Lest We Never Forget: An Historical Perspective of JPL Space Data Recorders

A Prediction for the Future

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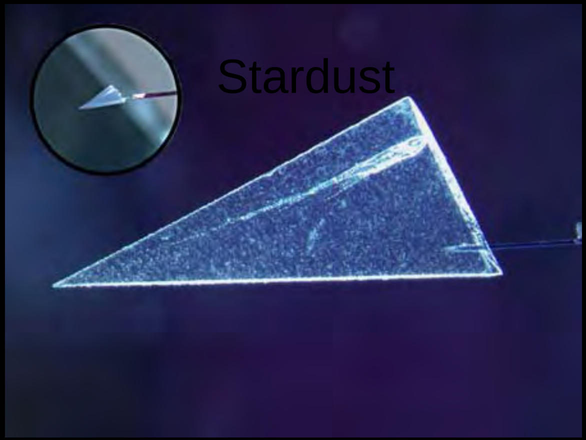
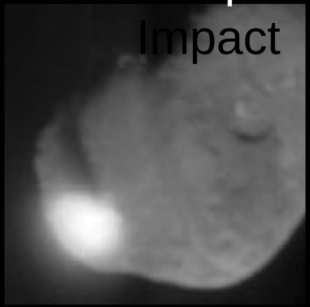
The History of JPL

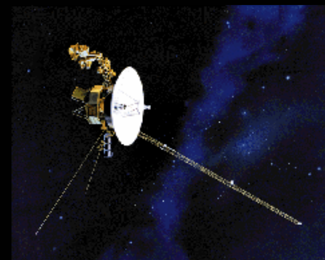
- Since its founding by Theodore von Kármán in 1936, JPL has launched some 66 satellites and countless instruments into space
  - Deep Space missions, include
    - Explorer, Mariner-series, Voyager, Cassini, Galileo, Magellan, Mars Rover, Mars Climate Orbiter, MRO
  - Earth-watch satellites include
    - Topex, NSCAT, SeaScat





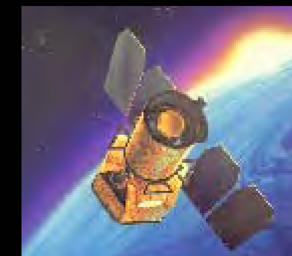
Family Portrait

SIRTF studying stars and galaxies in the infrared



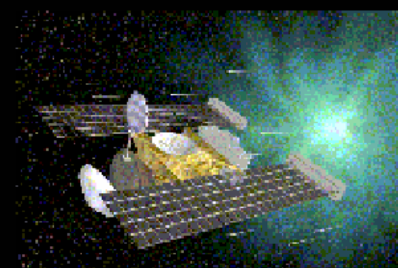
Two Voyagers on interstellar mission

Cassini studying Saturn

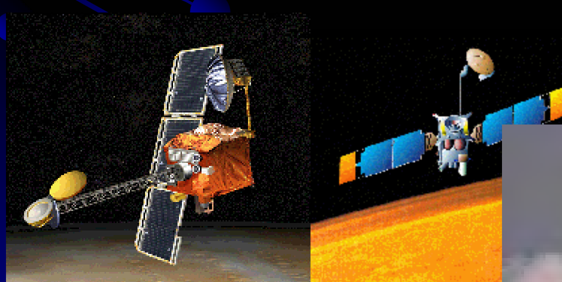


GALEX studying UV universe

Ulysses and ACRIMSAT studying the sun



Stardust returning comet dust

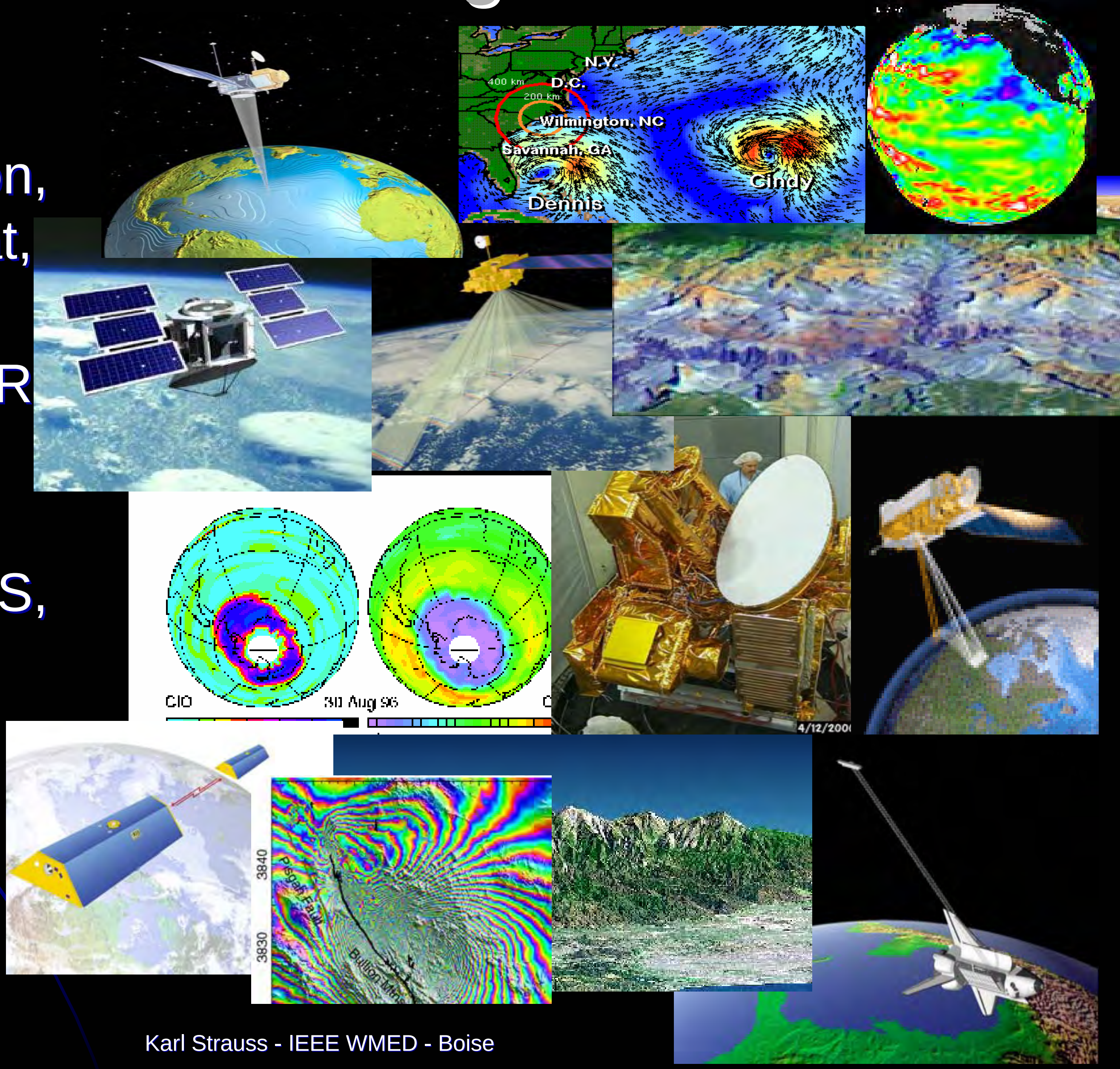


Mars Global Surveyor, Mars Odyssey, Mars Reconnaissance Orbiter in orbit around Mars; "Spirit" and "Opportunity" rovers on Mars

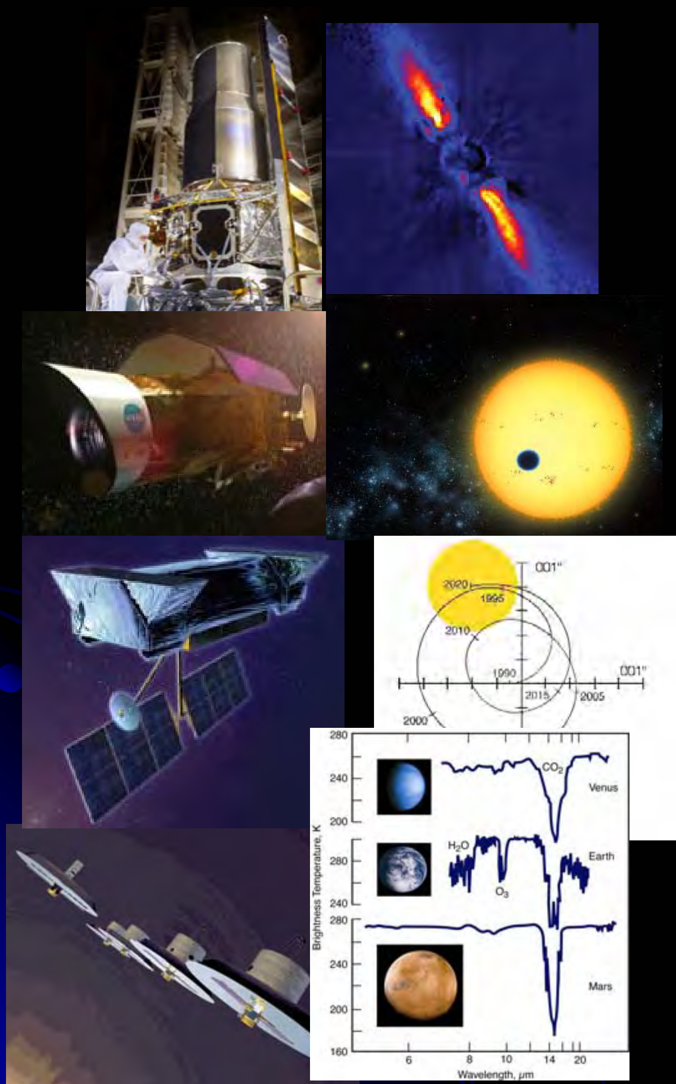
Topex/Poseidon, QuikSCAT, Jason 1, and GRACE (plus Seawinds, ASTER, MISR, and AIRS instruments) monitoring Earth

JPL Earth monitoring missions

- **Oceans** (Topex/Poseidon, Jason, QuikScat, SeaWinds)
- **Climate** (ASTER, MISR, AIRS, CloudSat)
- **Chemistry** (MLS, TES)
- **Solid Earth** (InSAR, SRTM, GRACE)



Studying neighboring solar systems

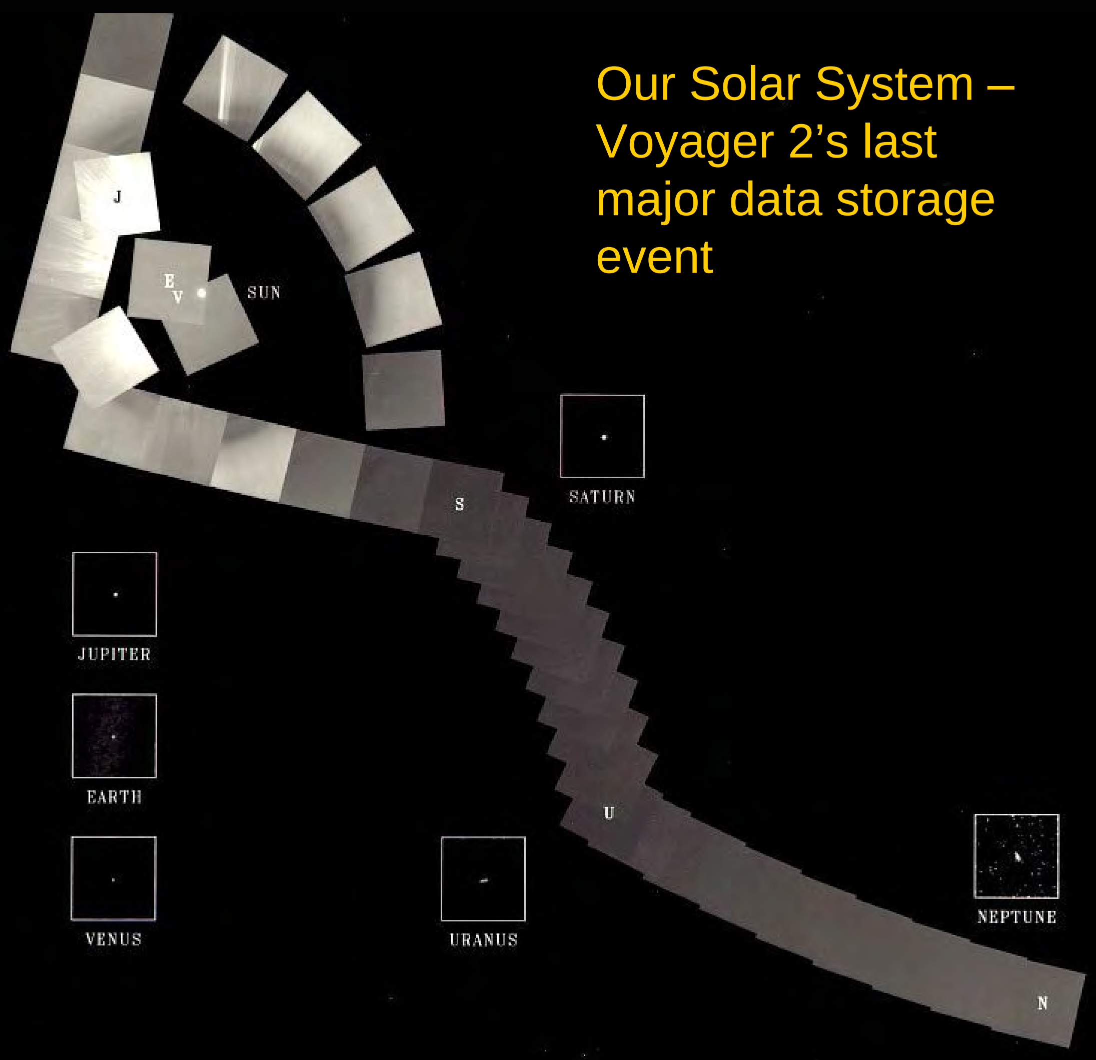


- Space Infrared Telescope Facility (SIRTF) seeks stellar planetary disks.
- Kepler, to launch in 2008, observes transits of planets across stars.
- Space Interferometry Mission (SIM), to launch in 2011, performs astrometry of extra-solar planets.
- Terrestrial Planet Finder (TPF), to launch in 2016, performs spectroscopy of extra-solar planets.

The Common Denominator

- They all have this in common: on-board data recorders
- From core memory to hard drives to Flash, the need to successfully store and process data has been at the very core of every mission
- *If you're not going to analyze the data, why even take it in the first place?*

A Bird's Eye View



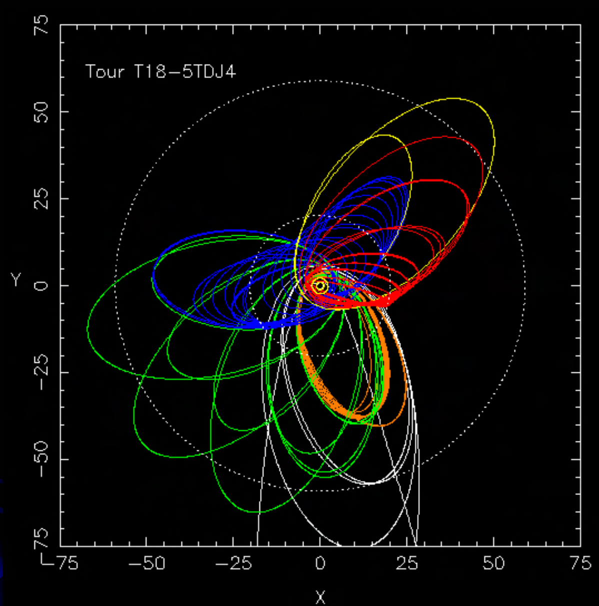
Our Solar System – Voyager 2's last major data storage event

Limitations

- Earth orbiting satellites generally experience unlimited access to ground stations
  - Either via direct links or via satellite-to-satellite relay
  - In either case, there are periods when the satellite will be out of communication with its Ground Station
- Deep Space satellites

have it worse

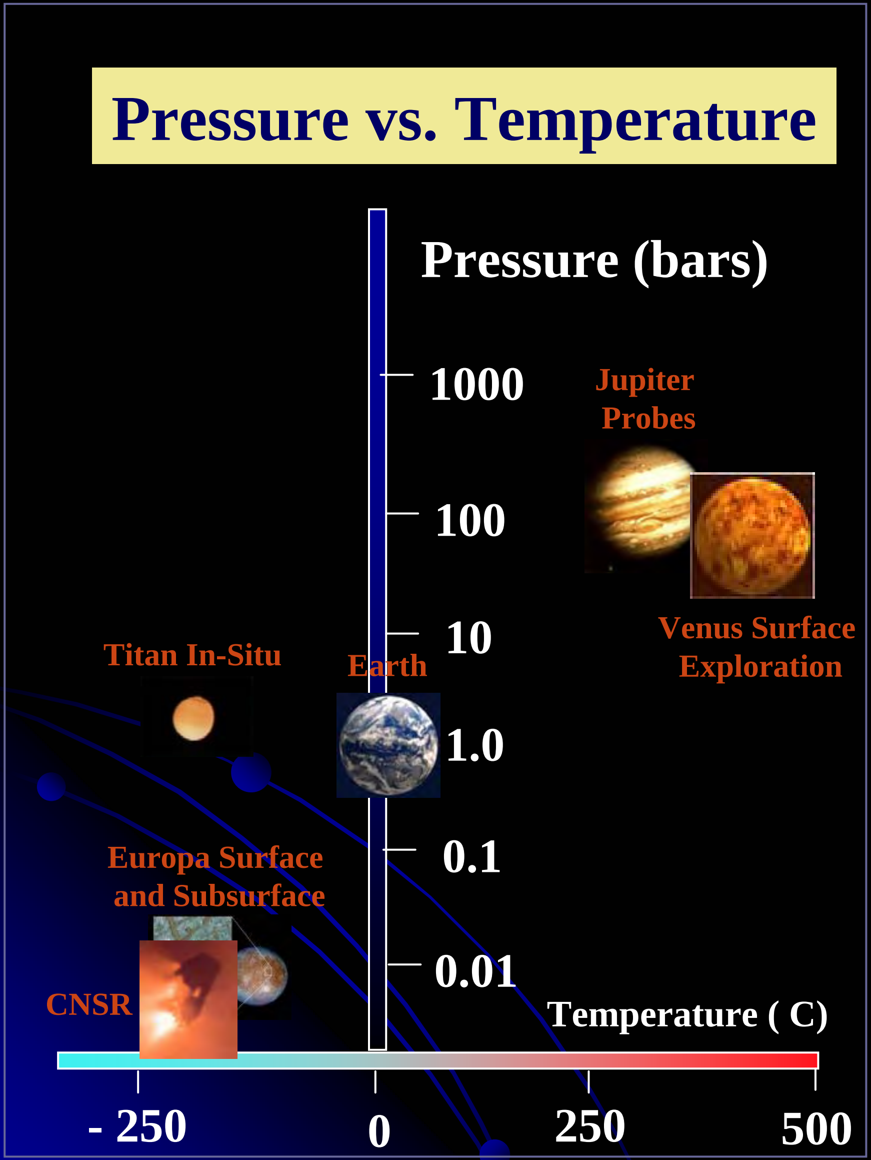
Where is a Worm Hole When You Need One?

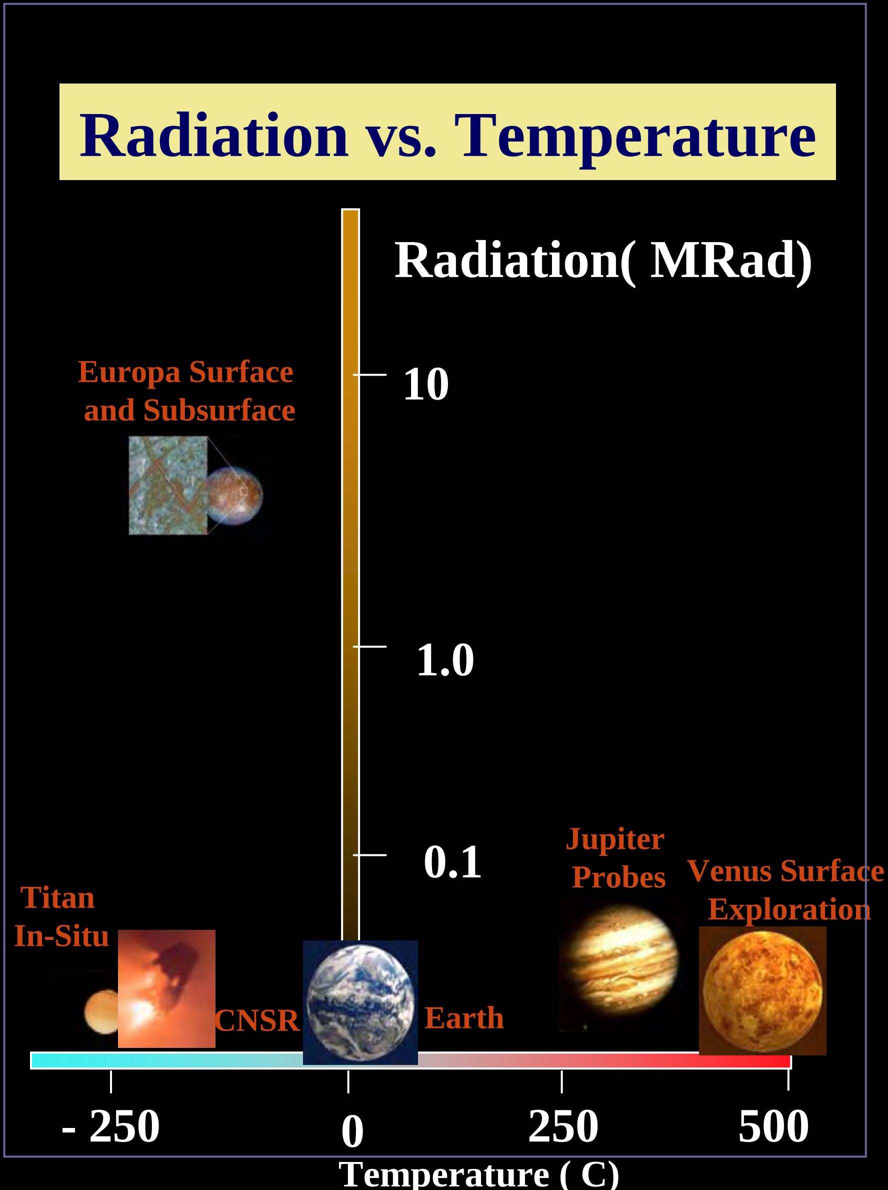


Cassini Flyby
(altitude = 1,900 km)
of moon Titan
April 30 2006

- Deep Space satellites have a Quadruple whammy
  - The farther out a spacecraft goes from Earth and the Sun:
    - the less power there is available to do its job
      - Solar arrays become ineffective
      - Nuclear generators are expensive and impose severe launch restrictions
    - The more difficult it is to transmit what it knows
      - The same equations that dictate the sunlight-energy available to a spacecraft also dictate the amount of energy that is available in the down-link signal once it reaches Earth
    - And, the longer it takes to respond to Cries for Help
      - One way light time to Saturn ~ 1 ½ *hours*
      - *Voyager one way light time over 27 hours*

The Biggest Whammy - Environment

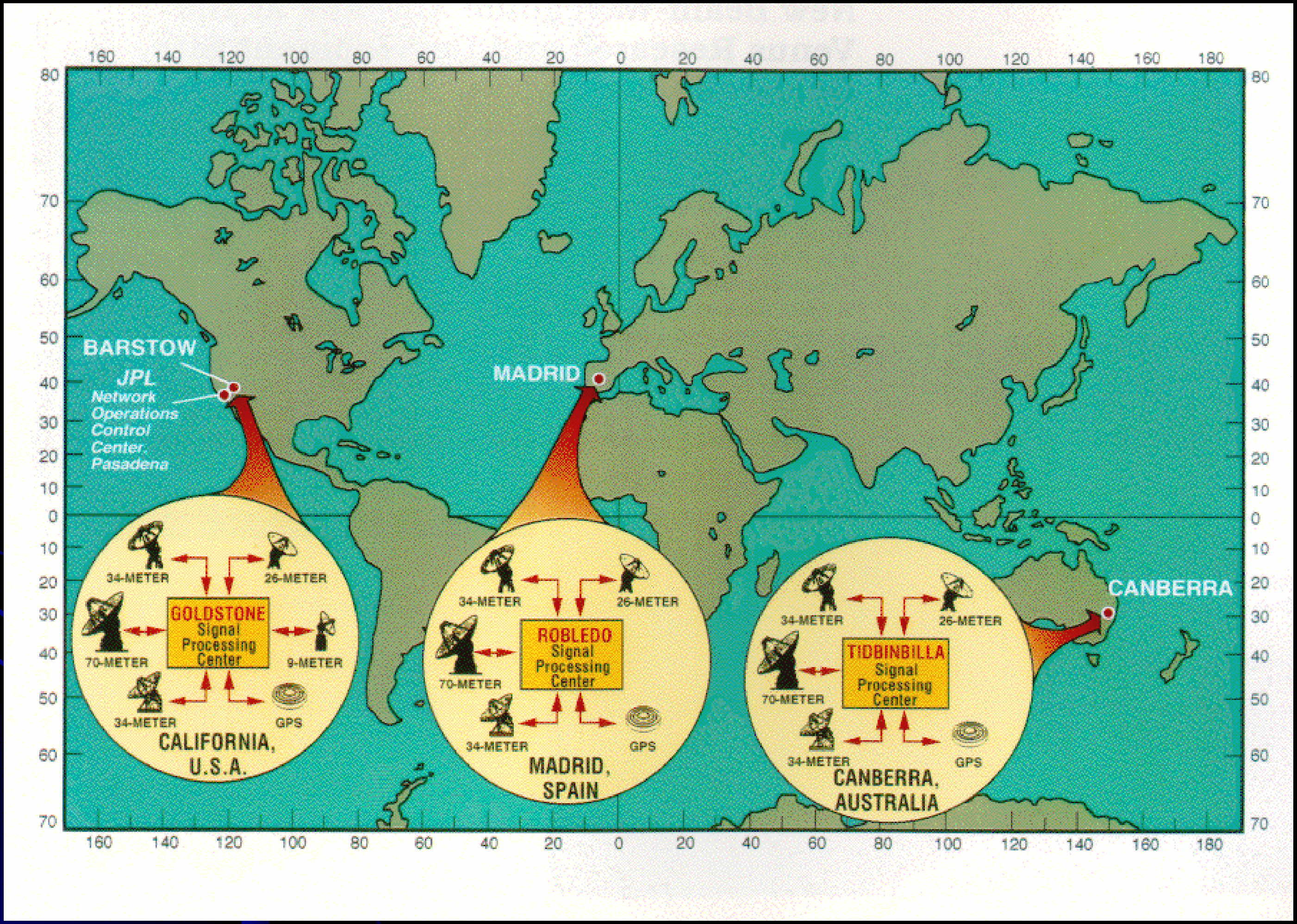




Deep Space Network
Part of the Data Environment

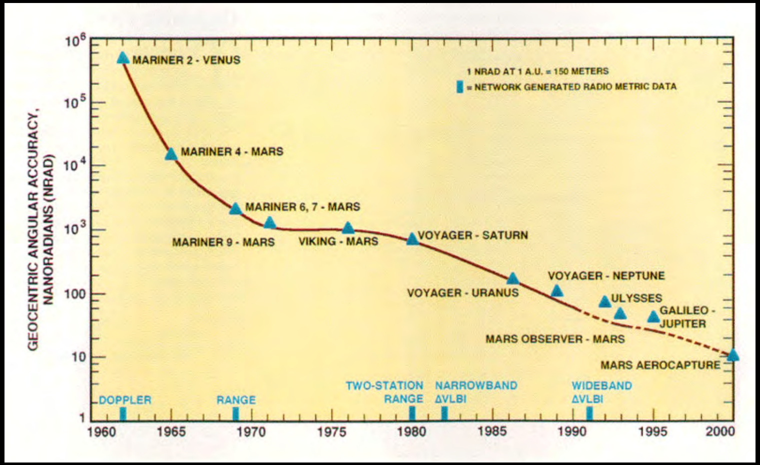
- **Founded in January 1958**, the DSN was established by the Government as a common-use facility so that all space missions would not have to endure the expense of establishing its own communications system
- The first DSN used mobile antennas mounted on tractor-trailers located in Nigeria, Singapore and California. These were used for the Explorer series of satellites which led to the discovery of the van Allen belts
- World events eventually led to the establishment of permanent facilities in friendlier locations
  - California (Goldstone/Barstow)
  - Spain (Madrid)
  - Australia (Canberra)

The World's Ears



Shhh! I think I hear something

- Each DSN location consists of
  - One 26 meter dish antenna
  - Four 34 meters dish antennas
  - One 70 meter dish antenna
- The location of the DSN stations at approximately 120 degrees of longitudinal separation affords, in theory, a constant view of any point in the sky
  - Sensitivity factoid: The current signal received from the Voyager spacecraft is less than one-tenth of one femto watt (0.1E10$^{-16)}$ watts)
    - [One million yoctoWatts)



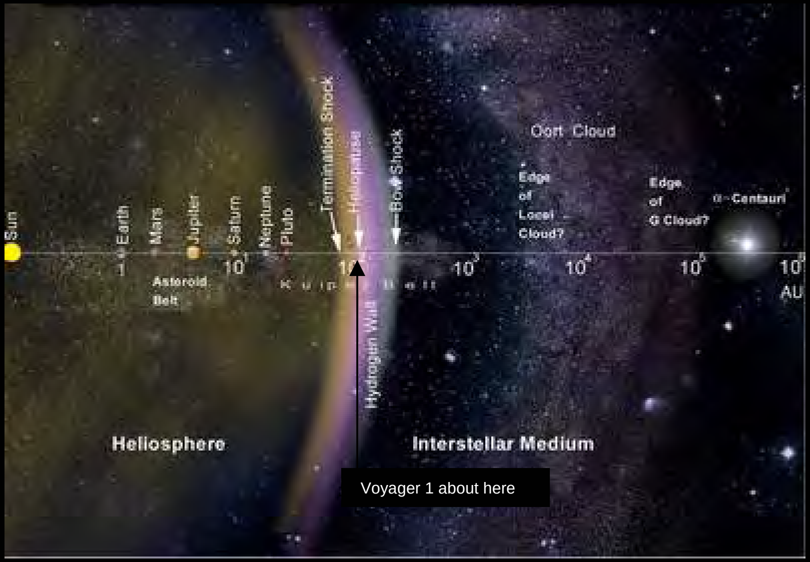
DSN Pointing Accuracy

Critical Path Management

- The whole DSN system, while robust, *is not infallible*
  - DSN Canberra was closed during Cassini encounters because of wildfires
  - DSN Madrid was closed during Magellan because of power failures
- So what do you do when you have a <u>Fallible</u> resource in the critical path?

Answer

- You back-up your data
- In this case, data is stored on each spacecraft until its safe reception is verified by Earth



Party Line

- What do you do when your Communications pipe is a Party Line?
  - You wait your turn
- DSN activities are a very constrained, time-limited resource whose utilization is planned to the minute years in advance
- So what do you do while you're on Hold?

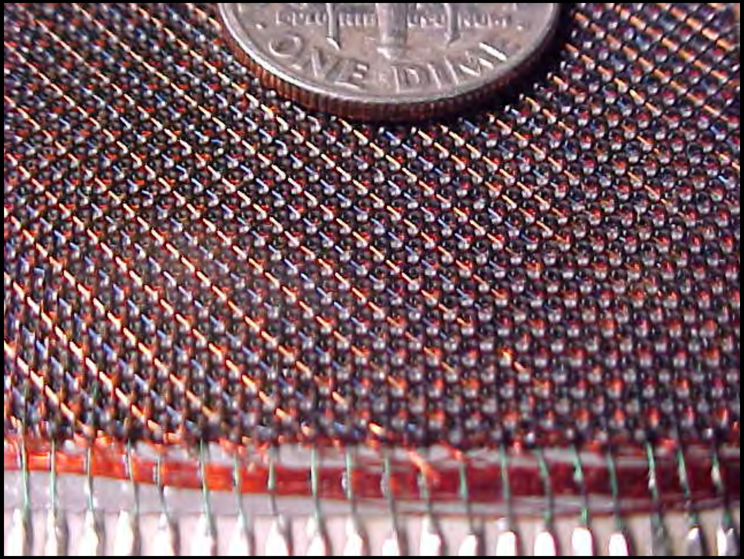
Answer

- You store your data

- JPL has some 20 spacecraft *today* that are relying on the services of the DSN.
- That does not include many spacecraft of other nations that are using DSN via treaty and agreement.

In the Beginning

- Early spacecraft relied primarily on two methods of data storage
  - Core and Tape Recorders
  - Core was used at first as it is lightweight and robust
  - The demand for data storage forced a move off of Core and onto Tape Recorders and then into Solid State
    - Is anyone aware that the Space Shuttle still uses Core Memory? In CPU cage = 104K words(32b), Mass Memory unit contains 700K words
      - Speed = 400 nS, average program length = 28K words



History of Data Storage Technologies at JPL

- Core & Tape
  - Few kilobytes to > 1 Gb
    - Voyager 500 Mb, 16-track
    - Galileo ~900 Mb, multi-track, active head positioning
      - Over one-third mile of tape!
      - GLL experienced Tape sticking during imaging sequence, causing loss of data
    - Magellan 1.2 Gb, multi-track, active head positioning
      - almost a half-mile of tape!

- Solid State
  - Cassini & Chandra Missions
  - First to use Solid State - 4 Mb DRAMs -- *640* of them!
    - Double-bit error detection, double-bit error correction Hamming
      - Entire SSR is Scrubbed for errors every 42 minutes

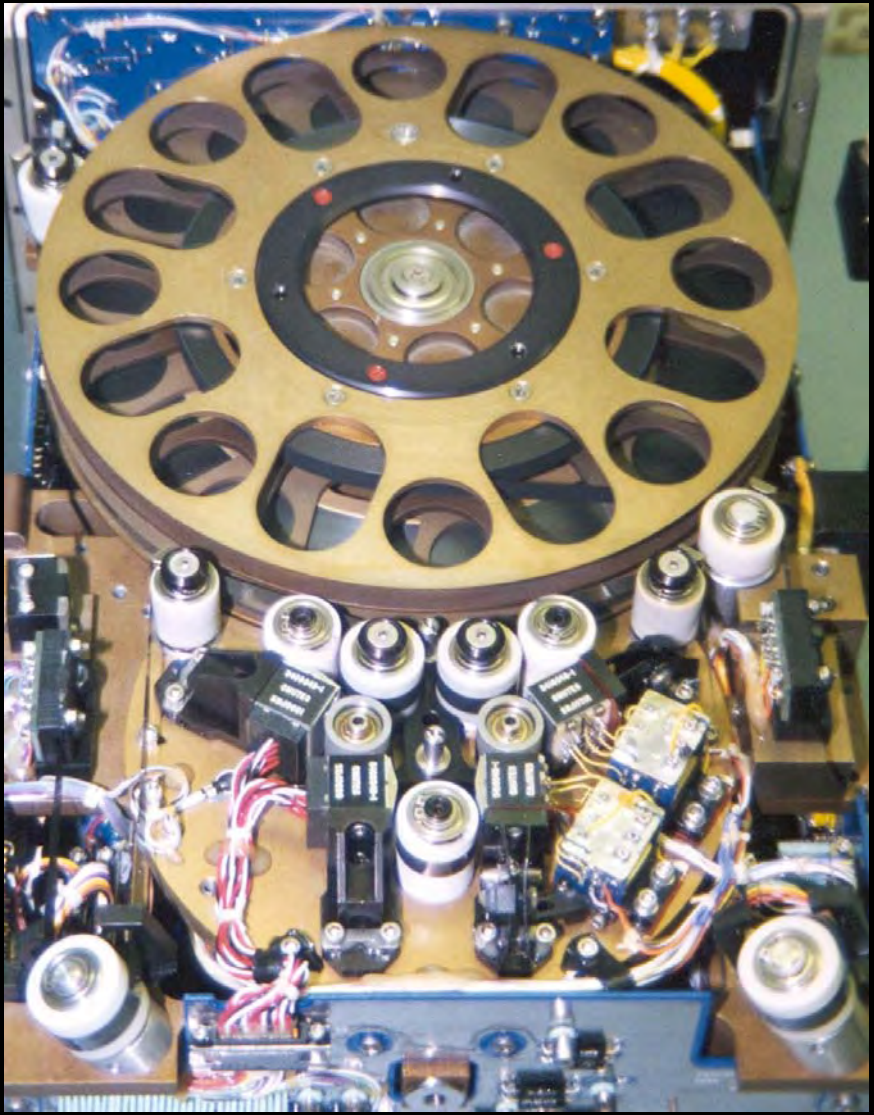
  - X2000 (Development Program)
    - 2 Gb, 3U "space" cPCI format
    - Uses twenty 128 Mb flash
      - Life-rating Varies from 100, 000 cycles LEO to 10,000 cycles in High Radiation
    - Issue is that *these* Flash devices are no longer made and very radiation sensitive

Historical Comparison

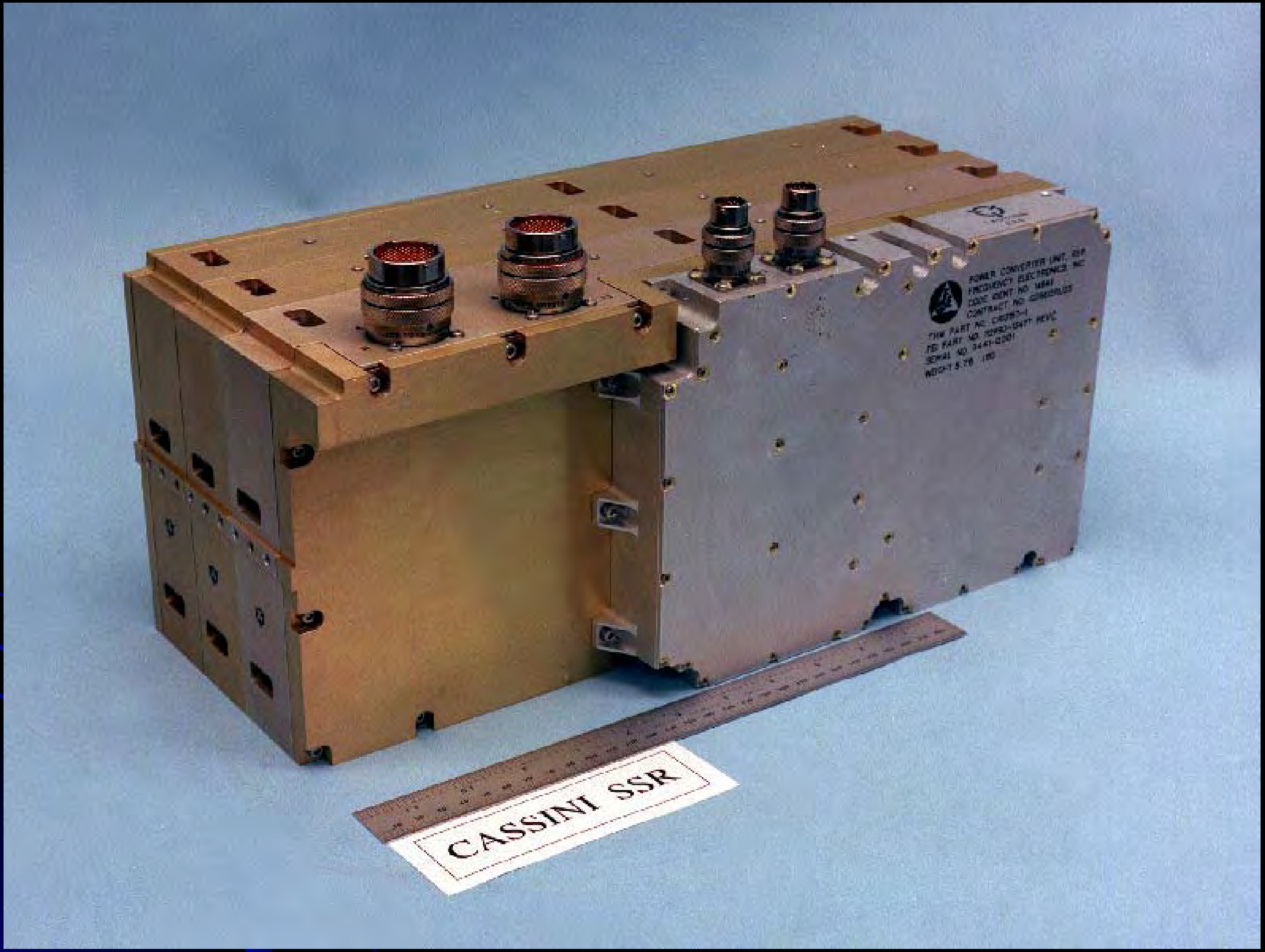
Item	MGN	CAS	MPF	X2000
Cpty	1.2Gb	2.5Gb	2Mb	2Gb
Media	Tape	DRAM	EPROM	Flash
Qty	~1/2 Mile	640	80	20
Pwr	35W, 28V	12W, 28V	7W, 5 & 12V	3W, 3.3V
Mass	22kg	17kg	4kg	1.7kg
Size	16x12x8	16x8x7	6U VME (2 cards)	3U PCI
VOLATILE	N	Y	N	N

Prior Art: GLL & MGN Recorder

- Galileo
  - one-third mile of tape
- Magellan
  - Almost one-half mile of tape

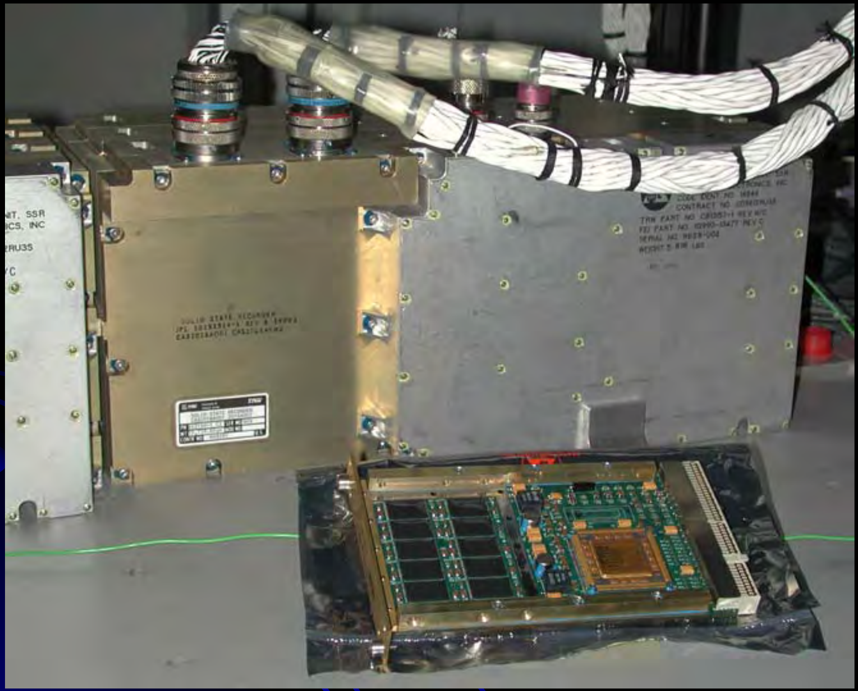


Prior Art: Cassini SSR



A Comparison of Generations

Both recorders 2 GB user data, EDAC protected



< Cassini SSR (ca. 1993)

17 kg, 12W, *VOLATILE*

(640) 4Mb chips

< X2000 NVMS (ca. 2000)

220g (unshielded), 3W,

NONVOLATILE

(20) 128Mb chips

Drivers in Data Recorders

IN THIS ORDER

- $
- Time to develop
- Capacity
- Volume
- Bit Error Rate
- Power

Money

- The implementation of any development is directly proportional to the amount of funds, and the timing of them
  - Many programs are “back loaded” meaning that the Proposers and the Grantors (NASA, Congress) almost invariably assume that more money will be available later on in years, than is available now
  - As a result, many early investigations are more proof of concept, than actual advancements
  - This also increases the likelihood of cancellation or delay

Time to Develop

- Given an appropriate amount of time, almost any new technology out there can be adapted to fit the need
- On the flip-side, once “assured” of “full funding” many timelines are so short as to preclude lengthy developments
- As a result, new technology developments for data storage quite often happen outside the realm and control of NASA and JPL

Capacity, Volume

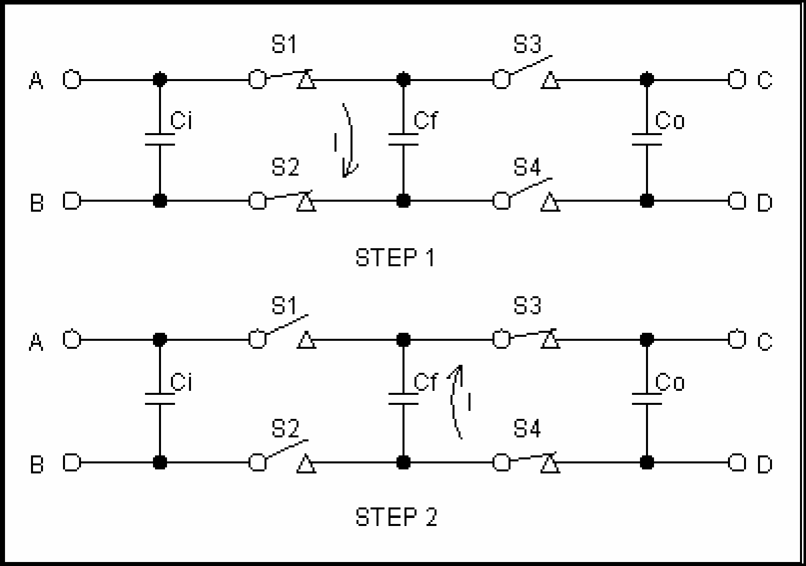
- For long term involvements the Tried and True is often selected over the New and Exciting
  - As a result, data storage elements within a spacecraft are as large as they can be versus as small as they could be

MP3 in Space

- Due to the shear cost of new technology development, we often see that a Commercial technology will be chosen, as opposed to one that is idealized for
- Hence, we must adapt our systems to use a “space unfriendly” product
  - Shielding, special screening, limit life, restricted use, robust support circuits
    - EDAC, latch-up recovery, etc etc

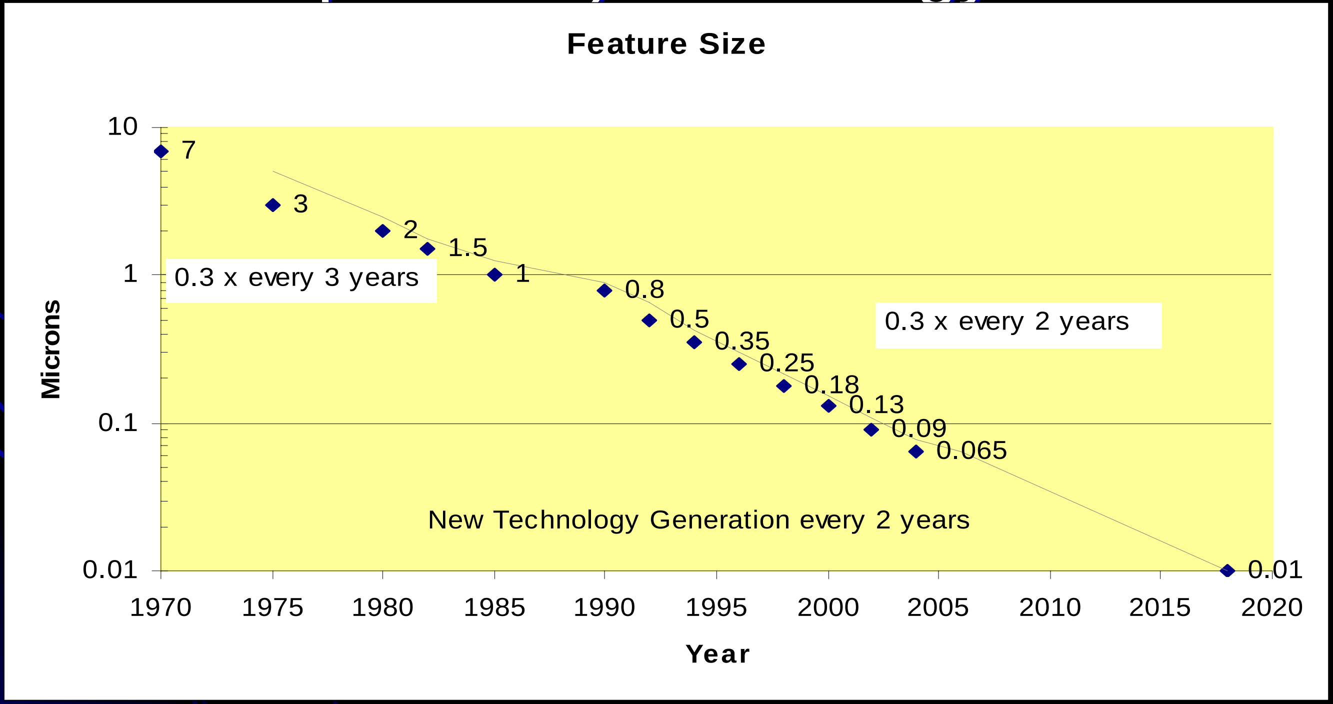
Flash: A Make-Do Miracle

- Flash: high density, high risk
- Issues: Charge Pump, Page Buffer, Leaky cells
  - Charge Pump: "Bucket Brigade" – the last capacitor in the chain has very thick oxide and hence very prone to leakage and charge trapping
    - Often dies at 7 kRads
  - Page Buffer: Data stored in the buffer prone to upset
  - Leaky cells: Given the NAND topology, if Bit and Word select transistor leak, multi-word disturb upset can occur



The Longer We Wait – Moore's Law explained

- IC technology continues to shrink.
- Delaying investment in development *today* means investing in a smaller (and more expensive to produce) technology *tomorrow*.



Bit Error Rate
The Hidden Monster

- The ability for a System to accept and correct erroneous data drives the implementation of it, the technology within it
- A System with poor Bit-error correction implementation requires the most robust elements within it.
- A System with a Robust Bit error correction implementation can use the sloppiest of storage elements
- In either case, the cost is either very large, very slow devices (C O R E!), or many extra elements to make up for the slackers

Other Technologies

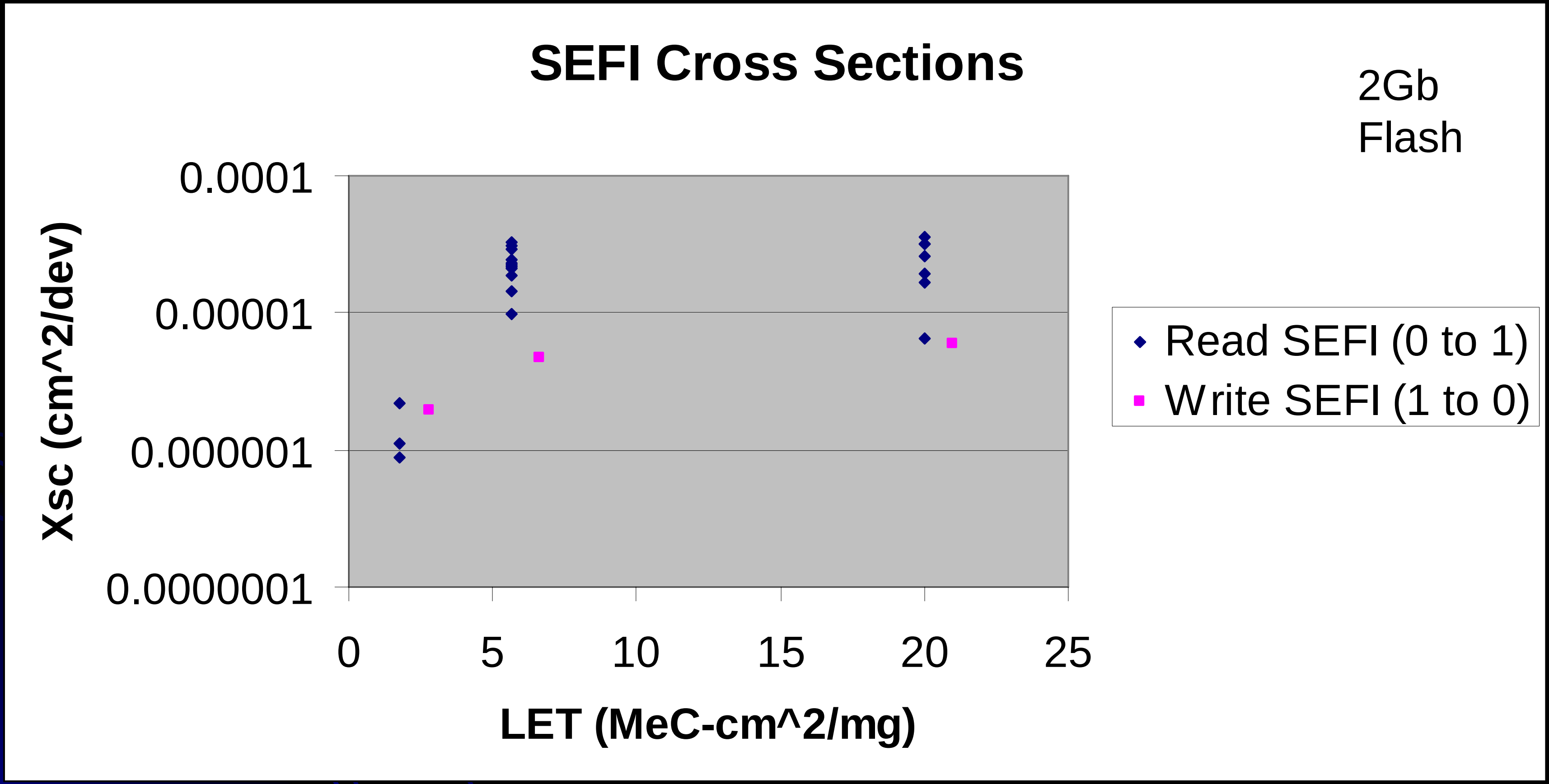
- A myriad of Acronyms abound for memory technologies: MRAM, ORAM, PRAM, FeRAM, FRAM, CRAM, and on and on and on…
- They all identify the pursuit to do something better
- Some work; others relegated to the Museum
  - Does anyone remember the Bubble Memory?

Intel 1 Mbit Bubble

But Materials Aren't the Only Problem

- An issue that was first noted with Cassini DRAMS: *SEFI* Single Event Functional Interrupt
  - A change in the Device's Internal STATE MACHINE
    - Forward? Back? Lost?
      - "Self-repair" (resynchronization) has more to do with the machine designer than it does with the state machine itself.
    - Changes in state machine are almost always disastrous for large amounts of data
  - One way out of this is to include the probability of SEFI in the Bit Error Rate requirement

Heavy Ion Testing to Determine SEFI

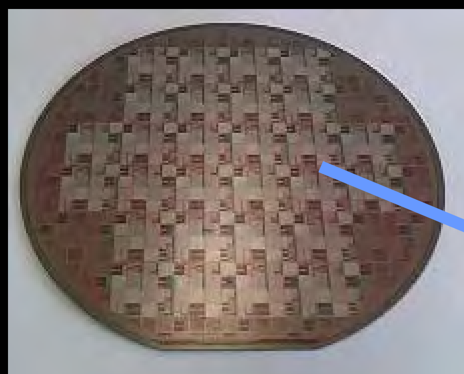


JPL Pursuits

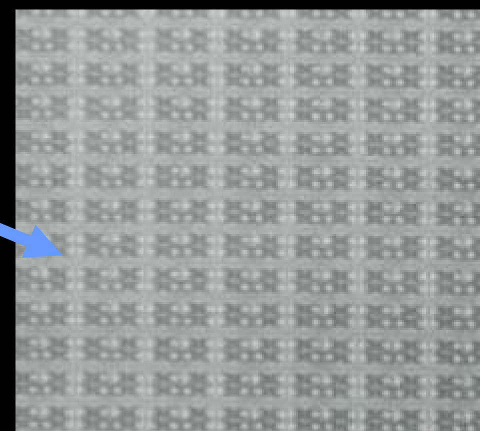
- In its need to find radiation tolerant memories that don't require copious amounts of shielding or exotic schemes to control Bit Errors and SEFIs – JPL has pursued:
  - MRAM: Magnetic memory
  - CRAM: An Ovonic – Phase Change memory
  - FeRAM: Ferro-electric memory
  - Hard Disk Drive

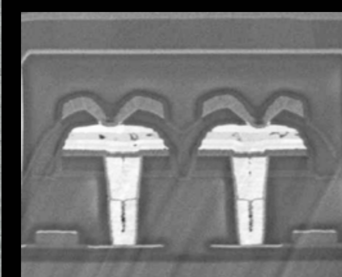
JPL Sponsored Ferroelectric on SOI

- Foundry: OKI
- FD-SOI, 200 – 300 kRads capable

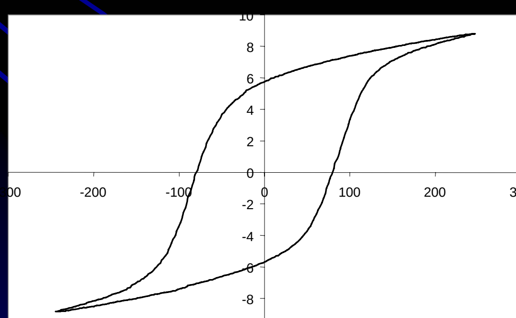


Test Wafer



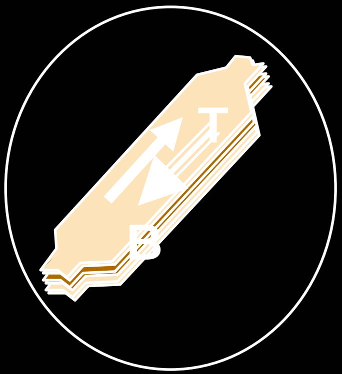


Ferro-electric capacitor array

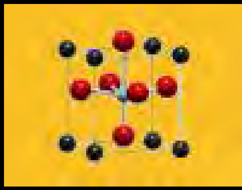


Endurance & Wearout Concerns

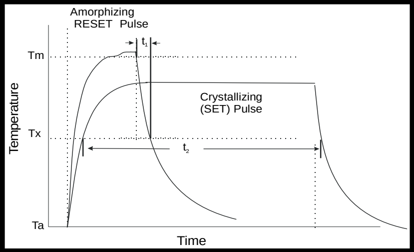
- MRAM (GMRAM):
  - Cycles: Unlimited (Some concerns re: localized heating, diffusion of mag layers)
  - Wearout- None identified: magnetic dipole alignment
  - Sensitivity Mechanism: Damage Clusters
  - Retention: > 10 years, 2mVread signal
    - Retention time temperature sensitive



- FRAM / FeRAM
  - Cycles: ~ 10^{10} to > 10^{12}
  - Wearout: Accumulation of residual charge
    - Incomplete polarization of crystal, esp. a defect boundary
  - Sensitivity Mechanism: Hydrogen from processing
  - Retention: > 10 years, near-Vdd signal
    - Refresh may be required as cells wearout



- Ovonic:
  - Writes: ~ 10^{10} to > 10^{12}
  - Wearout: Damage Clusters
  - Sensitivity Mechanism: Incomplete Heating, profile across die
  - Retention: > 10 years, near-Vdd signal



The Issue Is…

- In the overall scheme of things, it is very expensive for any one program to fund the development of new technology.

- For any technological development to be successfully implemented at JPL –
  - It must be compelling *or*
  - Have an outside sponsor *and*
  - It should not be entirely reliant upon one project for survival

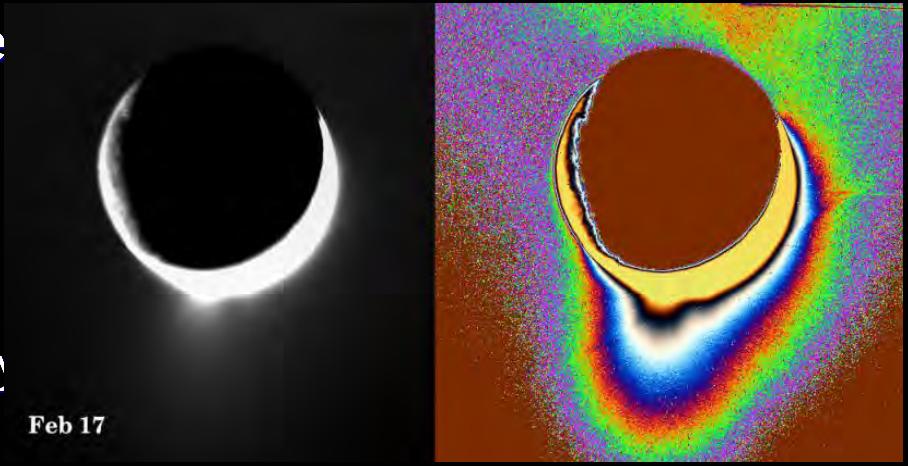
Developments Caught in the Headlights

The cancellation of the Prometheus program impacted several major developments

1. CRAM – BAE Systems. This development continues with AFRL money. 4Mb Engineering samples can be ordered now with 3Q06 delivery
2. FeRAM –
    1. Oki: Remarkable retention characteristics; dopant profile change to accommodate Back Channel threshold affected radiation characteristic
    2. TI: This was a slow starter. As a result the product never left the design stage. TI continues to pursue Ferroelectrics for their own purposes
3. Seagate HDD: In a surprising turn of events, we actually found a company that was willing to at least see what it takes to make a Hard Disk Drive space friendly: long life, good radiation tolerance. The answer: it is Entirely Feasible

Where we go from Here

- The two main projects at JPL do not require radiation tolerant memory and therefore (unfortunately?) Flash is probably good enough
- But don't give up!
  - JPL's Cassini mission recently discovered WATER spewing out of geysers on the Saturnian moon Enceladus
    - A complete surprise – we were all jazzed about what was causing the smog around Titan



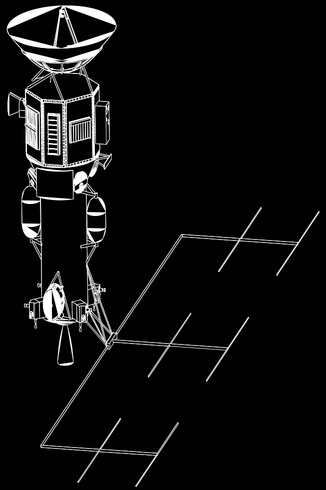
Spectrographs of Enceladus Water Geyser

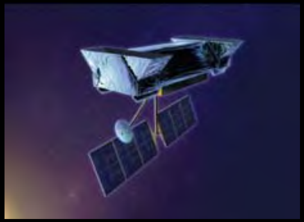
Enceladus or Bust?

- Saturn has a nasty radiation environment – though not nearly as bad as Jupiter – but it is bad enough that Flash just won’t do.
- And a Biological science mission would require tens of gigabytes of data storage
  - Would a disk drive be the right answer?

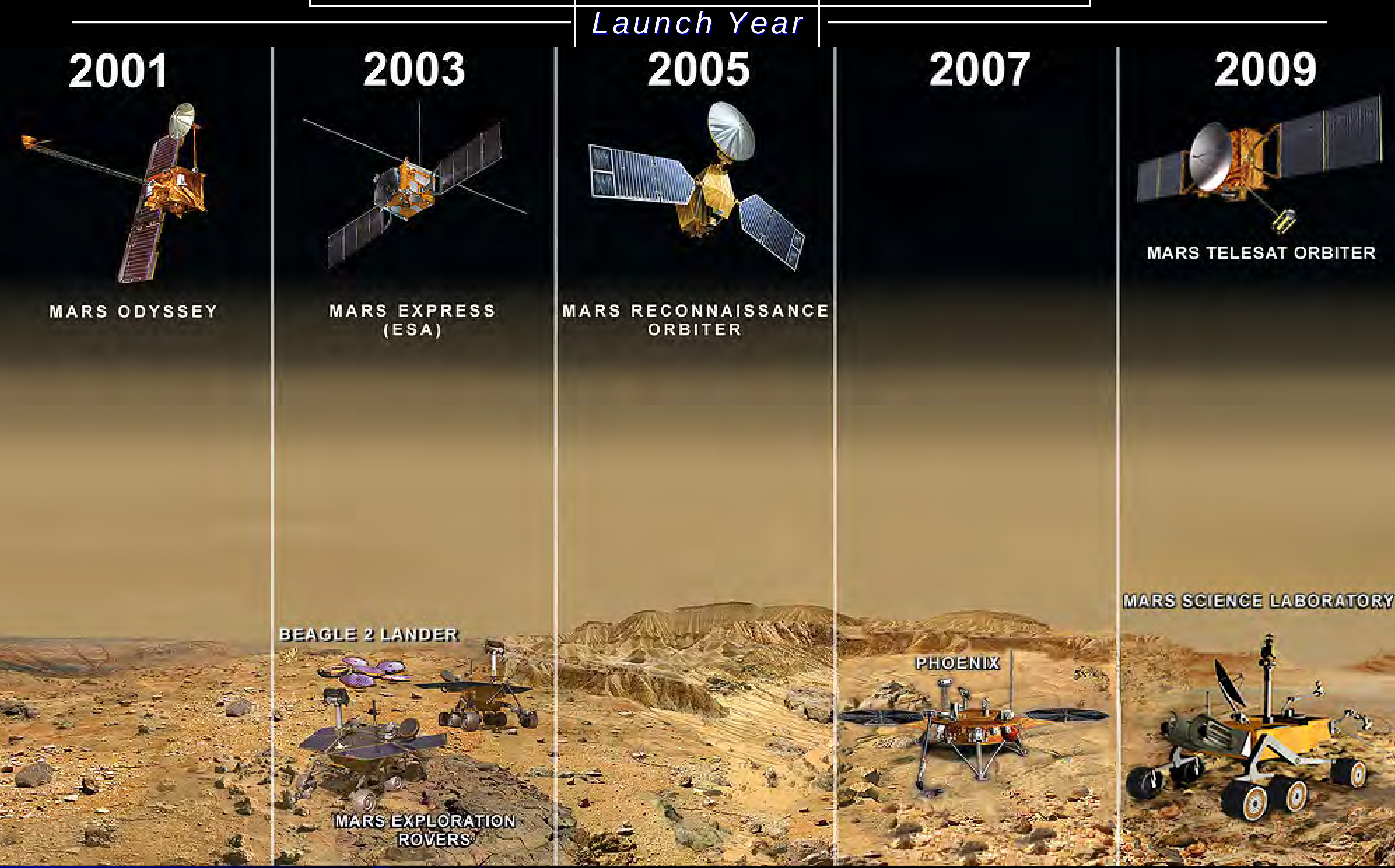
Planned Future Missions and Data Capacities

- Mars Science Laboratory – 2009 -- 32 Gb (using X2000 cards)
  - Twice as long and three times as heavy as the Mars Exploration Rovers
  - Mars Science Laboratory will collect Martian soil samples and rock cores and analyze them for organic compounds
- SIM PlanetQuest – 2011 -- 16 Gb (using X2000 cards)
  - Search for Large Planets encircling other stars
- Europa Orbiter –- 24Gb
  - Planned Science Mission to Radar Survey Ice Fields for Liquid Oceans





Mars Exploration Program



Memory Development Needs

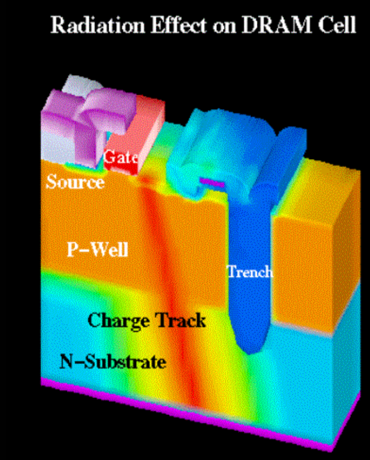
- The Truly Universal Memory
  - Near term goal is development of radiation tolerant high-speed non-volatile memory
    - A Replacement for High Speed Volatile as well as Non-Volatile memory devices
  - 32Mb & 64Mb Ferro-electric devices have been proposed
    - <10 nS cycle time, 1E13 endurance, 1 to 10 year retention
  - Approx $6 million (US), 30 month program proposed to develop “Flash Replacement Device”

- A Space Rated Hard Disk Drive
  - Rugged, dependable
  - Radiation Tolerant

Radiation is a Concern for Commercial Manufacturers, *too!*

- JPL: Natural Space Environment:
  - Trapped particles
    - Protons, electrons, heavy ions
  - Transient Particles
    - Solar event protons and heavy ions
    - Galactic Cosmic Rays
- Commercial: High Altitude and Terrestrial Environment
  - Secondary Particles
    - Neutrons, protons, pions
  - Ground Level Contamination
    - Transuranic decay products
- Commercial companies are more and more concerned with radiation upsets from the environment and sensitivity of the smaller circuits.
  - *They will devise commercially viable solutions to **certain parts** of the overall radiation problem that JPL can leverage.*
  - *JPL still must find overall <u>space</u> solutions.*

Did you know that the Concorde suffered particularly severe Nav-System in-flight failures due to data upsets caused by Cosmic Rays?



Did you know that the even 2nd Generation DRAMs suffered data upsets eventually traced to the package itself?

The Solution? We’re Here to Help & To Listen

- Given the readily seen synergy between space and commercial pursuits a *Partnering* with Industry is actively being pursued and Invited