SCIENCE PLANNING AND SEQUENCING FOR CASSINI

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ABSTRACT

This paper will address the science planning and sequencing aspects of the command generation process for the scientifically diverse Cassini Mission. The mission's prime objectives are to study the Saturnian system and deliver the Huygens Probe into its major moon Titan. Together, the spacecraft and probe will be the largest and most complicated craft ever launched to another planet.

The presentation will begin with an overview of the Cassini spacecraft and its scientific instrumentation. This will be followed with a description of the October 1997 mission. Next, the structure of the science planning and sequencing process, with special emphasis on science's role, will be outlined. Finally, this presentation will conclude with a discussion of some of the unique challenges faced by the Ground System during Cassini's four-year orbital tour.

Key Words: Astronautics, planetary exploration, operations, science planning, Saturn

1. Cassini Spacecraft

The Cassini spacecraft is a 3-axis stabilized craft with a design lifetime of 12 years. It is divided into four core elements. The first element is a rigid four meter diameter High Gain Antenna (HGA) for reception of commands from Earth, transmission of science and engineering data from the spacecraft, relay antenna for the probe data and the source of the output RADAR signal. The HGA is attached to the Upper Equipment Module (UEM).

The UEM is the second core element. This element is a 12-sided bus which provides storage for the major electronic components (e.g., Command and Data Subsystem (CDS), Attitude and Articulation Control Subsystem (AACS), Solid State Recorders (SSRs), etc.). It also provides the mounting structure for the 11 meter long Magnetometer Boom, one articulable reaction wheel, the Remote Science Pallet, the Fields & Particle Pallet and their associated orbiter science instruments.

The third element, located under the UEM, is the Propulsion Module (PM). This module contains all the bi-propellant fuel for the mission and will be used for all major trajectory correction maneuvers. The Cassini fuel load consumes a significant amount of spacecraft mass. For comparison, the Voyager spacecraft had a total mass of 825 kg (100 kg of mono-propellant). The Galileo spacecraft had a launch mass of 2561 kg (959 kg of bi-propellant). Cassini and the Huygens Probe will have a total mass of 5120 kg (3000 kg of bi-propellant, approx. 60%).

The last major core element is the Lower Equipment Module (LEM) and is located underneath the PM. This module houses the two 490 N main engines, the four thruster clusters for attitude control, three reaction wheels for non-propulsive maneuvers and the three Radioisotope Thermoelectric Generators (RTGs) which together at launch will produce approximately 850 watts of electrical power.

1.1 Scientific Investigation

The Cassini science instruments were selected based on their ability to increase our knowledge of the Saturnian system by at least an order of magnitude in their respective areas. Each investigation performs unique science by itself and complements the other investigations by performing many synergistic observations.

The instruments can be divided into three classes; Passive Remote Sensing instruments which must be pointed at a specific target-body and then processes the externally generated source signals; Active Remote Sensing instruments also must be pointed at a specific target-body to collect data but in this case, the source signal processed is generated onboard the spacecraft; and finally the Fields, Particles & Waves instruments which measure the in situ environment.

1.1.1 Passive Remote Sensing Investigations

There are four Passive Remote Sensing investigations. All of them are co-aligned with the narrow angle camera boresight and mounted onto the Remote Sensing Pallet (located on the UEM). Alphabetically, the first investigation is the Composite Infrared Spectrometer (CIRS) which has two linear 1 x 10 arrays. The total field of view (FOV) of each array is 2.9 x 0.3 mradian. The arrays are separated from each other by 0.67 mradians. The remaining CIRS FOV is circular and has a diameter of 4.3 mradians. With these FOVs, this instrument covers the infrared spectrum from 10 to 1000 micrometers. Its primary objective is to generate spectral maps to study temperature and composition of Saturn and Titan's atmospheres, satellite surfaces and ring particles.

Next is the Imaging Science Subsystem (ISS). This subsystem is composed of two CCD cameras. The wide angle camera has a 61.2 mradian square FOV with a spectral response from 0.38 to 1.1 micrometers and the narrow angle camera has a smaller FOV of 6.1 mradians square but a slightly wider and "bluer" spectral coverage. Its response ranges from 0.2 to 1.1 micrometers. ISS's primary objective is to obtain multi-spectral images of Saturn, its satellites and rings.

The third Passive Remote Sensing instrument is the Ultraviolet Imaging Spectrometer (UVIS). It has two rectangular FOVs. The narrow FOV is 0.5 x 64.2 mradians while the wider FOV is 6.42 x 64.2 mradians. The instrument's spectral coverage ranges from 0.055 to 0.19 micrometers. The investigation's major objectives are to obtain spectra and low resolution imaging to determine structure, chemistry and composition of Saturn's atmosphere and rings.

The last Passive Remote Sensing instrument is the Visual and Infrared Mapping Spectrometer (VIMS). This investigation also has two FOV. The smaller infrared FOV is 32 mradians square and covers a spectral range from 0.95 to 5.2 micrometers. The visual channel has a 42.7 mradian square FOV and covers 0.35 to 1.05 micrometers. VIM's prime objective is to study the composition and surface structure of Saturn's atmosphere, rings and satellite surfaces.

1.1.2 Active Remote Sensing Investigations

The Cassini payload has two Active Remote Sensing investigations. The first is RADAR. This instrument uses the HGA to transmit and receive a 13.8 GHz Ku-Band signal at a specific target-body. Its primary objective is to perform radar imaging, altimetry and radiometry observations of Titan's surface.

The other investigation is the Radio Science Subsystem (RSS). This investigation uses the HGA to transmit a signal through a medium (e.g. interplanetary space, rings, atmospheres) to be received by Earth-based receiving stations. In this case 2.3 GHz S-band, 7.18 to 8.42 GHz X-band and 32 to 34.3 GHz Ka-band frequencies are used. The investigation's primary objectives are to study Saturn's atmosphere, ionosphere, ring system and its gravitational field. In addition, the gravitational fields associated with the icy satellite, Titan's atmosphere and ionosphere will be studied. During cruise, a search for gravitational waves will be attempted.

1.1.3 Fields, Particles & Wave Instruments

There are six Fields, Particles & Waves (FP&W) instruments on the Cassini spacecraft. These investigations usually require some type of internal articulation or spacecraft rotation to obtain spatial information about the distribution of the phenomena being measured.

The Cassini Plasma Spectrometer's (CAPS) primary objective is to study in situ the plasma environment within and near Saturn's magnetic field. The investigation is composed of three detectors integrated together and mounted on the Fields & Particle Pallet. The three detectors are the Electron Spectrometer (ELS), the Ion Mass Spectrometer (IMS) and the Ion Beam Spectrometer (IBS). The combined system will articulate back and forth up to 200 degrees in a "windshield wiper" type of motion.

Next is the Cosmic Dust Analyzer (CDA). It consists of an aperture that has a 100 degree FOV and is sensitive to particle impacts, masses, speeds and charges. The device is mounted directly to the UEM and can be articulated back and forth up to 270 degrees. Its primary objective is to study in situ ice and dust grains in the Saturnian system and in interplanetary space.

The third FP&W investigation is the Ion and Neutral Mass Spectrometer (INMS) and is mounted to the Fields & Particle Pallet. Its prime objective is to study in situ the composition and concentration of charged particles and neutral gases, primarily near Titan.

The Dual Technique Magnetometer (MAG) uses both a Vector/Scalar Helium Magnetometer (VHM) and a Fluxgate Magnetometer (FGM) to study Saturn's magnetic field and its interaction with the solar wind. These instruments are located on a deployable 11 meter Galileo-type MAG Boom. The FGM is located somewhere past the boom halfway point while the more sensitive VHM is located at the very end.

The fifth FP&W investigation is the Magnetospheric Imaging Instrument (MIMI). This investigation is divided into three separate devices, the Charge-Energy-Mass Spectrometer (CHEMS), the Ion and Neutral Camera (INCA) and the Low Energy Magnetospheric Measurement System (LEMMS). Only CHEMS and LEMMS are mounted on the Fields & Particle Pallet. INCA is mounted directly to the UEM. LEMMS has the capability to be articulated to gain spatial information on time scales shorter than permitted by the spacecraft turn rates. MIMI's primary objectives are to obtain global magnetospheric imaging and in situ measurements of Saturn's magnetosphere and solar wind interactions.

Finally, the Radio & Plasma Wave Science (RPWS) investigation is composed of three deployable dipolar antennas, a cluster of Magnetic Search Coils and a deployable Langmuir Probe. All components of this investigation are mounted to the UEM. The primary objective of this investigation is to study plasma waves, radio emissions and dust in the Saturn system.

1.1.4 Huygens Titan Probe Instruments

The 2.7 meter Huygens Titan Probe is being built by the European Space Agency. It has a mass of approximately 300 kg and houses six scientific investigations. They consist of the Aerosol Collector and Pyrolyser (ACP), the Descent Imager and Spectral Radiometer (DISR), the Doppler Wind Experiment (DWE), the Gas Chromatograph and Mass Spectrometer (GCMS), the Huygens Atmospheric Structure Instrument (HASI) and the Surface Science Package (SSP). Together this collection of instruments, combined with Cassini's remote sensing instruments, will make the most comprehensive study of Titan's atmosphere and surface to date.

2. VVEJGA Mission

The sheer mass of the Cassini spacecraft precluded the use of a direct trajectory to Saturn. In order to obtain sufficient energy, a multiple gravity assist trajectory had to be selected. The Cassini trajectory, known as Venus-Venus-Earth-Jupiter Gravity Assist mission (VVEJGA), requires almost seven years of cruise to reach Saturn. The impacts of this trajectory are a more stressful thermal environment for the spacecraft, less power at end-of-mission due to the degradation of the RTGs, a longer cruise and more complicated ground operations.

2.1 Interplanetary Cruise

The launch period for the Cassini mission opens on 1997 October 6. The current plans call for a launch with a Titan IV/Centaur with strap-on Solid Rocket Motors Upgrades (SRMU). However, the mission has maintained the flexibility to use the lower performance Solid Rocket Motors (SRMs) should the SRMUs not be available for launch.

Upon liftoff from the Kennedy Space Center in Florida, Cassini will have to perform the first of its many maneuvers 25 days after launch. During the initial cruise portion of the mission, there will be minimum instrument calibration, characterization and maintenance. Cruise will consist primarily of engineering and navigation activities. There are no plans at this time to obtain science during the interplanetary cruise or at any planetary encounter prior to two years before Saturn orbit insertion.

The Venus1 swingby will occur six months after launch and will bring Cassini within 300 km of the planet on 1998 April 21. The swingby past Venus will put Cassini on a 14 month orbit, taking the craft out past the orbit of Earth and then back in for its second rendezvous with Venus.

Between Venus encounters, at Launch+14 (L+14) months, the majority of the instrument checkouts will be performed. At L+18 months, limited instrument checkouts will be completed and routine simple instrument maintenance will begin. Two months later at L+20 months, on 1999 June 20, the Venus2 swingby will occur.

The second swingby of Venus occurs when the Earth and Venus are close to each other in their respective orbits. Consequently, the Earth swingby occurs only two months after the Venus2 swingby (1999 August 16). The close placement of these encounters will drive ground operations in order to prepare the required maneuvers prior to and following each encounter. Earth avoidance after Venus2 is another prime concern and which will complicate the maneuver strategy. In total, there will be 15 spacecraft maneuvers between launch and L+30 months.

After the Earth swingby, Cassini will head out of the inner solar system. The last gravitational assist will be with Jupiter a little more then three years after launch (2000 December 30). The aim point at Jupiter will be more than 20 million km (>140 Jupiter radii) from the planet. Cassini will arrive at Saturn on 2004 June 25.

2.2. Orbital Operations

The current tour is known as 92-01, has 63 orbits around Saturn and though not approved by the investigators, is typical of the type of science opportunities possible at Saturn.

Cassini will approach Saturn's south pole from the dayside prior to beginning its four-year tour of the system. The initial approach will allow some unique ring science observations as the craft approaches the planet at a relatively high inclination. The craft will climb above Saturn's ring plane at which point the Saturn Orbit Insertion (SOI) maneuver will occur. This maneuver will last approximately 70 minutes and will commence at periapsis.

The SOI maneuver will place the craft in a 152 day orbit about Saturn. This first orbit, referred to as petal 0, sets up the correct geometry for the delivery of the Huygens Titan Probe. Approximately 134 days into petal 0, the Huygens Titan Probe will be released from the Cassini spacecraft. For the next 21 days the probe will continue by itself on a ballistic trajectory into the atmosphere of Titan. Upon atmospheric entry, timers on the probe will activate the six science instruments, release the heat shield and the main parachute.

During the Descent Phase, which lasts approximately 2.5 hours, the Huygens Titan Probe will relay atmospheric composition, temperature and pressure information back to the Cassini spacecraft. In order to acquire the data, the craft will be turned such that the HGA acts as the relay antenna for the probe. The information will be redundantly stored on board the SSRs to be played back at a future date.

After the probe mission, the early orbits are designed to precess in a counter-clockwise fashion (as seen from Saturn's north pole) in order to obtain low solar phase angle coverage of the planet. After petal 10, the orbits will be changed to precess in a clockwise direction. This precession continues till late in the mission when the orbit periods are shortened in order to increase the petal inclination. By the end of the mission, an inclination of greater than 75 degrees will have been achieved.

Over the course of the four year mission, Cassini will perform 33 Titan swingbys. The altitudes of the Titan swingbys will range from 950 km to greater than 5000 km above its surface. Almost a third of the Titan passes will be at an altitude of 950 km. There also will be opportunities for 10 Earth- and 10 Sun-Titan occultations.

There also will be four targeted and 29 non-targeted satellite encounters. The targeted satellite encounters will be of Enceladus, Dione, Rhea and Iapetus, and will occur at an altitude of 1000 km or less. The non-targeted encounters are all under 100,000 km. Voyager 1 and 2 combined had only four Saturnian satellite encounters less than 100,000 km.

The beginning of the tour also provides for five Earth- and Sun-Saturn/ring occultations. Near the end, when the spacecraft inclination increases, the number of occultations will be 27 Earth- and 9 Sun-Saturn/ring occultations.

3. Science Planning & Sequencing

The science planning and sequencing aspects for the Cassini mission will be based on a fundamentally different approach from its predecessors Voyager and Galileo. The concept is analogous to the one used for Mars Observer and is based on distributed science operations. This will allow the investigators to perform their science operations remotely at their home institutions via networked connections to the Project information system.

This differs from past missions where investigators had to periodically travel to JPL to be apprised of the sequence development status. During cruise portions of a mission, these meetings might have happened two or three times a year. The level of travel increased to the point that during planetary encounters, investigators were resident at the laboratory for weeks and even months at a time.

A distributed science operation approach should mitigate the need to transfer to or duplicate instrument expertise from the home institution at JPL. Investigators will be responsible for identifying science opportunities, planning science observations and generating instrument commands.

3.1 Mission Planning

The Ground System (GS) will be responsible for mission success at the system level. As such, mission planning will involve defining a physical environment that allows each investigation to operate successfully acquiring its desired data.

In order to accomplish this critical task, mission planners, working with the investigators, spacecraft engineers and navigators, will compile information pertaining to science objectives from which a desired trajectory can be developed. This trajectory must also take into account the conditions in interplanetary space and during orbital operations. As an example, spacecraft thermal considerations and instrument performance characteristics in radiation environments will be evaluated and incorporated into the trajectory selection.

Along with the definition of a trajectory, high priority science observations, especially those tied to geometric events, will be identified such that spacecraft resources (e.g. instrument power, data volume, pointing, etc.) can be allocated to meet the objectives of the investigators and the mission.

To accomplish this difficult task, mission planners will have to work very closely with the remotely located investigators.

3.2 Science Planning

Science planning will require an intensive amount of work identifying science opportunities, critical observations and negotiating spacecraft resources.

The Science Planning and Operations Team (SPOT), which is located at JPL, first produces a working timeline from mission plans. This timeline will contain all major spacecraft maneuvers, maintenance activities, operational modes, navigation requests and Deep Space Network (DSN) passes. The working timeline can best be thought of as the backbone on which the science observations will be placed.

Once generated, the working timeline, combined with resource envelopes/allocations, will be placed in the Project Data Base (PDB) to allow the investigators access to the information. At this point the investigators will define observation opportunities, optimal observing sequences (within allocated resources) and note which engineering activities need to be shifted (within their stated tolerances) to resolve initial observation conflicts.

It is envisioned that a number of software tools will be available to help the investigators identify observation opportunities. One such tool planned for development at JPL is called SOA (Science Opportunity Analyzer). This program will incorporate (user-definable) planetary system physical models to allow the user to search for specific observing conditions and to characterize observing conditions at a particular time and location. The program will also be able to produce animated displays of planetary system targets as seen from a user specified vantage point.

Upon completion, the updated information in the PDB will be accessed by SPOT; resource utilization, observation conflicts and constraint violations will be identified. Once determined, the Science Operation (SO) Teams (Principal Investigators and Facility Engineering Operation Teams) will resolve conflicts, specify instrument states and generate specific activities which will contain macro-level instrument parameters.

It will be critical for SO Teams to confirm that their observations do indeed fit into their allocated resources. This will be accomplished by using instrument models for all managed resources, such as power. Any observations found, by system-level checks at JPL, to violate a specific resource envelope will be subject to removal from the sequence. The GS will only be responsible for checking system-level commands for compatibility with system-level resources and constraints.

The SO Teams will then place their detailed instrument observation definitions into the PDB as instrument-specific Observation Defining Records. These records are accessed by SPOT to generate an integrated Activity Plan (AP). The AP will be science's input into the sequence generation process.

3.3 Sequence Generation

The sequence generation process uses the Activity Plan to produce engineering and facility instrument sequence inputs. These inputs are expressed as spacecraft activities and parameters and are combined with the required ground events. From these inputs, an integrated sequence is generated using the Mission Sequence System (MSS). The MSS generates the sequence and performs a majority of the system level constraint checks. All MSS output products are reviewed for validity by the operation teams. In addition, a high-speed spacecraft simulator will be used to confirm the operation team's conclusions. The final output product is the Ground Command (GCMD) File, and once approved by the Project, is transmitted to the spacecraft.

A limited number of changes to the GCMD may be possible prior to sequence execution. These modifications may be needed to account for changes in the Saturnian system for which no apriori knowledge of the event was known.

4. Challenges

As with any new approach, many challenges lay ahead during the GS's implementation. For Cassini, the situation is exaggerated due to the deferred development of major portions of its ground system until post-launch.

Of the many challenges faced by the Cassini GS, the approach for resolution of conflicting activities will be one of the more difficult to solve. In most of the past planetary missions, sequence conflicts were resolved in a centralized location where all participants could argue "head-to-head" until a solution was agreed upon.

For Cassini, "head-to-head" meetings will not be practical during the four years of orbital operations. Other than for SOI observations and Huygens Titan Probe data, no one science observation is so critical that a compromise can not be found. It will be necessary to resolve sequence conflicts remotely at the investigator's home institution.

One approach for doing this is the early identification of high priority science opportunities and critical engineering activities. Once determined, the JPL-based mission planning function can assign initial operational modes, power envelopes, primary targets and associated data volumes. Once these envelopes have been assigned, the resulting profiles can be placed in the Project Database for remote access by investigators.

It is important to note that this approach does not eliminate all sequence conflicts; it only reduces the number of conflicts between high and low priority activities. However, this will reduce the number of iterations the sequence goes through during its development.

The savings come from the very nature of the sequence development process. This process involves proceeding from lower to a higher level of detail. Conflict resolution often results in a need to return to a lower level of detail to fix the problem, rendering much detailed information obsolete. The early identification of high priority activities, and timely elimination of conflicts between them, will be needed to help resolve the sequencing issues in the short period of time available for sequence development.

Following are some of the other obvious GS challenges that have to be addressed.

4.1 No Articulating Instrument Platforms

Cassini was initially designed with a high precision pointing platform for the Passive Remote Sensing instruments and a spinning Turntable for FP&W investigations. The removal of these platforms simplified the design and reduced the hardware cost of the spacecraft.

However, one effect of these changes is that during orbital operations, the spacecraft will spend up to 16 hours per day maneuvering off Earth-point to acquire Remote Sensing data. The remaining eight hours will be spent on Earth-point, replaying the Remote Sensing data and collecting FP&W data as the craft slowly rolls about the HGA axis.

The division between the collection of FP&W and remote sensing data, coupled with the potentially greater risk of spending up to 16 hours per day out of contact with the Earth, will add complexity to the spacecraft's flight software and ground operations.

4.2 Power Limitations

Cassini's electrical power output is insufficient to power all the instruments simultaneously during orbital operations. Thus, operational modes have been defined in which each investigation has been allocated a power level for the duration of the mode. The current operational modes are: Optical Remote Sensing, Downlink FP&W (i.e., simultaneous with SSR playback), FP&WI (I for INMS on), RADAR and RSS.

Each SO Team will be responsible for ensuring that their investigation does not exceed its assigned power envelope. The GS will not be able to model instrument power levels commanded by the investigators. However, resource envelopes will account for the expected ranges of power utilized by each instrument during a given mode. System-level checks will be performed to ensure that power levels do not exceed spacecraft capability, triggering a system fault protection algorithm.

4.3 Distributed Science Teams

The concept of remote science operations based on distributed science teams is modeled on the structure of the GS for Mars Observer (MO). At this point in time, MO has just begun cruise operations and is about 10 months away from orbital operations. It may require several months of orbital operations before the full advantages and possible weaknesses of this concept become apparent. Cassini will be eager to incorporate lessons learned from MO into its GS Design.

In MO's case, the instruments are independent of each other, have fixed resource envelopes and the mission is defined as a systematic mapping mission. Designing the remote science operations concept for the Cassini mission, with highly interdependent science observations, tight spacecraft resources and a multi-target mission, will be a challenge.

5. References

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