Report of the Cassini Extended Mission Senior Review Board
March 8, 2007

Introduction

The Cassini Extended Mission Senior Review Board was commissioned on January 18, 2007 by Dr. James Green, Director of the Planetary Science Division of NASA Headquarter's Science Mission Directorate. The Board was tasked "*to evaluate the scientific merits of the extended mission in the context of goals and objectives contained in the Solar System Exploration Roadmap and in the NRC Planetary Decadal Survey*", and given nine specific criteria (identified in bulleted, italicized text below) to be used in its evaluation.

The Review Board met on February 15, 2007 at the Jet Propulsion Laboratory in Pasadena, California, where it heard oral presentations and met in executive session to discuss its preliminary recommendations and outline the final report presented here. The report considers three broad areas: progress on the prime mission; characteristics of the extended mission; and availability of resources. We conclude with a set of four Recommendations.

Assuming suitable consideration of the Board's recommendations, **the Board's final assessment is to accept the proposed Extended Mission tour as baselined.**

Progress on Prime mission

The Board was asked to evaluate the science value of the extended mission over and above the prime mission. As such we first provide a brief assessment of progress on meeting the prime mission objectives. These objectives were organized into five discipline areas in the original Announcement of Opportunity: Saturn interior and atmosphere; rings; magnetosphere; Titan; and icy satellites. Oral presentations during the review provided a brief but incomplete summary of the progress in meeting prime mission objectives in these five areas. Our assessment is based on a combination of material from the presentations with information gathered subsequent to the review by the Board.

At least six out of the seven specific science objectives related to the planet's interior and atmosphere have been fully or partially accomplished. Although ionosphere investigations and radio occultations were not explicitly addressed at the review, at least five journal publications have reported results from them. One objective (radiative balance in the atmosphere) was not addressed at the review.

Stellar and radio occultations have resolved 3-D ring structure, revealing the vertical extent of rings, particle size distributions, and dynamical processes such as spiral density waves produced by gravitational interaction between rings and embedded moonlets. Spectral mapping has revealed compositional variations of ring particles. Investigations of dust and meteoroid interactions are underway. These observations have partially or fully achieved at least four out of five ring science objectives. Interactions of rings with the magnetosphere, ionosphere, and atmosphere were not explicitly addressed at the review.

At least two out of four magnetospheric objectives have been fully or partially achieved; *viz.* determine the relationship of the magnetic field orientation to the Saturn kilometric radiation (SKR), and investigate magnetosphere interactions with Titan, icy satellites, and rings. The other two are posed essentially as measurement objectives; presumably they relate to other magnetospheric investigations, but the connection is not obvious.

The Cassini spacecraft and the Huygens entry probe, between them, have fully or partially achieved all objectives for Titan. Highlights, of course, include radar discoveries of surface features that were clearly formed by erosion by a flowing fluid, and lakes of methane at high northern latitudes.

The review focused on the spectacular discovery of geysers at the South Pole of Enceladus, and its implications for the interior structure of the satellite. Other objectives for icy satellites include mineralogical compositions, gravitational and magnetic fields, and satellite ionospheres (if any), along with their interactions with the magnetosphere and ring system. A Google search turned up only news reports and a single conference abstract that dealt with results from Cassini investigations of other icy satellites.

Overall the progress is excellent. However, the Board noted gaps in the reported progress on some science objectives, namely, the ionosphere of Saturn; the deep atmosphere; interior structure; He abundance and results from radio science occultations. The Board received very helpful and thorough supplemental information in these areas following the review.

Extended Mission

We present our discussion here in the context of the evaluation criteria outlined in the charge to the Extended Mission Review Board, which appear in the bulleted, italicized text below.

- *Evaluate the scientific merits of the extended mission in the context of the goals and objectives contained in the Solar System Exploration Roadmap and the NRC Decadal Survey.*

During the extended mission Cassini will make 26 close flybys of Titan and 7 flybys of Enceladus as well as further studies of Saturn. The science information retrieved will contribute to the following Science Objectives listed in the Solar System Exploration Roadmap:

2.1: Habitability: Is there life elsewhere in the cosmos.

2.2.4: How did life begin and evolve on Earth and has it evolved elsewhere in the solar system.

The Cassini extended mission will contribute also to two of the four crosscutting themes that are identified in the 2003 NRC Decadal Survey for planetary science. Specifically, it will help inform our efforts to understand “Volatiles and Organics: The Stuff of Life” and “The Origin and Evolution of Habital Worlds.”

- *Science coverage of the Saturn system, including polar regions, magnetosphere, and Titan not accomplished during the prime mission.*

The extended mission includes the following new opportunities above and beyond the prime mission:

- Direct passes over the northern pole and more detailed study of the southern hemisphere of Titan, which is required to define site selection for a future Titan Explorer Mission.
- Direct passage through the plume of Enceladus.
- Extended coverage of the equatorial dusk magnetosphere.
- First direct passage at low altitudes through the Saturnian auroral zone.
- Observation of unique seasonal geometry as the Sun crosses the ring plane.
- Close in periapsis pass dedicated to planetary science.
- Unique geometry of radio occultations.

- *The science value of the extended mission over and above the prime mission.*

The Extended Mission will enhance science return in the following ways:

- Detailed investigation of Titan including the polar regions, where radar lakes occur, to search for long term changes, and surface chemistry including ethane, methane and ammonia.
- Direct passage through the plume of Enceladus to identify variability of the geyser source and measure vent temperatures to test liquid water vs clathrate hypotheses.
- Better determination of the variable radio period of Saturn and its relation to the rotation rate of the deep interior.
- Investigation of seasonal change in the atmosphere (storms, winds, lightning).
- Extended coverage of the entire equatorial magnetosphere to help determine internally driven from solar wind driven processes.
- Investigation of the processes that cause Saturnian auroral emissions.
- Investigation of seasonal changes in the rings and possible development of spokes.

- *The responsiveness to discovery.*

The planned flybys and detailed investigation of Enceladus and Titan are a direct result of important discoveries made in the prime mission.

- *The programmatic benefits accrued from an extended mission.*

The cost of the extended mission (~$170M over 2 years) is much less than a comparable new mission to Saturn. Detailed investigations of Titan and Enceladus offer a unique opportunity to better define plans for future missions. The science information retrieved will contribute to the planning for future missions such as the Titan Explorer (3.4.2 SSE Roadmap; Deferred High Priority mission in the NRC Decadal Survey), a Saturn Ring Observer (Deferred High Priority mission in the NRC Decadal Survey), and the New Frontiers candidate mission of a Saturn Flyby with Probes (3.3.7 SSE Roadmap).

Availability of resources

The Review Board was asked to assess

- *The functionality of the spacecraft and instruments.*
- *The state of consumable resources on the spacecraft.*
- *The ability and readiness of the program to plan, implement, and execute the extended mission, including data analysis and data archiving.*
- *Options, plans, and potential costs for future mission extensions and end-of-mission scenarios.*
- *Adequacy of resources, including workforce and budget considerations.*

The Cassini spacecraft, launched in 1997, has been operating virtually without problems for over nine years. Other than the normal exceptions of tanks, structure, high gain antenna, etc., all of the engineering systems are redundant, and except for a potential problem with one reaction wheel, full redundancy is still intact. The spacecraft architecture includes four reaction wheels, three of which are necessary for full capability. One wheel exhibiting signs of bearing wear, a phenomenon known as cage instability, was taken off-line and replaced with the redundant fourth wheel which is performing normally. The three operating wheels do show evidence of drag torque spikes, which theory supports as acceptable performance and not indicative of incipient problems. All are well within the design allowable operating lifetime.

To date there has been only one hardware failure in the spacecraft, namely one memory submodule amounting to 16 Mb out of a total of 4 Gb. The impairment to operability is minimal. This and the wheel effect are no doubt early life time failures, indicating that the operating subsystem elements are in the bathtub region of their respective reliability curves.

The only other anomalous behavior has to do with an occasional set or reset of some of the solid state power switches, thought to be single event upsets triggered by cosmic ray disturbances. These events do not affect the performance of the switches, but they do require countermanding from the ground. The project has since modified the on-board fault protection and correction software to deal with the switches powering critical subsystems, rendering them basically transparent to spacecraft and mission operations.

All mission consumables are being expended at the predicted rates. Power resources are trending at better than originally-predicted rates, and can support the proposed extended mission comfortably. By 07/01/08, over 10% of the hydrazine on-board will remain to carry out the proposed mission, and RTG power starting at 850 W at launch on 10/15/97 will have decreased to only 693 W by 07/01/08. Based on this and on the normal performance of the spacecraft to date, there is every reason to expect continued normal operation throughout the proposed extended mission, and indeed beyond that.

The instruments, while lacking the redundant features of the engineering subsystems, have been performing almost equally as well with a few notable exceptions. In particular the Ka band transponder component of the Radio Science Subsystem has failed, resulting in reduced sensitivity for gravitational measurements. The impact of this loss to the extended mission science objectives is reported to be minimal. Likewise the impact of losing one detector of the HRD unit detector of the Cosmic Dust Analyzer is reported to be minimal. Other failures include the LEMMS actuator and the loss of one of the two magnetometers.

While projections for continued operation of the remaining instrument functionality lack the confidence expressed for the engineering subsystems because the instruments don't have redundancy, the absence of recent problems does suggest that the instruments, too, may be operating largely in the bathtub regions of their reliability curves.

The project Team has done an excellent job of planning the extended mission. The proposed costs and workforce requirements for two additional years of full science operations, assuming all instruments remain mission capable, are comparable to the expenditures of the past few years of mission operations, in what is foreseen as a fairly routine extension of the ongoing operations.

To date, the project has done little in the way of planning or costing for future mission extensions beyond the proposed extended mission. This appears to be in concert with direction from HQ. Likewise options for end-of-mission scenarios have been looked at only in a cursory fashion, although it does appear that there are a number of end of mission scenarios that are possible and which would be consistent with the known planetary protection requirements.

Data have been deposited into the Planetary Data System (PDS) in discreet amounts referred to as "Archives". With the completion of Archive #7 (Jan. 1, 2007), half of the primary mission data archiving will have been achieved. Some problems ("liens") still exist on these deposits, including:

1. CDA HRD: Archives 1 – 7 are affected by the slow institution of their archive pipeline. A "catch-up" delivery is scheduled for April, 2007.
2. RADAR: The delivery of altimetry data has been delayed due to accuracy issues with the pulse-shape model, affecting Archives 1 - 7. These data should be delivered in April, 2007.
3. MAG: Archives 5 – 7 are affected by the necessity of removing spacecraft maneuver artifacts, in order to derive accurate calibration data. No date provided for the completion of this effort.

Archiving of most available data, however, has been completed in a timely fashion.

It is clear from the detail and level of planning, and the operating success to date, that the project has the ability to execute the extended mission with a high degree of confidence. The plans and proposed costs fully cover the data archiving requirements and continue the current level of data analysis activity throughout the extended mission operations period. Data analysis beyond the end of the extended mission operations period will depend on a continuing program of robust R&A funding.

Recommendations

Recommendation #1 Enhancements to the Extended Mission

The Board emphasizes the importance of obtaining key measurements that are highly diagnostic of Saturn's evolution and interior structure. Relevant measurements at Saturn by the Voyager spacecraft included (1) a determination of Saturn's atmospheric helium/hydrogen ratio, and (2) a determination of the rotation period of Saturn's deep metallic-hydrogen envelope via a measurement of rotation of Saturn's magnetic field. However, both of these measurements are now in question. The Voyager-derived helium/hydrogen ratio is now considered unreliable because of uncertainties in the Voyager temperature-pressure profiles as obtained by radio occultation, and Cassini has reported values for Saturn's magnetic rotation period that differ markedly from the Voyager result.

The Board finds that the Cassini team recognizes the importance of these issues and is working on analysis of data relevant to both. The Board stresses the importance of a further measurement that addresses interior structure: a determination of Saturn's spin angular momentum by measuring the precession of the planet's spin vector. This would be a valuable datum that would mitigate uncertainties in the deep rotation period. This measurement is best done over a long temporal baseline and might be considered as part of an extended mission.

Recommendation #2 Balance of Resources for Extended Mission

The Board received only a short budget briefing during the review, and is consequently not in a strong position to make detailed recommendations regarding the extended mission budget. As noted above, the budget and staffing for the extended mission are proposed to be a straightforward continuation of the level of effort currently being expended on the prime mission, with no substantive changes.

Although there was not consensus among the Board on this issue, generally speaking, the Board was not persuaded that a mission with four years of experience requires the same level of operations staffing as it does at the beginning of the prime mission. It would seem to be a reasonable expectation that as experience is gained, operations staffing could be streamlined. Other large missions (HST and Chandra are two examples) have a history of streamlining operations with time. As well, the Galileo mission reduced operations staffing significantly during its extended mission phase. We therefore recommend that as the mission moves from prime to extended phase, the staffing levels for every aspect of the mission be thoroughly reviewed and rejustified. If feasible, more resources should be provided to enhance the science return of the mission via increased funding of the science teams, the Cassini Data Analysis Program, and perhaps increased resources for improving the accessibility and utility of the data archive (see Recommendation #4 below).

The Cassini mission has been extremely successful to date. Although the desired outcome of this recommendation is an increase in science output, the Board cautions that extreme care should be exercised in implementing any shifts in resources in the extended mission to avoid inadvertently reducing the productivity of the mission by causing disruption in the ongoing procedures. It is imperative that the existing, well-established processes for observation design and sequence development and validation are not adversely affected.

Recommendation #3 Contingency Planning

In order to accommodate possible unknown losses of spacecraft or instrumentation functionality, plans for the extended Cassini mission should include options for descoping the science objectives. No trade studies have been done to demonstrate what might be mechanically feasible or scientifically optimal if any instruments or spacecraft components fail during the extended mission. While optimizing all possible combinations of instruments and functions is not productive, some consideration as to priorities and mixes of capabilities as descope options or contingencies during the proposed extended mission should be developed and considered.

Additionally, the panel feels that it is important to develop a contingency plan to deal with possible budget reductions for the extended mission, e.g., funding for only one year as contrasted to the nominal two year extended mission. This and any other contingency plan should maximize the scientific return with a focus on Titan and Enceledus.

Recommdation #4 Data Archiving

The Board recommends that the PDS be directed to devise methods of data archiving for all its projects, including Cassini, that would ensure that any scientist in the distant future (say 50 years from now) be able to easily retrieve and use mission data from any instrument without need for specialized software or support from the existing instrument teams. This level of accessibility and ease of use is not currently being met by the PDS, including for Cassini mission data.

The Cassini Extended mission should be used as an opportunity by NASA to rectify problems that exist in the data archives. First and foremost, all scientific teams should be required to input data to the PDS that are in a common, easily understandable format. Currently, some teams have negotiated with NASA to preserve their data in arcane formats (e.g., data cubes readable only by customized software specific to the science team, which requires outside scientists to use software developed by the teams themselves, thus ensuring that access to the data is difficult at best). Second, the data should all be required to be stored in both a raw and a calibrated format. The reduction level of data products currently varies depending on team. Archiving higher level data products allows an outside scientist to use the data scientifically without needing to guess what data reduction must be done to ensure the data are usable, and then fight to accomplish this reduction as a first step. Additionally, storing the raw data with ancillary information about acquisition conditions, location on a planet/satellite's surface, instrument and spacecraft parameters, allows a future investigator to refine data reduction if future techniques provide for improved reduction. These are areas where, for historical reasons, the science teams have been allowed to vary in product and format. NASA should use the opportunity of an extended mission negotiation to require the teams to archive usable, easily accessible data from their instruments.

Finally, the PDS should be redesigned to allow a scientist to find data from a specific instrument and of a specific object with ease. This includes search capabilities cross-cutting the PDS nodes (e.g., the availability of both imaging and spectral data for an object should be accessible in one search). Funding to ensure these capabilities should be made available to the PDS.

Final Assessment

Assuming suitable consideration of the Recommendations above, **we recommend accepting the proposed Extended Mission tour as baselined.**