



NEPP

# Radiation Effects Predicted, Observed, and Compared for Spacecraft Systems

Presented at the  
Space Parts Working Group  
Hardness Assurance Committee

September 10, 2002

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This work was conducted by the Jet Propulsion Laboratory, managed by the California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA), under the NASA Electronics Parts and Packaging (NEPP) program, Code AE..



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# INTRODUCTION

- **Paper documents radiation effects (anomalies, failures) at system/subsystem level for selected spacecraft (see table)**
- **Most available information on parts; only few on systems**
  - **CRRES (Combined Release and Radiation Effects Satellite) program plus a few others**
- **Purpose: to gather predictions/calculations, observations, & make comparisons where possible**
- **Goal: to improve knowledge of space radiation effects to provide guidance in designs of future spacecraft**

## CAVEATS

- **No criticism intended or implied for any cited spacecraft**
  - **Most anomalies/failures noted not experienced until well after intended design life (or else do not seriously impact mission)**
  - **Systems survived despite part failures or anomalies**
  - **Human ingenuity has often been key in mitigation of part failures or system anomalies (workarounds)**



# Selected Missions with Associated Radiation Issues

<b>Mission</b>	<b>Launch Date</b>	<b>Purpose</b>	<b>Radiation Issue(s)</b>
<b>Galileo</b>	<b>10-18-89</b>	Planetary exploration (Jupiter)	Safe-holds; analog switches may fail due to total dose (has already exceeded its design requirement)
<b>TOPEX-Poseidon</b>	<b>8-10-92</b>	Earth observation (oceanography); 1336 km, 66°	Permanent failure of optocouplers
<b>Mars Pathfinder</b>	<b>12-4-96</b>	Mars surface exploration	Modem anomaly (on Mars); later concluded <u>unlikely</u> to be caused by radiation.
<b>Cassini</b>	<b>10-15-97</b>	Planetary exploration (Saturn and its moon, Titan)	Transients in comparators (Solid-State Power Switches) & double-bit errors in Solid-State Recorder
<b>Deep Space 1</b>	<b>10-24-98</b>	Technology demonstrations, ion propulsion, interplanetary exploration (comet)	Latchup in stellar reference unit, upset in solar panel control electronics, safe-hold.
<b>QuikScat</b>	<b>6-19-99</b>	Earth observation (oceanography)	GPS receiver failure, 1553 bus lockups
<b>Mars Odyssey</b>	<b>4-7-01</b>	Map chemicals & minerals, look for hydrogen/water	Entered Safe mode, due to processor reset caused by latch upset in DRAM.
<b>GRACE</b>	<b>3-17-02</b>	Gravity mapping (~485 km, 89°)	Resets, reboots, double-bit errors in MMU-A, some GPS errors & A-ICU failure (possible).



# Galileo

- **Extremely successful, nevertheless some anomalies observed**
  - Several safe-holds – believed due to Single-Event Upset
  - No latchups or gate ruptures
  - One part (a DG181 analog switch) has reached its parametric design limit due to total dose accumulated over several mission extensions (over 600 krads, 4X design dose of 150 krads)
- **Used radiation-hardened parts or standard parts screened for hardness – met all requirements**
  - Even hardened parts often have some residual susceptibility to SEUs (e.g., gate upset, clock edge, etc.)
- **Approach continues to work very well**



**Repeating success requires modified approach, due to changes in the semiconductor industry & resource limitations.**



# TOPEX/Poseidon

- **Principal anomaly has been failures of optocouplers due to proton-induced displacement damage (degraded Current Transfer Ratio, CTR)**
- **Used in two types of circuits**
  - **Status circuits more sensitive, failed earlier (2-3 years after launch)**
    - **Correlated well with estimated time to failure  $\approx 1.8$  years**
  - **Control circuits less sensitive – 1<sup>st</sup> failure occurred after 8.75 years, well within predicted window of 8.5-10 yrs.**
- **Spacecraft continues to function & provide data after a decade on orbit**
  - **Workarounds developed have been effective**



- **Recommend high drive currents & derating of minimum CTR**
- **Shows need to consider displacement damage in susceptible parts, as well as need to look beyond just “Total Ionizing Dose”**
  - **Important to consider primary environmental components (protons, electrons, heavy ions) rather than just their results (ionization, etc.)**



# Mars Pathfinder

- **No anomalies observed attributable to radiation effects**
  - **One observed anomaly**
    - **Nondestructive**
  - **Not believed due to radiation**
- **Used many hardened parts or parts screened for hardness**
  - **Cassini heritage where possible**



**Success attributed to robust mission assurance efforts**



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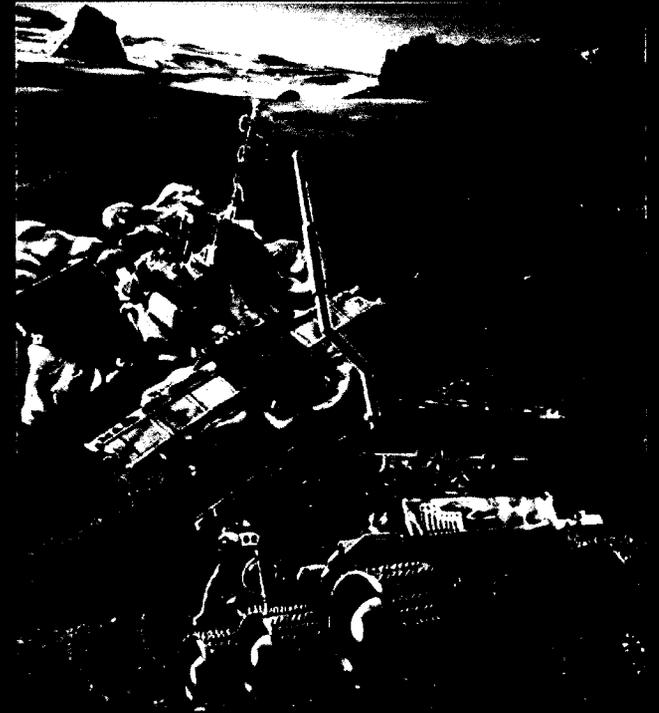


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# Mars Pathfinder

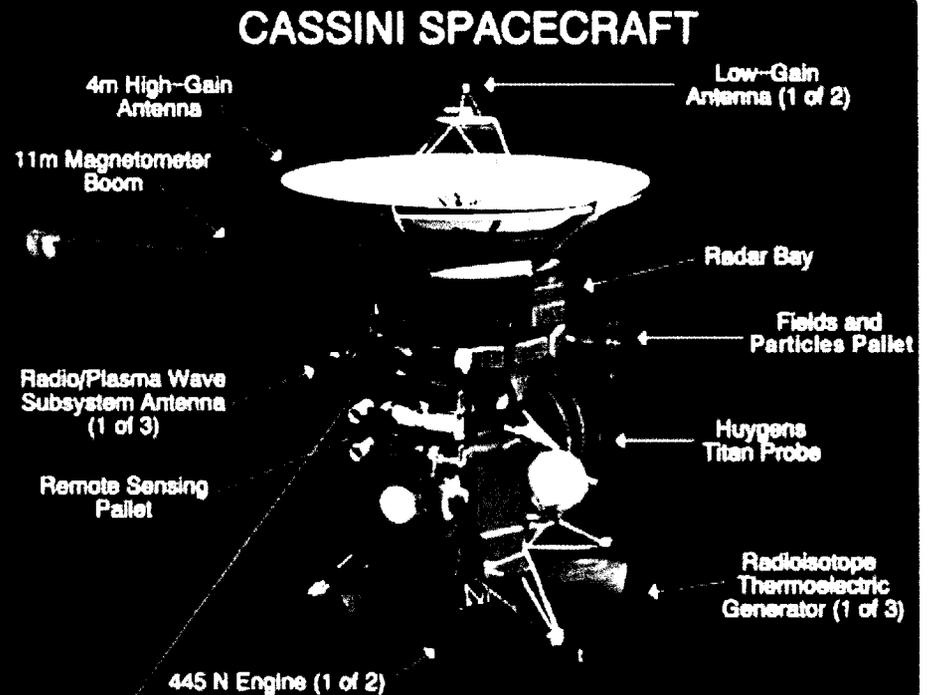
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# Cassini

- **Uses Solid-State Recorder (SSR) instead of mechanical tape recorder**
  - Correctable single-bit errors in line with prediction
  - However, double-bit error rate much higher than predicted
- **Cassini also contains numerous Solid-State Power Switches (SSPS)**
  - Switches have tripped 7 times in almost 5 years
  - Not predicted, but subsequently investigated





## **Cassini Solid-State Recorder**

- **Single-bit errors corrected by EDAC (Error Detection and Correction)**
  - ~280/day observed in late '97 vs. ~800/day predicted
- **High rate of uncorrectable double-bit errors unexpected**
  - Should have been virtually no double-bit errors
  - Instead, observed about 2 a day
- **Used 1M x 4 DRAMs made by Oki – (high density at the time)**
  - Known susceptible to Multiple-Bit Upsets (MBUs), but bits physically separated (not within 4-bit segments), plus design used error scrubbing
- **Mystery investigated, solved**

(cont'd.)

## Cassini SSR (cont'd.)

- **Architecture used DRAMs in unusual manner**
  - **Each word stored across 5 DRAMs (32 bits data + 7 bits for EDAC, total of 39 bits)**
  - **To store word, 2 passes are made (20 bits each)**
    - **1<sup>st</sup> pass stores 20 bits across 5 DRAMs (4 per DRAM)**
    - **2<sup>nd</sup> pass stores next 19 bits (40<sup>th</sup> bit not used)**
  - **However, 2<sup>nd</sup> pass for word accesses very next 4-bit segment in each DRAM**
  - **Unfortunately, each bit in 2<sup>nd</sup> segment physically adjacent to corresponding bit in 1<sup>st</sup> segment**
  - **Thus, MBU can corrupt 2 bits in a 39-bit word, which EDAC cannot fix**
  - **Study concluded problem can be avoided by switching least significant address line with any other address line**

**Shows need to carefully consider how parts are being used in system architectures**

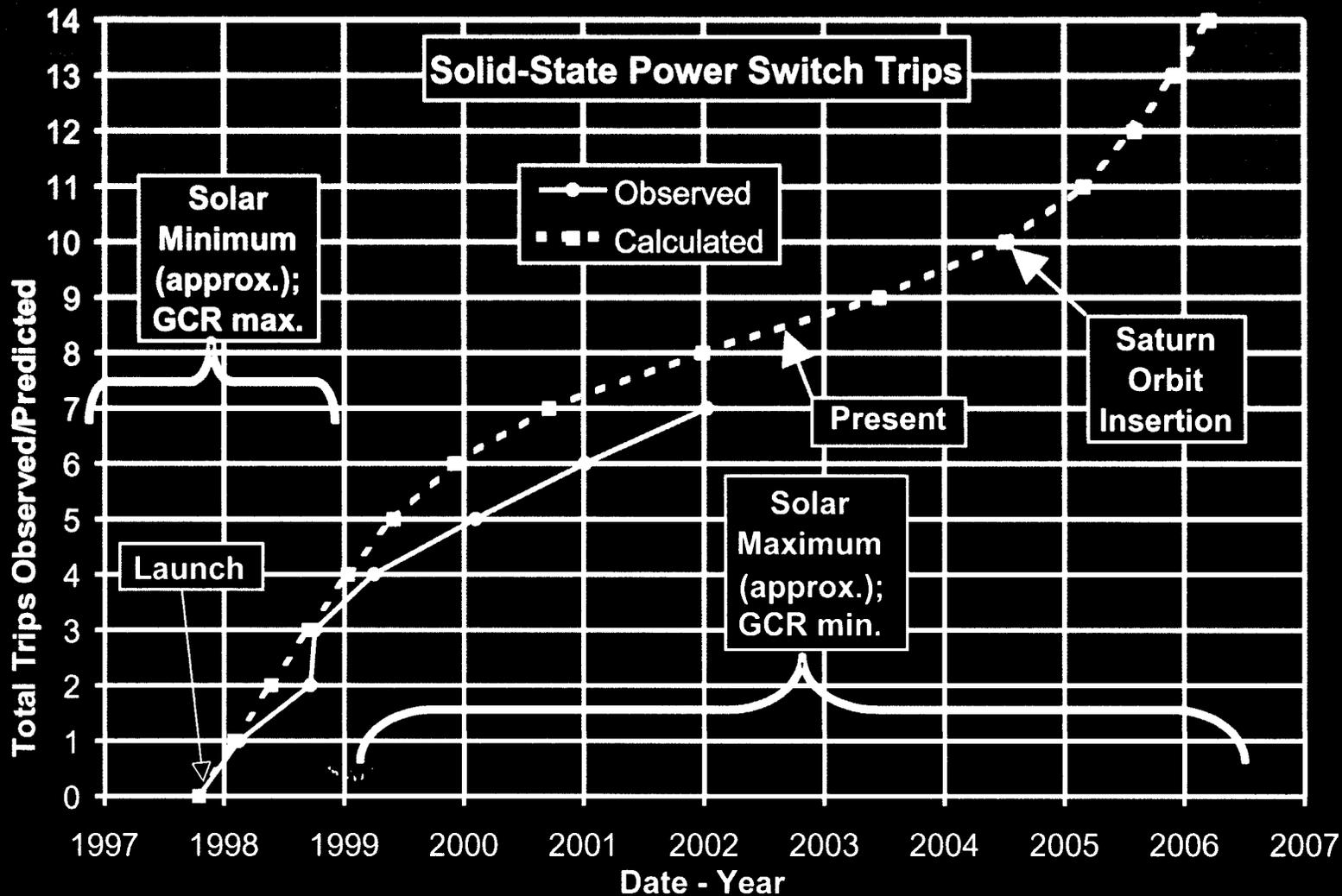


# Cassini Solid-State Power Switch Trips

- **Seven trips in almost 5 years (206 switches)**
- **Subsequently investigated**
  - **Caused by single-event transients (SETs) in LM139 comparators**
  - **Trips always occur in same mode (Off-to-trip)**
  - **Trip rate appears to change with time**
- **Comparators tested at Brookhaven**
  - **Results consistent with earlier work by Aerospace**
- **Trip rates earlier calculated for maximum & minimum galactic cosmic ray (GCR) fluxes**
  - **Figure compares observed trips versus number calculated, based on expected modulation of GCR flux**
  - **Calculation correlates well with observed trip rates**
  - **Suggests trip rate will remain at low level for remainder of voyage to Saturn (arrival expected July 4, 2004)**



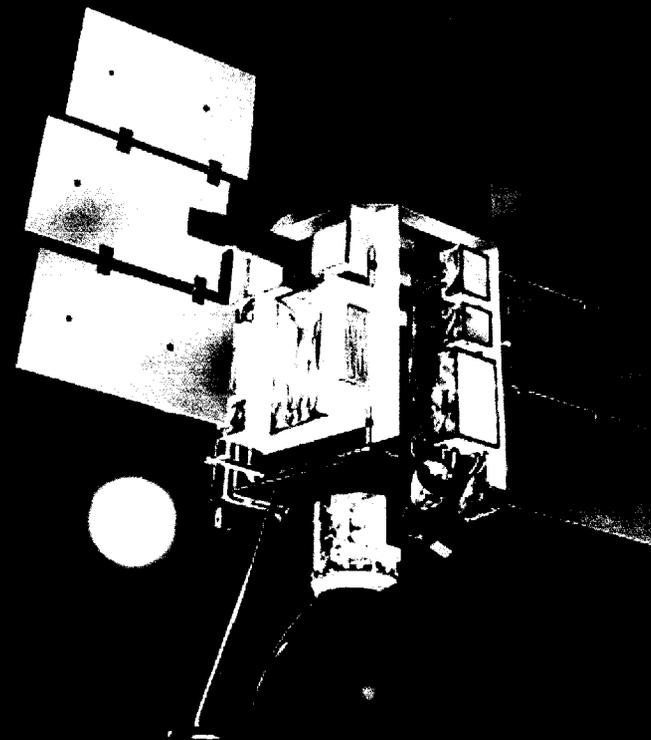
# Comparison of Cassini SSPS Trips (observed vs. calculated)





# QuikScat/Seawinds

- **Several anomalies noted by Ball Aerospace**
  - **SEU in computer 3 days after launch**
    - **Correctable error in unused memory**
    - **No mission impact**
    - **Other miscellaneous SEUs noted, corrected by EDAC**
  - **SEU rate in Solid-State Recorder lower than expected**
    - **$1.5 \times 10^{-7}$  errors/bit-day (predicted  $1.2 \times 10^{-6}$ )**
    - **All corrected by EDAC in SSR**
  - **Upsets in 1553 bus**
    - **Error detection normally prompts data retransmission**
    - **Therefore, no mission impact**
  - **Star-tracker anomalies – noisy data, background high readings**
    - **Recovers automatically, no mission impact**
  - **GPS receiver failure (Motorola Viceroy model)**
    - **Consistent with latchup**
    - **Switched to redundant unit, no mission impact**



**Shows advantage of redundant subsystems on spacecraft**



# GPS Receivers

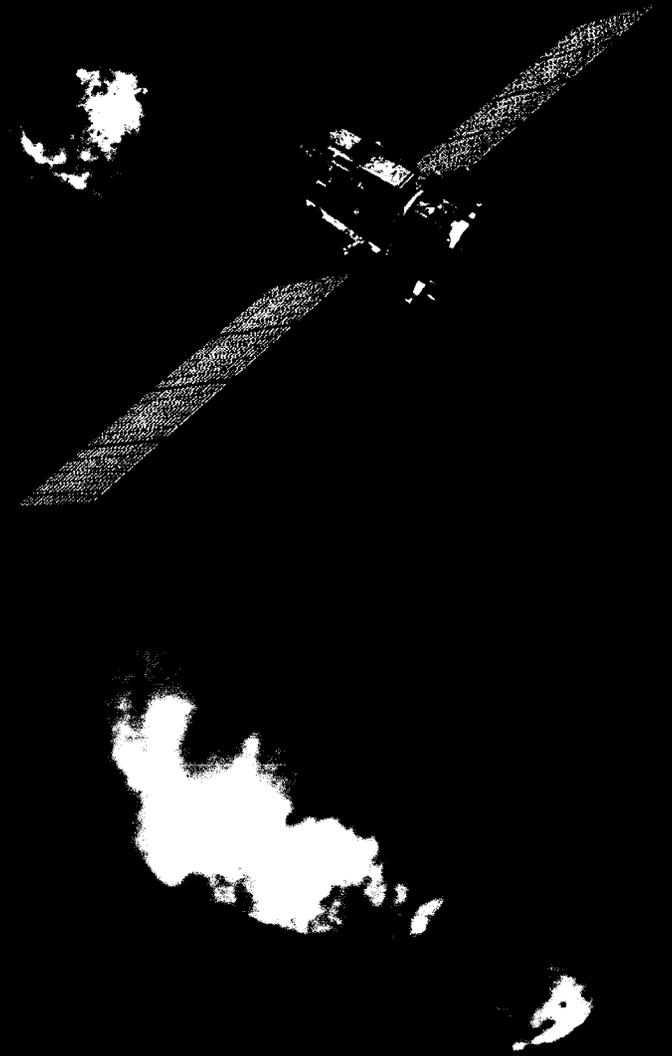
- **Interesting subsystems that contain many CMOS parts**
  - **Requires TID & SEE testing (latchup testing at minimum)**
  - **Without test data, latchup risk is high**
  - **Some test programs have reported microlatchup in many parts**
    - **Unclear whether classical latchup (i.e., 4-layer action), single-event functional interrupt (SEFI), or snapback**
    - **All 3 cleared by power cycling**



# Deep Space 1

- **Technology demonstration spacecraft**
- **SEU in Gimbal Drive Electronics FPGA resulted in loss of power from 1 solar panel – caused safe-hold**
- **Commercial stellar reference unit (SRU) failed during extended mission**
  - Believed due to latchup
  - Power-cycled twice in attempt to revive, but unsuccessful
  - SRU had intermittent problems starting soon after launch
  - All were investigated, but no resolution
  - Failure consistent with latchup, but other failure modes could not be ruled out
- **Completed extended mission to Comet Borrelly by ingenious use of other sensors (on-board camera/spectrometer) to determine attitude** →

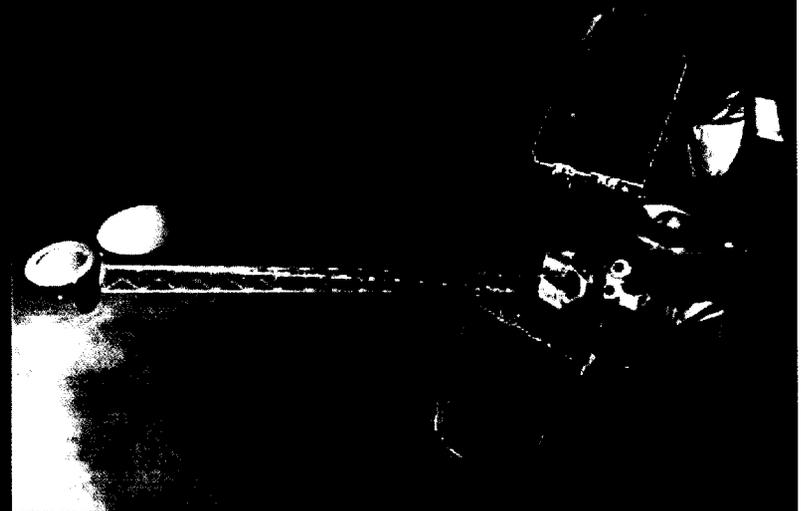
Shows value of ingenuity in solving unexpected problems





# Mars Odyssey

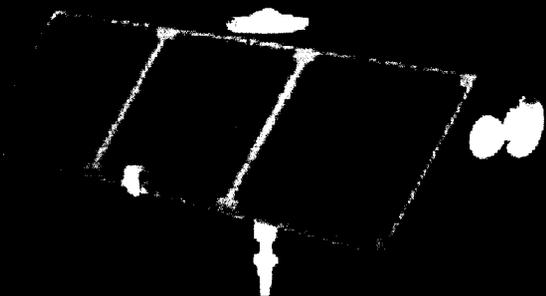
- **Successfully arrived at Mars Oct. 24, 2001**
- **On way to Mars, Odyssey experienced a MEEB (Memory Error External Bus) event**
  - **Caused by cosmic ray upset of a diagnostic latch in a DRAM, resulting in a burst error**
  - **Consistent with ground radiation test results on IBM LUNA-C DRAM used on Odyssey**
  - **Software revised to mitigate future events**





# GRACE

- **Gravity Recovery And Climate Experiment**
  - **2 satellites launched Mar. 17, 2002**
  - **Use GPS receivers (modified BlackJack) for precision gravity mapping**
- **Parts range from commercial to S level with some rad-hard types also used**
- **Design utilized heritage flight hardware, EDAC, redundancy, plus latchup circumvention in some modules**
- **Several anomalies noted – some due to radiation, some to other reasons**
  - **Numerous resets, GPS errors, failure of one accelerometer ICU**
    - **Primary accelerometer control unit failed**
      - **Limited diagnostic information precludes definitive conclusion**
        - ✓ **Latchup & component failure both possible**
    - **Parts list shows several untested, but suspected latchup-susceptible parts**
  - **Currently operating successfully in Science mode**





## GRACE (cont'd.)

- **Parts lists reviewed by JPL; number of parts noted for high radiation risk (primarily latchup)**
  - **Partly offset at system level by redundancy & latchup circumvention circuitry**
- **However, redundancy provided to protect against all kinds of failure, not just radiation**
  - **Can lose a primary unit early in mission (even at launch)**
  - **Mission then dependent solely on secondary unit**
- **Latchup circumvention increasingly popular**
  - **Success strongly dependent on several factors:**
    - **Speed/proximity of detection/circumvention circuitry,**
    - **Full latchup testing of parts, including testing some to destruction to determine design margin,**
    - **Testing of parts in subsystem, &**
    - **Post-test assessment of latent damage**
      - **JPL has documented latent damage in several parts types after circumvented latchup testing**

**Latchup circumvention not recommended unless full testing program completed per above**



# GPS Receivers

- **BlackJack receiver also used on earlier mission (CHAMP)**
  - **No destructive latchup after more than 4 years in orbit (accumulated over 3 different satellites; >20 powered ASIC-years)**
  - **GRACE-1 receiver resets about every 1-3 days; GRACE-2's about once a week**
    - **Some upsets caused by loss of GPS signals, others by known software problem, remainder due to single-event upsets**
  - **Receivers do not use EDAC**
- **ESA Space GPS Receiver (SGR) testing**
  - **SRAM calculated to have about 1 bit-error per day in LEO**
    - **Not significant problem unless continuous data required**
- **Latchup concern**
  - **BlackJack tested 13 part types**
    - **7 types did not latch, others rated moderate risk**
    - **ASIC latched in several different ways, some nondestructive**
      - **Nondestructive latches cleared by power-cycling**
      - **Assumed power down during solar flare to minimize risk (CHAMP)**



# Observations

- **Permanent damage predictions fairly accurate**
- **Galileo approach very effective; however, difficult to repeat in same manner, due to changes in semiconductor industry & resource constraints**
- **Nevertheless, Cassini & Mars Odyssey show hardness requirements can still be met by judicious part choices, careful analysis/testing, & appropriate application in system designs (including deratings/design guidelines)**
  - **Study of Cassini anomalies has provided improved understanding of relationships between parts & system**
- **TOPEX/Poseidon showed importance of considering proton displacement damage, not just “Total Ionizing Dose,” as well as need to derate parts for radiation**



# More Observations

- **Design era/component complexity do not appear to have significant influence on failures/anomalies**
- **However, more anomalies tended to occur when less effort spent on radiation assurance**
  - **Helped identify appropriate level of assurance resources to control radiation risk**
- **Latchup/gate-rupture assessment remains high priority, with testing strongly recommended**
- **Latchup circumvention not recommended**
  - **Requires caution & extensive testing to validate**