Multiple Orbits, Multiple Targets, Living with Risk Every Day

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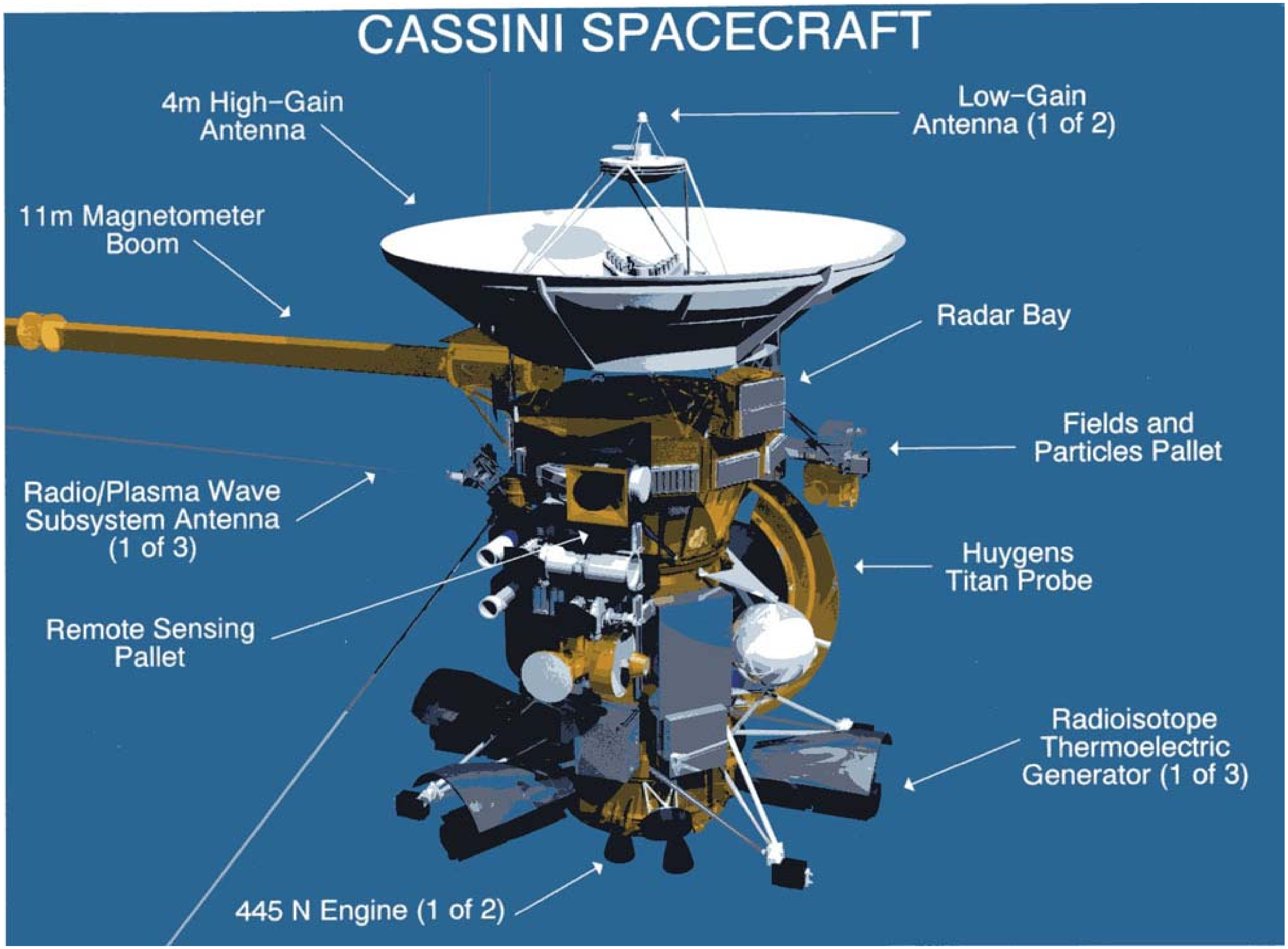
International Participation in
Cassini
Saturn Orbiter and Huygens Titan Probe
Denmark
Belgium
France
United States
Germany
Italy
Israel
United Kingdom
Poland
Netherlands
Czech Republic
Austria
Spain
Finland
Switzerland
Ireland
Sweden
Norway



CASSINI SPACECRAFT
4m High−Gain Antenna
Low−Gain Antenna (1 of 2)
11m Magnetometer Boom
Radar Bay
Fields and Particles Pallet
Radio/Plasma Wave Subsystem Antenna (1 of 3)
Huygens Titan Probe
Remote Sensing Pallet
Radioisotope Thermoelectric Generator (1 of 3)
445 N Engine (1 of 2)

Cassini/Huygens Spacecraft Overview

- **Largest outer planet spacecraft ever built**
- **Weighed 5574 kg at Launch (3132 kg Propellant)**
  - Today's weight is around 2588 kg with 458 kg Propellant left
  - 3 maneuvers (Deep Space Maneuver, Saturn Orbit Insertion, Periapsis Raise Maneuver) used 2083 kg of propellant
- **58 microprocessors**
- **Twelve Science Instruments**
  - Fields and Particles
    - CAPS, CDA, INMS, MAG, MIMI, RPWS
  - Optical Remote Sensing
    - CIRS, VIMS, ISS, UVIS
  - Radar
  - Radio Science
- **Huygens Probe (built by Aerospatiale for ESA)**

Power and Main Computer

- **Power supplied by three Radioisotope Thermoelectric Generators (RTGs)**
  - 875 Watts at Launch, 692 Watts at End of Mission (July 2008)
  - Excess power distributed to shunt regulator/radiator
  - Power distribution using 192 Solid State Power Switches
    - Switches act a circuit breakers, but no moving parts
    - Critical loads have redundant switches and automatic turn-on circuitry

- **Command and Data Storage (CDS)**
  - Two redundant 1553 Buses with fully redundant hardware
  - Flight computer (EFC) IBM 1750A architecture
    - 512k RAM
  - Processes all telemetry for the spacecraft engineering sub-systems and instruments
    - On-board data storage and playback using 2 Solid-State Recorders
      - 2.3 Gbits total, 2.1 Gbits available for telemetry (each SSR)

Attitude Control and Propulsion

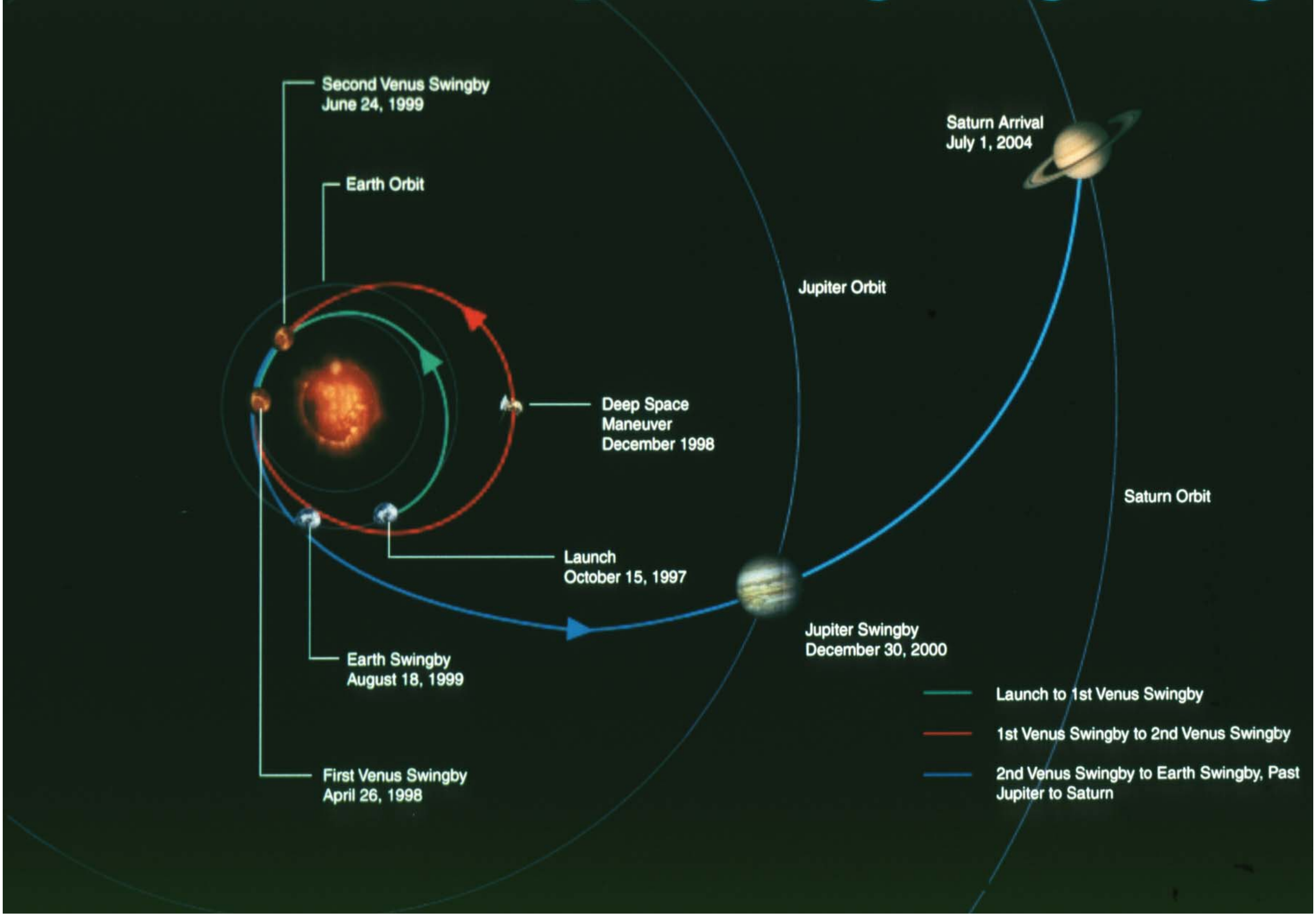
- **Two redundant 1553 Buses with fully redundant hardware**
- **Flight computer (EFC) IBM 1750A architecture (same as CDS)**
- **Attitude determination**
  - Attitude determined by Stellar Reference Units
  - Attitude rates supplied by Hemispheric Resonator Gyros (HRGs), aka Inertial Reference Units
- **Attitude Control**
  - 3 axis stabilized using thrusters or 3 reaction wheels (RWAs)
    - Small (1 Newton) thrusters used when pointing isn't as important or when faster turns are needed
    - RWAs provide pointing stability better than 100 microradians over 1000 seconds
- **Propulsive maneuvers**
  - Uses small thrusters or bi-propellant main engine (445 Newton) for trajectory control

The spacecraft turns to Earth for a typical 9 hour tracking pass, to downlink telemetry data and receive commands.

Deep Space Network –
3 complexes: Barstow, Ca, Madrid, Spain and Canberra, Australia
Each complex has a 70 meter antenna, and multiple 34 meter antennas.


Launch October 15, 1997

Cassini Interplanetary Trajectory



Seven Years of Cruise - Plenty of time, right?

- **Deferred Flight Software (FSW)**
  - Pre-launch, planned for 2 complete in-flight re-loads for both AACS and CDS
    - Carried full development teams for AACS and CDS
    - Four major test beds
  - Full "tour" capabilities were not available until 4/2000

- **Science and Engineering Expectations were different**
  - The Engineering team planned for a "quiet" cruise with little or no Science
    - But the spacecraft was performing very well, and Science wanted to take real data at both Venus and Earth flybys
  - Lesson learned?
    - Plan for success
    - Spacecraft capabilities will always be used!

In-flight Anomalies

- **PR-1 Regulator leak indicated within hours of first pressurization**
  - Suspected particle contamination
  - Work around was to close latch valve and enable Overpressure fault protection
  - Leak has not affected any pressurized maneuver performance to date, including SOI
  - Oxidizer side is currently isolated from Helium system
  - Only “Red Flag” Risk in mission
  - No mitigation needed, regulator was a great regulator, just not a very good seal

- **Solid State Recorders showed higher than expected Double Bit Errors**
  - DRAM chips were known to be very “soft”, but design flaw made uncorrectable double bit errors worse
  - Mitigation
    - Added software routine to “scrub” copies of engineering and instrument flight software

In-flight Anomalies

- **Solid State Power Switch (SSPS) trips**
  - SSPS have normal / tripped status indicators
    - Investigation showed flip-flop circuit susceptible to GCRs and predicted a rate of 2 SSPS trips per year, on or off
    - 23 SSPS trips, 18 OFF at the time, 5 ON, to date
    - Once an SSPS has indicated trip, must clear with off command
  - Mitigation
    - CDS updated fault protection in 2000 (V7) and again in 2007 (V10) to check all 192 trip states and to take action according to a table

In-flight Anomalies

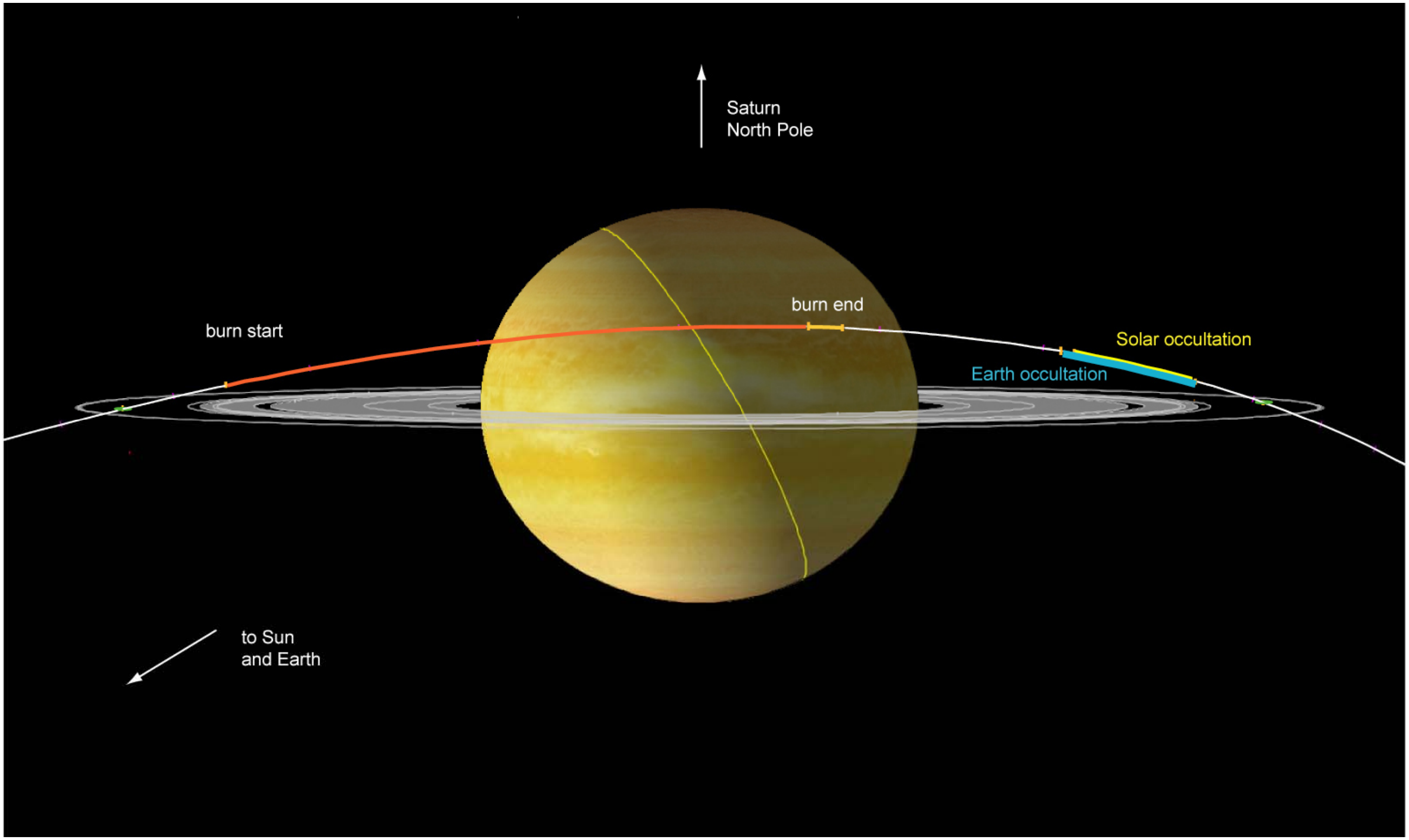
- **Reaction Wheels (RWA)**
  - Prolonged “dithering” of RWA-2 around 0 rpm on 12/16/00 caused excessive drag torque and spacecraft unexpectedly transitioned to RCS control
  - Following the RWA-2 anomaly, RWA-1 showed long drag torque settling time and drag torque spikes continuing to present time
  - During 2001 - 2003, RWA-3 showed drag torque spikes and drag torque “oscillations” that were eventually determined to be cage instability
  - Project made the decision to switch from RWA-3 to RWA-4 July 2003
  - RWA-4 and RWA-2 have also seen drag torque spikes

  - Mitigation
    - Developed ground tool to predict RWA speeds and to minimize time spent at low (+/- 300 rpm) RWA
    - Added RWA biases (change in speeds)
    - Added more drag torque compensation in software
    - Last resort - remove science

Getting to Saturn - Rules change!

- **Requirement for spacecraft telecommunication during Saturn Orbit Insertion added in 2001, post-launch!**
  - No “steerable” antenna, no design plan for telecommunications
  - To use High Gain Antenna for telecommunications to Earth required major off-set from desired burn pointing, costing up to 87 m/sec
  - Mitigation:
    - Demonstrated to JPL management and NASA headquarters that Low Gain Antenna signal would be enough to distinguish “acts of God” versus “acts of man”
      - Used Radio Science Open Loop receivers to track carrier and Doppler shift
      - Signal was just 10 dB above DSN noise floor!

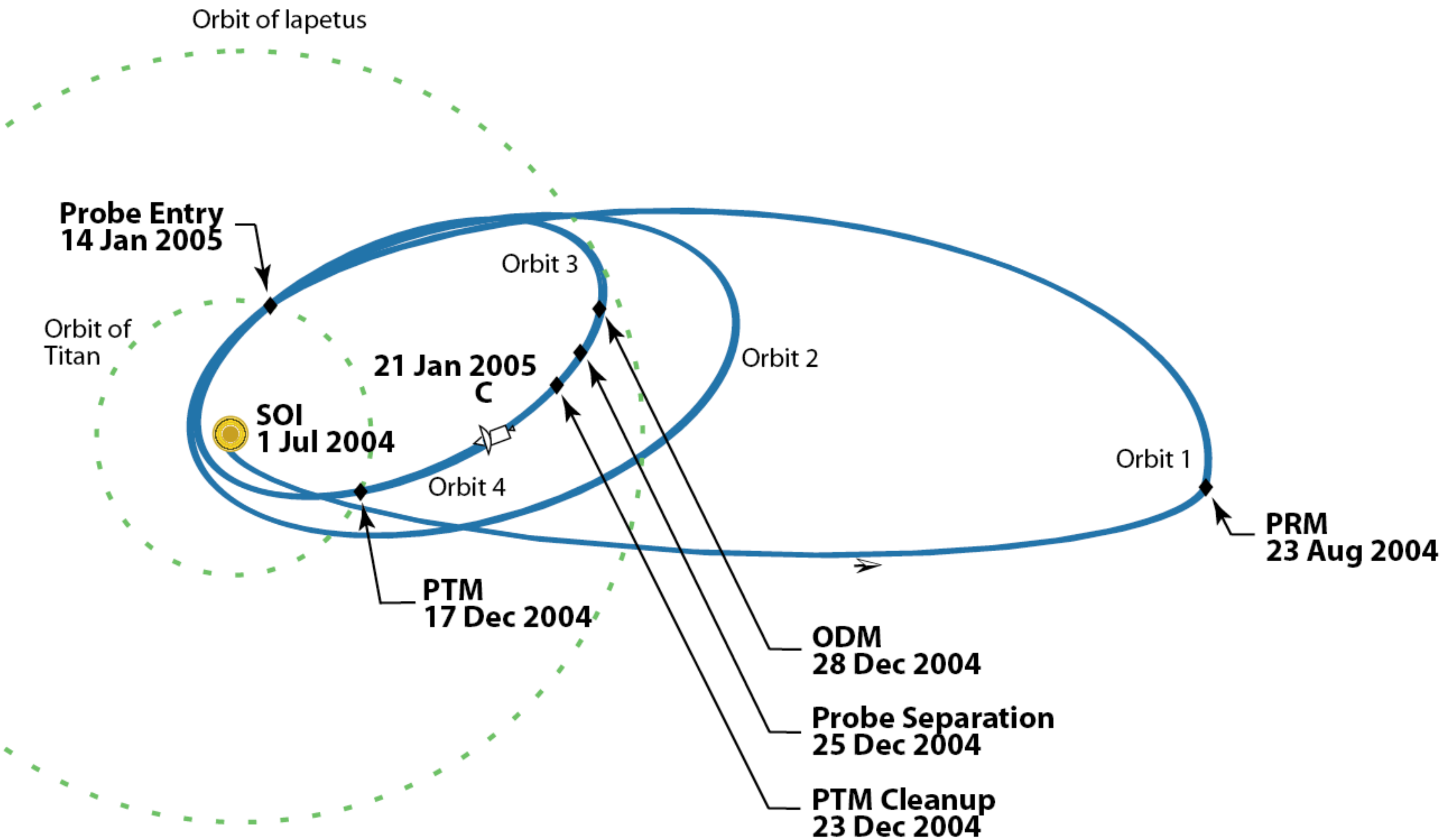
SOI Geometry



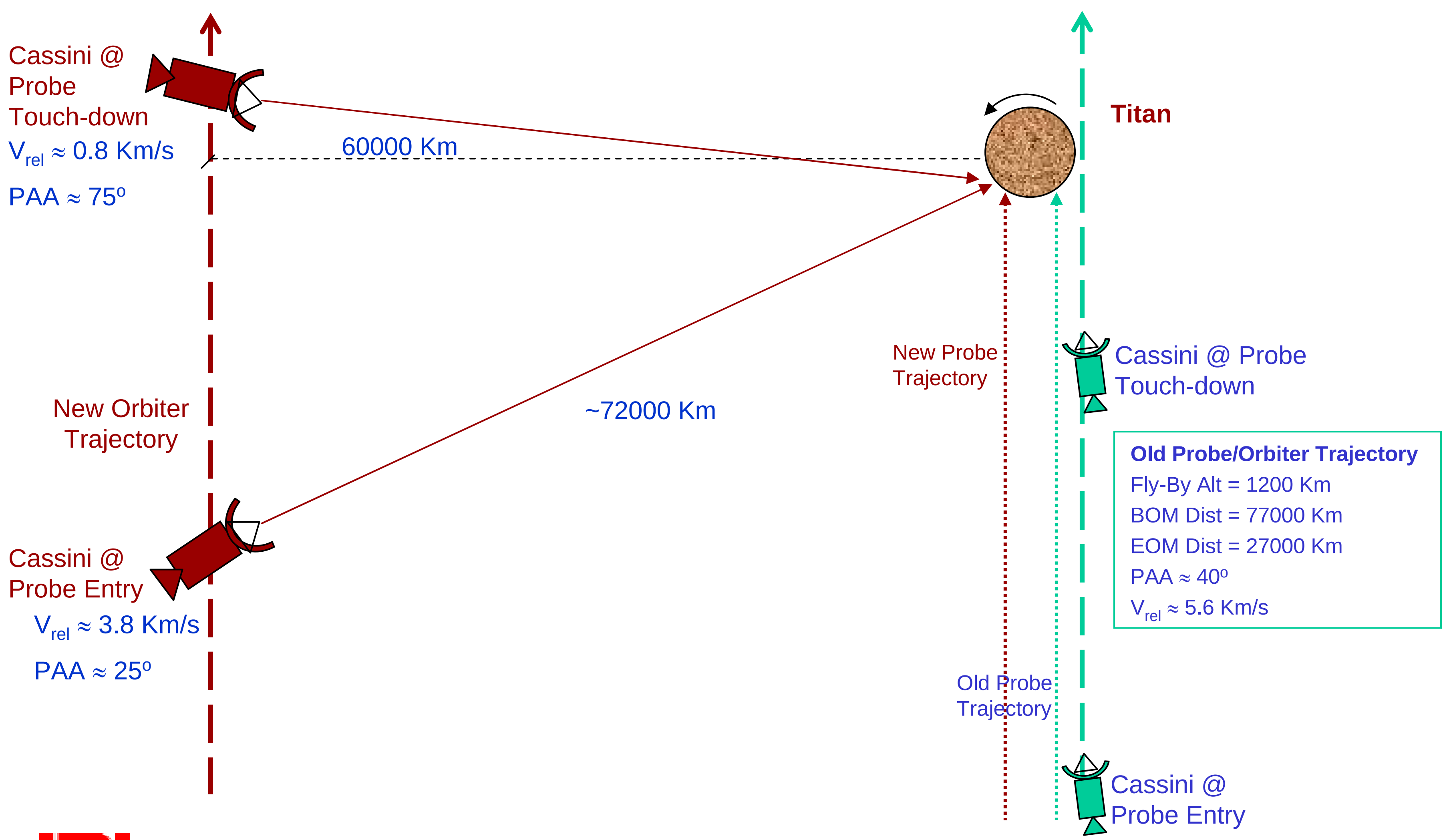
Probe Mission

- **Huygens Probe**
  - In-flight testing in early 2000 showed bit synchronizer did not track expected Doppler
  - Many options and possible solutions were explored
    - Ultimately, only changing the orbit design and removing most of the Doppler shift could save the Probe mission
    - Navigation re-designed the first two orbits into three orbits
      - Targeted Titan encounters T1 and T2 became Ta, Tb, Tc
      - Probe mission would be conducted on Tc
      - The re-design rejoined the original tour at T3

SOI to Huygens Entry



New vs. Old Mission



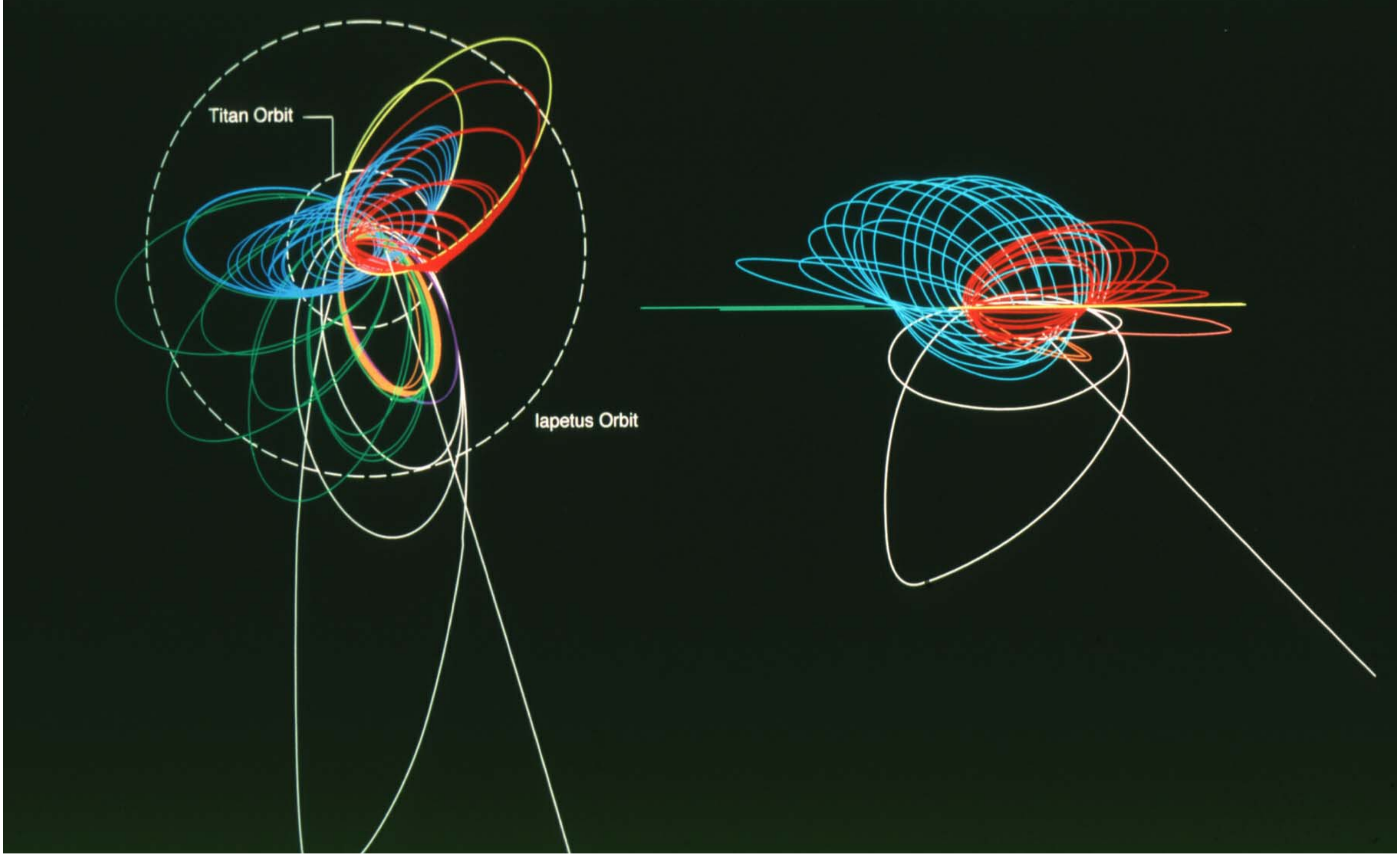
Getting to Saturn

- **The tour selected was very complex!**
  - 75 orbits, 45 Titan flybys, numerous targeted icy satellites, 150 maneuvers
- **Science Planning started in 1999, breaking down the tour into disciplines**
  - Titan, Icy Satellites, Rings, Saturn, Magnetospheres, Surface
    - Cross-Discipline team was used to cover times not listed above
  - Engineering needs, downlinks and maneuver times were factored into each orbit
    - Ultimately, 21 different ground tools were developed to build the 41 sequences used in prime mission
    - Science Operations Plan was completed in late 2004
    - Often, as many as 6 sequence processes ran concurrently
    - Three update opportunities before sequence uplinked to spacecraft

Mission Comparison

	CHARACTERISTIC	VOYAGER	GALILEO	CASSINI
MISSION	Orbits	6 (flybys)	11	75
MISSION	Average Orbit Duration	120 days (flyby)	8 weeks (5 wks - 8 wks)	3 weeks (1 wk - 3months)
MISSION	Operations Environment	Centralized	Centralized	Distributed
MISSION	Prime Mission Duration	2 years	2 years	4 years
MISSION	Total Mission Data Volume	~4,000 Gbits	2 Gbits	~3,000 Gbits
SPACECRAFT	Scan Platform	Yes	Yes	No
SPACECRAFT	Maximum Turn/Slew Rates	1°/sec	1°/sec	0.4°/sec-RCS 0.2°/sec-RW
SPACECRAFT	Power Modes	1	8	12
SPACECRAFT	Recorder Volume	.5 Gbits	.9 Gbits	4 Gbits
SPACECRAFT	Imaging Instruments	2	2	8
SPACECRAFT	Science Instruments	11	12 Orbiter 6 Probe	12 Orbiter 6 Probe
UPLINK PLANNING	Science Plan Development Time	9:1	5:1	3:1
UPLINK PLANNING	Sequence Loads/Orbit (Average)	10 loads/flyby	3 (1 encounter, 2 orbital cruise)	4-5 weeks (n orbits/load)
UPLINK PLANNING	Targets & Periapses/Load (Average)	10 loads/flyby	1periapse, 1satellite	2 periapse, 2 satellites
UPLINK PLANNING	Sequence Load Size	2.5 Kwords	16 Kwords	150 Kwords
UPLINK PLANNING	Science Operations Staff (JPL)	~60	60	23
UPLINK PLANNING	Investigation Team Size	~150	187	254

Multiple Orbits, Multiple Targets

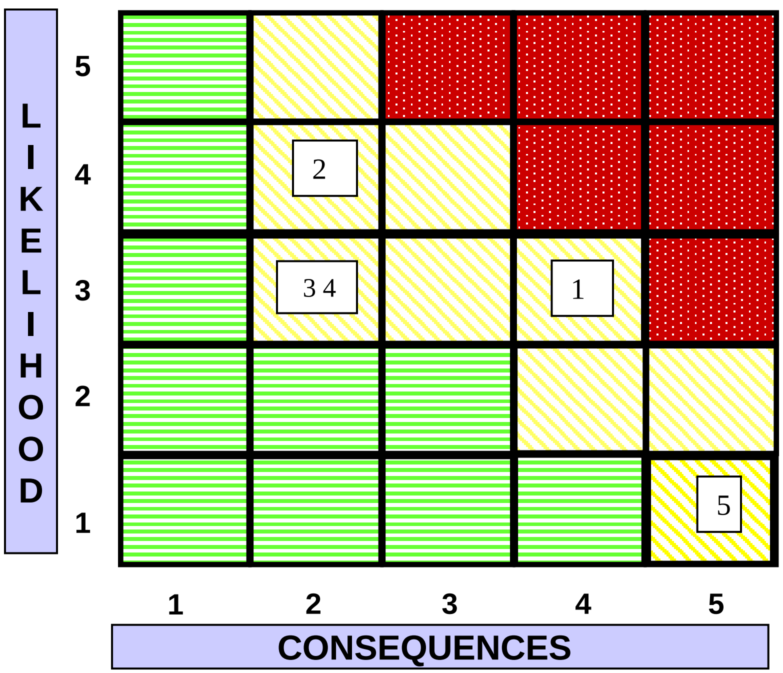


Formal Risk Tool

- **In 2000, Mission Assurance Manager realized need for formal tracking tool to track growing list of Cassini risks**
  - Prior to development, each team kept track of risks in multiple forms
    - Some formal presentations
    - Some Excel spreadsheets
    - Some just in the head of the Cognizant Engineer!
- **Raytheon developed web-based formal Risk tracking tool with standardized inputs**
  - Each Cassini team input risks, then meetings were held to discuss each risk
- **141 Risks have been evaluated (12/19/2007)**
  - 52 risks active
  - 52 risks retired (Cruise specific, SOI, Probe Relay)
  - 37 risks rejected - most duplicate input from different teams
- **Result is automated reporting tools and increased visibility to management**

SCO Risk Review

- **Risk Serial No. 13**
- **Risk Title – Loss of one or more RWAs**
- **Description of Risk**
  - Loss of one or more Reaction Wheel Assemblies (RWA) could impact mission objectives and impact science return.
- **Qualitative Assessment**
  - Qualitative Assessment of Impact and Likelihood (5X5)
  - **3** - Likelihood - Significant Likelihood
  - **4** - Impact - Significant reduction in mission return
  - Yellow
- **Risk Status**
- **Anomalous behavior of the RWAs has been observed, through documented increased frictional torque, during Jupiter cruise operations. Subsequent investigations into wheel behavior, by in-flight, ground and by similarity testing has led to certain recommendations for wheel usage during cruise and tour. These recommendations were to 1) minimize wheel usage during the remaining cruise time (March, 2001 through January , 2004), and 2) "bias" the RWAs when they are being used to minimize the slow rpm speeds (+/- 300 rpm). Both these recommendations were accepted during project level meetings from January through March of 2001. In July, 2003, based on a significant degradation trend in RWA#3, the articulatable spare RWA #4 was moved to RWA#3 position and used to replace RWA#3. This left us in position to be able to return to RWA#3 if another RWA failed catastrophically. Throughout the past two years, we have continued to monitor the RWA's and to optimize the Wheel speeds to minimize time in the +/- 300 RPM region. This region is considered by the manufacturer to be "low rpm" and undesirable to stay in it for any length of time.**



Rank & Trend		Risk ID	Approach	Risk Title
1	⇨ (Unchanged)	**13**	M	Loss of one or more RWA
2	⇧ (Increasing)	**8**	M	Commanding Error
3	⇧ (Increasing)	**7**	M	Sequence Error
4	⇨ (Unchanged)	**1**	M	Loss of Key Personnel
5	⇨ (Unchanged)	**29**	M	Ring Particle Collision – S/C

Criticality
- High
- Med
- Low

L x C Trend
- ⇩ Decreasing (Improving)
- ⇧ Increasing (Worsening)
- ⇨ Unchanged
- ☐ New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

For more information about the Cassini Huygens mission
http://saturn.jpl.nasa.gov

Also, see “Basics of Space Flight” available for JPL Public website