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Operational Thermal Control of Cassini Titan Flybys

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ABSTRACT

The Cassini spacecraft will make 45 targeted flybys of Saturn's largest moon, Titan. 25 flybys will have a relatively low closest approach target altitude in Titan's atmosphere. An operational thermal control strategy has been developed for these flybys. The challenge met was to provide flyby operational thermal control that enabled science and remained within design limitations and Project constraints. Thermal engineers adopted a Systems-level approach that insured appropriate risk mitigation and information accuracy. This paper focuses on the technical thermal control evaluation and strategy, the Systems-level approach taken, and lessons learned and recommendations in an operations environment.

INTRODUCTION

The pre-launch thermal design verification of the spacecraft's ability to fly through the upper atmosphere of Titan did not fully address the current Project constraints and anticipated operational scenarios. Thermal concerns include hardware integrity, instrument performance and the magnitude of power transients caused by environmental heating induced temperature transients in the Radioisotope Thermoelectric Generators (RTGs) that power the Cassini spacecraft. A thermal strategy for Titan flybys had to be developed from within the operations environment for a spacecraft already designed and flying.

A thermal control strategy has been developed for the Cassini spacecraft so it can safely fly through the upper atmosphere of Titan. The strategy was developed by the Thermal/Devices Team within the Cassini Project in Mission Operations at the Jet Propulsion Laboratory. This paper focuses on the technical evaluation and strategy, the Systems-level approach taken, skills retention, and lessons learned in an operations environment. The challenge met was to provide flyby thermal control that enabled science and remained within design limitations and Project constraints.

EVALUATION APPROACH

The thermal approach was a Systems-level approach to take advantage of the Mission Operations' "Team" architecture, recognizing other teams and organizations were also impacted. Information was required regarding applicable Project policies and requirements, risk constraints, the Titan atmosphere, targeted flyby trajectories, statistical uncertainties, mission planning, attitude scenarios, and power profiles. Interfaces were established with personnel from Mission Planning, the science community, and Navigation (NAV) and Attitude Control (AACS) Teams to gather and share needed information. These interfaces insured the teams and organizations involved were properly informed, used consistent information, and shared expertise.

The strategy was to define a thermally acceptable performance envelope for Titan flybys, based upon the orbiter design and current planning, and use it for thermal evaluation. The approach would use visual graphic attitude evaluations to minimize the need for thermal simulations. Defining scenarios, anticipated and bounding, would be evaluated using thermal simulations.

The thermal effort required software selection, use of model visual display applications, environmental heat load generation, thermal model predict generation, analysis automation, evaluation and reporting of results and conclusions, skills retention, and lessons learned.

MISSION AND TRAJECTORY

The purpose of the Cassini mission is a scientific investigation of Saturn, its rings, its moons, and the environment around it. The Cassini spacecraft was launched on October 15, 1997 and will arrive at Saturn on July 1, 2004. The baseline mission at Saturn is scheduled to end at midnight June 30, 2008 [1].

The spacecraft is composed of the orbiter and the Probe. The Cassini orbiter carries a complement of 12 science instruments (optical, fields and particles, radio science, and imaging radar). The Huygens Probe is scheduled to soft land on Titan on January 14, 2005 [1]. The Probe will be released after the second targeted

Titan flyby, so the majority of the mission at Saturn will be without the Probe onboard [1].

Several planetary gravity assists, two from Venus, one from Earth, and one from Jupiter have been required to enable the spacecraft to reach Saturn. The cruise trajectory is shown in Figure 1 [1]. The spacecraft heliocentric distance will range from 0.67 AU in the inner solar system to 10.07 AU at Saturn.

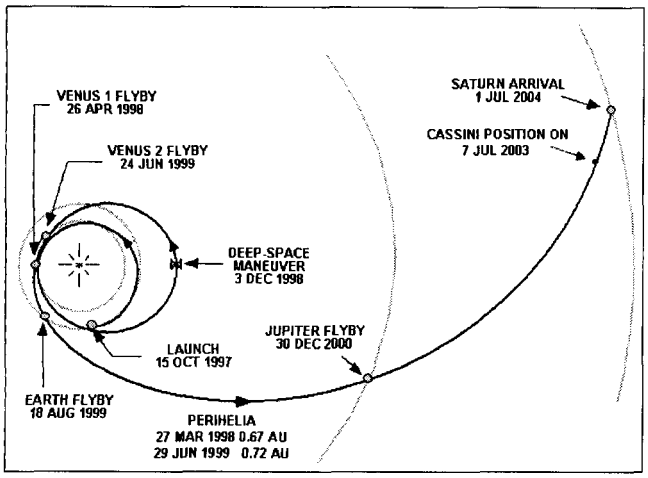

Figure 1: Cassini Cruise Trajectory

The spacecraft will orbit Saturn 75 times in the baseline mission [1]. The heliocentric distance variation at Saturn will vary between 9.01 and 10.07 AU [2]. Over a period of 43 months the spacecraft will perform 45 targeted flybys of Titan for science purposes and to produce desired changes in the trajectory using Titan's gravitational influence [1]. Titan's diameter is approx. 40% that of Earth's and the atmosphere is denser than Earth's atmosphere. Targeted flybys are the lowest flybys, where the spacecraft's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) at closest approach (C/A). 25 of these targeted flybys will have a sufficiently low C/A target altitude that the atmospheric induced free molecular heating (FMH) is the dominant heat load and is of thermal concern.

SPACECRAFT CONFIGURATION

The spacecraft configuration is shown in Figure 2. The spacecraft coordinate system is also shown with the +Y axis pointing into the plane of the paper.

The High Gain Antenna (HGA) is used for communication, radio science (RSS), and imaging radar (RADAR). It also supports a low gain antenna (LGA1) and two Sun Sensors (SSHs) and serves as a micrometeoroid shield. Below it (+Z direction) is the 12 bay electronics Bus. The upper RADAR bay, two Inertial Reference Units (IRUs), and some Probe support electronics are mounted on top of the Bus. Below the Bus is the upper support structure assembly (USSA) that supports the science pallets and additional Probe and science electronics. Below this is the central body that houses the propulsion system (PMS) and supports the Probe. Supported by the central body and lower equipment module (LEM) are the four thruster clusters. The LEM also supports the PMS, the three RTGs, another low gain antenna (LGA2), and three Reaction Wheels (a spare Reaction Wheel is located near the RSP). Below these are the Main Engine Assembly (MEA) with two main engines (redundancy) and an articulating MEA Cover that provides micrometeoroid protection for the nozzles when closed.

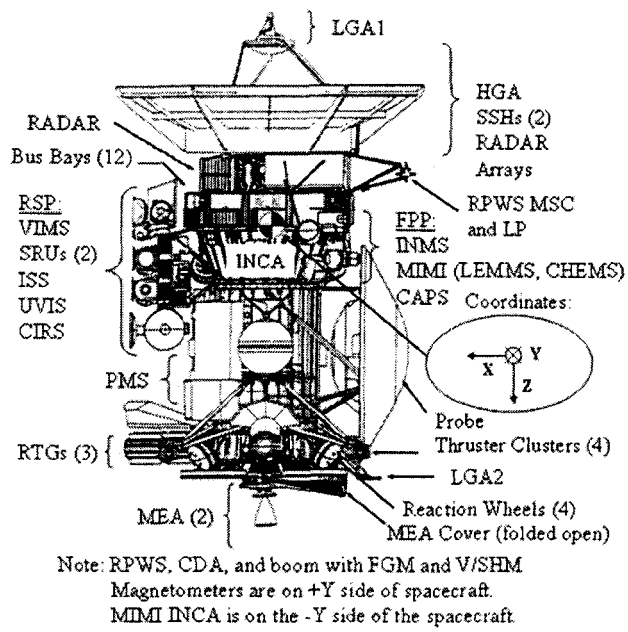

Figure 2: Cassini Spacecraft Configuration

The science pallets are the Remote Sensing Pallet (RSP) and the Fields and Particles Pallet (FPP). The RSP supports the optical instruments (ORS instruments), which are the Visual and Infrared Mapping Spectrometer (VIMS), the Imaging Science (ISS), which is composed of narrow angle and wide angle cameras, the Ultraviolet Imaging Spectrometer (UVIS), and the Composite Infrared Spectrometer (CIRS). The RSP also supports two Stellar Reference Units (SRUs) used for attitude control. The FPP supports fields and particles instruments, which are the Ion and Neutral Mass Spectrometer (INMS), the Cassini Plasma Spectrometer (CAPS), and two of the Magnetospheric Imaging Instruments (MIMI), which are the Charged Energy Mass Spectrometer (CHEMS) and the Low Energy Magnetospheric Measurement System (LEMMS). The MIMI Ion and Neutral Camera (INCA) is mounted on the USSA on the –Y side. The Radio and Plasma Wave Science Instrument (RPWS) has a Magnetic Search Coil (MSC) and a Langmuir Probe (LP) on the –X side of the spacecraft just below the HGA. The RPWS instrument and the Cosmic Dust Analyzer (CDA) are mounted on the +Y side on the USSA. The Magnetometer Boom is

mounted above the Bus and extends out on the +Y side and supports the Fluxgate (FGM) and Vector/Scalar Helium (V/SHM) Magnetometers. (Hardware on the +Y side is hidden in Figure 2). The fields and particles instruments are known as the MAPS instruments.

SPACECRAFT THERMAL DESIGN FEATURES

The spacecraft must tolerate the large variation in heliocentric distance and turn with respect to the Sun to perform trajectory correction maneuvers (TCMs) and to perform science pointing, as the instrument pallets do not articulate. It must also tolerate planetary albedo and infrared environmental heat loads and FMH during targeted flybys of Venus, Earth, and Titan.

The majority of the spacecraft is covered with Multi-Layer Insulation (MLI) blankets to minimize the thermal sensitivity to varying environments. (MLI is not shown in Figure 2 for hardware clarity purposes.) Thermal sensitivity is reduced over selected temperature ranges by louvers used on the Bus, on the FPP, on the RSP, and between the RSP and central body.

Electrical heater power requirements were minimized by the use of Radioisotope Heater Units (RHUs) used on various hardware, Variable RHUs (VRHUs) used on thruster clusters, and RTG waste heat used to heat the central body. Replacement and supplemental heaters were used where appropriate to maintain temperatures for various operational and non-operational hardware modes. Proportional performance heaters were used in certain instruments to maintain temperatures within relatively tight ranges.

The HGA is conduction isolated from the Bus and serves as a shade when the spacecraft is Sun pointed. Inside a 5 AU heliocentric distance the spacecraft must be close to Sun pointed on a continuous basis and can turn off Sun for only limited periods based on heliocentric distance. When off Sun within 5 AU, the Sun must impinge on the –X side of the spacecraft with the solar vector essentially in the XZ plane. This protects the RSP ORS and SRU radiators and apertures from direct solar impingement. It also helps control temperature cycles for the CIRS, ISS, and VIMS instruments on the RSP. Certain temperature cycles are consumables with a certain number of cycles not to be exceeded during the mission. By design, the fields and particles instruments and the Probe are more tolerant of direct solar impingement. The Probe serves as a solar shade for maneuvers within 5 AU. The –X side of the spacecraft has been designed to be heat load tolerant post Probe release. Beyond 5 AU there are attitude constraints provided by Flight Rules and Project requirements to protect apertures and radiators on the RSP from direct solar impingement. The spacecraft's thermal design and early thermal performance in flight have been previously documented [3, 4, and 5].

POLICIES AND REQUIREMENTS

The Project Policies and Requirements document [6] requires:

1) The risk to hardware resulting in temporary performance degradation due to flying through Titan's atmosphere shall be ≤ 5%.

2) The Mission Design shall not include Titan flyby altitudes lower than 950 km, or as compatible with revised Titan atmospheric models and risk.

3) Instruments shall be designed to withstand the following Sun exposures at a solar distance of 0.61 AU:

a) For instruments with boresights along the –Y axis, continuous Sun exposure durations within the specified half cone fields-of-view: 7 s at 4.3 mrad (0.25°), 18 s at 23 mrad (1.32°), 23 s at 32 mrad (1.83°), 30 s at 44 mrad (2.52°), and 105 s at 175 mrad (10.03°).

b) For instruments with radiators normal to the +X axis, 360 s of equivalent continuous Sun normal to the radiator surfaces.

4) The spacecraft and all its engineering subsystems shall be capable of operating and the science instruments shall be capable of surviving in the thermal environment between 0.61 AU and 10 AU while meeting the mission requirements for TCMs, telecom, fault recovery response, and science data collection.

In part 2, the 950 km altitude limit has been interpreted as a target C/A altitude. The durations of part 3 apply to the RSP ORS instruments and are intended to prevent instrument damage under fault conditions. These durations can be considered a function of heliocentric distance. Part 4 relates the general thermal robustness required of the spacecraft design.

The Project functional requirements document for thermal control [2] contains flight allowable temperature ranges the hardware must stay within during the flight. These are a function of hardware state (operating or non-operating) and activity. It also puts constraints on spacecraft attitude with respect to the Sun within a heliocentric distance of 5 AU.

Using known properties associated with surface materials, FMH, planetary albedo, and IR heat loads can be converted to equivalent solar heat loads. Given the solar heat load relationships to heliocentric distance and applicable durations, this provides a means of relating all environmental heat loads to these parameters for assessment purposes.

Flight Rules [7] provide Sun avoidance constraints even at Saturn to avoid consumable thermal cycles and the overheating of sensitive surfaces on ORS instruments (CIRS, ISS, and VIMS) on the RSP. They will be discussed as they were at the time of the evaluation. There are Sun avoidance regions about the +X axis and the –Y axis. For radiators on the +X side of the RSP, the Sun should not directly impinge on these surfaces unless the solar vector is at least 88 degrees off of the +X axis (+X axis is the surface normal). For apertures on the -Y side of the RSP, the Sun should not directly impinge on these surfaces unless the solar vector is at least 12 degrees off of the –Y axis. The onboard AACS Constraint Monitor will insure the Sun avoidance constraints are complied with in operational flight and during Safing procedures. These constraints apply only to direct solar impingement. The Constraint Monitor will not protect against other heat loads such as FMH. It is up to the thermal strategy to make sure the FMH does not disrupt instrument use or cause damage.

The Cassini Physical Constants Document [8] requires the use of the Yelle Model of the Titan atmosphere for all applicable Project related design and analysis work. This model has been used to determine the atmospheric density versus altitude profile used in the thermal modeling.

FLYBY TRAJECTORIES

The NAV Team provided hyperbolic trajectory information for all targeted Titan flybys. This included the trajectories relative to Titan, the spacecraft velocity relative to Titan at C/A, the C/A altitude, vectors for the location of the Sun and the Earth relative to Titan, and the heliocentric distance for each C/A point.

Table 1 provides the information used during the evaluation for the 45 targeted Titan flybys at C/A with respect to date, targeted altitude, spacecraft velocity relative to Titan, and heliocentric distance.

UNCERTAINTIES

Based upon NAV Team evaluation, a 3 sigma (standard deviation) conservatism with respect to the C/A target altitude was used, which results in a 30 km reduction in the C/A target altitude modeled with respect to the density profile used in the analysis.

A tour maximum C/A velocity relative to Titan of 6.426 km/s was recommended by the NAV Team. This is higher than the highest nominal predicted C/A velocity of 6.371 km/s for flyby 42. It is a consequence of taking the 3 sigma uncertainty associated with C/A altitude into account for the trajectory.

Table 1: Targeted Titan Flybys

Titan Flyby ID	DATE			S/C Altitude at C/A	C/A Velocity	S/C Heliocentric Distance
	YYYY	MM	DD	(km)	(km/s)	(AU)
Ta	2004	10	26	1200.0	6.044	9.045
Tb	2004	12	13	2346.3	5.950	9.049
Tc	2005	1	14	65000.0	5.683	9.052
T_03	2005	2	15	950.0	6.002	9.056
T_04	2005	3	31	2502.9	5.907	9.069
T_05	2005	4	16	950.5	6.057	9.071
T_06	2005	8	22	960.9	6.053	9.089
T_07	2005	9	7	4164.4	5.875	9.091
T_08	2005	10	28	1472.2	5.897	9.091
T_09	2005	12	26	10656.3	5.597	9.112
T_10	2006	1	15	2081.0	5.807	9.105
T_11	2006	2	27	1851.4	5.863	9.124
T_12	2006	3	19	2009.9	5.822	9.119
T_13	2006	4	30	1891.1	5.841	9.136
T_14	2006	5	20	1881.2	5.836	9.135
T_15	2006	7	2	1949.8	5.828	9.146
T_16	2006	7	22	949.8	5.962	9.150
T_17	2006	9	7	952.4	5.984	9.160
T_18	2006	9	23	949.8	5.981	9.163
T_19	2006	10	9	950.4	5.985	9.167
T_20	2006	10	25	967.4	5.993	9.170
T_21	2006	12	12	950.3	5.971	9.180
T_22	2006	12	28	1578.4	5.920	9.184
T_23	2007	1	13	960.8	5.983	9.188
T_24	2007	1	29	2788.7	5.834	9.191
T_25	2007	2	22	982.7	6.249	9.183
T_26	2007	3	10	955.8	6.255	9.186
T_27	2007	3	26	952.6	6.255	9.190
T_28	2007	4	10	951.7	6.254	9.193
T_29	2007	4	26	950.2	6.252	9.197
T_30	2007	5	12	951.7	6.251	9.201
T_31	2007	5	28	2457.3	6.127	9.205
T_32	2007	6	13	950.7	6.249	9.208
T_33	2007	6	29	1947.2	6.180	9.212
T_34	2007	7	19	1308.2	6.241	9.226
T_35	2007	8	31	3229.9	6.096	9.227
T_36	2007	10	2	965.6	6.317	9.235
T_37	2007	11	19	1020.8	6.304	9.247
T_38	2007	12	5	1299.6	6.296	9.251
T_39	2007	12	20	983.0	6.330	9.255
T_40	2008	1	5	950.7	6.323	9.260
T_41	2008	2	22	959.7	6.362	9.272
T_42	2008	3	25	950.1	6.371	9.281
T_43	2008	5	12	950.2	6.362	9.294
T_44	2008	5	28	1320.3	6.319	9.298

Based upon information from the AACS Team and Mission Planning, a 1.645 sigma conservative atmospheric density profile of the Yelle Model was used

different, it is desirable to minimize the number of Safing attitudes to minimize the number of software patches.

The Thermal/Devices Team investigated each targeted Titan flyby geometrically. Images of the spacecraft geometric model at C/A were articulated to find attitudes where the RSP was completely sheltered from the RAM, the –X side of the spacecraft was exposed to the RAM, and the HGA was Earth pointing. A review of these results with the AACS Team revealed the number of attitudes required was impractical. A practical approach was resolved to select three candidate attitudes, with each being used for a contiguous group of flybys. These attitudes were selected by AACS to satisfy the Safing criteria and avoid excessive exposure of the RSP to the RAM. A thermal evaluation of these attitudes began with the completely sheltered RSP approach as a fall back position.

The three attitudes are inertial in space and have the HGA (-Z axis) Earth pointing in all cases. They are defined with respect to the Earth-Mean-Equator (J2000) inertial reference frame. For targeted Titan flybys (see Table 1), Ta, Tb, Tc, and T3 through T24 the spacecraft +X axis is to J2000Z, for flybys T25 through T38 the spacecraft -X axis is to J2000Z, and for flybys T39 through T44 the spacecraft -X axis is to J2000Y.

For each flyby and associated Safing attitude the trajectory was geometrically simulated and images of the spacecraft geometric model looking down the velocity vector toward the spacecraft at C/A were produced. The flybys that had the greatest exposure (largest projected areas) of the RSP to the RAM were selected for thermal simulation for each of the three Safing attitudes. An additional selection criterion used was the thermal severity of the Titan flyby environment at C/A. The indicators were the velocity relative to Titan and the altitude at C/A. In total, five flybys were selected and thermally simulated.

Four additional inertial flyby thermal simulations were necessary to better understand the thermal strengths and weaknesses. These provided essential bounding information in addressing the issue of turning within the atmosphere. Two simulations provided maximum exposure of the RSP to the RAM. These simulated the +X axis directly into the RAM and the -Y axis directly into the RAM. Two more simulations were performed that put the +X and –X sides of the spacecraft substantially into the RAM, but with unique, more realistic, and additionally informative attitudes. A thermally severe trajectory was selected for each simulation with consideration given to the Sun location.

Figure 4 is an example of an image of the spacecraft geometric model at C/A with the -Y axis to the RAM as viewed looking down the velocity vector toward the spacecraft. This image can be compared with the configuration in Figure 2 with MLI taken into account.

OPERATIONAL SCENARIOS – Thermal engineers interfaced with the AACS Team, Mission Planning, and science personnel to obtain the definitions of anticipated operational flyby scenarios associated with science activities. These included attitude profiles and power modes. Operational flybys were expected to be less tolerant thermally than Safing flybys, given the flight allowable temperature range for thermally sensitive operational hardware is typically smaller than the non-operational range.

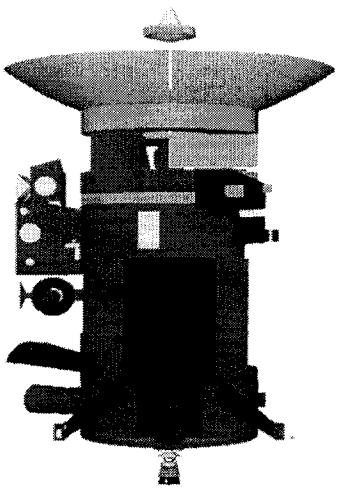

Figure 4: Spacecraft Model Image at C/A with -Y Axis to RAM as Viewed Looking Down Velocity Vector

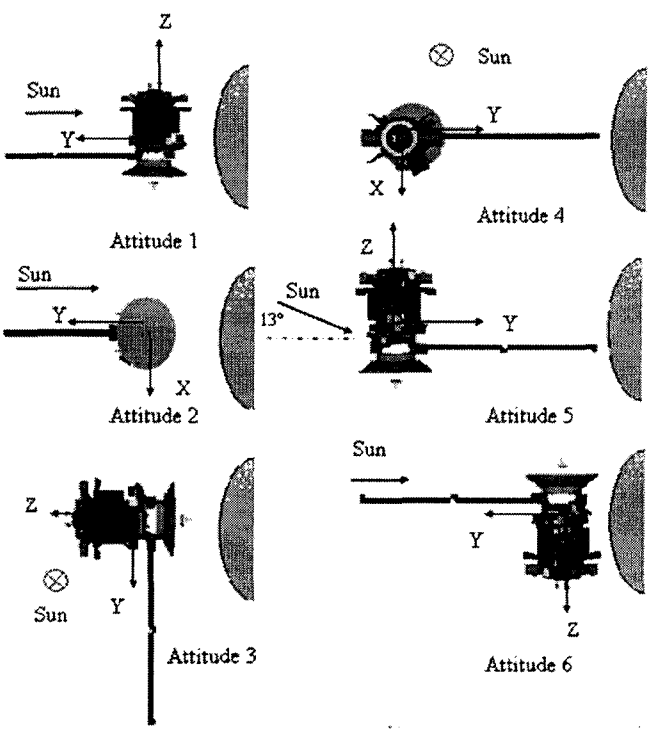

Figure 5: Six Inertial Operational Attitudes and Sun Orientations at C/A

Based upon this information and the knowledge gained from the Safing evaluation, six operational inertial flyby attitudes were simulated first and are shown graphically in Figure 5. While not operationally realistic, these attitudes provided essential bounding information about the operational thermal strengths and weaknesses of the science instruments and engineering hardware.

Two operational power modes were used in flyby simulations for the inertial attitudes. These are the ORS (RCS) power mode and the RADAR (RCS) power mode. For attitude 2, flyby simulations were made for both power modes. The power mode is critical in generating the proper temperatures and in determining what flight allowable temperature limits apply. Table 2 contains a summary of the inertial simulations performed in terms of attitude, Sun position, and power mode.

Table 2: Inertial Titan Flyby Operational Simulations

Case	Inertial Attitude	Sun Position	Power Mode
1	-X axis along velocity vector. -Y axis to Titan at C/A.	Sun incident on +Y side of spacecraft. Sun vector along –Y axis.	ORS (RCS)
2	-Z axis along velocity vector. -Y axis to Titan at C/A.	Sun incident on +Y side of spacecraft. Sun vector along –Y axis.	ORS (RCS) RADAR (RCS)
3	-X axis along velocity vector. -Z axis to Titan at C/A.	Sun incident on -X side of spacecraft. Sun vector along +X axis.	RADAR (RCS)
4	+Z axis along velocity vector. +Y axis to Titan at C/A.	Sun incident on +Z side of spacecraft. Sun vector along –Z axis.	ORS (RCS)
5	+X axis along velocity vector. +Y axis to Titan at C/A.	Sun avoidance constraint case*	ORS (RCS)
6	+X axis along velocity vector. -Y axis to Titan at C/A.	Sun incident on +Y side of spacecraft. Sun vector along –Y axis.	ORS (RCS)

* Sun incident primarily on –Y side, with Sun vector in Y/Z plane and pointing 13° off the +Y direction and 77° off –Z direction

Certain operational flybys will have science instruments pointing at Titan. Two operational attitude profiles requiring thermal simulation have the ORS instruments pointing at points on Titan as the spacecraft flies by. This type of pointing is known as "Spot Light" pointing and can thermally be a worst case from a pointing perspective. The worst-case is where the point being observed on the surface is directly below the C/A so the distance between the point observed and the spacecraft at C/A is the altitude. This type of pointing is more severe thermally than pointing elsewhere on Titan because it increases the projected area of sensitive surfaces exposed to the RAM. If this pointing is thermally acceptable, then pointing elsewhere on Titan will be thermally acceptable also.

The ORS pointing attitude profiles were simplified by constraining the spacecraft attitude simulations to a simpler, but thermally conservative flyby profile. The Yelle Model of the atmospheric density extends to an altitude of 3000 km. At that altitude the FMH is negligible. In the simulation the attitude of the spacecraft at an altitude of 3000 km was assumed constant during the flyby until it reached a point in time where the actual attitude would have the ORS instruments totally shielded from the RAM by the spacecraft. At that point, the simulation assumed the spacecraft was rotated to the attitude it would have at C/A. This C/A attitude was maintained after closest approach until it had flown the same amount of time it had been in this attitude prior to closest approach. At that point the spacecraft was rotated and left at the pointing attitude it would have when it reached the 3000 km altitude again while leaving. This approach allowed the modeling to be simplified, saving significant analysis time and it was thermally conservative with respect to the projected areas of sensitive surfaces exposed to the RAM. If the results were to reveal thermal problems then the simulation would have to be fine-tuned by following the actual attitude profile more closely. ORS pointing simulations used the ORS (RCS) power mode.

Using the above simulation approach, two ORS "Spot Light" pointing attitude scenarios were simulated. One is where the –X/-Y region of the spacecraft leads during the approach, with the Z axis perpendicular to the velocity vector. The spacecraft is rotated about the Z axis to point the ORS instruments at Titan's surface. The other is where the –Z/-Y region leads, with the X axis perpendicular to the velocity vector. The spacecraft is rotated about the X axis to point the ORS instruments at Titan's surface. Figures 6 and 7 display the flyby geometry used in the two simulations.

Two Sun position cases were analyzed for the scenario where the spacecraft is rotating around the Z axis (Figure 6). Case 1 is where the Sun is positioned where it shines on the +Y side of the spacecraft at C/A. This would cause a violation of the AACS Constraint Monitor with respect to the +X axis after closest approach. This was done deliberately to see the thermal response of not constraining the Sun appropriately. Case 2 is where the Sun is shining on the +Z side of the spacecraft and no constraint violation occurs.

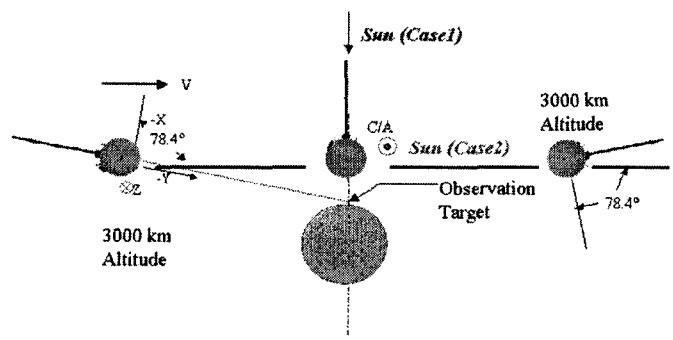

Figure 6: ORS "Spot Light" Pointing Attitude with Rotation About Z Axis

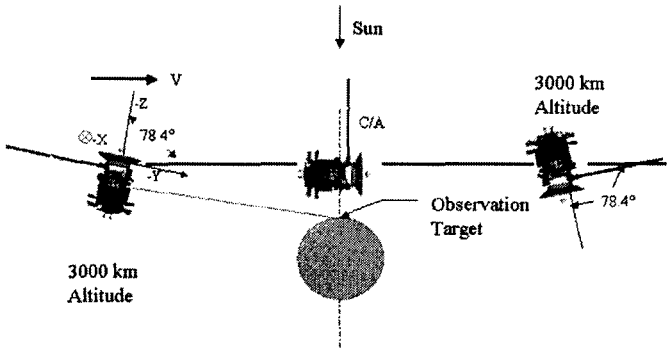

Figure 7: ORS "Spot Light" Pointing Attitude with Rotation About X Axis

An operational Nadir pointing RADAR flyby also required evaluation. This is where the HGA points Nadir to Titan through the entire flyby. The ORS instruments are not exposed to the RAM and two inertial attitudes provide good bounding cases for the other hardware of concern. These were simulated with the RADAR (RCS) power mode and are cases 2 and 3 in Table 2.

For RADAR passes there is also a "Side-Look" slewing motion that must be accounted for. At the time of this evaluation not all aspects of the slew motions were known. If it is assumed the spacecraft is nominally Nadir pointing and the –Z/–X region of the spacecraft is leading as it approaches Titan, then the anticipated slews resulting from rotation about the X axis (pitch) range from approx. -10° to +10° and are not a concern thermally. No slews about the Y axis (yaw) were expected. The thermal concern is the magnitude of rotation about the Z axis (roll). Roll limits were not fully defined at the time of the analysis, but were not expected to exceed ±10°. Not to exceed roll limits required evaluation. Figure 8 depicts attitude variation due to roll and pitch "Side-Look" motion at C/A as viewed looking down the velocity vector toward the spacecraft.

THERMAL MODELING CONSIDERATIONS

The Thermal/Devices Team's flight correlated, Systems-level thermal math model of the spacecraft was used for all thermal simulations. This is a 480 node thermal model. A correlated geometric model having 570 nodes was used for external heat load determination. These models did not include the Probe. The results are valid for the first two targeted flybys where the Probe will be onboard. The time dependency of the RHU and RTG decay was taken into account.

Thermal analysis software selection was weighted by schedule constraints, current familiarity, automation considerations, and skills retention. Thermal analyzer software was selected that would generate the transient nodal temperature profiles and produce plots of the temperature trend of each node. Software utilizing Monte Carlo solution techniques was selected that would produce time dependent histories of direct solar, Titan IR, and albedo heat loads on a nodal basis for the flyby scenarios. This software was also used to produce spacecraft geometric images at attitude. Direct calculation of the FMH exceeded the software capability. The calculation of FMH on a surface is analogous to the direct solar heat load calculation. Substituting molecular flux for solar flux (magnitude and direction) and accommodation coefficient for solar absorptance, the FMH heat loads were calculated by the existing software. Each of the four fluxes was generated separately so they could be checked individually.

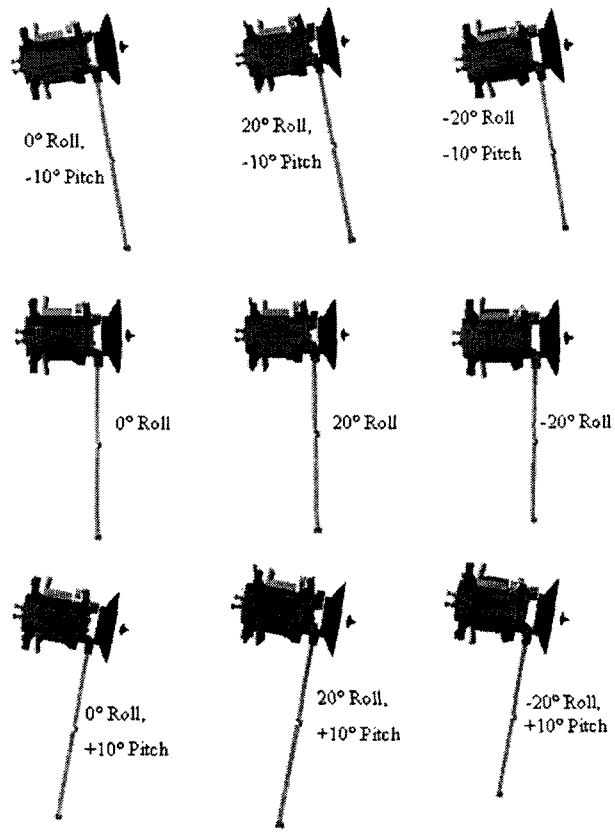

Figure 8:RADAR to Nadir Attitude Looking down Velocity Vector at C/A with "Side-Look" Variations

Spreadsheets were used to perform coordinate transformations, set up coordinate inputs for heat load generation, transform heat load outputs into thermal model inputs, and compile the thermal simulation results into comprehensive report-ready formats. The processes were captured in spreadsheet formats and macros.

All flyby thermal simulations were transient simulations. Pre flyby steady-state start temperatures were computed and used to begin each simulation at the start of the transient computations. All thermal simulations covered a period of ±1.5 hours about C/A. This insured the simulations started and ended beyond where the environmental heat loads had significant

levels. The FMH is thermally significant for approx. ±10 minutes maximum (altitude dependent) about C/A. The Titan IR and albedo were accounted for over a period of approx. ±1 hour about C/A.

Material dependent thermal radiative properties were used for the exterior surface materials. An accommodation coefficient of 0.90 was used for the absorption of the FMH. The absorbed heat loads resulted from both directly incident heat loads and those resulting from diffuse multiple reflections due to the interaction with the spacecraft surfaces. This includes the effective diffuse reflections of the FMH also.

Some additional parameters were required for the thermal model. A heliocentric distance of 9.045 AU corresponds to the Titan flyby that will occur closest to the Sun (Table 1). An incident solar flux value of 16.75 W/m^2 normal to a surface was used and corresponds to the heliocentric distance of 9.045 AU. The albedo factor for Titan used in the analysis was 0.29. The Titan surface IR irradiance used was 3.10 W/m^2.

All the environmental heat loads were included in the simulations, but FMH is the dominant heat load for flybys of concern. Peak incident FMH heat loads under the most conservative assumptions reached a value of 514.5 W/m^2. Conversion to an incident direct solar equivalent heat load was surface material dependent. Solar equivalent peak values for some surfaces of concern corresponded to a heliocentric distance of 0.764 AU. This is under transitory conditions, but is well below the comfortable distance of 5 AU.

A C/A altitude of 1292 km was considered an upper altitude limit for thermal concern. At 1292 km all of the peak incident environmental heat loads converted and summed to an incident direct solar equivalent heat load corresponded to a value of 54.7 W/m^2 for materials of concern, which corresponds to a 5 AU heliocentric distance. A flyby simulation was made with a specific C/A altitude of 1292 km as a sanity check to verify this was a thermally safe upper limit altitude. Inertial attitude case 6 of Table 2 was used.

Flyby specific trajectories and Sun locations were modeled for the Safing cases. For operational flybys a thermally worst-case trajectory scenario was selected for the simulations. It assumed a target C/A altitude of 950 km and a maximum C/A velocity of 6.426 km/s. The Sun was positioned as desired for thermal evaluation purposes in each case.

The Langmuir Probe (not in the model) and a closed MEA Cover assembly were evaluated separately by hand. Conservative environmental conditions were applied under steady-state conditions. The MEA Cover was open in the thermal model simulations to expose the PMS to the thermal environment.

RESULTS AND CONCLUSIONS

A method was developed to enable an efficient and reliable evaluation of a thermal simulation to be made. The thermal model was surveyed and a definitive subset of nodes that would accurately, reliably, and concisely represent the spacecraft thermal hardware response was selected for evaluation purposes. A spreadsheet was used to format the thermal simulation output for evaluation purposes. The output product provided a correlation of flight telemetry channel, model node number, hardware component description, hardware subsystem, state of the hardware component, the temperature range experienced, and the flight allowable temperature limits. The state is operating or non-operating or, in the case of PMS hardware, an at-ignition, firing, or non-firing state. A space was provided to note if a thermal problem existed with that component. In certain situations nodal temperature plots were examined and subsystem personnel were contacted and the results discussed with them.

While applied Project constraints and flyby scenarios have changed significantly, this evaluation reaffirms the validation of the thermal design with respect to Titan flybys concluded during the development phase.

SAFING EVALUATION - The onboard AACS Constraint Monitor will protect the spacecraft from direct solar heat loads, including during turns resulting from Safing, but not from FMH.

The first situation to consider is where Safing has already occurred and the spacecraft flies through the Titan atmosphere in the Safing attitude and with the Safing power profile. The second situation to consider is where all or part of the Safing process occurs while the spacecraft is in the atmosphere. With respect to the duration requirement associated with instrument –Y axis boresights, hand calculations showed the turning rate is sufficient by a factor of 10 or more to guarantee the requirement is met under all worst-case thermal loads when turning from an operationally thermally safe attitude to a final Safing attitude. To evaluate the +X axis radiator exposure duration requirement, the bounding inertial attitude flyby simulations were required.

It has been concluded that no thermally induced consumable issue or requirement violation is expected and the three candidate Safing attitudes are acceptable for the Titan flybys they were selected for with target C/A altitudes as low as 950 km. None of the simulations resulted in unacceptable thermal results. In certain post Safing situations some RSP ORS instruments may need to cool down to the flight allowable upper operational temperature limit before being turned back on. The thermal performance envelope provided by the Safing

for evaluation purposes. This conservatism was applied in generating the density profile in a manner that insured temperature varied linearly with sigma per Yelle's recommendation [8]. In this case, a sigma of 1.645 corresponds to the risk management required 95% confidence limits based upon the area under the standard normal distribution, assuming a 5% risk factor on the upper end of the distribution only. This assumes the density risk is on the high end. Figure 3 is a plot of this density profile compared to a mean density profile. INMS measurements will be taken during the first Titan flyby to assess if additional analysis is needed.

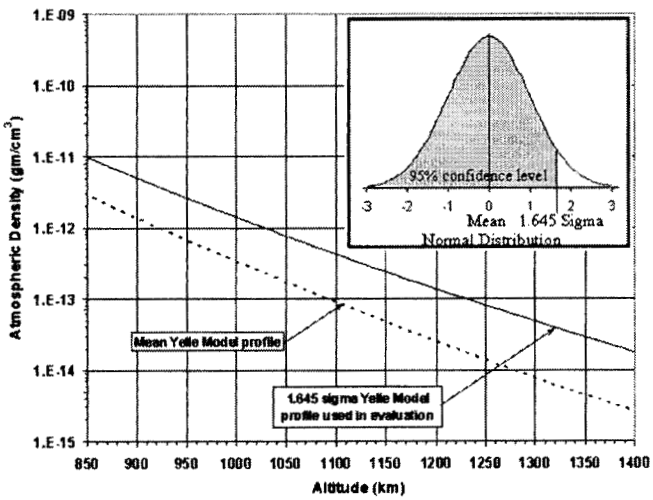

Figure 3: Yelle Model of Titan Atmospheric Density

Linear trajectories (rather than hyperbolic) were used for the flyby thermal simulations. This was due to software inability to model hyperbolic trajectories and to simplify the determination of the environmental heat loads, which vary with position along the trajectory. The deviation of the linear path from the hyperbolic path was carefully evaluated and the differences in environmental heat loads are of negligible magnitude. While individual components vary, typically the modeling error associated with this simplification was a small fraction of 1°C associated with the temperature rise induced by a flyby.

With respect to thermal math model simulations, for thermally sensitive bulk hardware nodes the uncertainty is typically ±5°C and for high-resolution nodes typically ±2°C. The model takes into account proportional performance heaters that maintain hardware temperatures in tight ranges.

POWER MODES

For the orbital tour the anticipated spacecraft hardware states are grouped into specific power modes of operation. Each power mode defines hardware states throughout the spacecraft and corresponding power usage. The power modes are designed to provide all necessary spacecraft functions and to insure the power output capacity is not exceeded.

Based upon information from the AACS Team, science personnel, and Mission Planning, two operational power modes were used for the operational flyby evaluation. These are the ORS (RCS) and the RADAR (RCS) power modes. In the ORS (RCS) mode the ORS and MAPS instrument groups are on and active, while the Radio Science and RADAR instruments are off. In the RADAR (RCS) mode the ORS instruments are on, but in Sleep (not active), the MAPS instruments are on and active, and the RADAR is on and active, while Radio Science is off. For both modes the HGA will be used. For both modes RCS refers to attitude control provided by the Reaction Control System (RCS) thrusters, as opposed to Reaction Wheels. Based on AACS evaluation [9] and scoping thermal calculations, at altitudes of thermal concern the spacecraft must use thrusters for attitude control.

At any time a fault may occur that results in the onboard System Fault Protection putting the spacecraft through a Safing procedure. If so, the spacecraft would be reconfigured for safety purposes to a specific power profile and attitude. The Safing power profile can be considered a power mode. All science instruments will be off, LGA1 will be used with the HGA off, attitude control will use RCS thrusters, and the spacecraft will point the HGA toward Earth.

FLYBY SCENARIOS

SAFING SCENARIOS - Safing scenarios required evaluation to determine Safing attitudes that were thermally acceptable for all targeted Titan flybys. Safing puts the spacecraft in an inertial attitude in space with the HGA pointing at the Earth for communication purposes. For each Titan flyby the spacecraft Safing attitude relative to Titan will be different and the location of the Sun relative to the spacecraft will be different.

Two fundamental situations required thermal evaluation. First, the Safing process has been completed before the spacecraft flies through the atmosphere. Second, the Safing process starts just before or in the Titan atmosphere and the spacecraft is turning while in the atmosphere. In the second case we do not know the precise attitude profile of the turn or the corresponding thermal transients. However, useful timing calculations can be made and certain attitudes can be simulated as limiting cases. In both situations, the Safing hardware states and power profile are achieved in approx. 4 seconds and then a turn is made to Earth pointing that takes no longer than approx. 720 s at a turning rate of 0.25°/s. Prior to Safing it is assumed the spacecraft is performing the operational flyby in a thermally acceptable manner.

The AACS Team provides Safing attitudes. To load them onboard the spacecraft requires a software patch. While the thermal influence of each Titan flyby is

evaluation provides a database for evaluation purposes if required in the future.

During the evaluation there was interest in having the option to Safe with the HGA either Earth pointed or Sun pointed. Additional specific simulations were not needed, as a review of the Earth pointing results revealed the Sun pointing would not change the conclusions. The difference in HGA pointing between the Earth and Sun is ≤ 6.3°.

OPERATIONAL EVALUATION - Operational flyby scenarios must constrain the exposure of the RSP ORS instruments to the RAM for the spacecraft to acceptably fly past Titan with target C/A altitudes as low as 950 km. This was confirmed by two inertial attitude simulations (cases 5 and 6 in Table 2) that revealed RSP ORS thermal violations. All other cases were acceptable. The AACS Constraint Monitor will protect these instruments from direct solar heat loads, but the design of the attitude profile must protect it from FMH.

Table 3 provides an example of simulation output for the case 6 inertial attitude. Model nodes 405, 410, 413, and 436 reveal temperature violations (overheating) induced by the flyby and are noted in the evaluation as problems. There are other temperature issues associated with nodes 271, 273, 403, and 457 that appear to be violations, but are understood, are not flyby related, and are not considered a flyby concern.

Evaluated flyby scenarios associated with instrument pointing toward Titan include "Spot Light" pointing at any point on Titan by ORS instruments, where the spacecraft rotates about either the X axis or Z axis normal to the velocity vector to maintain pointing, and HGA (-Z) pointing Nadir to Titan with "Side-Look" X and Z axis rotations for RADAR science. Nominal Nadir pointing has the -Z/-X region of the spacecraft leading on approach and the "Side-Look" slews caused by pitching about the X axis are anticipated to be approx. ±10°. The limit of "Side-Look" rolling about the Z axis was not yet fully defined, but it is recommended that it not exceed ±20° to protect the optical instruments from the RAM. These operational scenarios can be flown with target C/A altitudes as low as 950 km with no thermally induced consumable issue or requirement violation expected.

It is recommended that any additional operational attitude scenarios below a target C/A altitude of 1292 km should be avoided if they increase the exposure of the +X and –Y sides of the RSP to the RAM beyond the current scenarios evaluated. Above a target C/A altitude of 1292 km there are no thermal constraints on attitude except the existing science imposed Sun avoidance constraints.

The thermal performance envelope provided by the operational scenario evaluations provides a database to evaluate the thermal acceptability of a wide variety of scenario variations future planning may envision.

RTG POWER TRANSIENTS - From simulations of both Safing and operational flybys the largest transient drop in power that can result from RTG thermal transients caused by a Titan flyby has been determined. This is a temporary 5 W drop in combined power output from the three RTGs onboard. This is based upon the simulation RTG temperature transients calculated and the correlation between transient temperature excursions and transient power excursions gained from previous flight experience.

SKILLS RETENTION

Information and planning are updated during flight based upon current knowledge. The ability to revisit this evaluation is required early in tour when the INMS instrument provides in situ measurements and the density profile of Titan's atmosphere is reassessed.

The current capability in terms of software, models, and spreadsheet capability have been retained. The current plan is to retain the evaluation capability throughout the baseline mission. Given the mission duration, the Thermal/Devices Team expects changes in personnel. Appropriate members are trained in the capability to perform required analyses.

RECOMMENDATIONS AND LESSONS LEARNED

Plan during the development phase to provide the capability and resources to support comprehensive analyses in the operations phase. Take into account mission duration, as short missions require a relatively quick response. For longer missions, workforce turnovers should be anticipated. Select software tools that you anticipate will best meet your needs and be supported during the entire operations phase. Planning should account for the organizational differences between the development and operations phases of a project.

Require Systems-level thermal math models early in the development phase for correlation with Systems-level testing and early flight. Significant knowledge retention of design details should be captured in the model. Utilize visualization tools to clarify geometric concerns.

Operations teams should work together for consistent policy and requirement interpretation, to benefit from each other's expertise and experience, and to insure awareness and accurate information transfer.

Table 3: Case 6 – Inertial Titan Flyby Operational Simulation Results

Model Node	Descriptive Title	Subsystem	Subsystem State	Model Output (C) Temperature Range		OPERATING (C) At Ig/Firing		NON-OP (C) Non-Firing		Problem
				From	To	3-210 Low	3-210 High	3-210 Low	3-210 High	
474	RSP -X Face Temperature	STRU (2001)	Op	17.8	18.0	-10	30	-20	40	No
911	RTG 1 RTD 2 Temperature	PPS (2004)	Op	246.3	247.6	N/A	260	N/A	N/A	No
921	RTG 2 RTD 2 Temperature	PPS (2004)	Op	245.7	246.4	N/A	260	N/A	N/A	No
931	RTG 3 RTD 2 Temperature	PPS (2004)	Op	241.1	241.9	N/A	260	N/A	N/A	No
153	IRU-A Temperature	AACS (2007)	Op	31.2	32.2	-5	45	-20	45	No
154	IRU-B Temperature	AACS (2007)	Non-Op	13.7	13.7	-5	45	-20	45	No
581	RWM1 Temperature	AACS (2007)	Non-Op	28.0	28.1	0	40	-10	50	No
582	RWM2 Temperature	AACS (2007)	Non-Op	26.7	26.7	0	40	-10	50	No
583	RWM3 Temperature	AACS (2007)	Non-Op	27.8	28.3	0	40	-10	50	No
584	RWM4 Temperature	AACS (2007)	Non-Op	23.9	24.3	0	40	-10	50	No
454	SRU-A Optics Barrel Temperature	AACS (2007)	Non-Op	3.7	15.2	-15	30	-20	40	No
453	SRU-A CCD Temperature	AACS (2007)	Non-Op	-12.6	-11.2	-40	-30	-50	40	No
456	SRU-B Optical Barrel Temperature	AACS (2007)	Op	4.7	16.0	-15	30	-20	40	No
457	SRU-B CCD Temperature	AACS (2007)	Op	-27.0	-25.8	-40	-30	-50	40	No
271	SSH1 Temperature 2	AACS (2007)	Op	-90.1	-89.3	-90	80	-90	80	No
273	SSH2 Temperature 2	AACS (2007)	Non-Op	-90.5	-87.8	-90	80	-90	80	No
542	Helium Tank Temperature (THE1)	PMS (2010)	Non-Firing	29.8	29.9	10/-40	45	10	45	No
571	PCA Temperature 1 (TPCA1)	PMS (2010)	Non-Firing	35.5	35.5	30/-40	45	30	45	No
572	PCA Temperature 4 (TPCA4)	PMS (2010)	Non-Firing	41.4	41.4	30/-40	45	30	45	No
611	REA-A Head End Temperature (TE1)	PMS (2010)	Non-Firing	-2.5	0.4	-1/N/A	39/N/A	N/A	N/A	No
631	REA-B Head End Temperature (TE3)	PMS (2010)	Non-Firing	-4.8	-2.0	-1/N/A	39/N/A	N/A	N/A	No
575	PIA Temperature (TPIA)	PMS (2010)	At Ig/Firing	28.7	28.7	10	35	5	45	No
650	THR Cluster 1 (+X, +Y) Temperature (TC1)	PMS (2010)	At Ig/Firing	36.2	36.7	20	70	20	70	No
660	THR Cluster 2 (-X, +Y) Temperature (TC2)	PMS (2010)	At Ig/Firing	36.3	36.3	20	70	20	70	No
670	THR Cluster 3 (-X, -Y) Temperature (TC3)	PMS (2010)	At Ig/Firing	36.1	36.1	20	70	20	70	No
680	THR Cluster 4 (+X, -Y) Temperature (TC4)	PMS (2010)	At Ig/Firing	36.2	36.7	20	70	20	70	No
517	Articulated RW Motor Temperature A	DEV (2012)	Non-Op	25.6	25.7	0	40	-20	40	No
643	MEA Cover Mech. Mot-A Temperature	DEV (2012)	Non-Op	22.7	22.7	-35	44	-48	55	No
11	Bay 01 Temperature	EPS (2014)	Op	34.1	34.2	5	50	5	50	No
21	Bay 02 Temperature	EPS (2014)	Op	30.3	30.5	5	50	5	50	No
31	Bay 03 Temperature	EPS (2014)	Op	35.2	35.4	5	50	5	50	No
41	Bay 04 Temperature	EPS (2014)	Op	32.5	32.5	5	50	5	50	No
51	Bay 05 Temperature	EPS (2014)	Op	28.1	28.1	5	50	5	50	No
61	Bay 06 Temperature	EPS (2014)	Op	25.4	25.4	5	50	5	50	No
71	Bay 07 Temperature	EPS (2014)	Non-Op	20.1	20.2	5	50	5	50	No
81	Bay 08 Temperature	EPS (2014)	Op	26.7	26.7	5	50	5	50	No
91	Bay 09 Temperature	EPS (2014)	Op	25.1	25.2	5	50	5	50	No
101	Bay 10 Temperature	EPS (2014)	Non-Op	20.6	20.7	5	50	5	50	No
111	Bay 11 Temperature	EPS (2014)	Op	21.1	21.5	5	50	5	50	No
121	Bay 12 Temperature	EPS (2014)	Op	27.4	27.8	5	50	5	50	No
595	PMS Electronics Bay Temperature	EPS (2014)	Op	34.0	34.4	5	50	5	50	No
204	HGA Reflector Rear Surface Temperature 1	ANT (2017)	Op	-184.6	-184.0	-199	-16	-199	125	No
231	HGA Reflector Rear Surface Temperature 2	ANT (2017)	Op	-138.3	-133.5	-199	-16	-199	125	No
241	X-Band FSS Temperature 3	ANT (2017)	Op	-154.4	-140.1	-208	-14	-208	129	No
242	LGA1 WG Temperature 11	ANT (2017)	Non-Op	-176.7	-168.7	-187	91	-206	91	No
585	LGA2 WG Temperature 12	ANT (2017)	Non-Op	3.7	3.7	-80	140	-80	140	No
807	MAG FGM Temperature	MAG (2035)	Op	-3.0	-1.9	-30	50	-30	80	No
804	MAG V/SHM Temperature	MAG (2035)	Op	5.6	5.8	-10	40	-30	55	No
410	ISS NAC CCD Temperature	ISS (2036)	Op	-89.6	-79.7	-93	-87	-120	50	Yes
409	ISS NAC FW Housing Temperature	ISS (2036)	Op	3.9	4.0	-10	40	-20	40	No
413	ISS WAC CCD Temperature	ISS (2036)	Op	-89.7	-79.7	-93	-87	-120	50	Yes
412	ISS WAC FW Housing Temperature	ISS (2036)	Op	14.6	14.7	-10	40	-20	40	No
436	VIMS IR Focal Plane Temperature	VIMS (2037)	Op	-211.9	-193.1	-215	-196	-218	35	Yes
435	VIMS IR Optics Temperature	VIMS (2037)	Op	-132.5	-129.3	-153	-113	-143	35	No
423	VIMS Main Electronics Temperature	VIMS (2037)	Op	22.3	22.4	-20	50	-20	50	No
427	VIMS SPE Temperature	VIMS (2037)	Op	18.2	18.3	-20	50	-20	50	No
425	VIMS V Electronics Temperature	VIMS (2037)	Op	23.2	23.8	-20	45	-20	45	No
430	VIMS V Focal Plane Temperature	VIMS (2037)	Op	-37.3	-29.4	-50	-20	-60	60	No
429	VIMS V Optical Head Temperature	VIMS (2037)	Op	15.2	16.4	-10	20	-30	45	No
437	Radiator Shield 1 Temperature	VIMS (2037)	Op	-148.5	-65.3	N/A	N/A	N/A	N/A	No
594	RPWS Antenna Assembly Temperature	RPWS (2073)	Op	26.9	27.2	-10	50	-15	60	No
710	INMS Electronics Box Temperature	INMS (2074)	Op	16.0	16.1	-20	40	-30	60	No
711	INMS Sampling Area Temperature	INMS (2074)	Op	11.2	11.9	-102	48	-102	60	No
721	MIMI CHEMS Temperature	MIMI (2076)	Op	22.9	23.0	-20	35	-25	40	No
591	MIMI Electronics Temperature	MIMI (2076)	Op	30.7	30.8	5	50	5	50	No
592	MIMI INCA Temperature	MIMI (2076)	Op	18.1	18.7	-20	35	-25	50	No
718	MIMI LEMMS Temperature (Rotating)	MIMI (2076)	Op	11.6	12.4	-20	35	-25	40	No
717	MIMI LEMMS Temperature (Non-Rotating)	MIMI (2076)	Op	17.2	17.5	-20	35	-25	40	No
740	CDA Electronics Temperature	CDA (2078)	Op	10.8	11.0	-15	40	-15	40	No
749	CDA HRD Temperature	CDA (2079)	Op	0.8	1.0	-25	40	-25	40	No
745	CDA Non-Rotating Temperature	CDA (2079)	Op	17.7	17.9	-10	50	-10	50	No
141	PRB RFE Temperature A	PROBE (2080)	Non-Op	-6.9	-6.8	-20	50	-20	60	No
131	RADAR RFES Temperature	RADAR (2081)	Non-Op	18.5	19.2	5	50	5	50	No
714	CAPS Temperature 1	CAPS (2082)	Op	-9.9	-9.8	-20	30	-20	40	No
715	CAPS Temperature 2	CAPS (2082)	Op	-15.4	-15.3	-20	30	-20	40	No
416	UVIS Temperature	UVIS (2084)	Op	19.6	19.8	-10	30	-20	40	No
421	CIRS Electronics Temperature	CIRS (2089)	Op	23.1	23.2	-10	40	-20	50	No
403	CIRS Optics Module Temperature	CIRS (2089)	Op	-105.8	-104.7	-104	-102	-108	35	No
405	FPA Temperature	CIRS (2089)	Op	-191.7	-148.8	-204	-187	-204	35	Yes

Plan the use of consistent coordinate systems and transformations within a project to save resources, simplify analyses, and reduce the potential for errors.

The analysis process should include step-by-step sanity checks and peer reviews to prevent errors and uncover software bugs. Document any platform and software related problems.

Automate processes to expedite, simplify, and improve interface and output products and calculations. Document processes and assume they will be used again.

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