a safe-spacecraft-vector to Sun, a Sun to Earth vector, and a set of Sun to J2000 coordinate axes. All of these default inertial vectors are long lasting conic vectors that cover a particular time period. Several vector segments can cover the same inertial object over any requested time period as needed. The tool outputs all the IVP commands required for a given command sequence. The activity parameters that are generated have associated error statistics. The user can see a timeline of body and inertial vectors that show how the vectors are sequenced into the flight software, how long they are resident in the flight software, and the total number of vectors active at any time.

The Reaction Wheel Bias Optimization Tool (RBOT) selects the optimal wheel bias to use for any given sequence segment; it is fully described in Ref 11.

II. Orbit Trim Maneuvers

Frequent Orbit Trim Maneuvers keep Cassini on the correct trajectory to complete the planned Saturn Tour. Considerable effort has been invested in detailed planning of the complete set of science observations associated with this Tour, so a robust OTM strategy is necessary to protect this investment by ensuring the spacecraft keeps to the planned trajectory. This requires meticulous maneuver planning and a robust system for ensuring that maneuvers can be implemented as planned, with short development times from availability of the final orbit determination solution through uplink.

One hundred sixty Orbit Trim Maneuvers (OTMs) have been planned between Cassini Saturn Orbit Insertion and the original end of mission, planned for July 2008. Each OTM, depending on the size of the burn, is either implemented on the bipropellant main engine or on the smaller, monopropellant reaction control subsystem thrusters. Keeping the spacecraft on the designed trajectory has been achieved using three maneuvers between each targeted encounter of Titan or an icy satellite. The cleanup maneuver is scheduled three days after the previous flyby, and corrects for most of the error resulting from the previous flyby; it generally has a high statistical component. The near apoapsis maneuver adjusts the trajectory for the next targeted encounter, and generally has a high deterministic component. The approach targeting maneuver is scheduled three days before the next Titan or icy satellite flyby and cleans up any errors resulting from the apoapsis maneuver. The Cassini Saturn Tour includes many 16 day orbits, during which maneuvers must be implemented approximately every 5 days, at any hour of the day – in fact they usually occur at the most inconvenient times. As well as the need to stay on the planned Tour, OTMs also serve to ensure trajectory accuracy requirements for target-relative pointing prediction, reconstruction, and control are met.

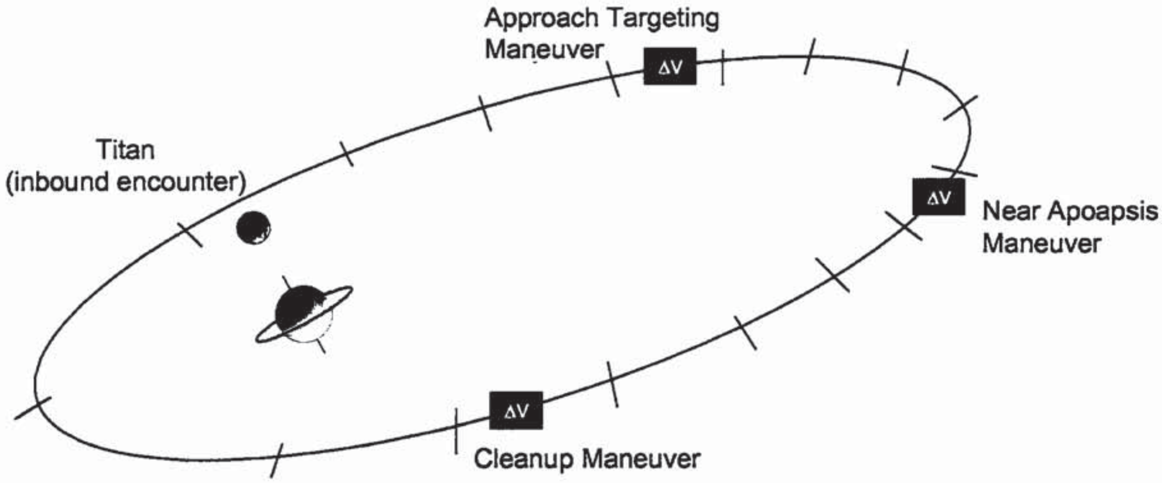

Figure 3. Nomenclature for Cassini Maneuvers, for an inbound Titan Encounter.

In order to facilitate prompt, accurate production of maneuver sequences from orbit determination solutions, a dedicated software tool was developed. The tool consists of Perl scripts that link and sequence the execution of other software used in the maneuver design process; navigation team maneuver design tools, AACS maneuver implementation tools, and software that generates spacecraft sequences. It generates the maneuver parameters and all related uplink and verification products in about 30 minutes from receiving an orbit determination solution.

Each maneuver takes place during a nine hour Deep Space Network (DSN) pass. A backup pass is also scheduled in case the maneuver is not executed during the prime window. Engineering operations that support the maneuver, such as placing the spacecraft in the correct power mode and thermal configuration, are placed in the spacecraft background sequence to execute at the beginning and end of the primary and backup OTM windows.

Following reception of the final orbit determination solution from the navigation team, the maneuver parameters are calculated and the uplink products generated. The uplink products are validated against Cassini flight rules with a series of automated checks. At the beginning of the primary OTM pass, the maneuver uplink lead verifies the health and safety of the spacecraft and uplinks the maneuver. The maneuver is executed during the same DSN pass as the uplink, and monitored in real time by the spacecraft team. The spacecraft does not perform a single turn from Earth pointing to the burn attitude; it is turned in two stages to avoid violating thermal requirements. The first turn is performed using reaction wheels and is about the spacecraft Z-axis (a roll turn), during which the spacecraft remains Earth pointed. The second is about the Y-axis (a yaw turn) and is performed on thrusters; during this turn the spacecraft moves off Earth pointing and telemetry is lost. The roll and yaw turns align the spacecraft pre-aim thrust vector with the delta V vector required for the burn. Following the burn, the same yaw turn is performed in the opposite direction to return the spacecraft to Earth pointing, and the same roll turn is performed in the opposite direction to return to the initial spacecraft secondary axis attitude. The engineering data from the off-Earth portion of the burn is recorded and played back at the end of the pass, along with any science data gathered before and after the maneuver.

In the unlikely event that the maneuver cannot be executed during the prime pass, for example if the DSN station was unable to uplink the maneuver sequence because of a station hardware failure, a backup maneuver can be prepared for execution during the backup pass. It has never been necessary to use a backup OTM pass.

III. Propulsion Subsystem Management

Cassini Reaction Control Subsystem (RCS) has sixteen 1-Newton monopropellant thrusters, divided into two redundant branches, and a Monopropellant Tank Assembly (MTA) consisting of a single 0.36m radius spherical tank. The tank contains an elastomeric diaphragm with monopropellant hydrazine on the thruster side, and pressurized gas on the other, for expulsion of bubble-free hydrazine to supply the thrusters in zero-g. Cassini RCS is used periodically for attitude control, to implement low delta-V maneuvers, and for reaction wheel momentum management.

The MTA is connected to the Recharge Tank Assembly (RTA) via two closed pyrotechnic valves. The recharge tank contains high pressure helium. Firing either of the pyro valves will un-isolate the recharge tank, and the pressure in the MTA and helium tank will equalize, thus recharging the monopropellant tank to provide fuel at higher pressures. Pressure in the RTA and MTA can be monitored by pressure transducer values in telemetry.

A. The need for Recharge

Titan atmospheric density estimates were made by the Cassini Ion and Neutral Mass Spectrometer (INMS), and the Ultraviolet Imaging Spectrograph (UVIS) using data from Titan flybys; and by the Huygens Atmospheric Structure Instrument (HASI) team using data from the Huygens probe descent into Titan's atmosphere. The AACS team also performed a series of Titan atmospheric density reconstructions from the attitude control subsystem performance data obtained during Titan flybys. These measurements suggested that the atmosphere may vary with latitude as well as altitude, and may not be symmetrical over the northern and southern hemispheres. This caused concern that the atmospheric density may be higher than expected for some of the planned flybys, which are to be as low as 950km, and the RCS may in some cases have insufficient control authority to overcome the atmospheric disturbance torques induced. In such a case, there would be a possibility that the spacecraft would lose pointing control, with a consequent loss of science data and the spacecraft entering Safe mode.

Recharge is necessary primarily to provide more control authority from the thrusters, as well as maintaining operation within the flight envelope. The maximum disturbance torques on the spacecraft are expected to occur during low Titan flybys, when the spacecraft will experience the free molecular flow regime in the moon's upper atmosphere. Under these conditions, the minimum safe altitude for the spacecraft is derived from the maximum density the spacecraft can fly through while maintaining the science pointing profile required and overcome the atmospheric disturbance torques.

The date of the earliest possible Monopropellant Tank Assembly recharge was determined from the maximum allowable operating pressure of the hydrazine thrusters. The date when this pressure would represent a ceiling to possible post-recharge pressures is dependant on the rate of hydrazine consumption during future mission events. Hydrazine consumption is modeled from the spacecraft characteristics, the mission profile, and the planned sequence of turns and maneuvers; in this case consumption was dominated by the T7 and T8 flyby hydrazine usage, which is large, deterministic, and well known.

The first Cassini 950km flyby will be the Titan-16 encounter, planned on 22 July 2006. This will be followed by the 1000km Titan 17 encounter on 7 September 2006. If the MTA recharge were not to occur, it would still just be possible to fly T16 at 950km without the spacecraft tumbling, but the subsequent T17 closest approach would have to be raised from 1000km to 1030km. For the rest of the Cassini Saturn Tour, all planned low altitude Titan flybys would have to increase in altitude by approximately 30 km, although there will be no appreciable increase (or even a slight decrease) in the delta-V needed to complete the prime mission. The changes needed to the geometry of Titan flybys would cause a substantial science re-planning effort, as detailed science operations for the Tour are already established for 950km Titan flybys.

B. Pyrovalve Operation & Ageing

MTA recharge is implemented by firing one of two pyrovalves to connect the RTA helium tank to the MTA hydrazine tank. The normally closed pyrovalve assembly controls the flow path until commanded to operate. Each of the valves in question has a single NASA Standard Initiator (NSI), which can be electrically initiated by a sequence of telecommands. The gas output of the pyrotechnic cartridge provides the linear motion of the valve's internal piston, and this piston in turn displaces the shear nipples normally keeping the high pressure helium in check, thus allowing flow to commence.

The NASA Standard Initiators used in the pyrovalves are an Apollo era design with a high reliability. Historically, more than 100,000 NSIs of this type have been fired on spacecraft missions in the past, and there have been no known failures. However, since the specified storage life is 10 years, and the Cassini NSIs were manufactured in 1992, the thermal and radiation environments of the NSIs in question were carefully reexamined and reviewed. Although no cause for extraordinary concern was found, contingency procedures to fire the redundant valve, and to fire the prime and redundant valve using different commanding techniques, were prepared.

C. MTA Recharge Operations

MTA Recharge was successfully completed on 10th April 2006. The single pyro valve PV40 was fired successfully. There was a nominal drop in pressure upstream of the pyro valve, from 2350 psia to 385 psia (+/- 17 psia) and a pressure increase in the Monopropellant Tank Assembly from 253 psia to 404 psia (+/- 2 psia). The post-firing pressures were well within the expected ranges, and the final hydrazine tank pressure was exactly as predicted. As predicted, there were significant thermal transients in the helium recharge tank, with temperatures dropping from initial conditions of 25 degC to a low of -2 degC, followed by gradual recovery. The hydrazine tank temperature only increased by about 3 degC due to adiabatic compression; this initially led to the hydrazine pressure being 406 psia but this transient condition ceased after about 30 minutes.

IV. The Huygens Probe

Attached to Cassini during cruise and early Saturn tour was the Huygens Probe, awaiting delivery to Titan. During an in-flight end-to-end communications test with the probe during the cruise to Saturn, a serious anomaly was discovered in the Huygens receiver. The recovery effort resulted in major changes to the Cassini trajectory, flight software, test program, and mission operations. Cassini released Huygens on 25th December 2004 UTC, setting up the correct entry conditions for the probe's arrival during Cassini's third flyby of Titan. As a result of the major engineering effort to recover the Huygens mission, on arrival at Titan on 14th January 2005, the probe studied the composition of the atmosphere, conducted unprecedented science observations, and the science data was returned successfully. The paper describes the Cassini flight system implementation of the revised Huygens mission.

A high priority mission objective for Cassini was to target and deploy the Huygens probe for Titan entry, and to subsequently receive the data the probe transmitted and relay it to Earth. The original mission design was such that Huygens transmitted science and engineering data via two redundant hardware chains with a six second delay between the signals. Probe Chain A and Chain B signals were to be received at Cassini via the High Gain Antenna (HGA). The Receiver Front End (RFE) diplexer was to split the signal, the signals were amplified by LNAs, and the amplified signals directed to the Probe Support Avionics (PSA) receivers. The PSA receivers were to decode the data and format the probe science and engineering data into probe Super packets and PSA housekeeping Packets, which were to be sent to the PSA Bus Interface Units (BIUs). These data were collected from the BIUs by the Orbiter Command and Data Subsystem (CDS), and subsequently stored on Solid State Recorders (SSRs) for relay.

D. Probe Relay Tests

A series of tests conducted in February 2000 confirmed the existence of a serious flaw in the PSA. The problem was inappropriately selected parameters coded into the RFE firmware and would have rendered the probe's data unrecognizable due to the effects of Doppler shift in the probe data signal arriving at Cassini. The vast majority of Huygens science data would have been lost if the problem had remained undetected and uncorrected.

The test design required Deep Space Network (DSN) ground stations to broadcast test data to Cassini that simulated the signal from Huygens to Cassini during the probe descent. When the test results were analyzed and the flaw discovered, in March 2000 additional testing was performed to confirm and characterize the problem. A European Space Agency (ESA) investigation team completed its work at the end of October 2000, and ESA subsequently convened an independent Enquiry Board, which reported its findings in December 2000.

With the problem fully characterized, the Huygens Recovery Task Force (HRTF) - a joint ESA/NASA team - was established in early 2001, to analyze the failure and to propose and evaluate possible recovery actions. The HRTF developed a redesigned probe mission to allow the Huygens probe relay to be performed while the Cassini orbiter flew by at a higher altitude than originally designed, thus reducing the Doppler effect on the probe signal. This trajectory modification maintained the tour science opportunities following Probe Relay. Increasing the altitude of Cassini during the Titan flyby and Probe Relay allowed for a reduction in the Doppler effect on the radio link and provided a more robust contact that potentially enabled all of the Huygens science data to be collected.

The early portion of the mission trajectory was redesigned to allow release at the third Titan flyby, Tc Instead of releasing the probe during November 2004 at the first Titan flyby. This allowed delivery of the Probe fifty days later than in the original mission and allowed the orbiter to rejoin the original tour at T3. Cassini's early portion of tour was subsequently redesigned to meet this requirement, by delivering the probe at the Tc flyby on 14th January 2005. Significantly, the planned engineering events leading up to the probe relay mission also had to be modified to fit the new timeline.

Additional engineering activities were required on both the probe and orbiter to support the redesigned Huygens mission. Orbiter flight software modifications were implemented to support the frequency tracking mode selection in the PSAs. Probe flight software changes were implemented to allow pre-heating of the probe before entry into Titan's atmosphere in order to thermally stabilize the frequency output by the Ultra Stable Oscillators. These changes required extensive ground testing and verification, and in-flight demonstration involving both the probe and orbiter.

Huygens was designed and built using the best data available on the composition of Titan's atmosphere. Data consisted primarily of the Voyager Titan flyby data and stellar occultation data from which atmospheric models could be derived. It was recognized that Titan's atmospheric structure at the time of the Huygens mission could deviate significantly from that which the probe was designed for, so the mission profile was checked by the collection and analysis of Titan atmospheric data from Cassini after early flybys. Data from the T0 untargeted flyby on July 1st, 2004, and the targeted Ta flyby on October 26th 2004 was used to validate the planned Huygens entry conditions.

E. Impact on Mission Operations

Such profound changes in the planned Cassini-Huygens mission required detailed re-assessment of the scheduled operational activities for the period from the completion of Saturn Orbit Insertion (SOI) on 1 July 2004 until the final receipt of the Huygens data at the Huygens Probe Operations Centre (HPOC) on 15 January 2005.

In order to ensure coordinated implementation of the Huygens recovery mission by the ESA and JPL teams, a Huygens Implementation Team (HIT) was formed, charged with refining and implementing the recovery effort. The HIT produced the Huygens Mission Operations Plan (MOP) [8], a joint ESA-NASA document which described all of the operational activities necessary to implement the Huygens mission. It was the plan that coordinated activities for both sides of the Cassini-Huygens interface, providing a clear and concise roadmap for implementation of the probe mission. The MOP addressed operational activities for both the Huygens probe and the Cassini orbiter, the engineering and management responsibilities, the operational and decision making processes, operational interfaces, and the detailed inputs and outputs for each planned activity. Where necessary, the MOP referred to established detailed procedures such as the Huygens Flight Operations Plan and Cassini Spacecraft Office standard procedures.

The MOP allowed operational detail of the mission to be available and accessible to both ESA and JPL team members. It ensured dialogue, review and scrutiny of operational products among all parties involved. The MOP forced the development of joint schedules and operations plans to eliminate any programmatic misalignment between the agencies. Detailed schedules for operational deliverables were specified down to the level of targeting coordinates and command files. The MOP divided the operations leading up to the probe mission into five phases.

One of the HRTF mission redesign recommendations was that the orbiter continually command the PSAs to a base frequency rather than searching for a signal at the expected Doppler frequency. Fortunately, there was a built-in test equipment mode (BITE Mode) available to the PSAs that enabled this. This test mode frequency was close enough to the redesigned probe mission frequency, but this test mode needed re-enforcement every ~10 seconds in case the PSAs periodically dropped lock. One of the orbiter Automatic Temperature Control (ATC) algorithms was modified to issue 2 BITE Mode commands to the PSAs every 12 seconds, otherwise 3734 separate BITE mode commands would have had to be issued to the PSAs during the 6 hours 46 minute period while the PSAs were powered on.

F. Final Checkout & Depassivation Phase

The final Checkout & Depassivation phase began on 14th September 2004 and ended on 16th December 2004. The major events in this phase were the Probe Checkout F15 and a test of the probe's Mission Timer Unit, Probe Battery Depassivation 1, The Final Probe Checkout, Probe Battery Depassivation 2, the Titan-A encounter, the Titan- b Approach Maneuver, and the Titan-b Encounter.

Checkout F15 took place on 14 September 2004, and was conceptually a rehearsal of the Final Checkout, duplicating F16 in many respects. The engineering data from the probe was used to assess the health of the probe system, and after confirming the probe's excellent health the decisions were made to use the transmitter Ultra-Stable Oscillator (TUSO) for the probe mission, and to load the MTU via CDMU A. Given the probe's good health there was high confidence that the mission could proceed at the primary mission opportunity at Tc.

Battery Depassivation 1 took place on 19 September 04. During battery depassivation, a 55W (2A x 28V per BDR) load is applied to each probe LiSO2 battery section for a few minutes to break the passivation layer on the battery electrodes. The purpose of depassivation is to remove the thin chemical passivating layer that forms within the lithium battery cells, on the surface of their electrodes, when no current flows. This layer, which builds up naturally over time, enabled the cells to retain their charge during the long Cassini cruise phase but could have been problematic for operations during the Probe mission if left in place.

Depassivation can be achieved by discharging each battery against a sufficiently high load for a short period of time. In practice, it first required the Probe and its instruments to be powered on using the Cassini bus, via its Solid State Power Switches (SSPSs), to establish a sufficiently high load on the Probe's bus. Each of the Probe's five power sections was then configured to connect the associated battery to the bus for a period of 5 minutes.

The procedure was in practice somewhat more complex because the Battery Discharge Regulator (BDR) within each power section was built to handle only one type of power source at any given time (i.e. a Probe battery or a Cassini SSPS). It therefore included commands to disconnect the associated SSPS before connecting the battery and visa-versa, as well as a set of commands that were loaded into the Pre-T0 Mission Timeline Table (MTT) to ensure that in the event of a Cassini Safing no battery would remain connected to the Probe's power bus – a situation that would result in a battery being completely discharged.

Depassivation 1 provided the opportunity to assess the battery health four months before the probe mission. Depassivation 1 was not part of the original mission, and was introduced after ground testing of flight spare batteries indicated that there was enough energy to support two battery depassivation activities. Early depassivation was advantageous as it allowed potential problems with the probe batteries and power subsystem to be discovered early in the mission timeline, but fortunately the operation showed the probe to be in perfect health.

The Titan-A flyby took place on 26th October 2004 at 15:30; inbound to Saturn with a 1200 km closest approach velocity of 6.1 km/sec. Science observations that took place around Ta were hoped to provide information to verify the existing Titan atmosphere models, to validate the probe entry conditions. The Cassini Ion and Neutral Mass Spectrometer (INMS) measured the composition of the atmosphere within +/- 10 min of closest approach. This gave the total density in the altitude range >1200 km, and the composition.

The probe Final Checkout, termed F16, took place on 23 November 2004. This further checkout data was used to confirm the health of the probe and the decision to proceed with the primary mission opportunity at Tc.

Battery Depassivation 2 took place on 5th December 2004, and was identical to the first depassivation. The purpose of the second depassivation was to remove any passivation layer that had built up on the battery electrodes since the first depassivation.

The Tb approach maneuver took place on 10 December 2004 to set up the correct conditions for the Tb flyby on 13th December, the maneuver was nominal.

G. Probe Targeting & Separation Phase

The Targeting and Separation phase ran from 16th December 2004 to the separation of the probe on 25 December 2004. The major events in this phase were the Probe Targeting Maneuver (PTM), the uplink of the Probe Relay Critical Sequence, the PTM Cleanup Maneuver, the configuration of the probe for separation, and Probe Separation itself.

The ~12m/s Probe targeting maneuver was executed on December 17, 2004 and placed the spacecraft on an impacting trajectory with Titan. A small cleanup maneuver of 0.138m/s was executed on 23 December.

Final commands to the Probe were sent on 22 December to complete preparations for release. The Huygens mission required the Probe to be powered-up before its entry into Titan's atmosphere; this was achieved via the probe's Mission Timer Unit, (MTU), which used redundant countdown registers to track the time from initial register loading to required power-on. During the ~20 day coast phase, between Cassini separation and Titan entry, the MTU was powered from three of the five batteries via power lines that are separate from the main Probe bus. The MTU was loaded when on battery power, in order to avoid an unnecessary voltage transient that may result from switching over from orbiter power.

Separation of the Probe from the Orbiter occurred on December 25, 2004. The Probe Spin/Eject Device (SED) separated the Probe with a relative speed of ~0.3 m/s. The Probe axis was pointed to achieve a zero-angle-of-attack entry and such that the velocity increment provided by the SED springs provides the final targeting to the entry aim point.

The last two maneuvers of the Orbiter before Probe entry provided the final orbiter targeting to the required aim point to achieve the radio relay link geometry. The first of these was the Orbiter Deflection Maneuver (ODM), which was executed three days after separation. This large main engine maneuver of ~24 m/s targeted the Orbiter for the planned flyby of Titan at an altitude of 60,000 km and timed the Orbiter's closest approach to occur just over two hours after Probe entry. The relative position of the Orbiter with respect to Titan during probe entry and descent was designed to provide a view toward the Probe for approximately four and a half hours after entry. The Orbiter HGA was planned to be pointed toward the predicted Probe landing site to capture the Probe telemetry during descent and for approximately 2 hours after Probe touchdown.

The spin-stabilized Probe was be targeted for a southern latitude landing site on the day side of Titan. In order to meet the probe dynamic entry conditions, minimize trajectory dispersion and thus enhance data relay link performance, the Probe entry angle into the atmosphere was planned to be -65° + 3° (99%). The term "entry" generally referred to the arrival of the Probe at the interface altitude of 1270 km, which defined the interface point for Probe targeting requirements.

Separation of the Probe from the Orbiter was not to jeopardize the functional or structural integrity of either spacecraft, and was to give the Probe the required post-separation trajectory and attitude, within allowable uncertainties, to achieve Titan entry. In order to accomplish this, the pre-separation position vector, velocity vector, and attitude must be such that, after the dynamics of separation have been applied, the Probe is left with the proper velocity to reach the aim point, and the proper attitude for zero angle of attack at atmospheric entry. The pre-separation attitude was achieved by rotating the combined spacecraft to an attitude which left the Probe at the desired post-separation attitude.

The Cassini AACS subsystem provided an estimate of the spacecraft attitude and turning rates with respect to the J2000 coordinate system. In Celestial-Inertial mode, the Stellar Reference Unit (SRU) and an on-board star catalog determined the spacecraft attitude in the J2000 reference frame. Attitude estimates were propagated by an Inertial Reference Unit (IRU) between SRU measurement updates.

The Reaction Control System (RCS) was used to control the combined spacecraft attitude before the separation event. Following the turn to the Probe separation attitude, a settling time was used to allow the spacecraft to attain a quiescent state with very low body rates on all axes. The firing of the thrusters was inhibited for 10 seconds immediately before Probe separation, and re-enabled 60 seconds after. During the period without thruster firings to control the attitude, the Orbiter tumbles in response to the separation impulse. Five minutes after the separation event the AACS was switched to detumble mode. The RCS thrusters were re-enabled and the spacecraft rates reduced to low, commandable threshold values. When the Orbiter rates were within the prescribed threshold limits, the AACS reentered Celestial-Inertial mode and a turn to the probe release attitude was initiated.

Post-separation imaging of the Probe was be used to improve the knowledge of its ephemeris, entry conditions at Titan, and ultimately the descent trajectory.

Failure to separate the probe from the orbiter at the planned time would have resulted in significant impact to both the Huygens and Cassini missions. If the cause of the failure was determined to be a relatively simple one, such as a hardware failure that can be corrected in a matter of days, the recovery would have been relatively clear. However, if the cause of the failure was due to more complex issues, such as higher than expected uncertainties in the probe targeting, there would have been a much larger impact.

A delay in probe separation long enough to jeopardize the Tc probe delivery would result in implementing one of the planned contingency missions, where the Saturn Tour would be modified yet again to create delivery opportunities in February and June 2005. Falling back to any contingency mission would have caused the orbiter to deviate from the nominal tour and thus lose planned science observations and increase the use of propellant.

H. Coast and Probe Relay Phase

Following separation, the separation delta-V telemetry was played back from the spacecraft and used by the navigation team to refine the post separation trajectories of the probe and orbiter. Imaging of the probe took place in order to assist in the post-mission probe descent trajectory reconstruction; it also provided further assurance that the separation event was nominal. The Probe Support Avionics (PSAs) were turned on for a short period in order to check the survival of the PSAs after the pyro shock event of separation. An Orbiter Deflection Maneuver (ODM) was performed to set up the correct conditions for a Titan C flyby consistent with the requirements of the probe mission.

A two day period was defined within which observations of Iapetus were to be made during the fortuitous viewing conditions that occurred during the Rev B apoapse of the redesigned early tour. The observations took place over the 2005 New Year 's Eve period.

ODM clean-up maneuver was implemented to reduce errors relative to the nominal probe-relay pointing. Critical Sequence activation took place on 6th January 2005 - once the Critical Sequence was activated, the orbiter could complete the probe relay mission without ground intervention, even in the event of equipment failure on board.

The probe relay mission took place on 14th January 2005, with the probe reaching the interface altitude of 1270km above the surface of Titan at 2005.014T09:05:56 SCET. On approach to Titan, the last downlink before Probe relay was over the Madrid DSN station (DSS 63). Following the playback of all data remaining on the solid state recorders, the Cassini orbiter turned nearly 180 degrees to point the HGA at the predicted Probe landing point. To prevent any interference with reception of the Probe data, no transmissions from the orbiter are allowed during Probe relay at any frequency; transmissions from the orbiter HGA at X-band were turned off by the Probe mission sequence shortly after the orbiter turned away from Earth. The orbiter pointed to the predicted landing site until that site was below the physical Titan horizon with respect to the orbiter. At that time, the orbiter stopped collecting probe data and began the turn back to Earth. 3h39m22s of probe mission data was collected. Results of the Huygens probe mission are summarized in Ref 9.

V. Conclusion

Cassini is a complex mission, kept on track by meticulous attention to engineering detail. Our approach to operational complexity is progressive automation of ground processes to the extent possible. Automation of ground processes has improved the efficiency and accuracy of operations. Developing tools and processes for the optimal selection of momentum bias has ensured efficient use of reaction wheel consumables.

The spacecraft is in excellent health and we look forward to implementing the remainder of the Saturn Tour and an extended mission.

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