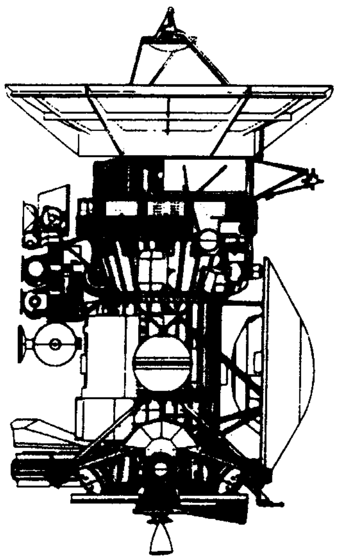
Operational Thermal Control of Cassini Titan Flybys



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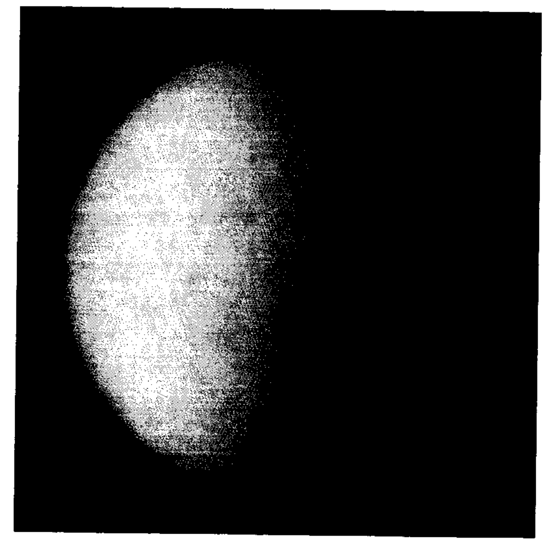


Jet Propulsion Laboratory
California Institute of Technology

CASSINI
MISSION TO SATURN

Challenge

- Cassini spacecraft (S/C) will perform 45 targeted flybys of Saturn's largest moon, Titan
  - Titan has a dense, planet-like atmosphere
  - S/C will fly through upper atmosphere where free molecular heating (FMH) is the dominant environmental heating
- S/C design doesn't fully address current Project constraints and operational scenarios
  - 25 targeted flybys with relatively low closest approach (C/A) altitudes are of thermal concern
  - Thermally induced power transients in Radioisotope Thermoelectric Generators (RTGs) are a power concern

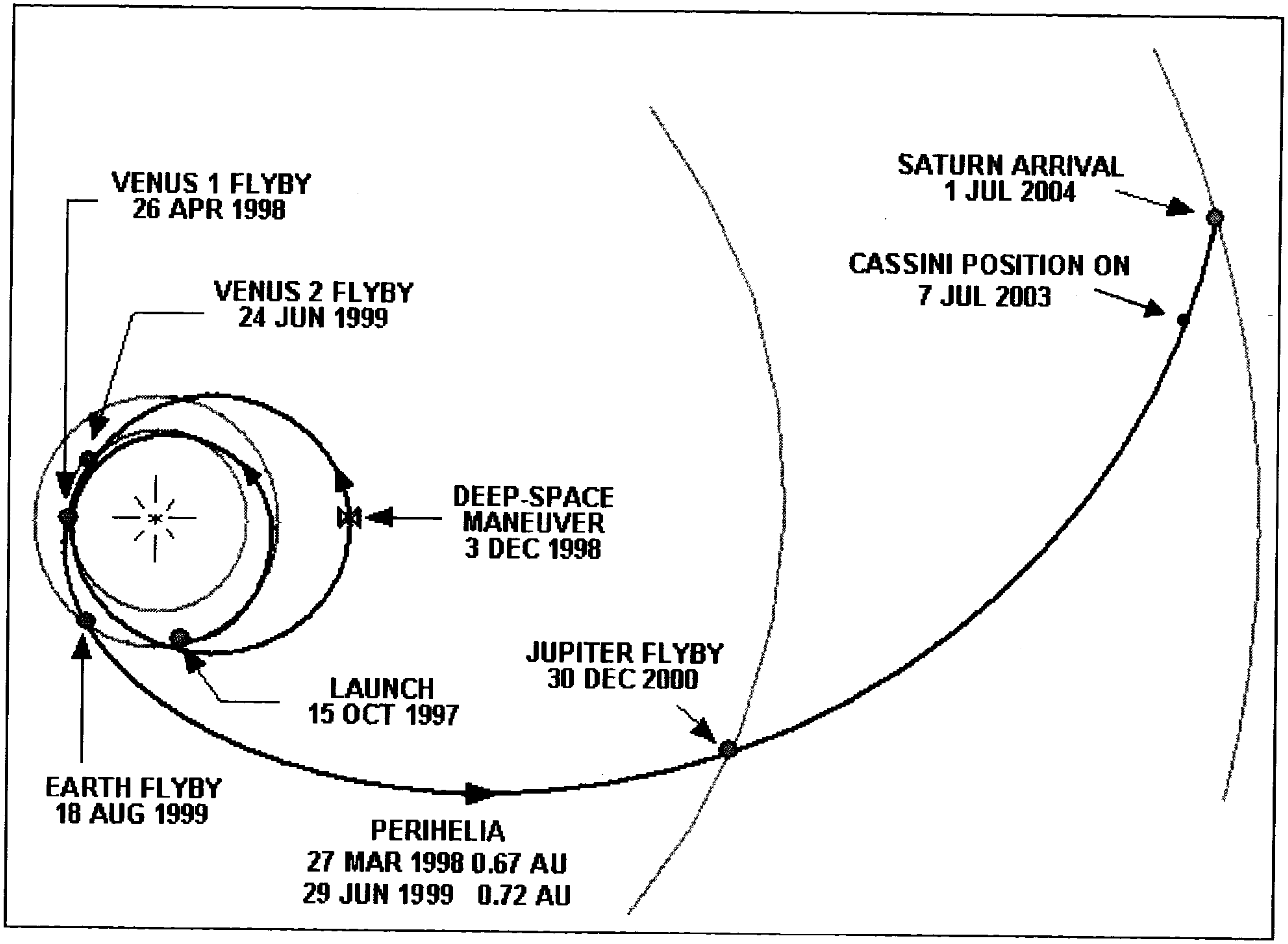
Solution

- Develop a Titan flyby thermal control strategy
  - That enables science
  - Remains within S/C design limitations
  - Complies with Project constraints
  - Comes from Thermal/Devices Team within Cassini Project in Mission Operations

Approach

- Define acceptable thermal performance envelope for Titan flybys and use for evaluation purposes
  - Based upon S/C design and current planning
  - Requires thermal simulation of defining flyby scenarios
- Use Systems-level approach utilizing Mission Operations "Team" architecture
  - Involve Project teams and organizations - share expertise
  - Account for S/C design, Project policies and requirements, risk constraints, Titan atmosphere definition, uncertainties, mission planning, and flyby trajectories and scenarios (attitude and power profiles)

Cruise Trajectory Requires Robust S/C Thermal Design



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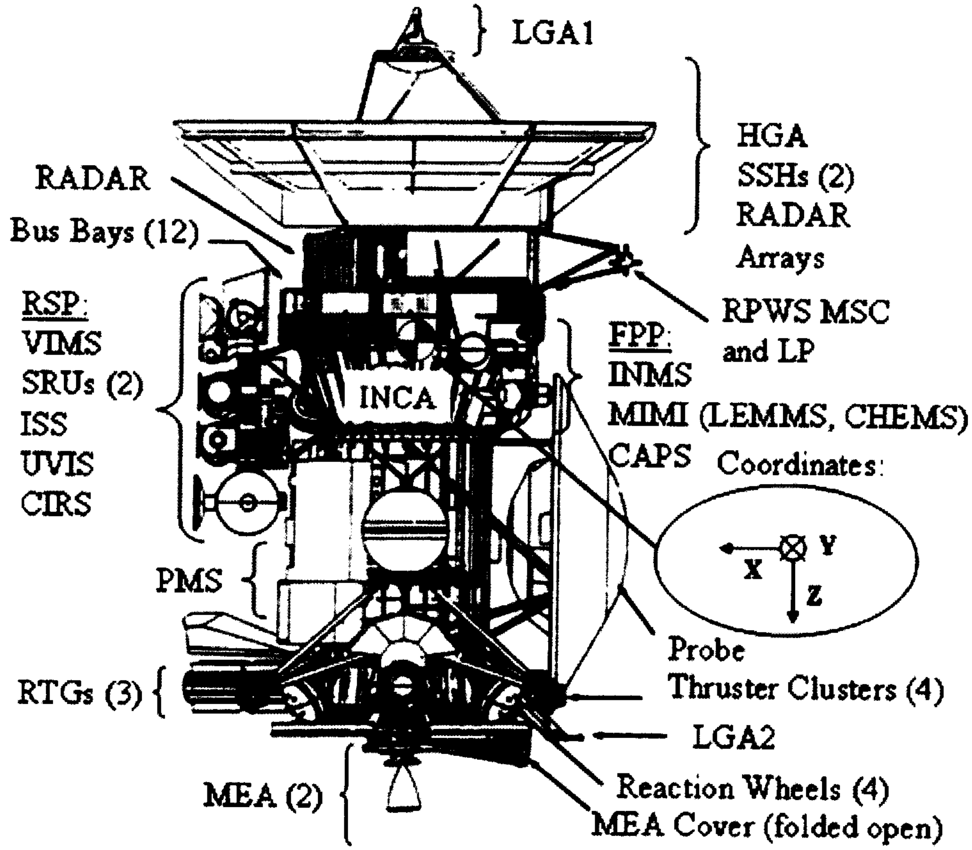
RSP Hardware Thermally Most Vulnerable



Note: RPWS, CDA, and boom with FGM and V/SHM
Magnetometers are on +Y side of spacecraft.
MIMI INCA is on the -Y side of the spacecraft.

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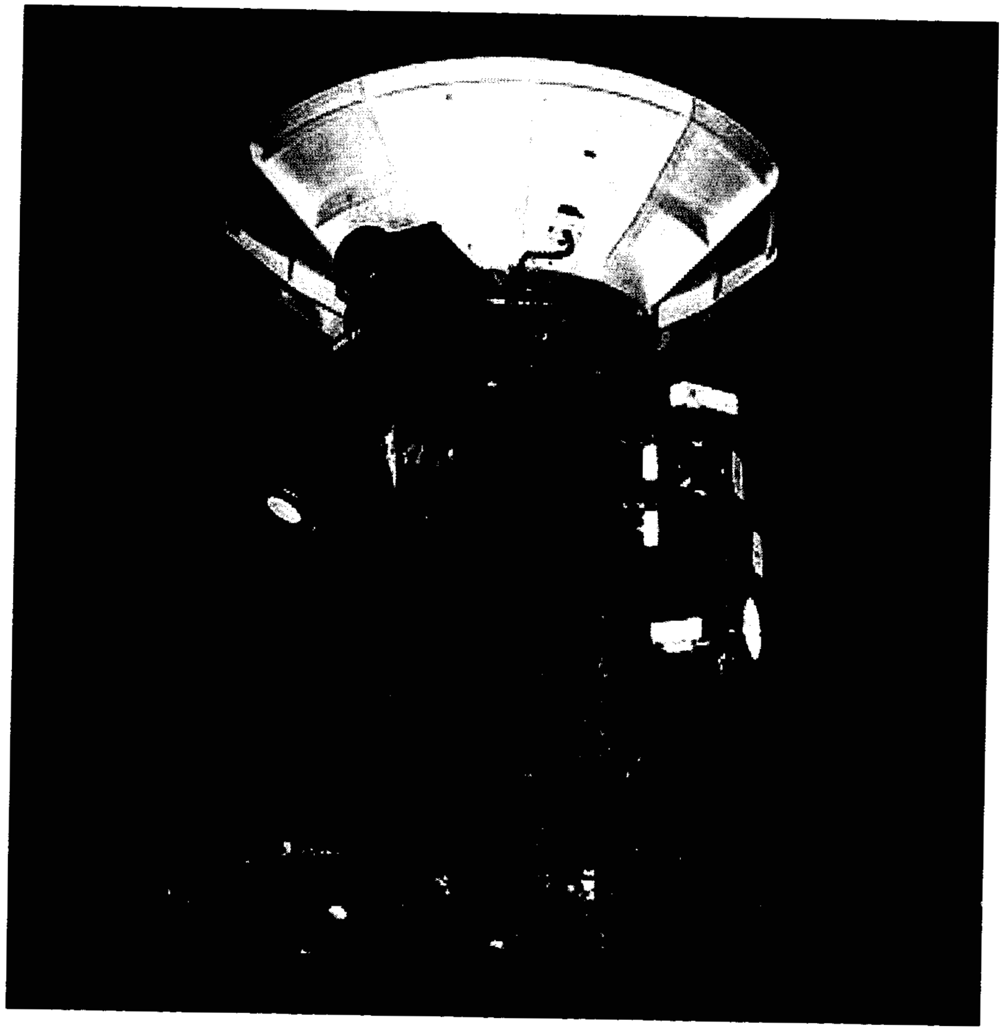
S/C Thermal Design Highlights

- Multi-layer insulation blankets (MLI) used to reduce thermal sensitivity to varying environments
- Louvers used on Bus, RSP, and FPP to reduce thermal sensitivity for selected temperature ranges
- Heater power minimized by use of Radioisotope Heater Units (RHUs), Variable RHUs, and RTG waste heat
- Repl. and Supl. Heaters and radiators used where required to maintain temperature levels
- Proportional heaters used to maintain temperatures in tight ranges
- HGA thermally isolated from Bus and serves as solar shade
- Probe side of S/C designed to tolerate solar heating for off-Sun maneuvers inside 5 AU – Probe released after second targeted flyby
- RSP instruments shaded from Sun inside 5 AU and sensitive at Saturn

Cassini S/C – Orbiter and Probe



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Highlights of Policies, Requirements, and Constraints

- Limit risk to hardware resulting in temporary performance degradation due to Titan flybys to ≤ 5%
- Limit C/A target altitudes to a minimum of 950 km
  - May change in future if atmospheric model updated
- Optical instruments designed to withstand defined solar exposure durations (function of heliocentric distance)
  - Based on angle off optical instrument boresights (-Y axis)
  - Normal to optical instrument radiators (+X axis)
- Flight Rules further constrain Sun exposure for optical instruments – enforced by onboard Constraint Monitor

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Uncertainty Considerations

- 3 standard deviations (30 km) applied to C/A target altitudes
- Tour worst-case S/C velocity relative to Titan = 6.426 km/s
- For Titan flybys, linear flyby trajectories assumed rather than hyperbolic
  - Typical resulting temperature variation less than 1°C
- Project uses Yelle Model of Titan atmosphere - 95% confidence limits applied to density profile
  - Conservatism applied assuming temperature varies linearly with standard deviation
- Thermal math model uncertainty typically ± 5°C in bulk nodes and ± 2°C in higher resolution nodes

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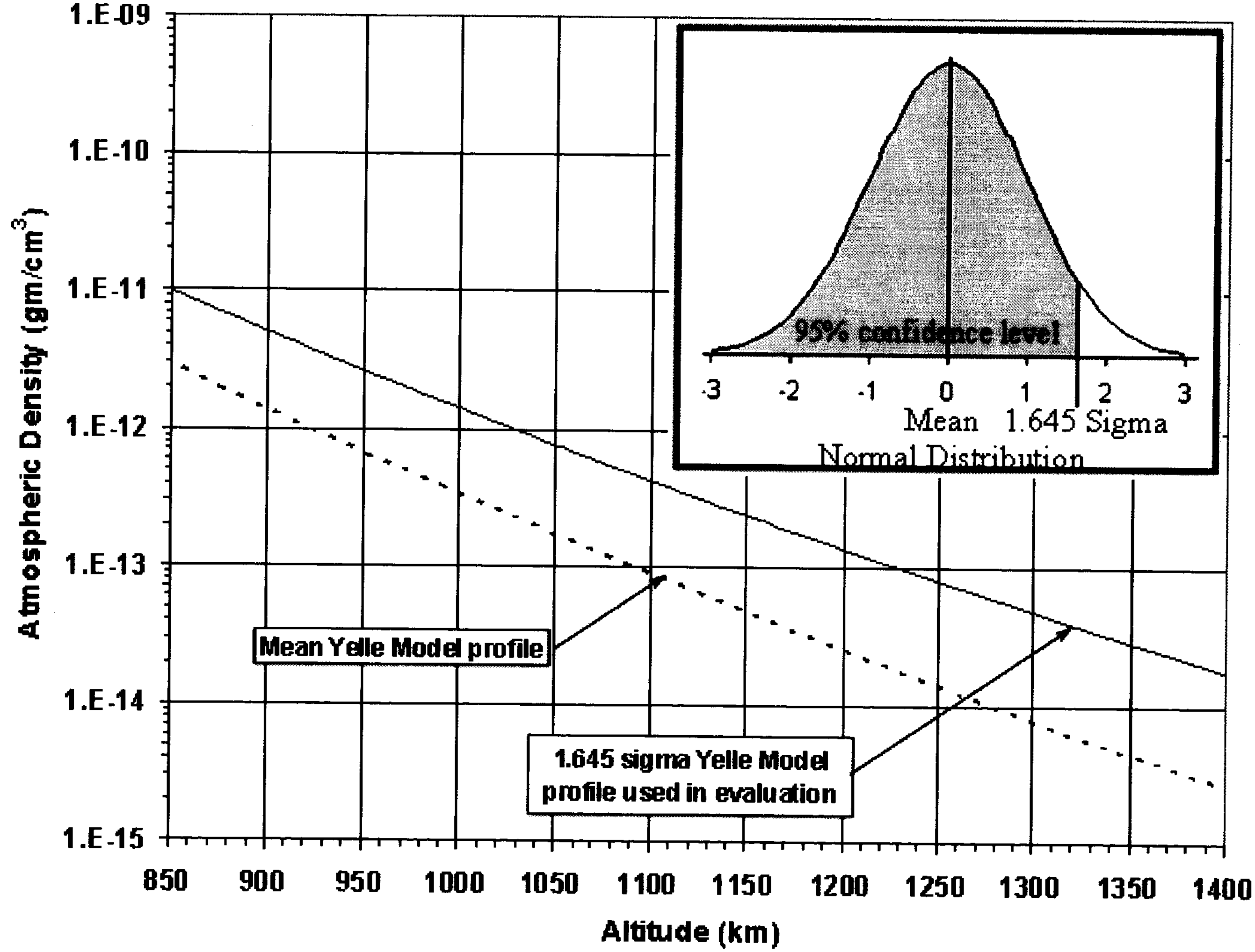
Yelle Model Titan Atmosphere Density



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S/C Will Use Power Modes

- S/C functions and their power usage for an operational activity constitute a power mode
- Two operational power modes applicable
  - ORS (RCS): Optical and Fields and Particles instruments are on and Radar and Radio Science are off
  - Radar (RCS): Optical instruments are not active, Fields and Particles and Radar instruments are active, and Radio Science is off
  - "RCS" refers to attitude control provided by thrusters
- Safing can be considered a power mode
  - All instruments off and on RCS control

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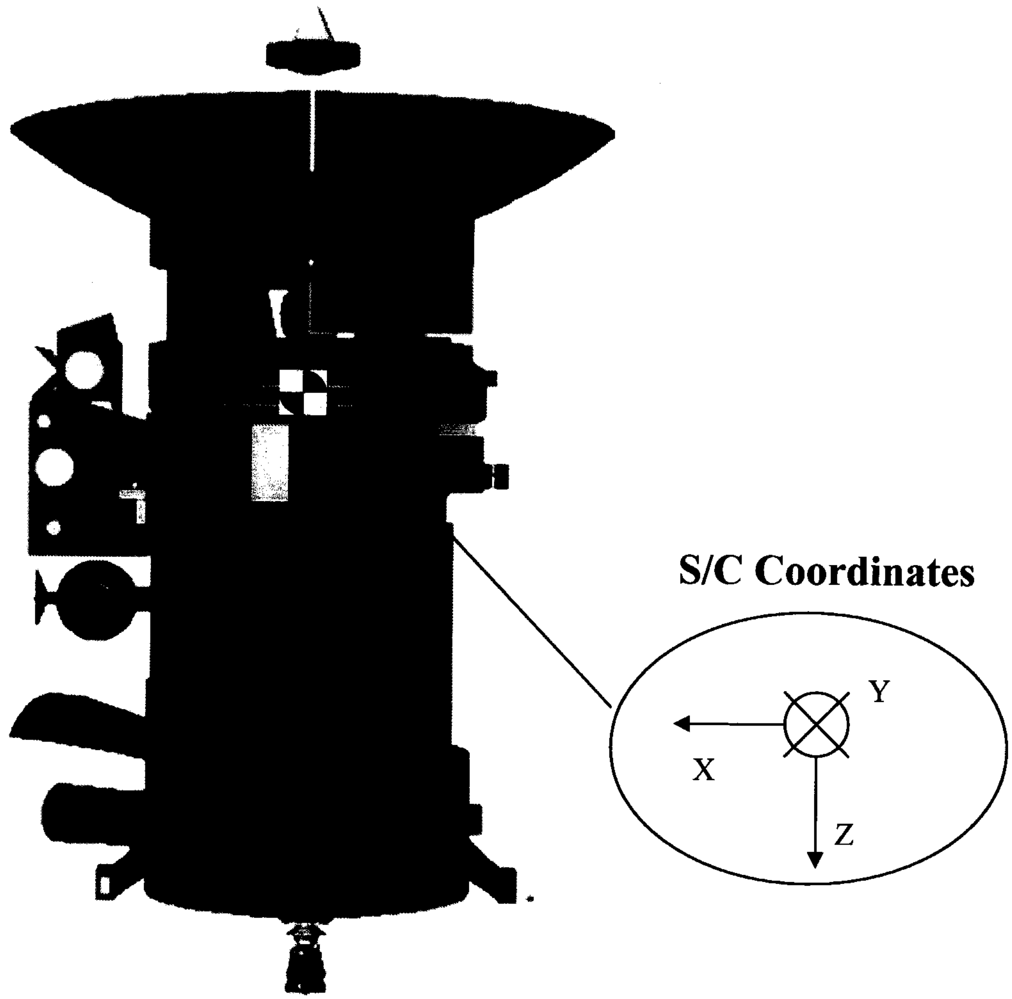
Safing Considerations

- Fault induced Safing can occur at any time
  - Onboard System Fault Protection puts S/C in "safe" state then turns S/C and points HGA toward Earth
  - Final attitude is inertial
- Two flyby scenario considerations required evaluation
  - Safing process complete prior to entering atmosphere
  - Part or all of Safing occurs in atmosphere
- Trajectory, Earth, and Sun locations defined for all 45 targeted flybys

Safing Considerations (Cont'd)

- Attitude Control (AACS) and Thermal/Devices Teams worked to minimize the number of candidate attitudes for all 45 targeted flybys
  - Considered both thermal and AACS concerns
  - Considered unique attributes of all 45 flybys
  - Flyby S/C model images used to help select attitudes
  - Thermally bounding attitudes also selected to better understand envelope of S/C thermal response
- 3 candidate attitudes applied to 5 actual flybys plus 4 bounding flyby attitudes required simulation for adequate Safing thermal envelope evaluation

Image Of S/C Geometric Model



Model image at C/A with -Y axis to RAM
as viewed looking down velocity vector

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Operational Considerations

- AACS, Mission Planning, and science teams all contributed to define operational flyby scenarios
- Two optical observation flyby scenarios required thermal simulation
  - Apertures point at a spot on Titan
  - S/C can rotate about either the X or Z axis to point
  - "Spot Light" pointing has potential for greatest exposure of optical instruments to the RAM
  - Conservative approximation of optical observation flyby scenarios thermally simulated with varied Sun locations

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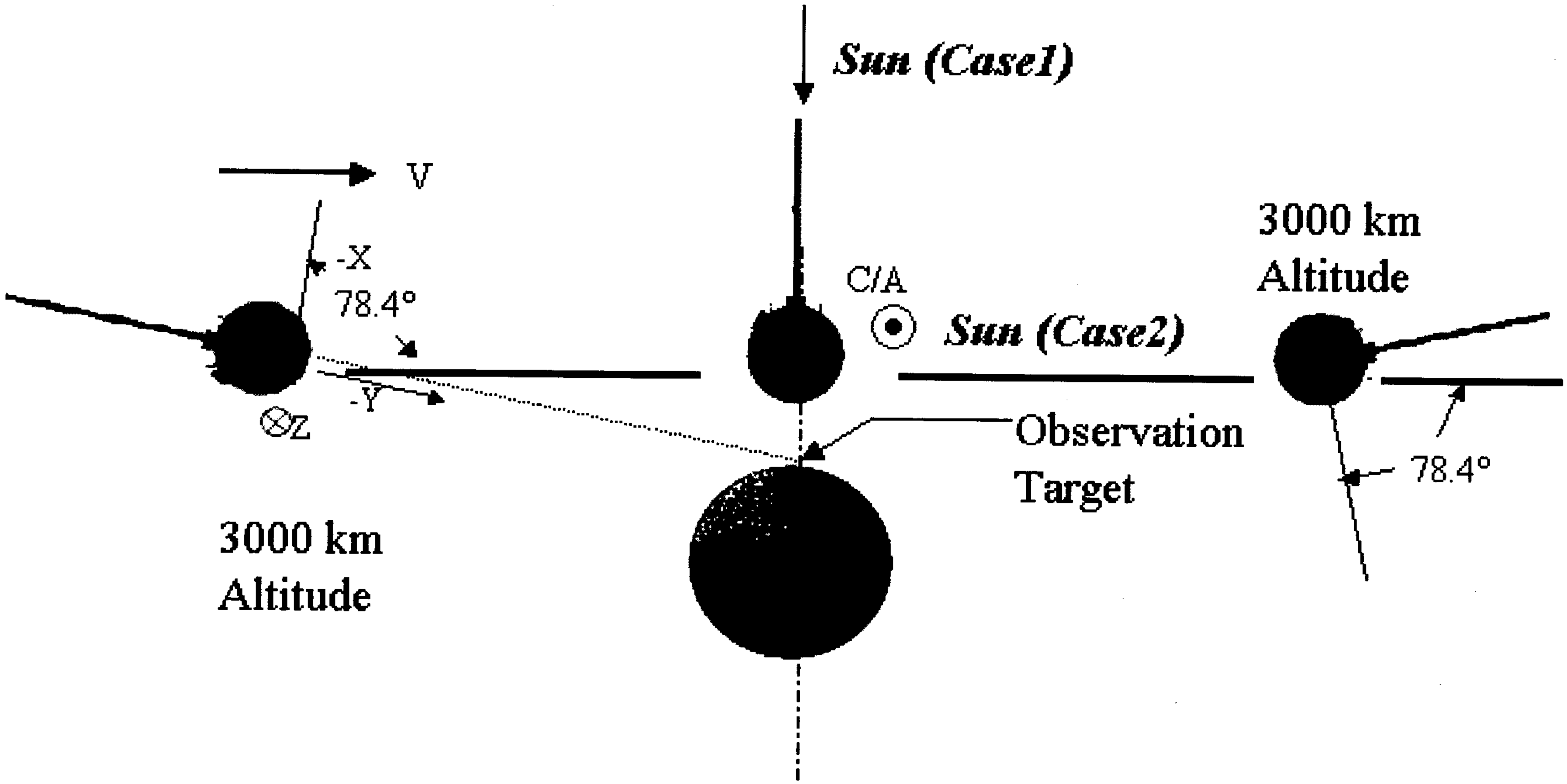
Operational Considerations (Cont'd)

- A Radar flyby scenario required thermal simulation
  - HGA nadir pointed and –X side of S/C leading
  - Included "Side-Look" slews: rotations about X and Z axes
  - Needed to define thermally safe limit of rotation about Z axis
- 3 operational flybys and 7 bounding flybys (using 6 inertial attitudes) required simulation for adequate operational thermal envelope evaluation
  - Thermally worst-case flyby trajectory used in all cases
  - Appropriate power modes and Sun positions used

Optical "Spot Light" Observation Flyby
S/C Rotation About Z Axis



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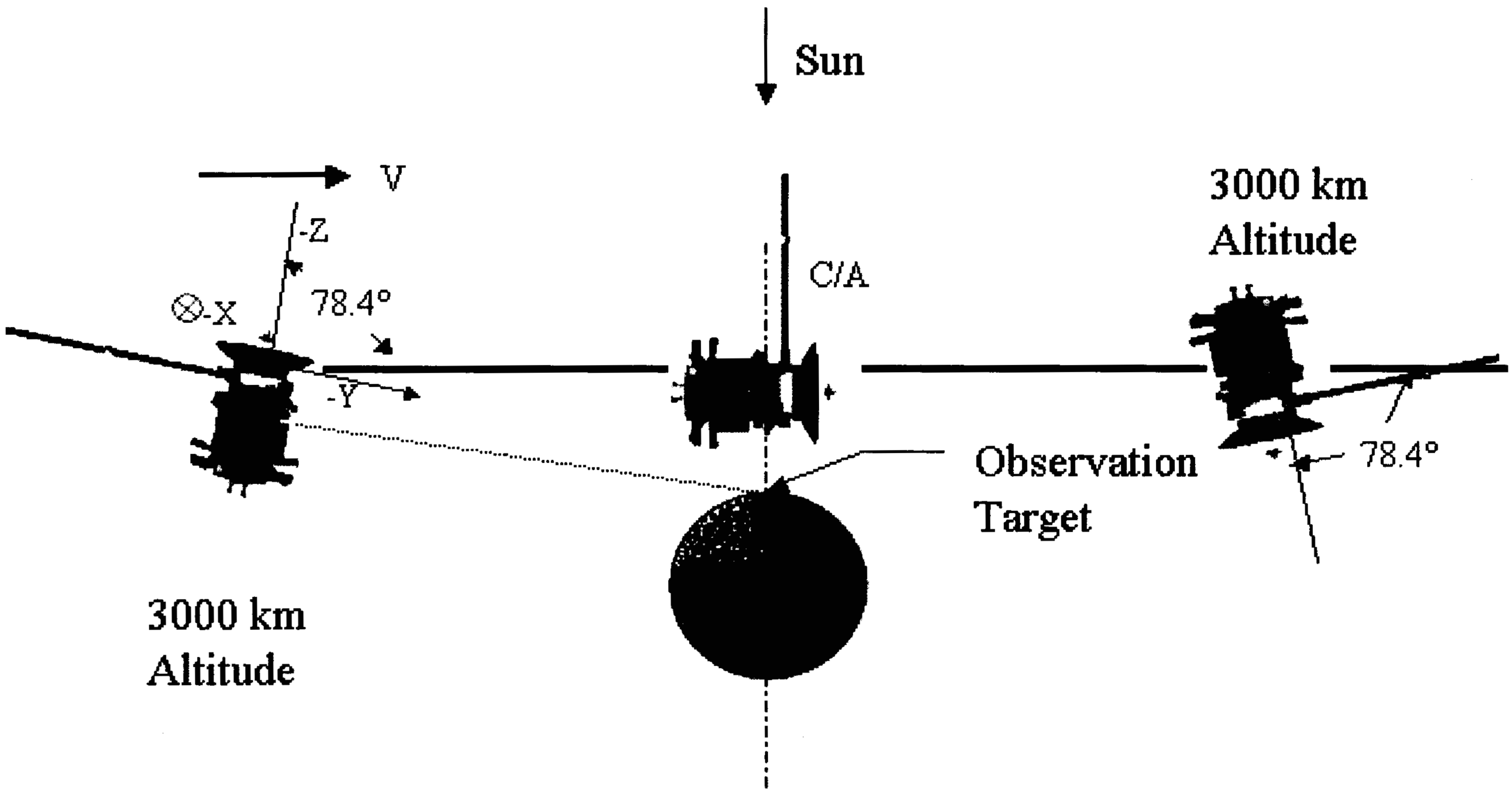
Optical "Spot Light" Observation Flyby S/C Rotation About X Axis



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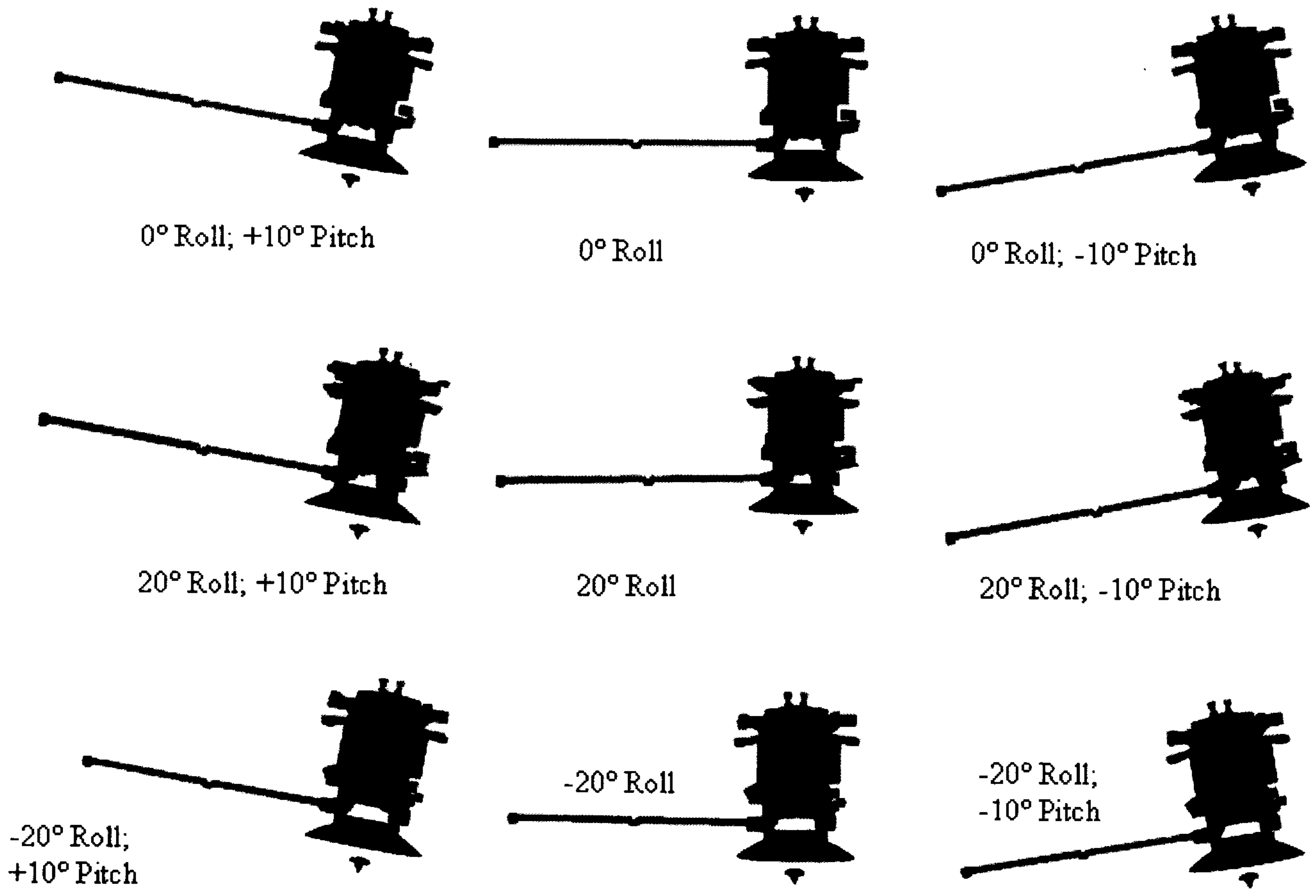
Radar Operational Flyby at C/A With "Side-Look" Slew Variations



Pitch about X axis, roll about Z axis

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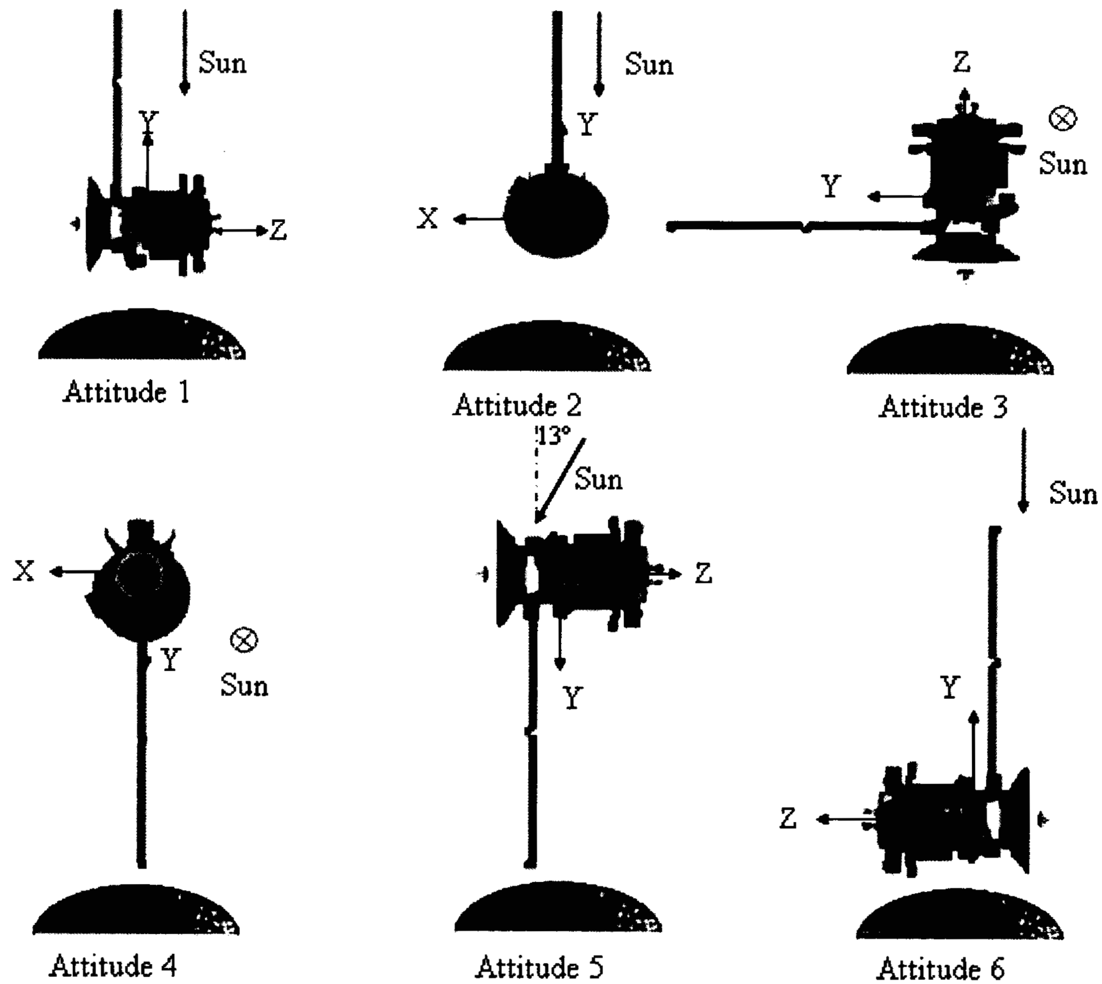
6 Inertial Operational Attitudes Used in 7 Bounding Flyby Simulations



C/A model images

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Thermal Modeling Considerations

- Simulations used flight correlated, System-level thermal math model and geometric model of S/C
- Direct solar, Titan IR, Titan albedo, and FMH environmental heat loads calculated individually
  - Diffuse multiple surface reflections taken into account
- Simulations were ± 1.5 hours about C/A
  - FMH ● 10 minutes max. about C/A (altitude dependent)
  - IR and albedo ± 1 hour about C/A
- Temperature differences and trend plots produced for each node

Thermal Modeling Considerations (Cont'd)

- Safing simulations used actual flyby trajectories
- Operational simulations used worst-case trajectory
- Incident FMH was converted to material dependent incident solar heat loads for comparison purposes with known solar sensitivities
- Temperature results formatted for comprehensive, reliable, and relatively easy evaluation

Thermal Evaluation Results

Safing flybys

- 3 inertial attitudes will suffice for all 45 targeted flybys
  - Each attitude acceptable for contiguous group of flybys
- C/A target altitudes as low as 950 km are acceptable
- It is acceptable for Safing to complete prior to entering the atmosphere or occur within the atmosphere
- HGA Sun pointing as well as Earth pointing acceptable

RTG output power transients

- Maximum temperature induced transient power drop in total RTG output power is not expected to exceed 5 W
  - Acceptable from power margin perspective

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Thermal Evaluation Results (Cont'd)

Operational flybys

- Attitude constraints must be applied to limit FMH and direct solar heat loads for optical instruments
  - Onboard Constraint Monitor does not protect against FMH
- Operational flybys evaluated (optical and radar) are acceptable for C/A target altitudes as low as 950 km
- Radar "Side-Look" rolls about Z axis can be as large as ± 20° off nominal attitude

Skills Retention Planning

- It is assumed evaluation will be revisited
  - Science planning continues
  - Flight may reveal new problems or opportunities
  - Information database improvement – Titan atmospheric density profile will be reevaluated from measurements taken during first targeted flyby
- Evaluation capability retained for baseline mission
  - Mission duration must accommodate personnel changes
  - Personnel trained to perform required tasks

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Lessons Learned/Recommendations

- Plan during S/C development phase to provide comprehensive analysis ability during operations
  - Take mission duration into account – response time
  - Select tools to meet needs throughout operations
  - Account for organizational differences between development and operations phases of a Project
- Require System-level models during development
  - Correlate with System-level testing and early flight
  - Knowledge retention of design details in model
  - Utilize model visualization tools to improve evaluations

Lessons Learned/Recommendations (Cont'd)

- Operations teams benefit from working together
  - Policy and requirement interpretation
  - Proper awareness and accurate information transfer
  - Benefit from expertise and experience

- Analysis process should include sanity checks and peer reviews
  - Prevent errors and uncover software bugs
  - Problems documented

Lessons Learned/Recommendations (Cont'd)

- Automate processes to expedite, simplify, and improve reliability of interface and output products and calculations
  - Document processes assuming they will be used again

- Assume surprises will occur – be prepared to respond successfully in a timely fashion