In-Flight Anomalies and Radiation Performance of NASA Missions - *Selected Lessons Learned*

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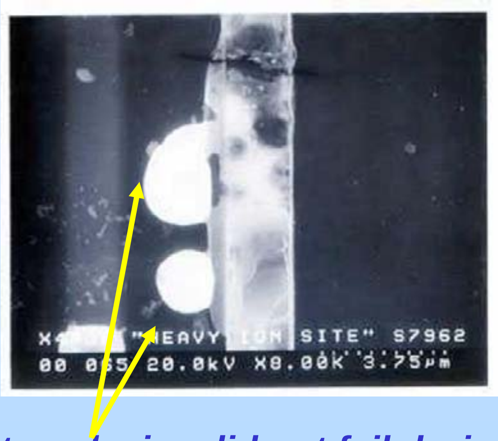
Outline of Presentation

- Investigative Approach
- An Optocoupler's Tale
- On the Matter of Small Probabilities
- What's with the Noise Spikes?
- The Meaning of an Upset in a Fiber Optic Link
- Considerations



Latent damage sites: device did not fail during ground irradiation, but at some time afterward during operation.

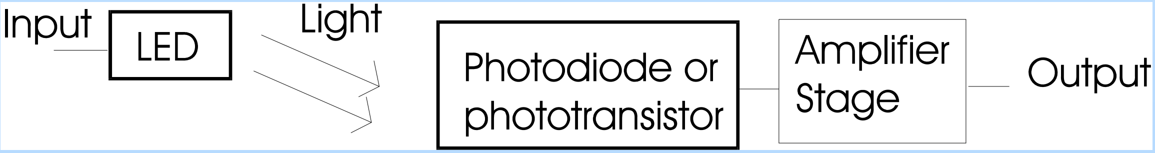
Could this have been observed in-flight?

Anomaly Resolution –
Root Cause Investigation for Radiation Engineers

- **Determine orbital location and time of event**
  - **Look for the obvious such as solar events or South Atlantic Anomaly (SAA)**
- **Review electronic parts list for potential sensitive devices**
- **Review identified device in specific circuit application**
  - **Factors such as duty cycle, operating speed, voltage levels, and so forth**
- **Obtain existing SEE, dose, and damage data or gather new data**
  - **Compare applications between in-circuit and ground data**
  - **Perform ground testing if needed**
- **Determine risk probabilities**
  - **SEE rates, etc**
  - **Failure potential**
- **Recommend mitigative action(s) if possible**

An Optocoupler's Tale - Background

- **Optocouplers**
  - **Used extensively for the isolation of signals between systems or boxes**
  - **Translate electrical signals to optical, then back to electrical**
- **What radiation-induced failure modes may exist?**
  - **Long-term degradation such as current transfer ratio (CTR) – output/input**
  - **Single particle events**
    - **Photodiodes, for example, have a history of being used as energetic particle detectors!**



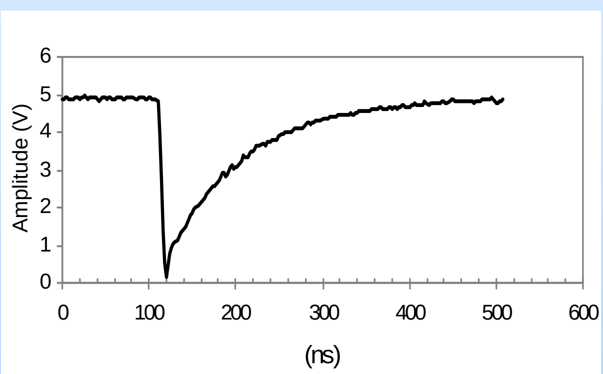
Typical Block Diagram of an Optocoupler

An Optocoupler's Tale – NASA's Most Famous Science Spacecraft

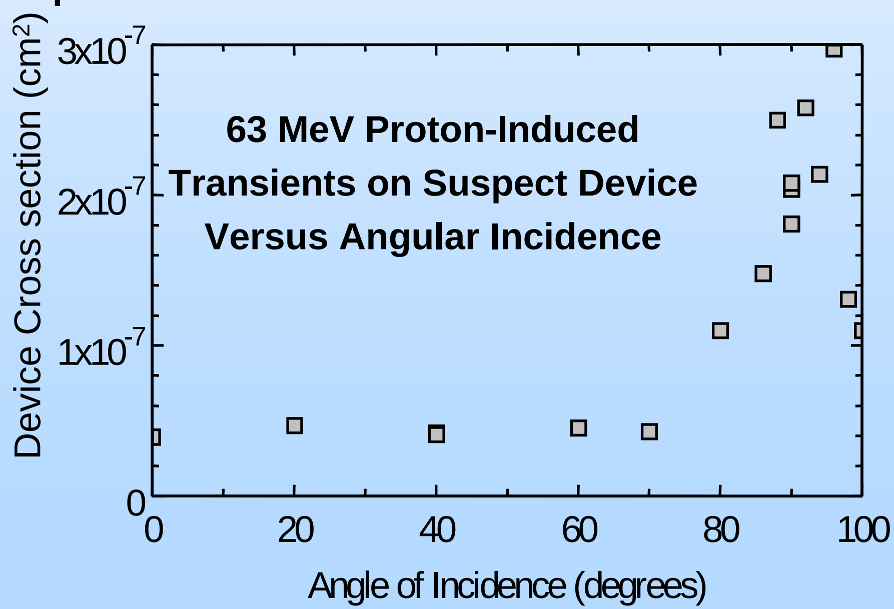
- **Hubble Space Telescope (HST)**
  - Flying for over 18 years
  - Tremendous scientific discoveries (as well as gorgeous images!)
- **HST has had several servicing missions (SM)**
  - New instruments
  - System upgrades and maintenance
- **On the SM2, launched Feb 14th, 1997, two new instruments were installed**
  - Multiple anomalies were observed during the on-orbit engineering calibration for these instruments
  - HST's main radiation concern is SAA

An Optocoupler's Tale – Resolving the Anomaly

- What steps were needed to determine **ROOT CAUSE** and action?
  - Review of environment during anomalies
    - All events occurred in the SAA
  - Review of parts list
    - Optocoupler highlighted as most likely candidate
  - Review of circuit application
    - SETs simulated showing possible cause
      - SET could trigger a high-voltage portion of the instrument and cause failure
  - Review or gather radiation test data
    - No data existed; accelerator test performed

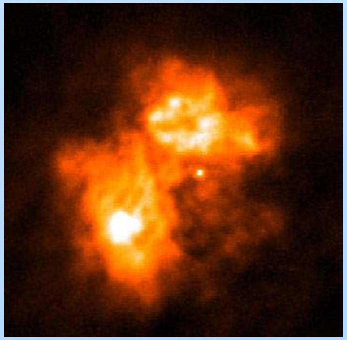


Typical Measured Transient During Proton Irradiation



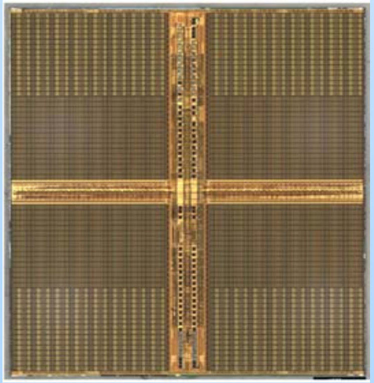
The Optocoupler – Final Analysis

- What steps were needed to determine ROOT CAUSE and action? - continued
  - Determine risk probability (i.e., upset rates)
    - Optocouplers are not just electrical
    - Considerations for tools beyond CREME96 began with this and related work
  - Determine actions to mitigate or reduce risk
    - In-flight hardware is not easily modified ;o(
      - FPGAs improve this ability (but not here)
    - Operational change installed via software update
      - No instrument operation during SAA
      - Critical science was NOT impacted, but some science data loss incurred



On the Matter of Small Probabilities - Background

- Solid State Recorders (SSRs)
  - A means for storing science data on-board a spacecraft
  - Use high-density memory ICs for density/power advantages
    - SRAM (early 1990’s)
    - DRAM (mid-1990’s and later)
    - Flash (being considered)
- DRAMs: What radiation-induced failure modes may exist?
  - TID
    - Traditional leakage increases, cell failures, etc…
  - SEE
    - Destructive: SEL, stuck bits
    - Upset: bit/multiple bits, block errors, mode errors, SEFI

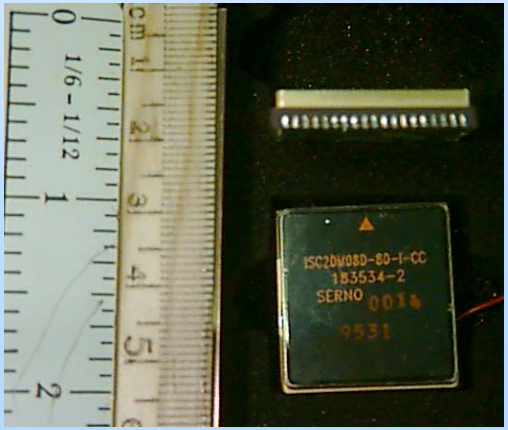


1 Gb SDRAM circa 2006
Feature size is 90nm

On the Matter of Small Probabilities –
NASA's Most Famous Science Spacecraft (yet again!)

- **On the SM2, Feb 14th, 1997, a new SSR was installed to increase data storage capacity**
  - **HST passes through the SAA several times daily**
    - **Bit upsets tracked fairly well with predicted rate based on ground data (3 samples, one proton energy)**
    - **HOWEVER, two more complex anomalies were observed**
      - **Each had ~ 100 bits in error (block)**
      - **Block was not corrected by a re-write**
      - ***Project in panic!***

HST SSR utilizes
Irvine Sensors DRAM Modules
Comprised of 16 Mb IBM Luna DRAMs



On the Matter of Small Probabilities–
Resolving the Anomaly

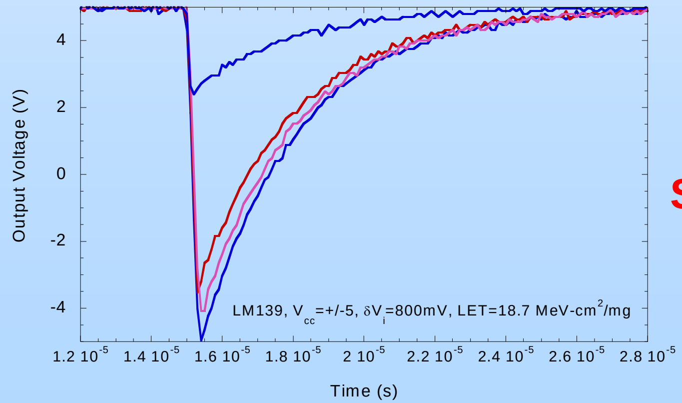
- **What steps were needed to determine ROOT CAUSE and action?**
  - **Review of environment during anomaly**
    - **SAA**
  - **Review of parts list**
    - **Memory controller was rad-hard**
    - **DRAM was not**
  - **Review of circuit application**
    - **Circuit application was the same as in ground testing (refresh rate, etc)**
  - **Review or gather radiation test data**
    - **Proton data: no observed block errors (sample size = 3 w/ 1x environment fluences)**
    - **HOWEVER, heavy ion data exhibited these type of events at low LETs**
      - **Proton events would be expected**
      - **New test data required for statistics on 1440 device usage**
    - ***With 1440 devices being used for this SSR application***
      - ***Expected event cross-section of ~a few E-13 cm^2 based on 2 events in 9 months versus (predicted) in-flight proton fluence***

On the Matter of Small Probabilities–Final Analysis

- Review or gather radiation test data (cont'd)
  - New test undertaken with protons with 100 die and to higher proton fluence levels
    - 9 events observed with proton fluences ~100x over expected HST expected levels
      - 2 different event signatures noted
        - » block (column/row) errors
        - » weak columns (suspect data – sometimes good, sometimes bad)
- Determine risk probability (i.e., upset rates)
  - Predicted error rate of 2.2/yr is the same order of magnitude as observed
- Determine actions to mitigate or reduce risk
  - Reset of mode register or power cycle clear the anomaly
    - Circuitry not included to provide reset
    - Power cycle determined to be feasible when needed
      - Data is Reed-Solomon (RS) Encoded
        - » Probability of RS failure is low
      - No action taken at that time

What's With the Noise Spike? - Background

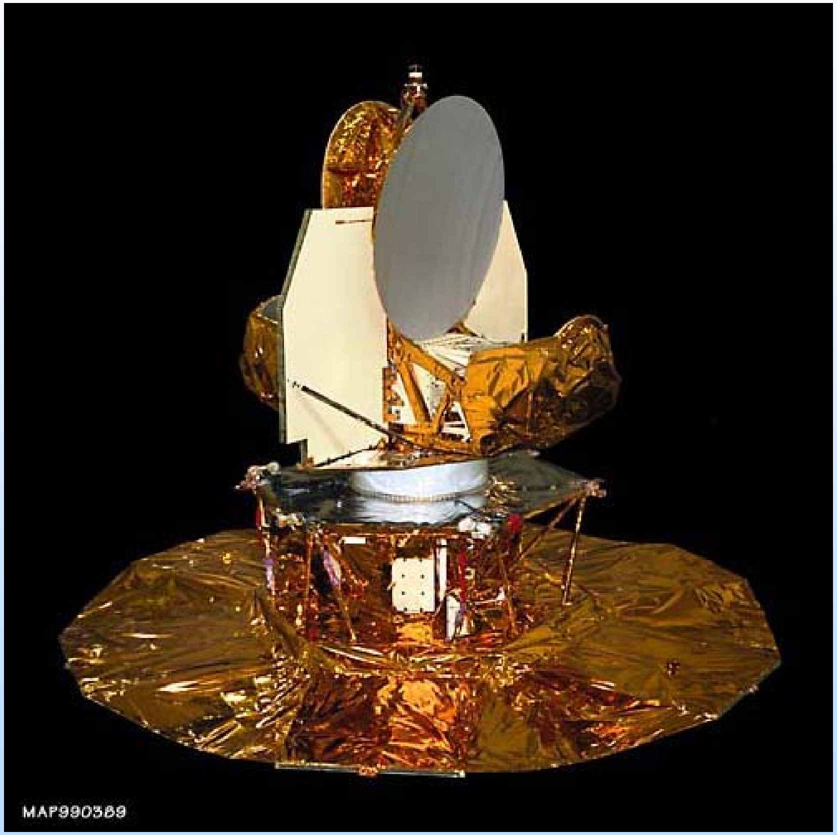
- Linear devices such as analog comparators are
  - Used extensively in instruments, power, data collection, and more
  - Compares the voltage levels between two analog signals
- What radiation-induced failure modes may exist?
  - Long-term degradation is focused on
    - Enhanced low dose rate sensitivity (ELDRS) and displacement damage (in bipolars)
  - Single events
    - Single event transients (SETs) are the prime concern.



Sample SETs induced by heavy ions in a PM/LM139 comparator

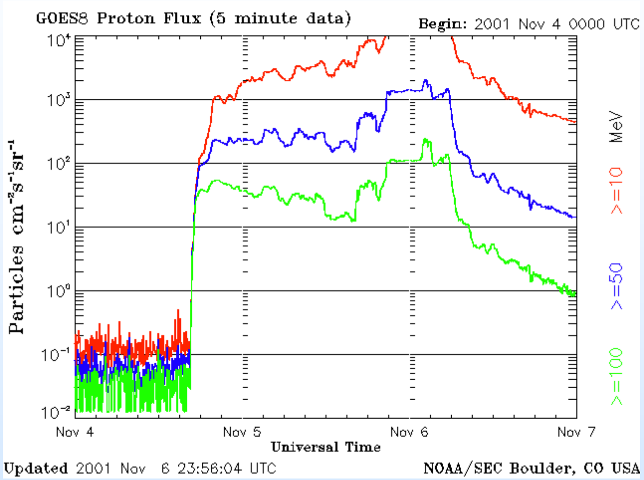
What's With the Noise Spike? – Microwave Anisotropy Probe (MAP)

- Launched June 30, 2001.
  - Had phasing orbits prior to insertion in final orbit.
- Reached its final orbital position on L2 end of September, 2001.
- An anomaly occurred causing a reset of the spacecraft processor on November 5, 2001.

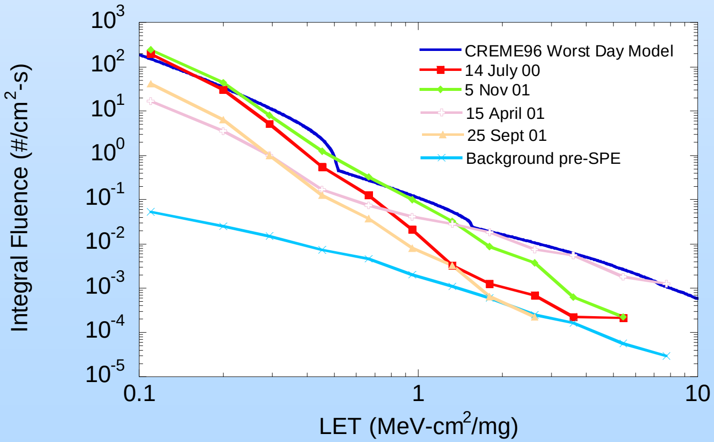


What's With the Noise Spike? – Resolving the Anomaly

- **What steps were needed to determine ROOT CAUSE and action?**
  - Review of environment during anomaly
    - Solar event
      - *Significant heavy ion component*
  - Review of parts list
    - Analog comparator (PM/LM139) identified as likely problem



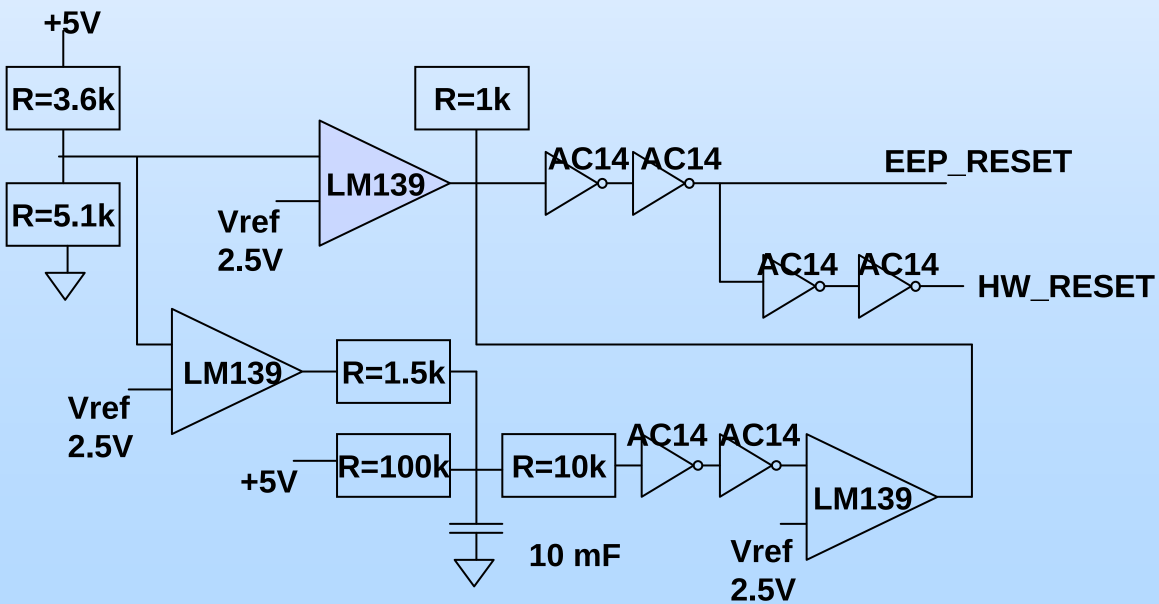
Data from NOAA/SEC/SWO

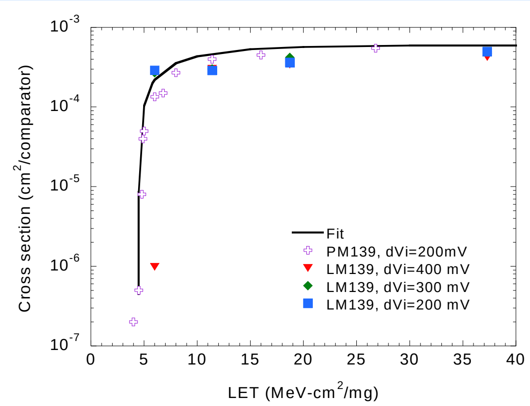


after Dyer, 2002

What's With the Noise Spike? – Resolving the Anomaly (2)

- Review of circuit application
  - Confirmed that LM/PM139 could be the cause
  - Application had changed since initial parts review pre-launch
- Review or gather radiation test data
  - No documented proton sensitivity
  - Heavy ion sensitivity documented as a function of the application using existing data plus new data gathered





Heavy ion data

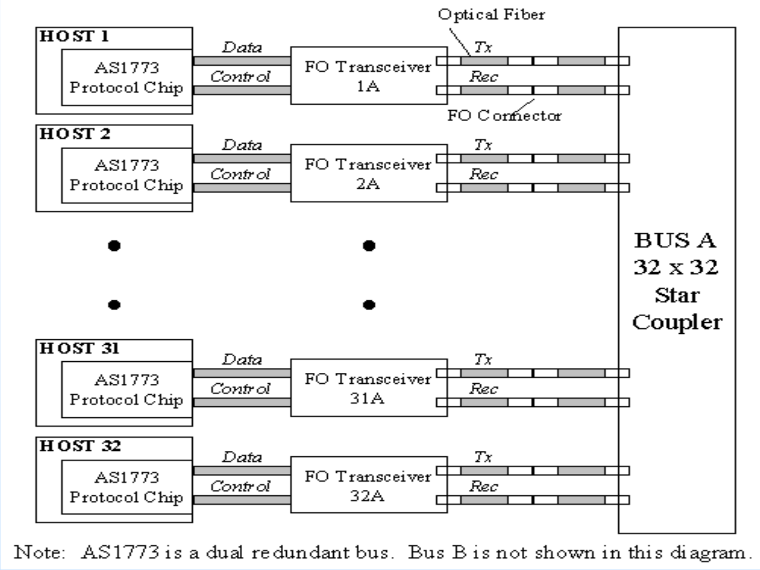
What's With the Noise Spike? – Final Analysis

- What steps were needed to determine ROOT CAUSE and action? - continued
  - Determine risk probability (i.e., upset rates with heavy ions)
    - Additional shielding analysis performed for particle transport
    - Assumption of sensitive volume thicknesses
  - Determine actions to mitigate or reduce risk
    - Event rates deemed acceptable by project
    - No action taken

Sensitive volume thickness (μm)	GCR SET rate CREME96, solar maximum (event/ comparator-day)	Solar Event CREME96, worst day (event/ comparator-day)
10	1.8E-3	5.1E-1
15	1.7E-3	3.0E-1
20	1.6E-3	1.8E-1
30	1.5E-3	6.5E-2
40	1.3E-3	4.4E-2
60	9.9E-4	3.4E-2

The Meaning of an Upset in a Fiber Optic Link (FOL) - Background

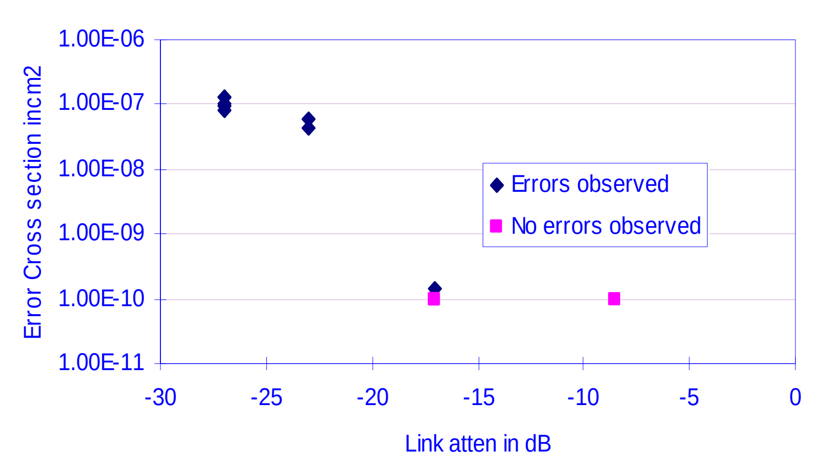
- FOLs
  - MIL-STD-1773 implementation (1 MHz) used since the early 1990's in many NASA systems
  - Transmits electrical data and command signals to/from optical
- What radiation-induced failure modes may exist?
  - Similar to optocouplers
  - SEUs imply single or multi-bit errors
    - Photodiodes, have a history of being used as energetic particle detectors.
    - Errors are temporal via photodiode
      - Transients may affect more than one clock cycle
    - High-speed electrical circuits also sensitive
    - Major impact is on data *bit error rate* (BER)



Representative FOL architecture

The Meaning of an Upset in a Fiber Optic Link (FOL)- Background (cont'd)

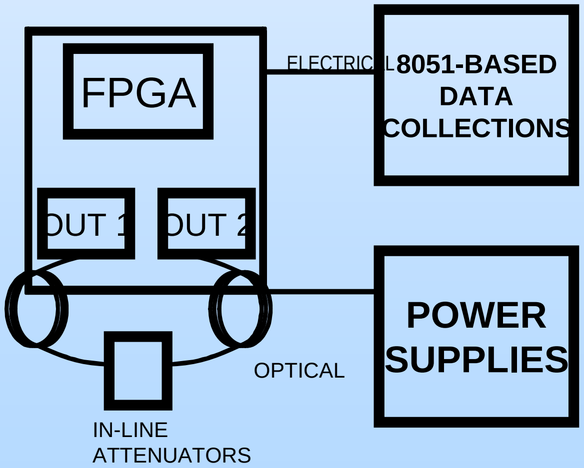
- **Original MIL-STD-1773 transceivers used Si photodiodes**
  - **Sensitive to direct ionization from protons**
    - **Implies high bit error rate (BER) for space applications.**
  - **Angle of incidence, optical power budget, and proton energy effects noted**
- **This forced the usage of protocol fault-tolerant features to be implemented (message retries).**
  - **Used successfully in NASA misions**
    - **BUT reduced effective bus bandwidth by ~50%.**
    - **For higher data rate systems, this hardening solution may not be applicable.**



Ground data illustrating the effect of optical power budget on radiation performance

The Meaning of an Upset in a Fiber Optic Link (FOL)- Making a Better Mousetrap

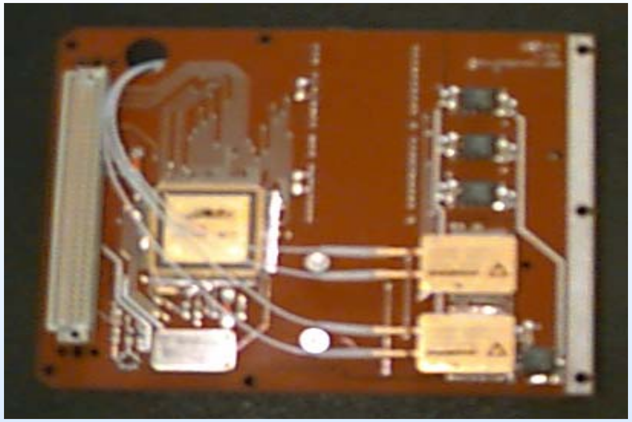
- **Hardening methodologies explored**
  - **Change of optical wavelength from 850 nm to 1300 nm light showed improved SEU tolerance**
    - **Reduced volume of photodiode**
  - **Receiver noise filtering techniques and optical power budgets also help**
  - **Higher data rate development (20 MHz) – AS1773**
    - ***Flown as an experiment on Microelectronics and Photonics Testbed (MPTB)***
      - **Boeing DR1773 Transceivers**

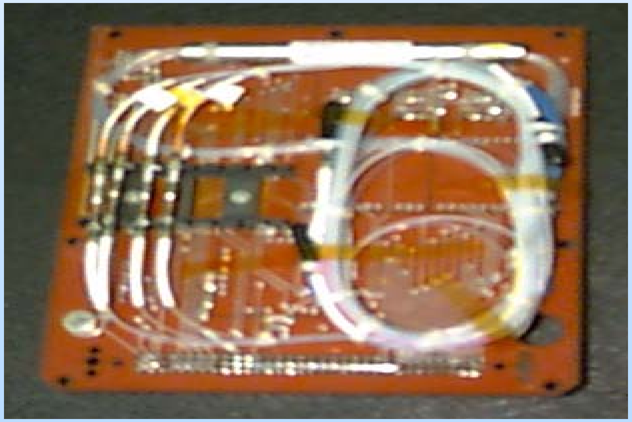


MPTB DR1773 Test Board

The Meaning of an Upset in a Fiber Optic Link (FOL) – MPTB Performance

- **MPTB launched in 1997**
  - **6 years of in-flight performance in a highly elliptical orbit (HEO)**
- **Transceivers were operated in two modes**
  - **ED mode used a physical contact (PC) polished fiber optic terminal**
  - **DE mode used a flat polished connector (air gap)**
    - ***Which do you think would work better?***





The Meaning of an Upset in a Fiber Optic Link (FOL) – In-Flight

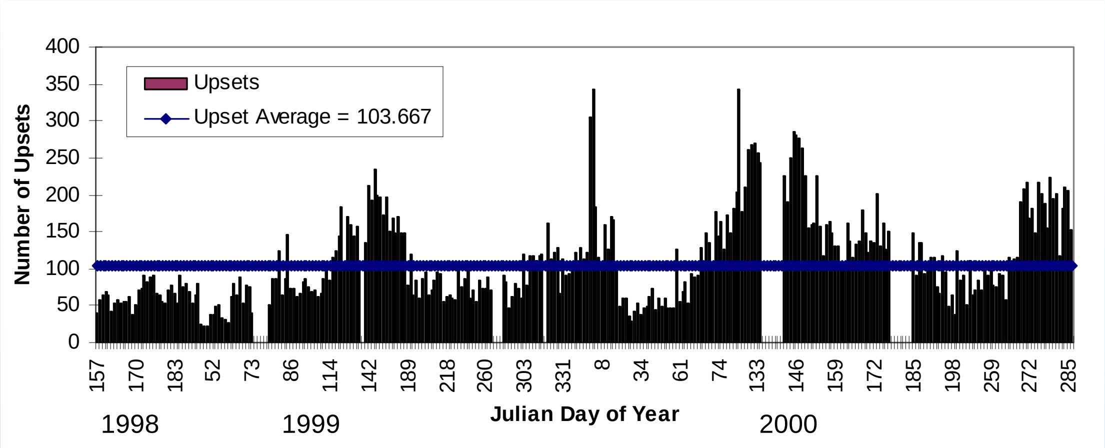
- **Did the hardening effort pay off?**

ED and DE bit error rates by Year

Year	ED BER	DE BER
1997	$1.738E^{-12}$	N/A
1998	$4.224E^{-14}$	$3.787E^{-11}$
1999	$3.855E^{-14}$	$5.303E^{-11}$
2000	0	$8.501E^{-11}$
2001	$8.168E^{-15}$	N/A
2002	0	N/A

Physical contact

Air Gap



MPTB Transceiver DE Mode 1998-2000 Orbits 0036-3111

Few errors were noted on the "good" PC

Considerations

- Methodical process for anomaly review takes into account
  - Environment
  - Selected parts
  - Design
  - Existing radiation test data and/or new data
  - Impact (i.e., risk probability)
  - Actions (mitigative or otherwise)
- Notes:
  - Design and parts list reviews are good for flight programs
    - BUT, any changes later in design process need to be reviewed as well
  - Protons aren't always the cause of anomalies during solar events
    - Solar heavy ions must be taken into account
  - System design and not just device radiation tolerance needs to be taken into account
    - Mechanical issues, for example, can be related (as in the FOL example)
  - Spacecraft charging effects not discussed, but should be considered as well
    - *Can charging in plastic packages be the next SEU?*