Twenty Years of Systems Engineering on the Cassini-Huygens Mission

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Abstract—**Over the past twenty years, the Cassini-Huygens Mission has successfully utilized systems engineering to develop and execute a challenging prime mission and two mission extensions. Systems engineering was not only essential in designing the mission, but as knowledge of the system was gained during cruise and science operations, it was critical in evolving operational strategies and processes. This paper discusses systems engineering successes, challenges, and lessons learned on the Cassini-Huygens Mission gathered from a thorough study of mission plans and developed scenarios, and interviews with key project leaders across its twenty-year history.**

TABLE OF CONTENTS

1. INTRODUCTION

Systems engineering has played a vital role in the Cassini–Huygens mission. Cassini-Huygens is a complex mission with international partnerships, a heavily instrumented spacecraft, and a myriad of science objectives. Systems engineering has been applied to manage this complexity and develop a mission system that effectively balances engineering and science to enable a ground-breaking mission to Saturn. This paper discusses the systems engineering practices implemented by the Cassini-Huygens project and some of the challenges that have been faced during mission development and operations. The lessons learned by Cassini-Huygens can be applied by future missions looking to efficiently utilize their project resources.

2. MISSION OVERVIEW

The Cassini-Huygens mission is an international collaboration between NASA, ESA, and the Italian Space Agency. The mission launched on 15 October 1997. After an almost seven-year interplanetary cruise, the spacecraft arrived at Saturn on 1 July 2004. After completing the four-year prime mission (PM; 2004-2008) tour of the Saturn system and the 27-month Cassini Equinox Mission (CEM; 2008-2010), the spacecraft embarked on the seven-year Cassini Solstice Mission (CSM) in October 2010.

The mission studies all aspects of the Saturnian system which can be organized into five disciplines: Saturn, Titan, icy satellites, rings, and magnetospheres. The eight years of science operations at Saturn completed so far have returned a wealth of science data. Cassini-Huygens science results have been featured in over 2,500 peer-reviewed journal articles. The CSM will continue to build on these science results as well as study seasonal phenomena in the Saturn system. The CSM is planned to continue until September 2017, by that time Cassini will have observed most of the northern winter/ southern summer season and all of the northern spring/ southern fall season. This will provide an unparalleled data set for studying seasonal change of giant planets.

3. CASSINI-HUYGENS SYSTEMS ENGINEERING PRACTICES

This section describes the requirements management, interface definition, and risk management strategies implemented by the project.

Requirements

Developing and maintaining requirements are a critical system engineering function and was especially important on Cassini-Huygens given the mission complexity. To manage requirements, Cassini-Huygens employed rigorous documentation practices. All top-level (level 2) project requirements were documented in the "Project Policies and Requirements" document. These requirements subsequently flowed down to the system and subsystem level. The system and subsystem requirements were captured in functional requirement documents (FRD). Each FRD provided the design criteria, functional requirements, and a functional description for the associated system or subsystem [1]. Several current and former Cassini project members interviewed for this paper commented on the meticulousness applied to requirements management and felt that this was essential to the project's success. One interviewee commented that FRDs were a more thorough method for tracking the system design as opposed to Functional Description Documents (FDDs) because FRDs explicitly stated the requirements and how requirements were allocated

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throughout the system. FDDs are not as explicit and it is left to the engineer to interpret requirements from the design description. This can lead to misinterpretations and failure to design a system that meets mission objectives.

The project assembled all FRDs into the “Cassini Orbiter Functional Requirements Book”. The book consisted of two volumes: system functional requirements (level 3) in volume 1 and subsystem functional requirements (level 4) in volume 2. Cassini also used a database, called Tracer, to trace requirements which marked the first time this method had been used by a JPL mission. Changes to requirements and the spacecraft design were closely tracked and all changes had to be approved by the Program Change Control Board (PCCB). All changes were described in an Engineering Change Request (ECR); the ECR also identified all teams and subsystems impacted by the proposed change. The proposed change was brought before the PCCB where all impacted teams had to give their approval or disapproval and project managers would give the final determination. After requirement changes were approved, Tracer and the affected documentation would be updated. The revised documents were distributed to project personnel to ensure the project was working to the current requirement set.

Interfaces

The project also strove to understand mission and project interfaces. For design interfaces, top-level Interface Requirement Documents (IRD) were used to capture interfaces, such as the one between the Cassini orbiter and the Huygens probe. The interface requirements were then flowed to lower level documents. However, even though the project took steps to document interfaces, a design error still arose between the Cassini orbiter and the Huygens probe (this will be discussed in subsequent sections of the paper). This demonstrates that communication between groups is also important since documentation may not completely capture all aspects of an interface.

Important interfaces also occur between project teams during operations. To that end, Operational Interface Agreements (OIA) were used to document interfaces between project teams and, in some cases, the product deliverables and receivables that were required for the interface to function successfully. For example, an OIA was written to define how reference trajectory changes would be delivered and incorporated into the mission plan and science planning process. OIAs have continued to be used throughout the mission to capture important processes and interactions that occur across teams.

Communications

Rigorous documentation of requirements and interfaces does not eliminate the need for effective communication. Communication across all system levels and interfaces is essential to mission success. Communications on Cassini-Huygens were sometimes challenging given that the mission is an international collaboration involving three space agencies, seventeen countries, and hundreds of scientists and engineers worldwide. For example, one interviewee noted that the Cassini and Huygens collaboration had a “meet at the interface” attitude. Better communication and increased insight into each other’s programs could have avoided some of the issues the project experienced with the Cassini/Huygens interface.

Systems engineers on Cassini-Huygens had to be able to bring people together, work as a team, and build consensus. By bringing team members together and collaborating at the system level many conflicts between teams and many technical problems faced by the project were resolved. These system-level meetings occurred across all disciplines (spacecraft, mission, science) during development and continued into operations. For example, in development, the spacecraft systems design team held weekly meetings to discuss issues and changes in the spacecraft design that had system-wide impacts. The meetings were strictly a forum for discussion between subsystem and instrument engineers and, by holding them weekly, gave a sense of continuity in the spacecraft design. In operations, mission planning forums are held to discuss system-wide topics impacting both science and engineering. Meeting topics include operations process changes, long-range planning, and system-level trade studies. The forums are attended by a wide swath of the team, such as spacecraft engineers, science planners, instrument team representatives, and project management.

Collaborative meetings, such as those described above, cut through all levels of the project organizational chart, allowing any engineer to voice concerns or ideas. By leveraging expertise from across the project, issues can be identified that may have otherwise been overlooked if the meetings were restricted to only project managers and leaders. This approach has greatly benefitted Cassini-Huygens throughout development and operations by giving team members a conduit through which they could voice their opinions. Other organizations have also recognized the benefit of encouraging input from all project levels. The importance of giving engineering experts at all project levels an opportunity to voice their ideas and concerns was highlighted in the report of the Columbia Accident Investigation Board [2]. JPL has recently established an Engineering Technical Authority path which gives engineers an avenue, independent from project and line management, through which they can voice concerns that they feel are not being adequately addressed elsewhere.

Risk

The Cassini-Huygens project was also rigorous in their application of risk management. Throughout the mission life cycle the project has endeavored to track and manage risk although the intensity of this effort has varied with more resources expended during development and for critical events than during current operations. Risk management is a team effort and all members of the Cassini-Huygens flight team are expected to participate in identifying, assessing, and mitigating risk.

In development, many different strategies were implemented to mitigate risk. The spacecraft design featured redundancy or cross-strapping in many subsystems. A risk list was created and maintained to track risk items and their mitigation strategies. The substantial amount of documentation, such as that described above for requirements and interfaces, also served to manage risk. Extensive testing, review, and contingency planning were performed for mission critical events such as Saturn Orbit Insertion and the Huygens Probe Delivery. This intensive effort allowed the project to identify event-specific risks and develop response plans in case of anomalies.

In operations, risk management is still an important function though it is not pursued as aggressively as it was earlier in the mission. Contingency planning is no longer performed given resource constraints and the lack of high-criticality events in the current mission phase. However, mechanisms put in place early in the mission to mitigate risk are still used today. The risk list is still maintained and periodically reviewed. Procedural checklists and reviews are required of all teams when building command sequences and important spacecraft events such as flight software updates are carefully tested in system testbeds before on-board execution.

4. SYSTEMS ENGINEERING IN DEVELOPMENT

The project faced many issues with system-wide impacts in developing the mission. The complex spacecraft design and the numerous interfaces between the subsystems and instruments presented challenges. This section will discuss several system engineering related problems that the Cassini-Huygens project encountered during development.

Cassini-Huygens Spacecraft Redesign

Cassini-Huygens is one of the most complex robotic explorers ever sent into space. The spacecraft went through several redesigns throughout the mission design cycle. A major redesign occurred in 1992 and the dramatic changes made in this iteration had a significant impact on future operations.

The original concept for Cassini was a three-axis stabilized spacecraft with a turntable for magnetosphere and plasma instruments, a remote sensing scan platform, and a steerable antenna for communications with the Huygens Probe (Figure 1). NASA budget limitations in 1992 required a redesign of the spacecraft to reduce costs. Many of the implemented cost-saving measures reduced spacecraft capabilities [3]. The two most significant changes in the 1992 redesign were the removal of the scan platform and turntable. The scan platform and turntable would have allowed the high-gain antenna, remote sensing instruments, and magnetosphere and plasma instruments to point independently of each other. This marked the first time an outer-planets spacecraft was designed without a scan platform. The steerable antenna for communications with the Huygens probe was removed in a subsequent design iteration. The removal of these items reduced the number of articulable elements on the spacecraft and reduced spacecraft mass resulting in cost savings [3].

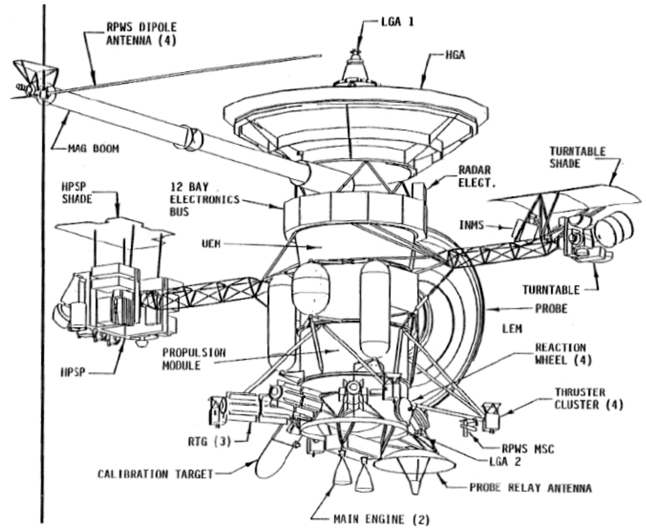

Figure 1. Cassini Spacecraft Design with Scan Platform and Turntable

In the final spacecraft design, the spacecraft stands 6.8 m high with a maximum diameter of 4 m and is three-axis stabilized (Figure 2). It is powered by three radioisotope thermoelectric generators. Telecommunications is provided by the 4 m high gain antenna, which is also used for radiometric navigation data, radio science, and RADAR science. Other engineering subsystems include the command and data system, the attitude control system, and the propulsion system. The propulsion system consists of monopropellant reaction control thrusters and bipropellant main engines. The main engines are used for large propulsive maneuvers. The reaction control thrusters are used for small propulsive maneuvers and attitude control. The attitude control system includes reaction wheels that are also used to provide attitude control.

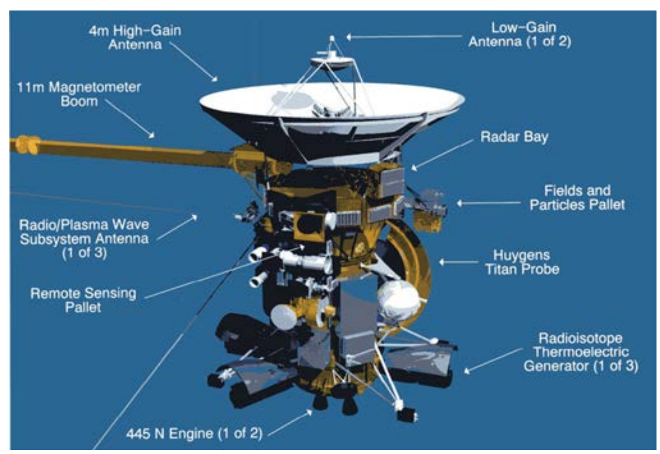

Figure 2. The Cassini Spacecraft

The Cassini orbiter carried the Huygens probe (Figure 3, [4]) which was jettisoned from the orbiter in December 2004 and descended to the surface of Titan in January 2005. This was the first landing of a probe on a body in the outer Solar System. The probe carried six instruments, batteries for power, a command and data subsystem, and a data relay subsystem. During atmospheric entry the probe was protected by a descent module that consisted of a heat shield and an aft cover. After these components were jettisoned, parachutes were used for the remainder of the descent. The instruments measured aerosol and cloud properties, winds, atmospheric composition and conditions, and surface properties and also conducted descent imaging.

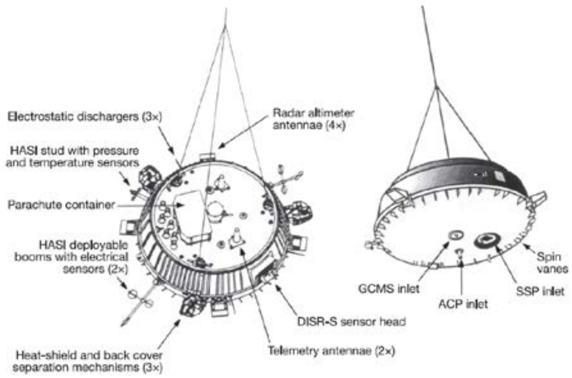

Figure 3. The Huygens Probe

The Cassini orbiter also carries 12 instruments that can be grouped into three categories: optical remote sensing (ORS), magnetosphere and plasma science (MAPS), and microwave remote sensing. All instruments are fixed to the spacecraft body. MAPS and ORS instruments are fixed to different sides of the spacecraft such that the instruments' pointing requirements are largely incompatible. The ORS instruments are co-aligned so they can often collect data simultaneously.

The removal of the turn table and scan platform resulted in complex science operations because instrument pointing was no longer separate from spacecraft pointing [5]. Without the scan platform, ORS and MAPS instruments cannot point independently of each other. Also, the removal of the turn table meant MAPS instruments could no longer rotate independently of the spacecraft; instead the entire spacecraft must roll. The loss of instrument pointing independence between instruments resulted in intense negotiations in order to allocate observing time and pointing control to the instruments. It also drove the need for advanced planning to allow time for trade studies and spacecraft resource negotiations, a larger operations workforce, and increased budgets.

While the elimination of the scan platform and turntable introduced many complexities into operations, current and former Cassini project members interviewed for this paper stated that it was thought that the removal of the turntable and scan platform in 1992 was essential for reducing costs and ensuring survival of the project. However, it was also noted that more forethought should have been given to the impact of the redesign on science operations. Development of the science planning process to be used in operations was delayed until after launch. Early studies conducted during mission development foreshadowed some of the complexities that would be faced in operations, but detailed work was not performed until many years later. If system operability and the impact of the spacecraft redesign had been considered earlier in the project lifecycle, it may have influenced design choices, the decision to delay operations planning, or the resources allocated to the operations planning effort.

Cassini Resource Exchange

After facing budget constraints in 1992, project management knew they needed to limit cost growth to ensure continued funding for the mission. Typically, for science payload development, a Science Instrument Manager is responsible for holding reserves (mass, power, data rate, funding) at the payload system level and allocating them if an instrument runs into development issues. This approach can lead to exhaustion of reserves and descoping of instruments if problems are encountered after all reserves have been allocated [6]. Instead of following the traditional system-level reserve management approach, Cassini decided to allocate all reserves to the instrument teams and make the instrument leads responsible for trading resources among themselves if they ran into development issues. The market-based system was referred to as the Cassini Resource Exchange. The resource exchange operated from 1993 – 1995 and resulted in the successful delivery of all orbiter instruments with little resource growth. Overall science payload cost growth was less than one percent and payload mass decreased by 7% [7].

While managing margins and reserves at the system level is a sound systems engineering practice and is generally the preferred management method, in this case allocating the reserves to the instrument level proved to be a successful strategy. This strategy required instrument teams to work together and consider trades across the entire science payload as opposed to focusing solely on their instrument. The strategy proved to be a more resource-effective method than the traditional approach of management allocating reserves on a per-problem basis.

Software Development

The majority of ground system software development was delayed until after launch due to budget considerations. However, development budgets were also constrained and many tool capabilities were not available once operations intensified. This resulted in a mix of tools: those that were developed formally with systems engineering practices and ad-hoc tools that were developed outside the formal process. The ad-hoc tools lacked formal validation which led to inconsistent results among tools, maintenance was more difficult, and lack of support documentation made training difficult [5].

Many of the tools developed for operations lacked coordination with other tools. This lack of coordination led to engineers needing to execute multiple tools to complete a single process or procedure. By running each tool in a standalone fashion, errors may not be revealed until several steps into the procedure which then requires the procedure to be restarted once the error is corrected. Each tool also pulls from its own set of support files even though many tools require the same support files. Thus, effort must be expended to ensure that each tool is using the same, up-to-date information. Tools should be architected together as a suite whenever possible. This allows for commonality between tools that can reduce software maintenance. For example, a common database of information from which tools can access support files would reduce the need to maintain multiple databases. Integration between tools could also simplify the user experience, by requiring only one command to execute a suite of tools or each tool using the same input/output format which reduces the need to reformat inputs for each specific tool. However, architecting a suite of tools can sometimes be more difficult than developing a single tool due the increased requirements and functions the suite must satisfy. Thus, appropriate resources must be allocated to software development to ensure that a tool suite is developed that meets the project's needs and that can be delivered on-time.

While ground software development on Cassini-Huygens has not been smooth, there have been successes. One example of a successful, formally developed, system-wide tool is the Pointing Design Tool (PDT). This tool is accessible to science planners and instrument teams and allowed the responsibility for the design of science observations and spacecraft turns to be distributed across teams. PDT also allows the user to visualize the activity and performs some flight rule checks, such as checking for sun-pointing violations.

Cassini-Huygens has continued to improve ground software throughout operations and has integrated some tools together resulting in the simplification of some operations processes. However, if adequate resources had been available from the beginning of software development, many of the growing pains experienced during development may have been avoided.

5. Systems Engineering in Operations

Even in operations, Cassini-Huygens has continued to apply systems engineering to solve technical problems and to refine operations processes. The operations phase has not been without surprises and the issues revealed have forced Cassini-Huygens to implement new operations processes and change mission plans to overcome them. Also, as the project has gained knowledge of the spacecraft system and the Saturn system, processes have been refined to better utilize the spacecraft and enhance science return. The issues faced during operations show that the systems engineering effort is continuous throughout all mission phases. Projects must be able to continuously adapt to changing spacecraft capabilities and mission profiles.

Reaction Wheel Management

Cassini uses Reaction Wheel Assemblies (RWA) for attitude control and spacecraft slews. In a given week, RWA control is used about 99% of the time and the other 1% of the time is controlled by the reaction control thrusters [8]. While operating the RWAs during the outer solar system cruise phase, it became apparent that the RWAs would need to be closely managed to maintain their health and increase the likelihood of their continued operation. The RWAs had started to show signs of degradation, particularly at low wheel speeds. The project determined that the RWAs needed to be operated such that the low wheel speeds could be avoided as much as possible. The Reaction Wheel Assembly Bias Optimization Tool (RBOT) and process was developed to manage reaction wheel momentum, speeds, and zero rpm crossings. The RBOT process was first initiated in 2002 and has continued to evolve throughout operations.

Since the establishment of RBOT there has been an ongoing trade between RWA health and science return. For most of PM, the focus was on maximizing science data collection not on limiting science for RWA health [8]. While RWA health was closely monitored, science took precedence and effort was made to optimize science return as much as possible. However, as PM progressed concern rose over the amount of time the RWAs were spending in low-RPM regions. To counteract this problem, the Attitude and Articulation Control Subsystem team (AACS) implemented more RWA biases (biases are used to set wheel speeds) but this strategy eventually became a concern because of the amount of hydrazine consumed by the biases. The project decided to take several steps to better manage the wheels including placing constraints on science data collection.

Current operations strive to better balance RWA health versus science data collection. AACS and the Science Planning team collaboratively developed a set of guidelines and constraints for science teams to follow when assembling science plans [8]. These rules minimize RBOT problems but may impact science return by requiring teams to use less-than-optimal pointing designs for their observations or to make more trades for observing time between instruments. At the beginning of each RBOT process, AACS is briefed on the science observations they will be analyzing along with identification of the highest science priorities. This informs the AACS teams as to which observations should be preserved above all others and which observations can be modified or removed to correct RBOT problems. The most common solutions to RBOT problems are small modifications in science observation pointing designs or removal of spacecraft rolls during downlinks (these rolls are used for MAPS data collection). While these changes impact science return, the majority of requested science observations are implemented as designed and overall science return has not been greatly diminished.

Due to changes in RWA performance, the project has had to rethink how to manage RWA health and how to continue to maximize science return. The RBOT process has been essential in managing RWA health and prolonging their operational lifetime. While science data collection may be less optimal than early in the mission, the science return continues to be extensive, covering all aspects of the Saturnian system. Also, taking steps now to extend RWA lifetime will enable the project to reach their objective of observing the Saturn solstice in 2017 which will yield a unique data set for the Cassini-Huygens mission.

Huygens Probe Receiver Anomaly

One of the biggest challenges faced in operations was the Huygens probe receiver anomaly. In February 2000, in-flight tests revealed an anomaly in the Huygens receiver onboard the Cassini orbiter. The receiver was unable to accommodate the Doppler shift in the relay signal that would occur during the probe mission. This design flaw would have caused the loss of a large fraction of the Huygens data and the mission would not have achieved one of its primary science objectives.

The Huygens probe receiver anomaly demonstrates the importance of understanding system interfaces, communication, and validation and verification. A number of design reviews of the communications link between the orbiter and probe were held, but the design flaw was never caught. Also, the design specifications of the receiver were never fully communicated to NASA because the radio manufacturer wanted to maintain confidentially of their design [9]. Finally, a full-up, ground test of the radio link between the orbiter and probe was never conducted. If it had been conducted, the error would have been relatively easy to fix on the ground. Also, the project was not planning to conducted end-to-end tests in-flight either. However, the efforts of an ESA engineer reversed this decision. The anomaly illustrates the vital importance of testing in realistic conditions, because without the tests the probe mission would have been a virtual failure.

Once the problem was detected, the project, ESA, and NASA realized that a fully collaborative effort was needed to recover the Huygens probe mission. The Huygens Recovery Task Force (HRTF), a joint NASA/ESA team, was convened in 2001 to analyze the anomaly and propose corrective actions. The task force recommended redesigning Cassini's trajectory to reduce the Doppler shift on the probe signal [10]. Unfortunately, a software fix to the probe support avionics was not possible due to the firmware used in the receiver. Since the redesign represented a significant change to the mission plan, the project instituted the Huygens Implementation Team (HIT), another joint-agency team. The purpose of HIT was to ensure a coordinated implementation of the Huygens mission. HIT performed systems engineering and mission analysis tasks for the redesigned mission [10].

For the mission redesign, Cassini's trajectory was changed such that the orbiter flew by Titan at a higher altitude than originally planned (Figure 4, [11]). A higher flyby altitude would reduce the Doppler shift on the probe signal. The HRTF investigated inserting a higher Titan flyby at the beginning, middle, and end of the PM. The option to redesign the beginning of the PM tour was chosen because it had the smallest impact on the orbiter science to be collected during PM [12]. The first 6.5 months of the PM trajectory were revised. An additional Titan flyby was added such that the originally designed first three Titan flybys (T1, T2, and T3) became four Titan flybys (Ta, Tb, Tc, and T3). The redesigned portion of the trajectory reconnected with the original design at T3 minimizing the impact to science in the remainder of the prime mission. In the new design, the probe mission took place at Tc on 14 January 2005.

Environmental Hazards

Cassini-Huygens faced risk from the uncertain environments that the spacecraft would face at Saturn. To mitigate this risk, the project endeavored to develop models to assess the risk and develop mitigation methods. An example of such an effort is the study of dust present in the Saturn system and the risk it poses to the spacecraft. Extensive analysis and trade studies have been performed to assess the risk to the spacecraft and how to balance this risk with science return.

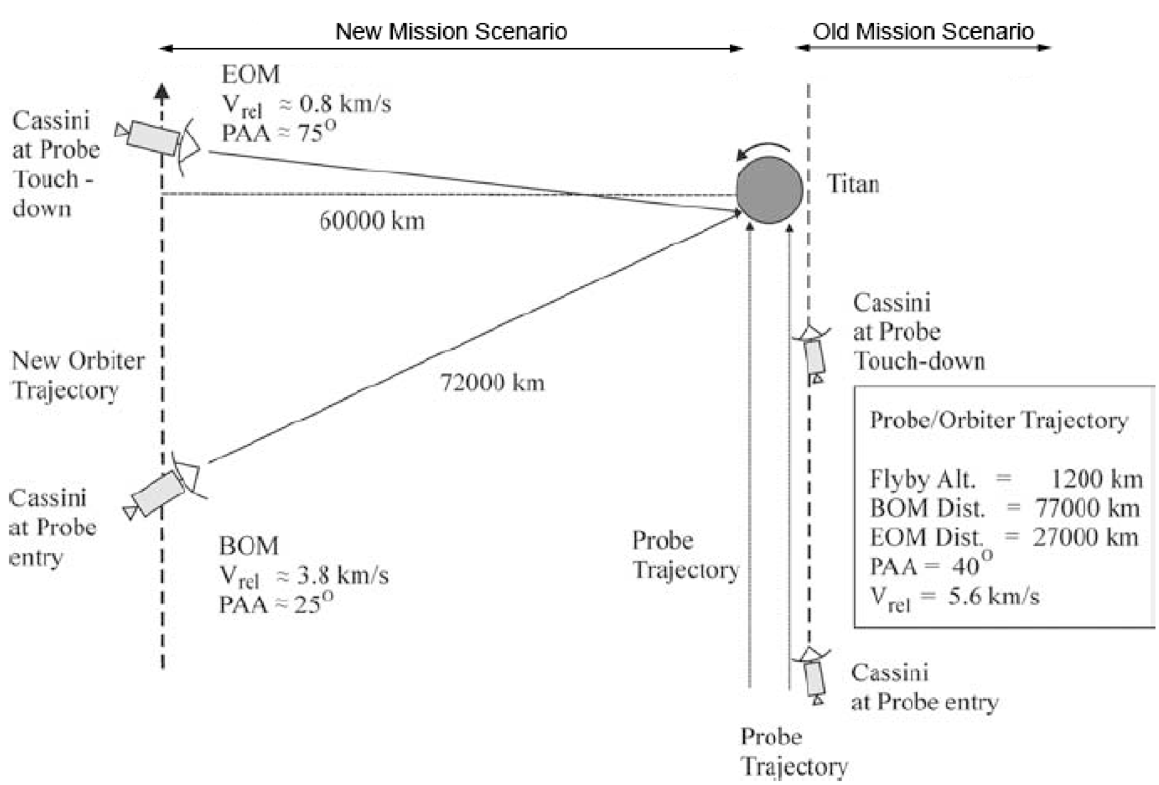

Figure 4. Comparison of Orbiter Trajectories during the Huygens Probe Mission

Saturn has the most extensive ring system of any of the outer planets. While the main rings pose a significant threat and cannot be traversed by the spacecraft, areas outside the main ring may be traversable but the dusty material in these regions needed to be quantified in order to determine safe crossing regions. Early ring models were developed using Pioneer, Voyager, and ground-based data. The models have been regularly updated using Cassini's in-situ measurements of the rings collected by a variety of the science instruments [13]. The dust hazard analysis also included a study of the spacecraft to identify vulnerable external surfaces and components. The analysis concluded that the high gain antenna (HGA) could protect vulnerable surfaces against dust hazards. However, using the HGA to shield the spacecraft limited science observations because the instruments cannot be pointed optimally. Thus, for less severe dust hazards, the project elected to use the main engine cover to protect the engine nozzles (the most vulnerable spacecraft component) and allow science-optimized pointing.

Through the development of ring models and analysis of the vulnerable spacecraft areas, the project developed a plan that would protect the spacecraft but also allow the spacecraft to fly more aggressive Saturn tour trajectories and enhance the science return of the mission. One of Cassini's prime science objectives was to characterize Saturn's dust environment and this would not have been achieved if Cassini had elected to avoid all regions which may have posed even a small hazard to the spacecraft [13].

Downlink Strategy and Data Management

The data management and downlink strategies used by Cassini to return science data have also evolved over the lifetime of the mission. Early operations concepts strove to simplify data management and return. However, trade studies and operational experience proved that by accepting more complex data management practices the science return of the mission could be improved. Thus, the changes implemented to the data management and downlink strategies have enhanced the amount of science data that has been returned during the mission.

Downlink Strategy—Data collected by Cassini is returned using downlinks over the Deep Space Network (DSN). The amount of data that can be returned over a downlink depends on the duration of the downlink and the available data rates. Data rates are affected by the type of ground antenna used for a downlink and the motion of the Earth and Saturn around the Sun. Even over the 9-hour downlinks typically used by Cassini, the data rates can vary significantly due to the position of Cassini in the sky as viewed from a DSN antenna.

In order to maximize data return, data rates should be chosen wisely to take full advantage of the downlink. Early operations plans called for two data rates to be used per pass. Implementing two data rates per pass was a simpler strategy than using more than two data rates. However, studies conducted post-launch showed that increasing the number of data rates that were used during a downlink would improve science return and ensure satisfaction of project requirements. Using more data rates per downlink improves science return because the data rate steps up more quickly as opposed to using a low data rate for a longer time before switching to a higher data rate. As mentioned above, selecting and optimizing the best data rates for each individual pass is a time-consuming task. The more complex planning was mitigated by development of a software tool to automate the selection of data rates for a downlink. The tool uses the viewperiod of a DSN antenna and the available data rates to pick the set of data rates that will maximize science return. By accepting more complexity in the downlink strategy the project was able to increase science return. As of October 2012, Cassini has returned approximately 3,500 Gb of data.

Data Management—Data is stored on-board the spacecraft on two solid state recorders (SSRs). The original operations plan called for all data, science and engineering, to be stored in a single partition on the SSRs. This meant all data would be interleaved together. Also, the amount of data collected in a day could not exceed the day's downlink capacity so that the SSRs would be emptied every day. No data, except for critical Saturn Orbit Insertion, probe relay, and optical navigation data, were given priority. As operational strategies were developed and matured, the project realized that requiring the SSRs to be emptied every day was not realistic, some science data should be prioritized, and that not all engineering data needed to be played back daily. Thus the project accepted a more complex data management strategy in order to increase science return.

Currently, Cassini uses two partitions which are identical on each SSR: a science data partition and an engineering data partition. The science data partition, which includes some high-priority engineering data, is played back over every downlink. The engineering partition is usually only played back in the event of an anomaly or an unusual mission event where engineering telemetry is of special interest. The real-time health and safety data received during downlinks is sufficient to confirm the spacecraft is performing nominally. However, in the event of an anomaly, the data on the engineering partition provides information essential to diagnosing the problem. The project also allows data carryover between downlinks. This means that the SSRs do not have to be emptied every day, but the amount of data collected can never exceed the capacity of the SSRs. Thus, data collection must be carefully managed to ensure the SSR is not overfilled and science data is not over written. Besides overall data management strategies, each instrument is also allocated a specific amount of data for each observation period. If an instrument exceeds their allocation, the command and data subsystem "data polices" them which means the instrument is restricted from sending additional data to the SSRs. This eliminates the possibility of an instrument overwriting another team's data because they exceeded their allocation.

The changes to data management have enhanced the mission's science return. By allowing carryover, unique science data can be collected that otherwise may have been lost due to daily downlink limitations. Only playing engineering data back when needed, allows for more science data to be collected as well. Since downlink capacity is not being used for engineering data, science data is played back faster which empties the SSR partition faster allowing for more science data to be collected.

6. LESSONS LEARNED

Understanding how systems engineering was applied on Cassini-Huygens and how the challenges described in this paper were overcome should be of interest to future space missions. These missions should consider the following advice when developing their systems.

- *Fully characterize systems interfaces.*

  Missions should fully characterize system interfaces through a combination of documentation, communication, and testing. All three are necessary because any one may not detect misunderstandings or design errors. This is evident in the Huygens probe receiver anomaly. The design flaw was never noted during design reviews and a full-up test was never conducted on the ground. While the characterization effort does consume resources, missions must trade the risk of not fully investigating system interfaces with the cost to do so. Resources were cited as a reason for why a full-up test was not conducted on the Cassini/Huygens communication link [9]. As a result, an in-flight trajectory redesign was required as opposed to a pre-launch software fix. Thus, a characterization effort in development may reveal relatively easily-correctable errors that could be unresolvable or expensive to correct in operations.

- *Consider system operability in development*.

  The system design can have a substantial impact on operations. During development, missions should consider how they plan to operate their spacecraft and how changes to the spacecraft or ground system design will impact operations. For example, the removal of the scan platform from Cassini-Huygens introduced many complexities into operations. These complexities increased the workforce and budget required to conduct mission operations. Thus, by considering operability of the system during development, missions can make better informed design decisions and may avoid introducing complexities in operations that will require compensation with larger workforces and budgets.

- *Apply appropriate resources and practices to ground software development*.

  Software is essential to the success of any space mission. Missions should ensure that adequate resources are available for ground software development and that a formal development process is followed; by doing so they may avoid some of the issues encountered by Cassini-Huygens. Due to resource constraints, Cassini-Huygens failed to complete needed ground system tools in time for operations and this was compensated for by the development of ad-hoc tools. These tools were developed outside the formal process and as a result were inconsistent and difficult to maintain. Missions should also architect tools as a suite. By including commonalty among tools, missions can reduce the resources needed to maintain the tools and also simplify the user experience which in turn reduces the work-effort needed to complete processes that depend on the tools.

- *The systems engineering effort is ongoing throughout the mission life cycle.*

  Missions must apply systems engineering practices throughout the mission lifecycle. Undoubtedly, the types of systems engineering issues that must be addressed will change throughout a mission, but they will never completely disappear. For example, systems will not always operate as anticipated and system-level analyses are usually required in order to balance mission objectives with the changed system capabilities. Cassini-Huygens had to adapt operations processes to accommodate management of reaction wheel use. If Cassini-Huygens had not adapted operations to accommodate the reaction wheels, the reactions wheels may have failed and the mission may not have achieved its current level of success. Also, operations experience can be used to better leverage system performance. Trades that were made in mission development can be revisited to enhance mission return. By continuing to apply systems engineering practices, mission can ensure that they are utilizing their system to the fullest extent possible and are achieving mission objectives.

- *Trade system complexity versus mission return.*

  Missions must balance simplicity and complexity in order to optimize mission return. Cassini-Huygens endeavored to simplify many aspects of mission operations. However, over time, the project realized that accepting complexity in certain areas, such as data management, would enhance science data return. Thus, through system analyses and acceptance of complexity where appropriate, missions can enhance their return and ensure objectives are achieved.

7. CONCLUSION

Cassini-Huygens rigorously applied systems engineering during mission development. This structured approach was instrumental in the success of the mission. In operations, systems engineering has continued to play an important role in refining mission practices and processes to enhance science return. Cassini-Huygens is not without lessons learned and there are aspects of the mission where systems engineering could have been applied better. However, despite these issues, the mission has been an overall success and has returned an unparalleled data set on the Saturn system.

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