Mars Exploration Rover
Spirit Sol 18 Anomaly

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Instruments (APXS, MB, MI, RAT)

- Pancam (pair)
- Navcams
- Pancam Mast Assembly
- Capture/Filter Magnets
- Front Hazcams
- Instrument Deployment Device
- In-Situ Instruments (APXS, MB, MI, RAT)

- Mini-TES fore-optics
- Low Gain Antenna
- High Gain Antenna
- Solar Arrays
- Rocker-Bogie Mobility System
- Warm Electronics Box
Phases of Sol 18 Anomaly Response

- Discovery
- Determination of Vehicle State
- Regaining Control of the Vehicle
- Diagnosis
- Repair and Restoration of Normal Operations
- Follow-up Mitigations
- Lessons Learned
Sol 18
- Weather issues at Canberra station during morning command load
- Off-nominal beep indicates failure to load commands
- Later use of Madrid station with mid-day, reduced command load
- Nominal beep indicates successful load — looks good
- No afternoon high-gain X-band DTE pass — hmm
- No afternoon Odyssey relay pass — uh oh

Not receiving X-band pass could be caused by any number of things, such as mispointing rover or Earth antenna, failed sweep, etc.
Not receiving UHF pass could be caused by timing error, orbiter or rover sequencing error, etc.
Not receiving either pointed to a much more serious issue:
- Two different radios, two different paths, two different planning processes
- Problem upstream of the radios indicates fundamental, mission limiting or mission ending disability
Determination of Vehicle State (1)

- **Sol 19**
  - Repeated attempts to communicate fail until mid-afternoon
  - No nominal or fault communications windows observed
  - Shortly before Earth set, send beep command at lower data rate, see it!

- **State:**
  - Not completely dead — important and encouraging bit of information
  - Commandable (we thought)
  - No other data on rover health, no modulated data received (no Odyssey relay pass again)

- **Sol 20**
  - Morning attempts with same beep command fail
  - Observe partial X-band window! — 30 min window cut off after 10 min
  - Data is gibberish, though one message decoded indicating reboot
  - Command another modulated X-band window and get 20 out of 30 min
  - Receive long-desired engineering and health update packet
Determination of Vehicle State (2)

- **State**
  - Rover has experienced multiple reboots
  - Battery is low, temperatures high — uh oh
  - Battery and temperature state consistent with much long rover up time
  - Vehicle is continually rebooting on 15/60 min cycles resulting in:
    - Failure to go to sleep — within a few sols will drain battery, lose thermal control
    - Intermittent commandability, due to reboots
    - Intermittent communication sessions, due to reboots
  - Don’t know why — must be something persistent between reboots (non-volatile memory or hardware failure)

- **Sol 20 continued**
  - Attempt to command the rover to sleep, to charge battery — fail
  - Attempt to delete afternoon Odyssey pass to save energy — fail
  - Losing the race against time — rover has a severe case of insomnia, is babbling incoherently, doesn’t understand simple commands most of the time, and energy going downhill
  - Odyssey pass works! (first time since Sol 17) — receive big chunk of valuable data

- **State**
  - Messages indicate reboots related to flash memory — makes sense, non-volatile
Regaining Control of the Vehicle

- **Sol 21**
  - Radio provides hardware commands — no software decoding required
  - One of those commands instructs next reboot to not use flash file system
    - Called "crippled mode" since small, volatile file system inadequate for science
  - Try issuing crippled mode commands in morning — no joy
  - Try again with immediately following system reset hardware command
  - Joy! — system reboots and appears normal
    - Communications sessions full length, normal data content — no gibberish
    - All commands work first time
  - First action: command Spirit to sleep a little after noon
    - Successful, has entire afternoon of sunlight to recharge batteries
    - Won the race against time

- **Not fixed** — will continue to wake up each morning in reboot loop
  - Need to issue crippled mode and system reset commands every morning until fixed
  - Can't use flash file system, severely limited science capability

- **Was not the last card we had to play**
  - Had another hardware command to reboot with default parameters instead of using remainder of flash and EEPROM (another piece of non-volatile memory)
Diagnosis

• Flight software team rapidly converges on theory within days:
  - Data provides important clues pointing to mount of file system on reboot
  - A failure to mount would result in repeating reboots observed
  - Mounting copies the flash file system directories into memory
  - If the size of the directories exceeds the fixed allocation, the mount will fail
  - A previously unknown behavior of the flash file system is the mechanism for unexpected directory growth

• Sols 22-26
  - Recovered use of high-gain antenna for more data return
  - Returned selected portions of flash for investigation
    - Returning all of flash would take weeks
  - Extensive work in the rover testbeds on Earth reproduces behavior
  - Four failed attempts at getting stack trace from Spirit to confirm theory
  - Without confirmation, we can’t be sure we know what caused problem
  - Without confirmation, problem could reoccur on Spirit or Opportunity
Repair and Restoration of NormalOps

• Sol 27
  - Final attempt at stack trace successful, confirms theory
  - Deleted several old cruise directories from flash file system
  - Reboot with flash file system succeeds! Normal operations restored

• Sol 28
  - Restored operations of Pancam and Mini-TES
  - Downlinked key science data from flash

• Sol 29
  - Determined state of arm
  - Conducted remote sensing science — back in business!

• Sol 30
  - Terminated low-power fault response
  - Continued science operations
Follow-up Mitigations

- Sol 31 and 32
  - Comprehensive test of flash memory hardware
  - Complete re-format of flash file system to start clean
- Monitored free memory daily
- Limited the creation of PMA and HGA slew data products
- Even by Sol 53, we still had not fully characterized the problem
  - Expected that deleting many data products would increase free memory
  - It didn’t
- By Sol 71, realized entire directories must be deleted
  - Memory not recovered by deleting individual files
  - Tested successfully on Opportunity by deleting PMA/HGA slew directories
- Sol 95-98
  - Loaded new version of the flight software that eliminated problem entirely
Final anomaly document completed July 5th (Spirit Sol 180)

Contributing causes to anomaly:
- Behavior of commercial flash file system software not fully characterized
  - Assumed that behavior a function of number of files and sizes files — not sufficient
- Allowed exception to no-memory-allocation-after-boot rule
  - Did not adequately investigate and characterize exception
- 10-sol "long-duration" test before landing not long enough or complex enough to reveal the problem
- Free memory not monitored before anomaly or in test (significant margin illusory)
  - No EH&A channel for free memory, available only in special data product
    - Had there been such a channel, an alarm limit would have caught this early
  - Not monitored in ORTs — could have seen inklings of this in test
  - Not monitored in flight, though available occasionally in data products
    - Could have caught this before Sol 18
- Cruise files not immediately deleted after landing (attempted on Sol 16!)
- Compressed development schedule limited testing and investigations
Lessons Learned (2)

Contributing causes to recovery:

- Crack team
  - Tremendous expertise and experience in the operations team
  - Team communication and trust built over years of development and months of flight
  - Use the developers with in-depth knowledge of the system: you built it, you fix it
- Rapid detection of anomaly and rapid response
- Fault protection responses and communications behavior assisted in telemetry, commandability, and reducing loads
- Surface of Mars is a very stable and predictable platform
  - No attitude uncertainty for solar power and low-gain communications
- Foresight in consideration of repeating reboot scenario and non-volatile states:
  - Accepted risk of mission loss due to repeating reboots, so not fully mitigated
  - Nevertheless, hardware commands provided to bypass non-volatile memory
    - The X-band radio was our only friend on that rover
  - Delays placed in reboot cycle of 15 and 60 minutes to permit recovery
  - Commanding enabled early in reboot process
- Extremely flight-like testbeds available in operations
Epilogue

- MER was required to operate both rovers through Sol 91, and drive each rover 600 meters across the surface.
- Spirit and Opportunity are still working and collecting valuable science as we speak, with all instruments operating:
  - Spirit is currently on Sol 264 and has driven 3.6 kilometers.
  - Opportunity is on Sol 243 and has driven 1.6 kilometers.
  - We expect them to continue to operate for many more months to come.
- Opportunity discovered evidence of an ancient body of water at Meridiani Planum, rewriting the textbooks on Mars and suggesting an environment that was suitable for life.
- Spirit drove to the Columbia Hills to find evidence of an ancient lake filling Gusev Crater — Spirit is at the hills now and is looking...