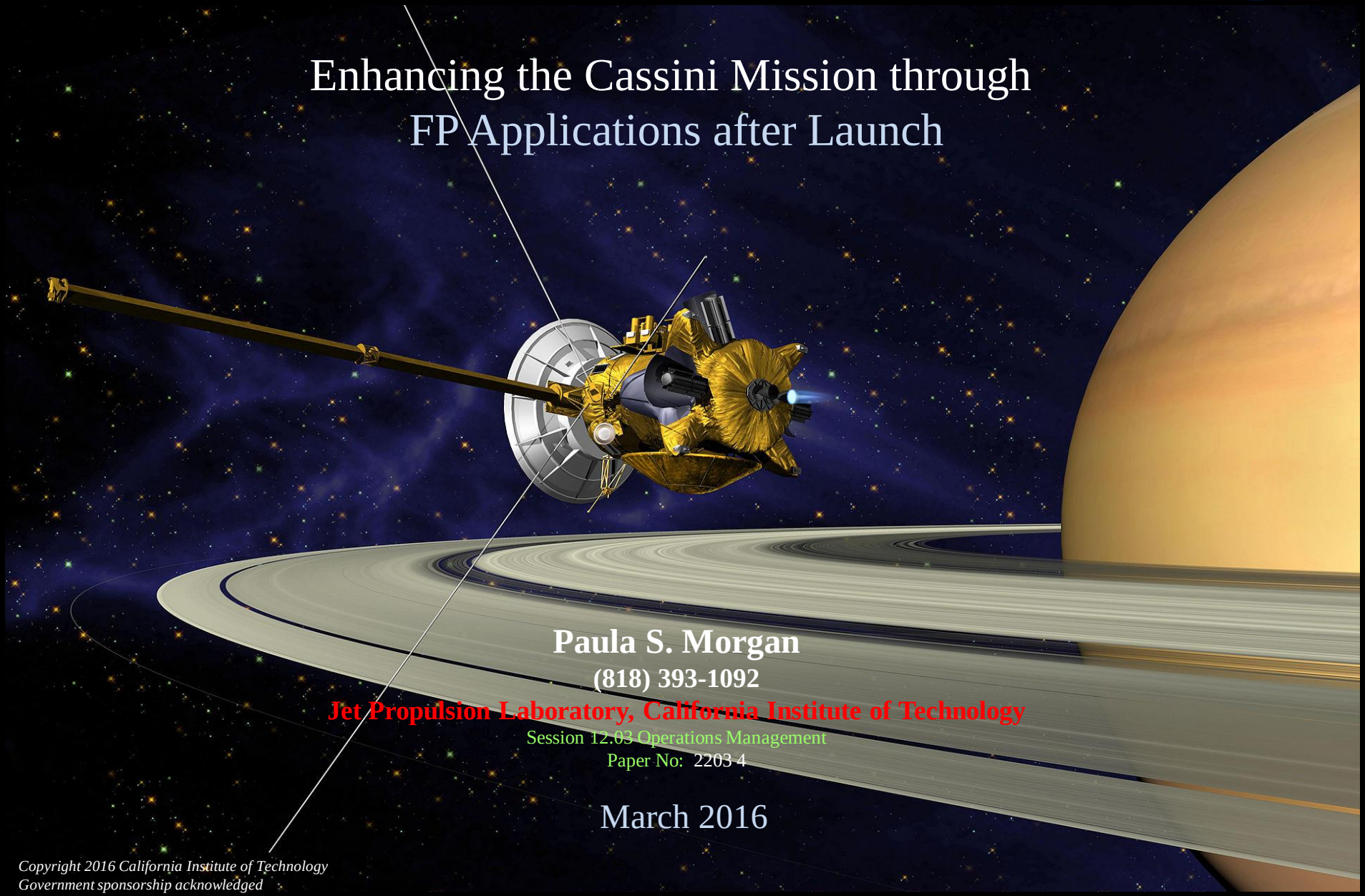
Enhancing the Cassini Mission through FP Applications after Launch



Paula S. Morgan
(818) 393-1092
Jet Propulsion Laboratory, California Institute of Technology

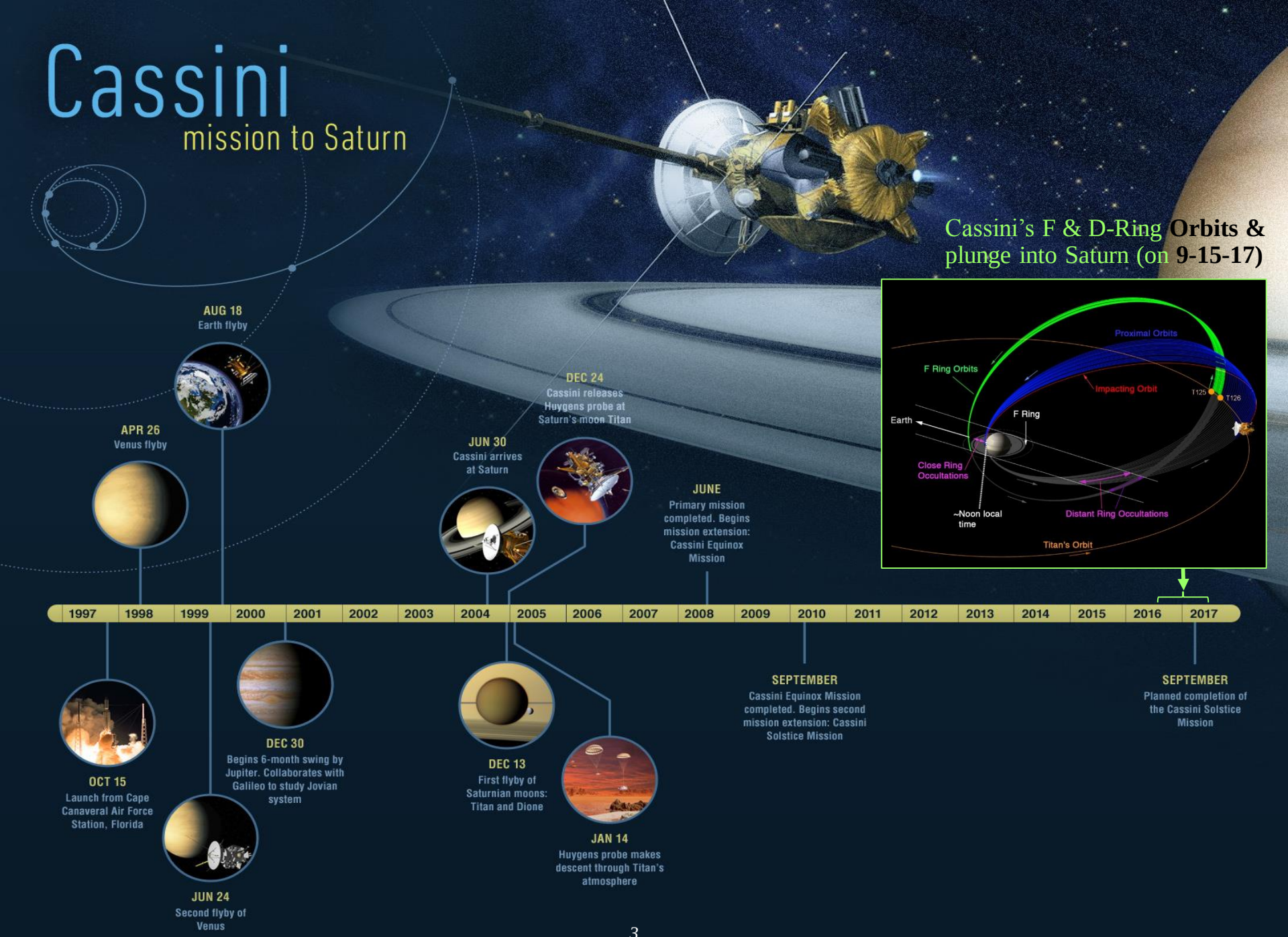
Session 12.03 Operations Management
Paper No: 2203-4

March 2016

Copyright 2016 California Institute of Technology
Government sponsorship acknowledged

Agenda

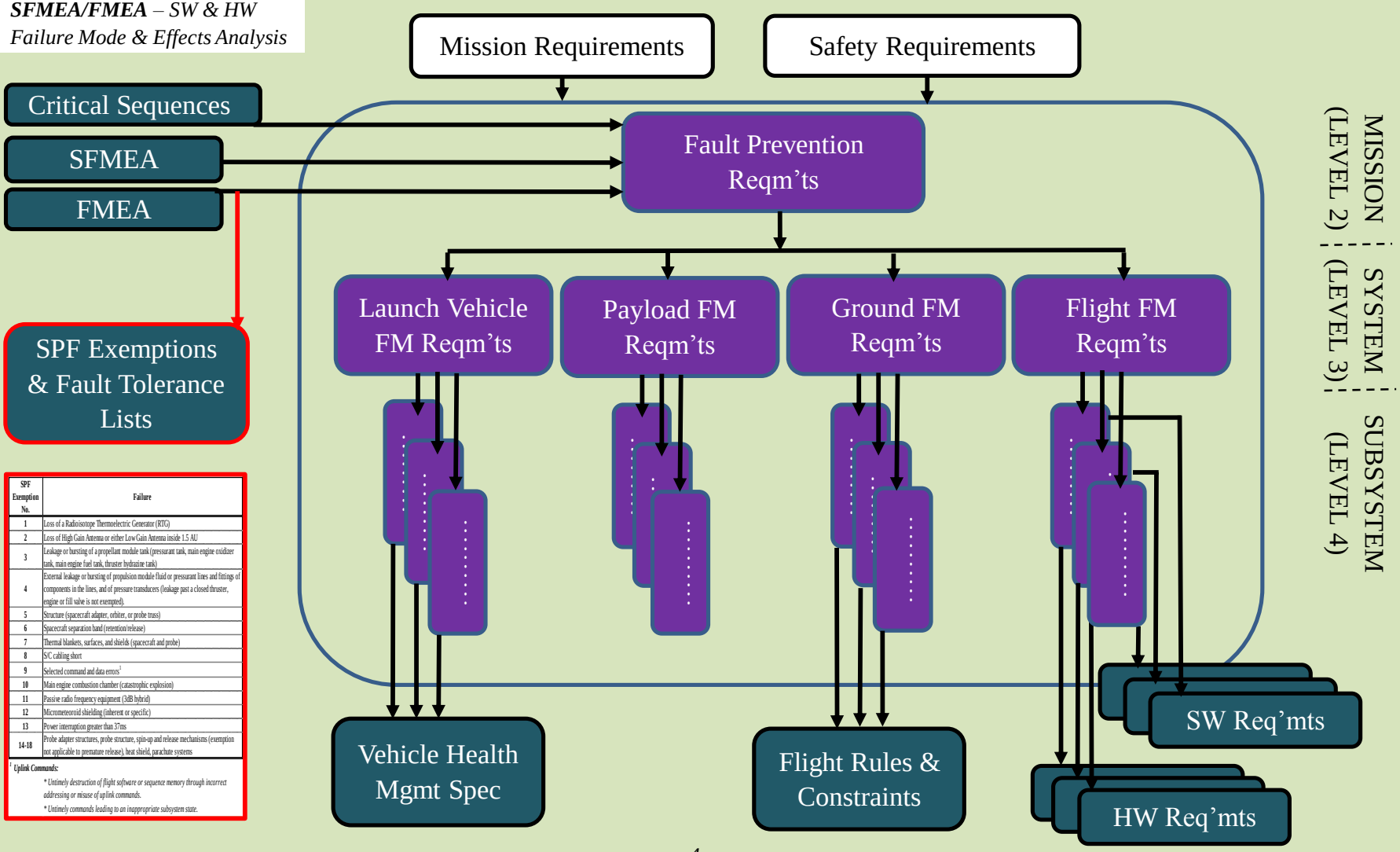
- The Cassini-Huygens Mission-to-Saturn
- Ensuring Mission Success Prior to Launch
- Several Unexpected (Untestable/Non-benign) Faults after Launch & Applied Fault Protection (FP) Solutions
- Conclusions


Cassini
mission to Saturn
Cassini's F & D-Ring Orbits & plunge into Saturn (on 9-15-17)
Proximal Orbits
F Ring Orbits
Impacting Orbit
T125
T126
Earth
F Ring
Close Ring Occultations
~Noon local time
Distant Ring Occultations
Titan's Orbit
AUG 18
Earth flyby
APR 26
Venus flyby
DEC 24
Cassini releases Huygens probe at Saturn's moon Titan
JUN 30
Cassini arrives at Saturn
JUNE
Primary mission completed. Begins mission extension: Cassini Equinox Mission
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
OCT 15
Launch from Cape Canaveral Air Force Station, Florida
JUN 24
Second flyby of Venus
DEC 30
Begins 6-month swing by Jupiter. Collaborates with Galileo to study Jovian system
DEC 13
First flyby of Saturnian moons: Titan and Dione
JAN 14
Huygens probe makes descent through Titan's atmosphere
SEPTEMBER
Cassini Equinox Mission completed. Begins second mission extension: Cassini Solstice Mission
SEPTEMBER
Planned completion of the Cassini Solstice Mission

Ensuring Mission Success Prior to Launch

- Prior to launch, rigorous efforts are taken ensure mission success (e.g. like analytical analyses, testing, implementation of autonomous Fault Protection routines) => *Theoretically, NOTHING should go wrong!*

***SFMEA/FMEA** – SW & HW*
Failure Mode & Effects Analysis



SPF Exemption No.	Failure
1	Loss of a Radioisotope Thermoelectric Generator (RTG)
2	Loss of High Gain Antenna or either Low Gain Antenna inside 1.5 AU
3	Leakage or bursting of a propellant module tank (pressurant tank, main engine oxidizer tank, main engine fuel tank, thruster hydrazine tank)
4	External leakage or bursting of propulsion module fluid or pressurant lines and fittings of components in the lines, and of pressure transducers (leakage past a closed thruster, engine or fill valve is not exempted).
5	Structure (spacecraft adapter, orbiter, or probe truss)
6	Spacecraft separation band (retention/release)
7	Thermal blankets, surfaces, and shields (spacecraft and probe)
8	S/C cabling short
9	Selected command and data errors[1]
10	Main engine combustion chamber (catastrophic explosion)
11	Passive radio frequency equipment (3dB hybrid)
12	Micrometeoroid shielding (inherent or specific)
13	Power interruption greater than 37ms
14-18	Probe adapter structures, probe structure, spin-up and release mechanisms (exemption not applicable to premature release), heat shield, parachute systems

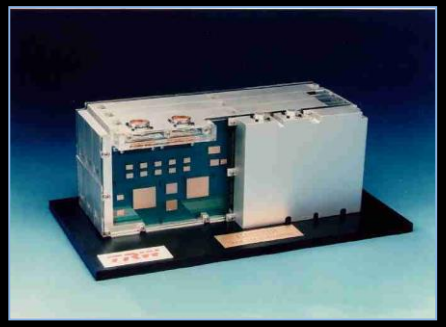
[1] *Uplink Commands:*
- *Untimely destruction of flight software or sequence memory through incorrect addressing or misuse of uplink commands.*
- *Untimely commands leading to an inappropriate subsystem state.*

Unexpected Fault after Launch => SSR Bit Errors

- In the case of the Cassini/Huygens mission, several untestable (significant) faults occurred starting after launch:

Time	Unexpected Fault	Consequences
Launch	High Number of Erroneous "Bit Flips" in Solid State Recorders (SSR)	Corrupted Science/Stored Computer & Instrument FSW

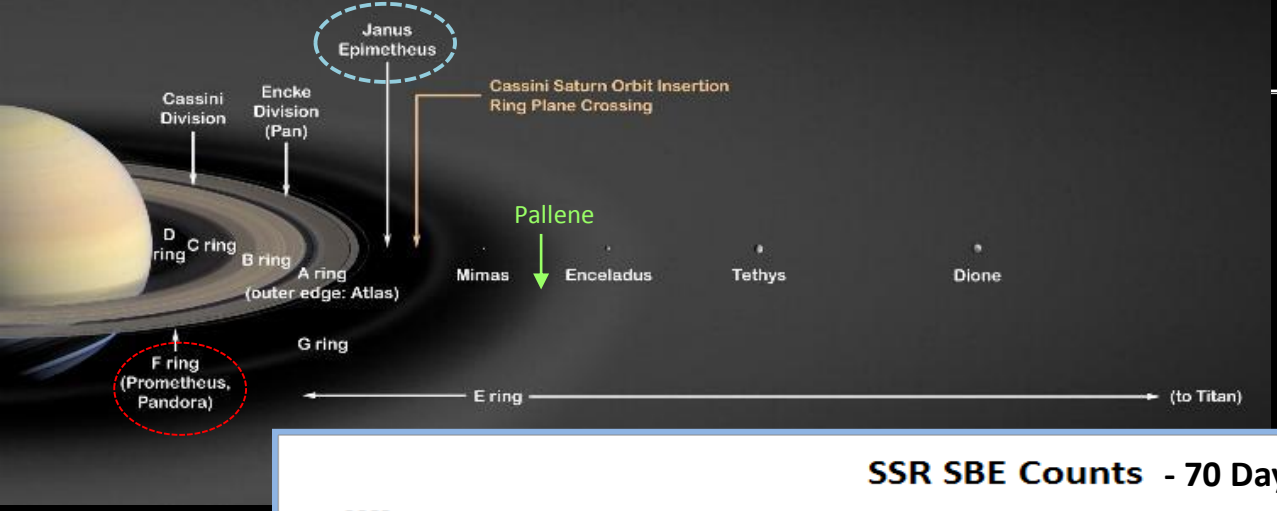
- Cassini's 2 SSRs are a high capacity, solid state bulk storage medium containing 2.01 Gbits of memory (each) to store computer FSW & collected science data



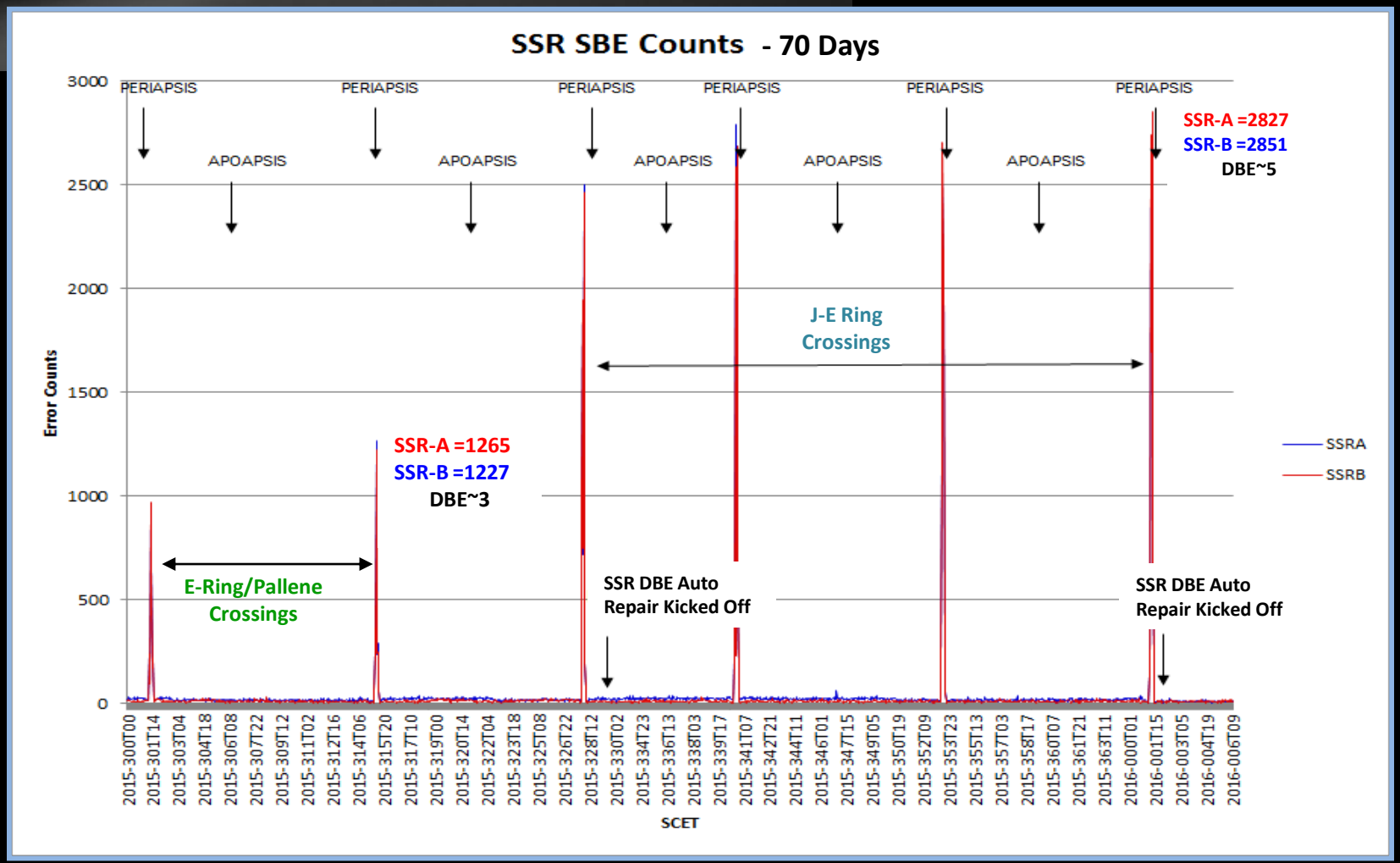
- SSRs are NOT rad-hardened and highly sensitive to "bit flips" from heavy ion and proton bombardment within the space environment; SSR spec error rate projections (per SSR):
  - "Single-Bit" Flip Error (SBE) rate = 6/wk. (20/hr. observed)
  - "Double-Bit" Flip Error (DBE) rate = 2/yr. (2/day observed)

- Cause => Design Flaw via Human Error in the memory mapping of both SSRs
  - The physical adjacency of some data and checksum bits was laid out so that <u>one cosmic ray hit</u> could cause two bit errors (DBE) to occur (a violation of design requirements)

- Error rates are expected to increase substantially in the presence of high radiation and dusty environments



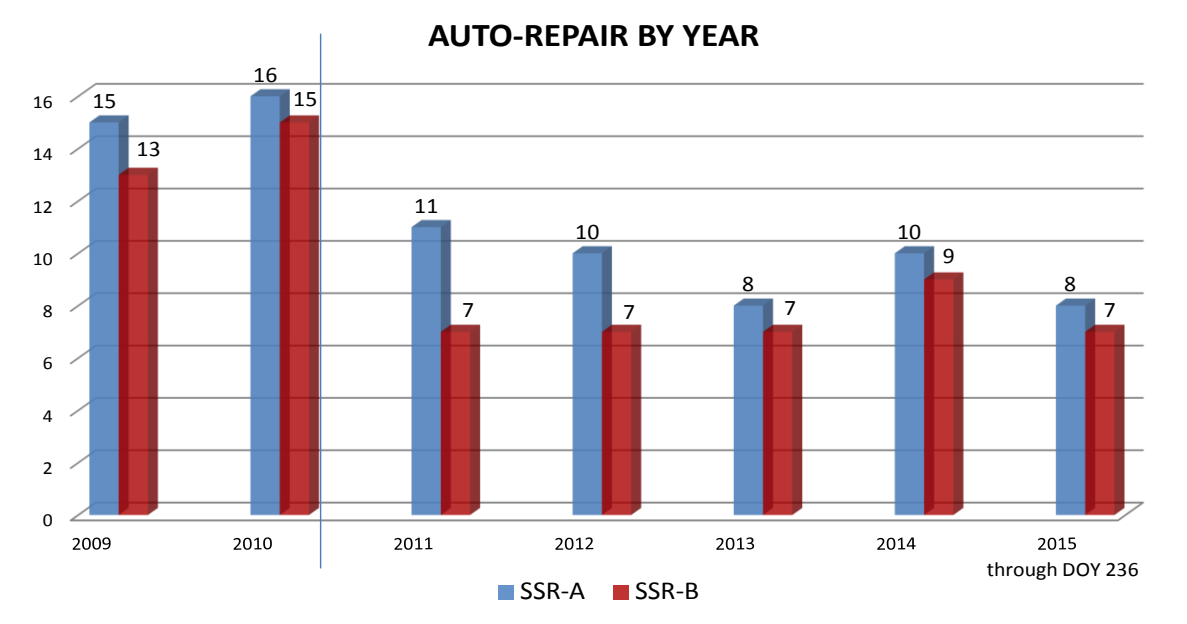
SSR SBE Bit Flips in December 2015



SSR DBEs: Fixing the Problem thru FP

- Each SSR's memory is divided into 128 "Sub-Modules" (SM)
  - The first 8 SMs contain computer & instrument FSW (4 copies)
  - The remaining 120 SMs contain collected science data
- "Error Detection & Correction" logic was installed by the manufacturer to repair the SBEs
  - But DBEs cannot be corrected! >> DBE occurrences must be monitored continuously by the ground team and fixed as they occur
- Therefore, a new "SSR DBE Auto Repair" FP algorithm was designed & uplinked
  - Repairs DBEs in the first 8 FSW SMs (and temporarily halts science collection/instrument FSW loading from SSRs)
  - The remaining 120 SMs contain science data and <u>cannot be fixed</u>

Event	SBE Count	DBE Count
Nominal Flight	30-50	2-4
Pallene/E-Ring Flybys	340-400	2-6
G-Ring Flybys	1800-2500	6-9
J-E Moon Flybys	2500-2900	6-10



Unexpected Fault after Launch => Leaking Regulator

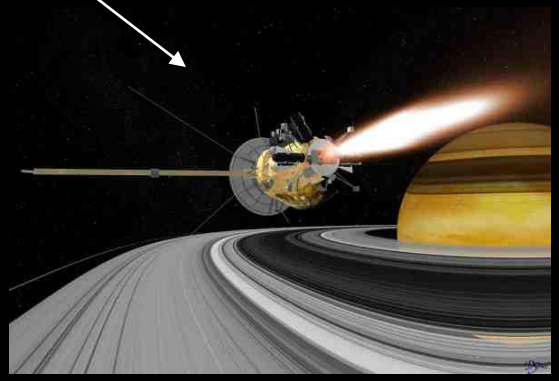
- At Launch + 3wks, a potentially mission catastrophic waived Single Point Failure of the Main Engine Prime Regulator to properly close occurred

Time	Unexpected Fault	Consequences
Launch+3wks	Main Engine's Regulator Leaks Significantly (an exempted SPF)	Fuel/Oxidizer Tank Burst from High Pressure Levels

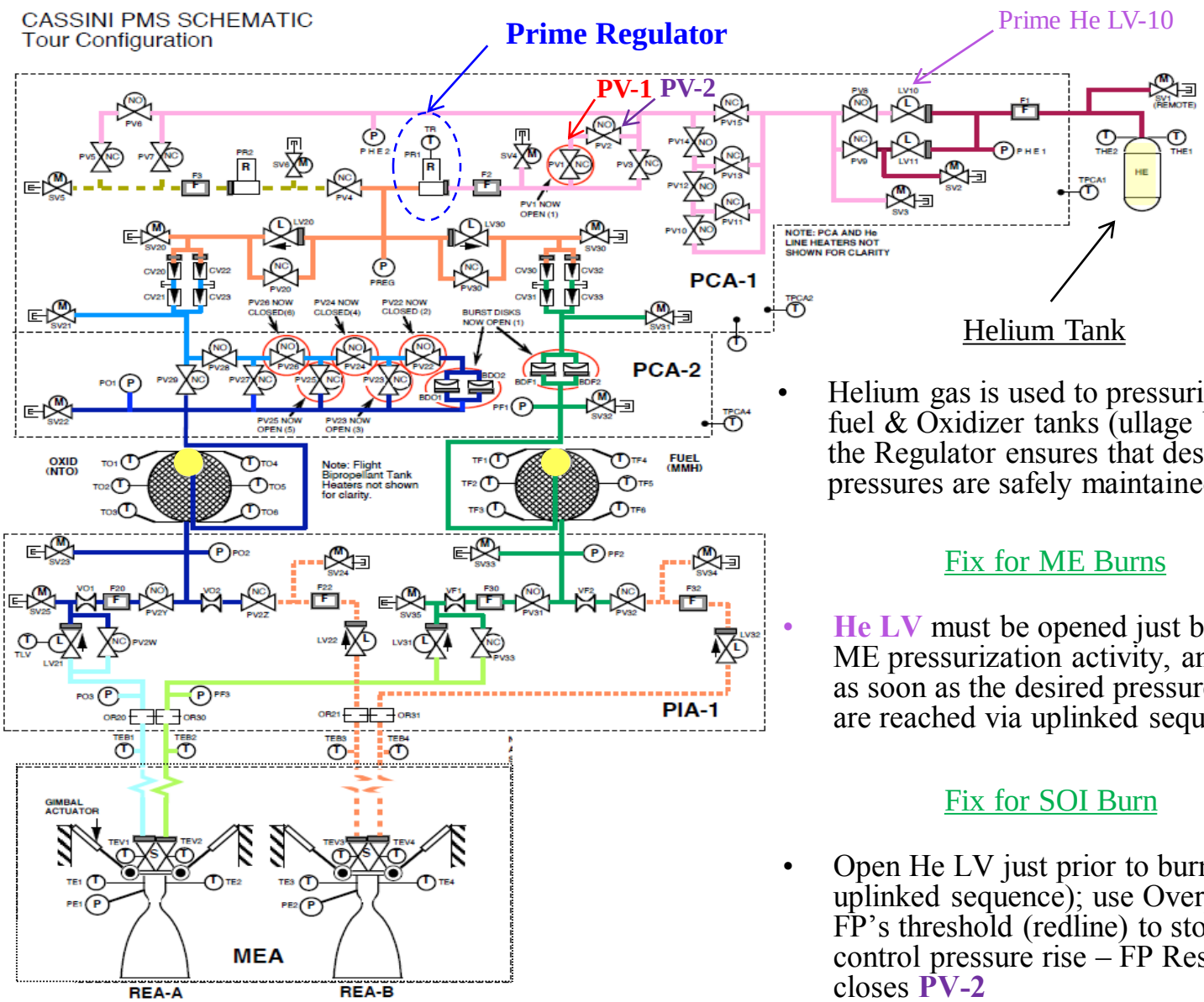
- The Regulator exhibited a significant leak rate when the fuel & oxidizer tanks were pressurized for the first time (firing PV-1 to open the Helium line => Fuel/Oxidizer tanks)
  - Leak rate = 1700cc/min vs. 1.70 cc/min "worst case leak rate" experienced in testing
  - Leak rate increased 6.6 times larger during the 90min Deep Space Maneuver 1 year later
  - In both cases, a particle was determined to have become trapped in the regulator when firing PV-1

- A considerable change in Main Engine (ME) burn strategy was required for the remainder of the mission
  - Several pressurized ME burns were scheduled throughout the mission
  - Time-critical Saturn Orbit Insertion (SOI) deceleration burn is a one time opportunity event

- Cassini's design was based upon Galileo's Teflon "soft-seat" regulator
  - Galileo's tests indicated this soft-seat design may produce a blocked flow passage due to seat extrusion (potentially mission catastrophic)
    - Galileo test data was unavailable to evaluate this problem
  - Cause => Cassini's replaced the "soft-seat" design with a "hard-seat" design (incompatible with PV particulates)



Regulator Leak: Fixing the Problem thru FP



- Helium gas is used to pressurize the fuel & Oxidizer tanks (ullage bubble); the Regulator ensures that desired pressures are safely maintained

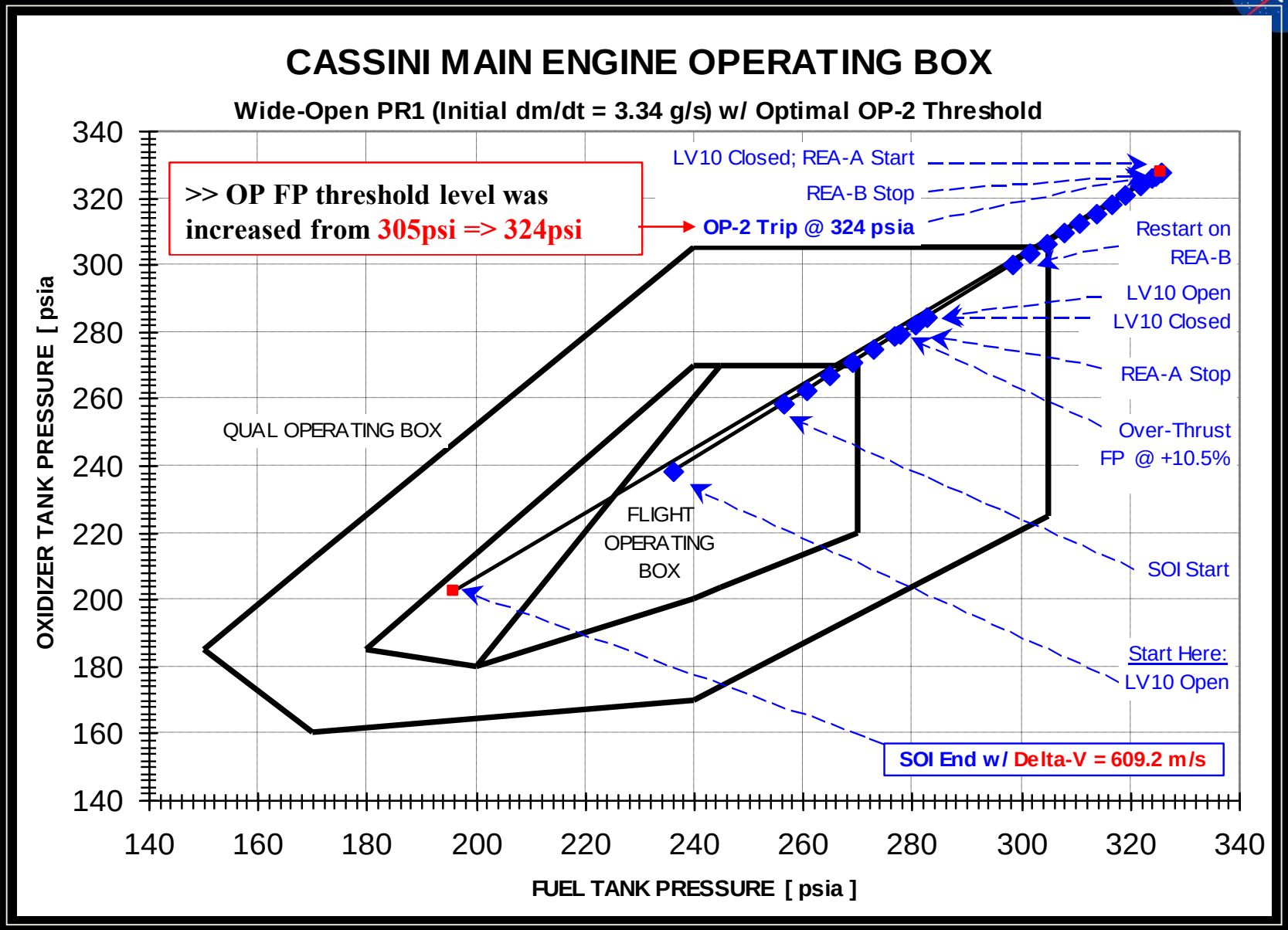
Fix for ME Burns

- **He LV** must be opened just before any ME pressurization activity, and closed as soon as the desired pressure levels are reached via uplinked sequence

Fix for SOI Burn

- Open He LV just prior to burn (via uplinked sequence); use Overpressure FP's threshold (redline) to stop out-of-control pressure rise – FP Response closes **PV-2**

Regulator Leak: Fixing the Problem thru FP



Unexpected Fault after Launch => SSPSs Sporadically Tripped Off

- At Launch + 4mo, the first of many spurious SSPS load trip-off events occurred due to the unforeseen environmental effects of galactic cosmic ray bombardment

Time	Unexpected Fault	Consequences
Launch+4mo	Spacecraft Loads Spuriousously Trip off	Possible Fault Protection Activation, Lost Science, Instrument Damage

- Cassini contains 192 SSPS switches - 36 SSPSs have sporadically "Tripped" off to date

- Some SSPS Trip events are non-trivial
  - SSPS Trips are unpredictable and occur sporadically
    - Cause => one or more photon hits on the Voltage Comparator
  - Results in a false indication that the current load is anomalously high
    - Switch transitions from "ON" or "OFF" => "Tripped," resulting in either a benign or serious condition depending on the SSPS Switch
    - Can cause loss of spacecraft signal, FP to trigger, etc.

Cassini SSPS Trip Events

Event No.	DATE	SSPS Switch	No. of Trip Events for this Device
1	February 14, 1998	SPARE 3	1
2	September 15, 1998	SRU-A	1
3	September 28, 1998	SPARE 23	1
4	March 31, 1999	SSR-A LINE A	1
5	February 5, 2000	REA A/B SEC OX VALVE HTRS	1
6	February 11, 2000	RWA 1 LINE 1	1
7	January 4, 2001	VDECU-B	1
8	January 9, 2002	VDE A MEVD LINE 1	1
9	April 8, 2004	PMS 10PS_BTA_HTR	1
10	April 29, 2004	PSU PSU-A_LC	1
11	June 2, 2004	RWA 1 LINE 2	1
12	November 11, 2004	Probe RFE Replacement Heater	1
13	February 26, 2005	PCA Panel Htr 1	1
14	November 3, 2005	RWA 4 LINE 1	1
15	March 2, 2006	HELVD_A_sw	1
16	April 30, 2006	RFS USO	1
17	June 21, 2006	SRU-B_RHtr	1
18	August 19, 2006	TWTA B line B	1
19	October 3, 2006	SRU A Decon Heater	1
20	November 25, 2006	RWA 4 LINE 1	2
21	September 11, 2007	TWTA B line A	1
22	October 5, 2007	CIRS Decon Htr 2	1
23	December 9, 2007	SRU-B_RHtr	2
24	March 20, 2008	TWTA B line A	2
25	March 27, 2008	CAPS Replacement Htr	1
26	November 29, 2008	MPD-B	1
27	November 22, 2009	VIMS	1
28	January 2, 2010	INMS_RHtr	1
29	February 5, 2010	CDA Replacement Htr	1
30	March 22, 2010	MIMI LEMMS_RHtr	1
31	July 12, 2010	FPP Backup Htr	1
32	July 20, 2010	CDS EU B	1
33	September 7, 2010	REA-A Prime Replacement Htr	1
34	March 31, 2012	HELVD_B_sw	1
35	December 14, 2012	CIRS 170K Decon 1 Heater	1
36	September 9, 2013	DST-A Line A Load Current	1

- Non-trivial SSPS Trip Events

SSPS Trips: Fixing the Problem thru FP

- Since nothing can be done to decrease or inhibit SSPS Trip occurrences, a new "SSPS Trip" FP algorithm was designed & uplinked
  - FP samples the state of each SSPS switch (1/sec)
  - If "Tripped", the FP provides a predetermined response (unique for every switch)

- Example: Cosmic Dust Analyzer's Replacement Heater SSPS Switch #189; tripped 2/5/10
  - Certain SSPS lines if tripped, will cause reconfiguration of selected spacecraft's loads (as shown below):

SSPS FP Actions for the CDA Replacement Heater

Switch Number	SSPS Switch	Log Event	Cmd Switch "Off"	Cmd Switch "On"	Cmd Alt. Switch?	Alt. Switch SSPS No.	Switch State
189	CDA Replacement Heater	Y	Y	Y	Y	186	OFF
186	CDA Electronics Load Current						

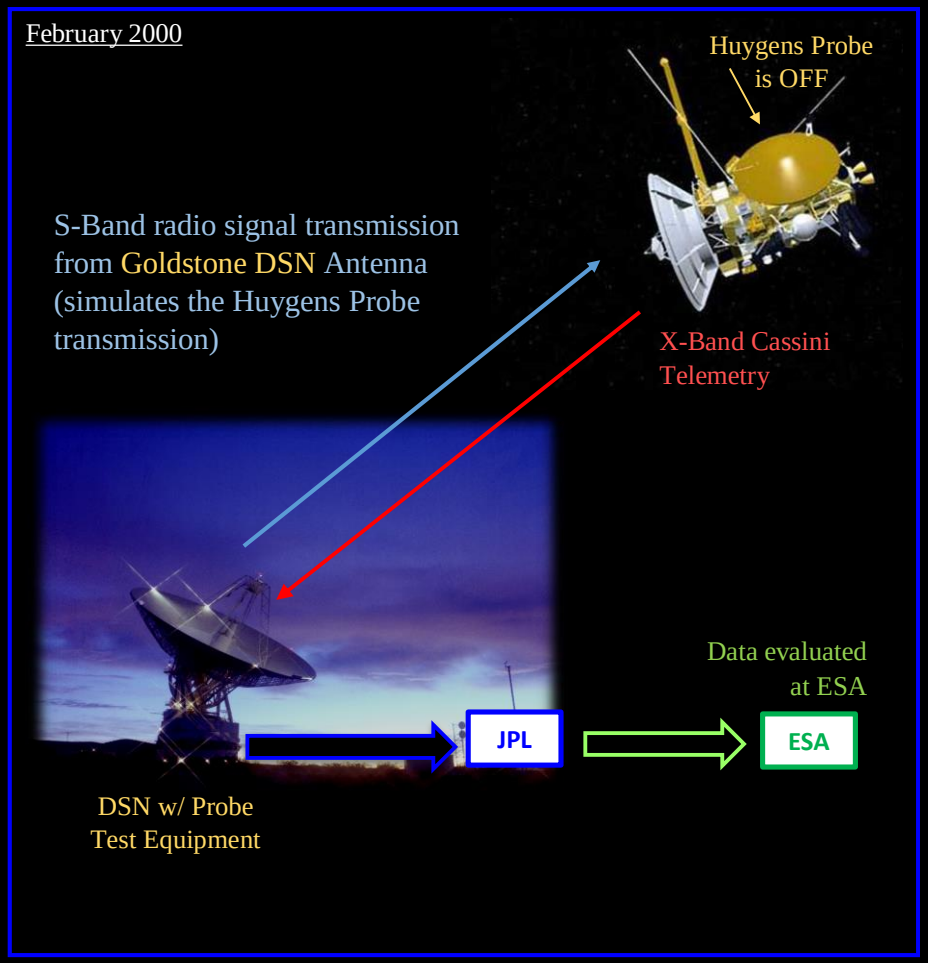
- SSPS Trip FP actions for Switch #189 is to:
  - Log the event
  - Clear the "Tripped" condition by turning Switch #189 => OFF
  - Turn Switch #189 = > ON
  - Command the specified Switch #186 => OFF (CDA Electronics)

- SSPS Trips are sensitive to high dust & radiation

Unexpected Fault after Launch => Probe Link Design Flaw

- At Saturn – 4yrs, tests performed to characterize the Cassini-Huygens Probe link showed substantial data losses with the planned mission relay-link geometry

Time	Unexpected Fault	Consequences
Saturn-4yrs	Probe Relay Link Design Error was Found	No Huygens Probe Science Data during Titan Descent



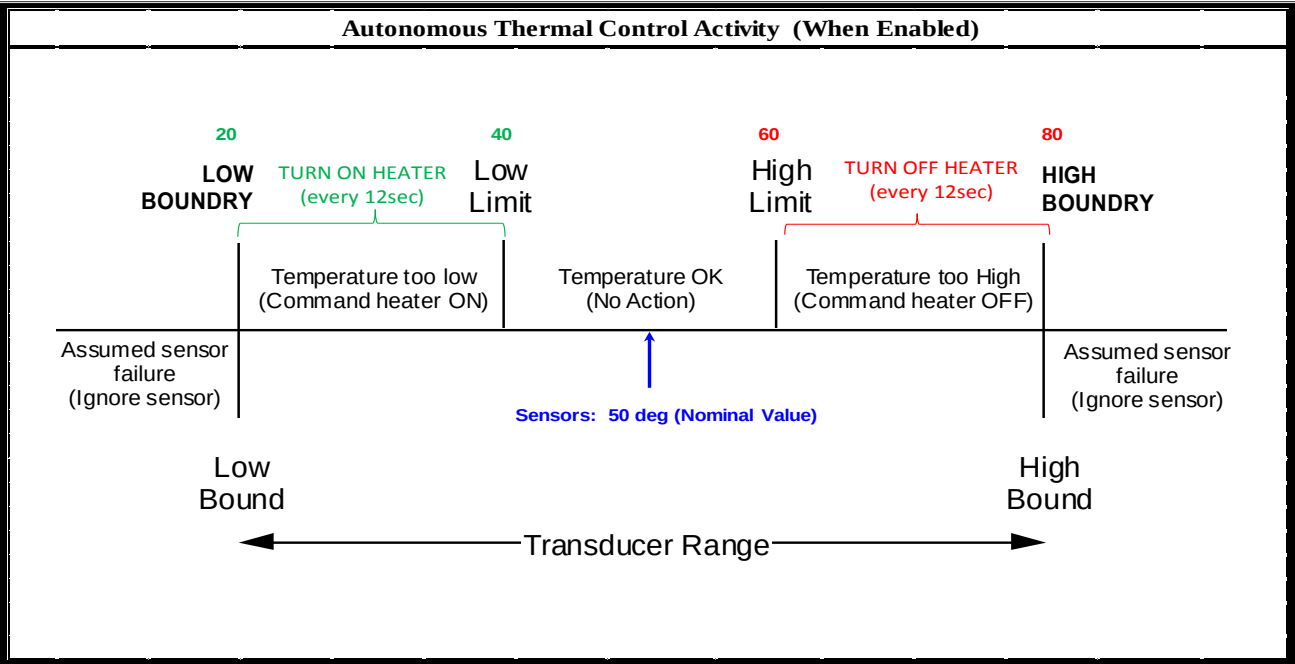
- Cause => Design Flaw - Digital circuitry has insufficient bandwidth to process data from the subcarrier once Doppler shifted by the nominal velocity difference between Cassini & Probe

- Fix:
  1) Redesign initial Tour trajectory to provide the Probe with a minimized Doppler shift
     - Requires 3 initial Saturn orbits instead of 2
  2) Probe's transmitters must be pre-heated prior to Titan descent (optimizes transmit frequency)
  3) Probe in Base Frequency "BITE Mode" (Zero Doppler)
     - Must stay in this mode continuously, <u>even in the presence of faults</u>

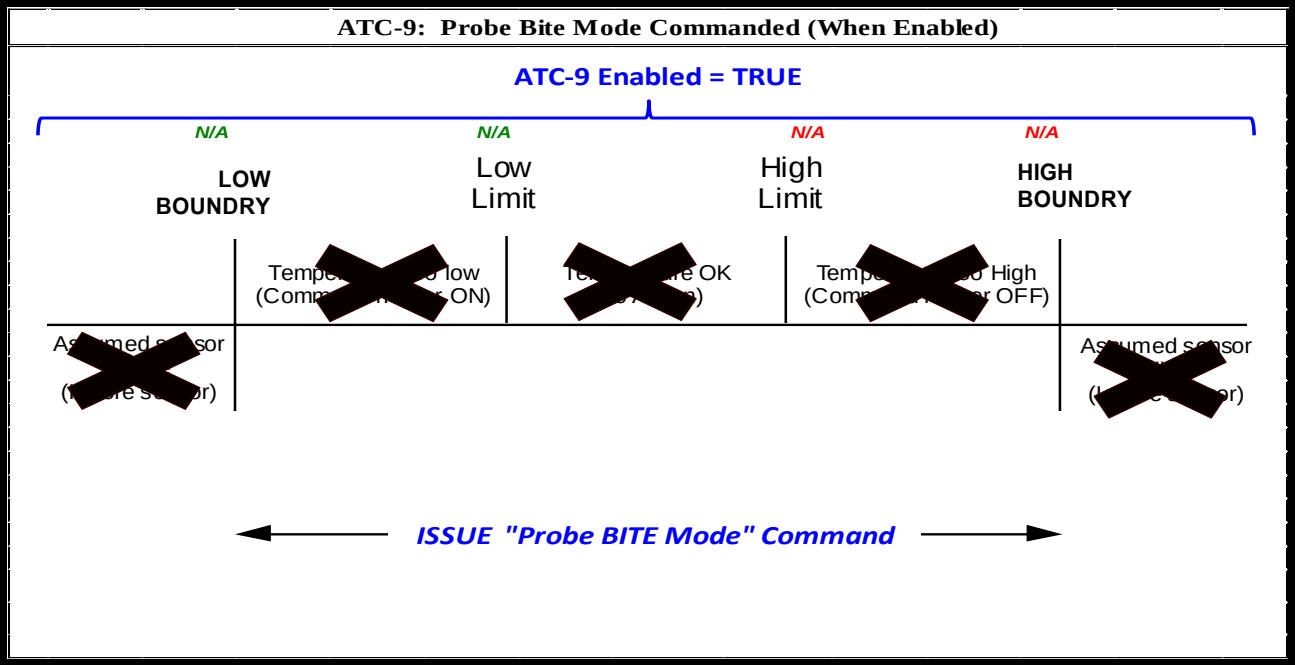
- Solution is to utilize FP's Autonomous Thermal Control algorithm (issues commands every 12seconds; even in the presence of faults)

Cassini-Probe Link: Fixing the Problem thru FP

Before



After



Unexpected Problem after Launch => Poor Link Margin @ Saturn

- At Saturn – 3 years, poor Spacecraft => Earth link margins will inhibit expedient recovery after FP activates (i.e. Safing Response activation)

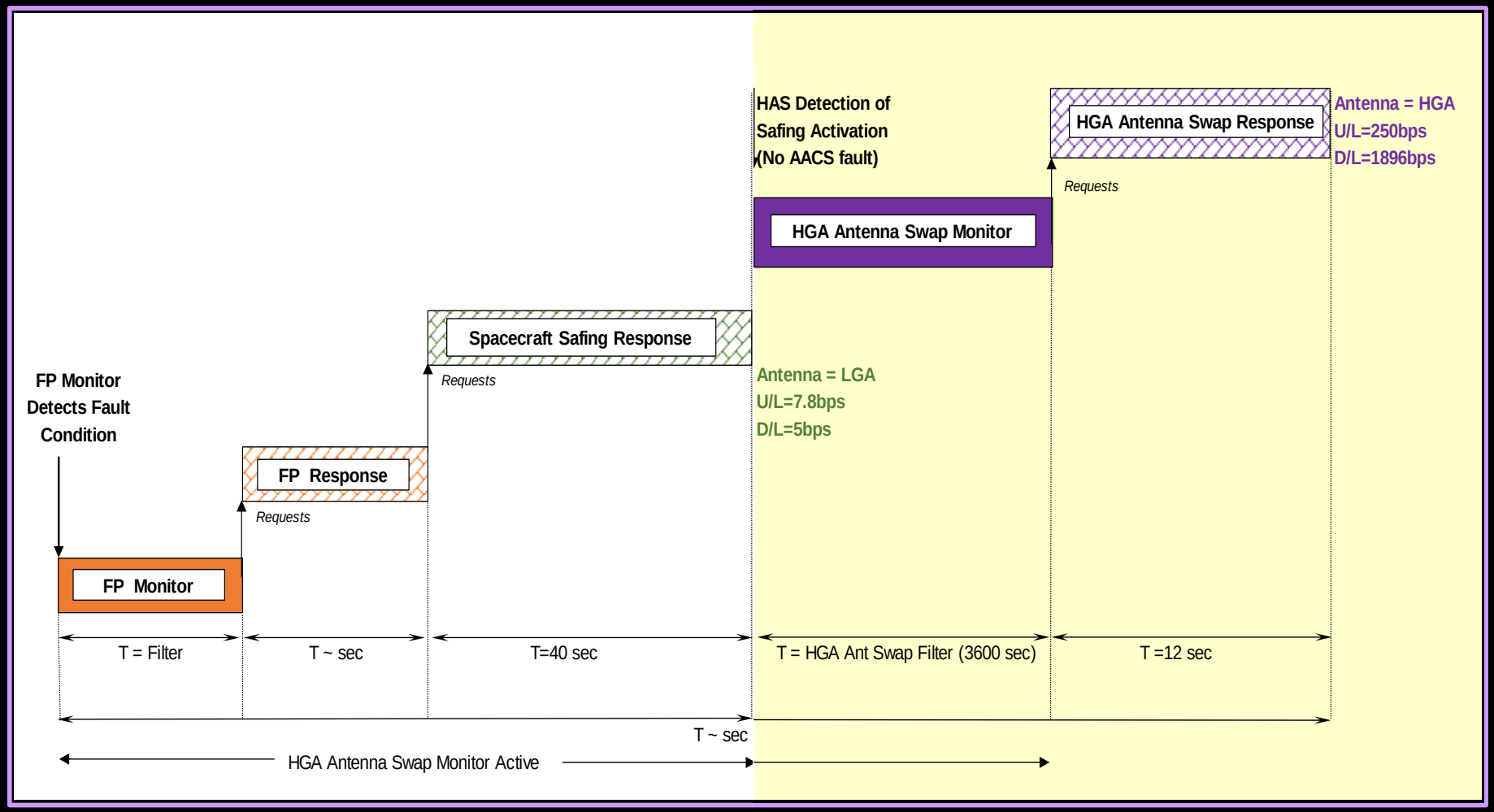
Time	Unexpected Fault	Consequences
Saturn-3yrs	Poor "S/C => Earth" Link Margin at Saturn Will Slow Fault Recovery	Lost Science/Potential to "fall off" Tour due to Lengthy Fault Recovery

- Safing Response terminates the onboard running sequence, powers off non-essential loads, subsystems are configured to appropriate states, etc.
  - Commands low D/L=5bps & U/L=7.8bps rates on the Low Gain (LGA) antenna
    - Okay for cruise, but deemed unacceptable for the Tour phases
    - 18 hours are required to receive 30 full decks of telemetry (needed to verify spacecraft states in order to start the recovery process)
  - Need to swap to the High Gain Antenna where possible to increase the D/L = 5bps => 1896bps and U/L=7.8bps => 250bps
    - All 30 frames delivered in ~10 minutes
    - Note: this strategy is undesirable for certain Attitude Control System (AACS) faults which must remain on LGA and lower rates

Poor S/C=>Earth Link: Fixing the Problem thru FP

- A "High Gain Antenna Swap (HAS)" algorithm was designed and uplinked to watch for activations of the Safing Response:

APPLICATION OF HGA ANTENNA SWAP ALGORITHM



Conclusions

Time	Unexpected Fault	Consequences
Launch	High Number of Erroneous "Bit Flips" in Solid State Recorders (SSR)	Corrupted Science/Stored Computer & Instrument FSW
Launch+3wks	Main Engine's Regulator Leaks Significantly (an exempted SPF)	Fuel/Oxidizer Tank Burst from High Pressure Levels
Launch+4mo	Spacecraft Loads Spuriousously Trip off	Possible Fault Protection Activation, Lost Science, Instrument Damage
Saturn-4yrs	Probe Relay Link Design Error was Found	No Huygens Probe Science Data during Titan Descent
Saturn-3yrs	Poor "S/C => Earth" Link Margin at Saturn Will Slow Fault Recovery	Lost Science/Potential to "fall off" Tour due to Lengthy Fault Recovery

- Pre-launch analyses & testing efforts conducted to preclude faults can be limited in their fidelity; several problems can still surface after launch, leading to:
  - Failed mission objectives
  - Arduous work-arounds
  - Lost/corrupted science data
  - Continuous monitoring of telemetry data to fix fault occurrences as they happen

- For Cassini, fixes were possible through FP solutions since
  - Enough time was available during cruise
  - Flexibility was built into the FP FSW design
  - Sufficient funding & schedule margin were available

- Thus, work-arounds for unforeseen problems can be avoided through FP solutions, in order to preserve missions like Cassini-Huygens and its 3 Tour phases