



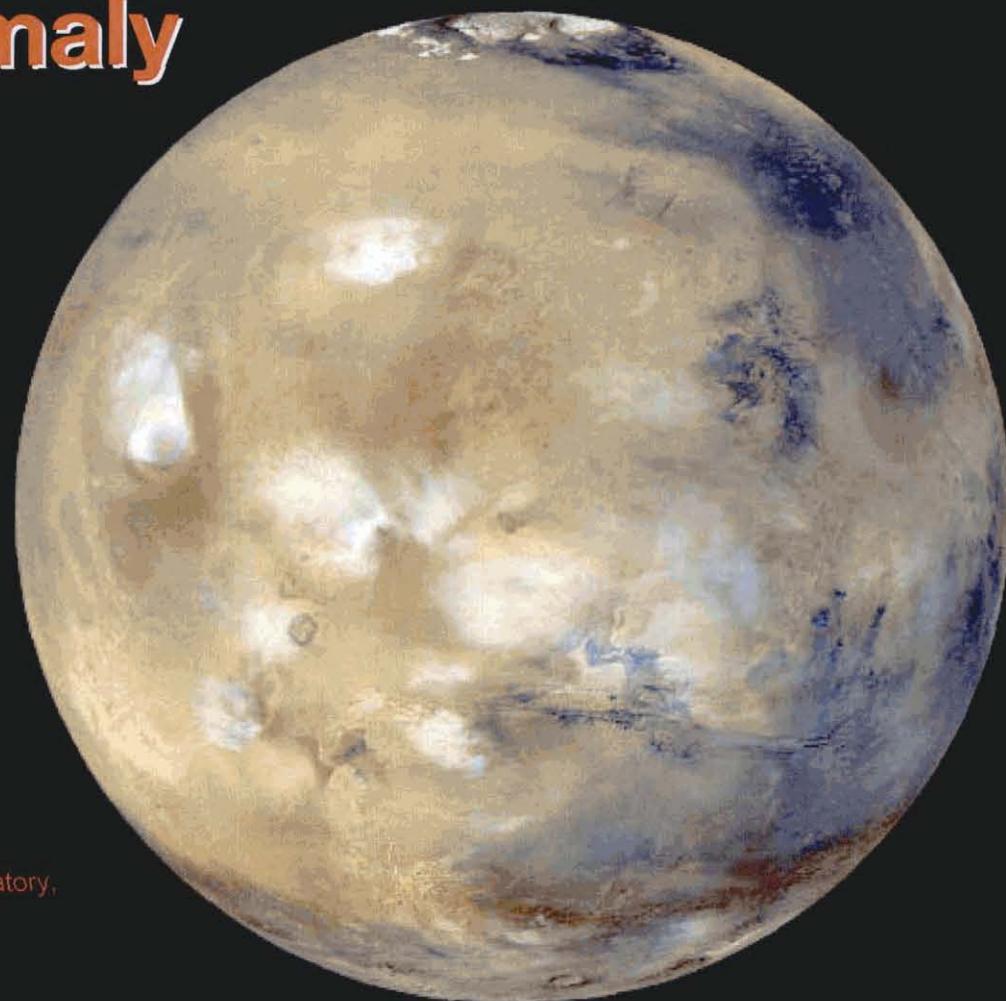
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Mars Exploration Rover

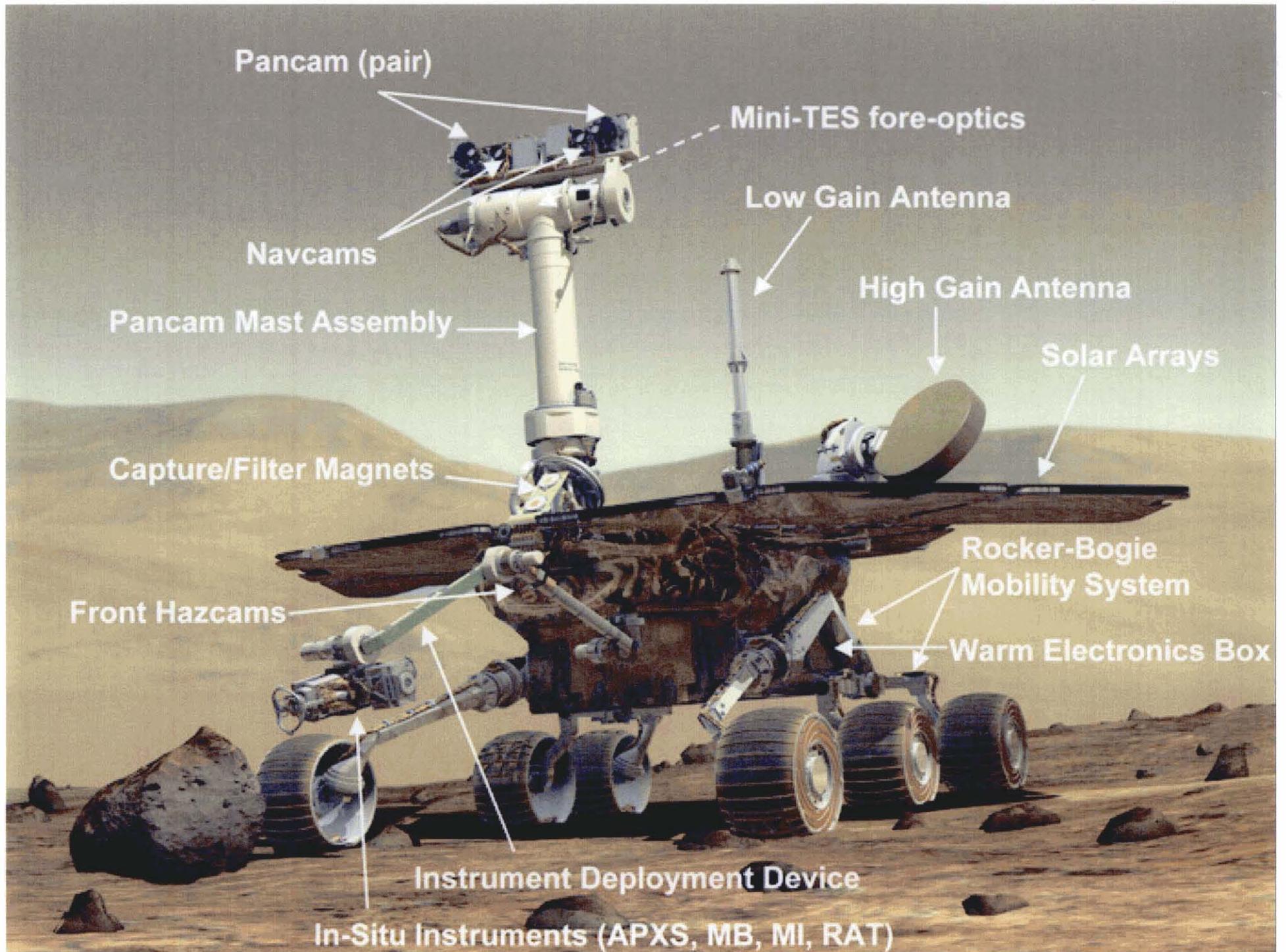
Mars Exploration Rover Spirit Sol 18 Anomaly

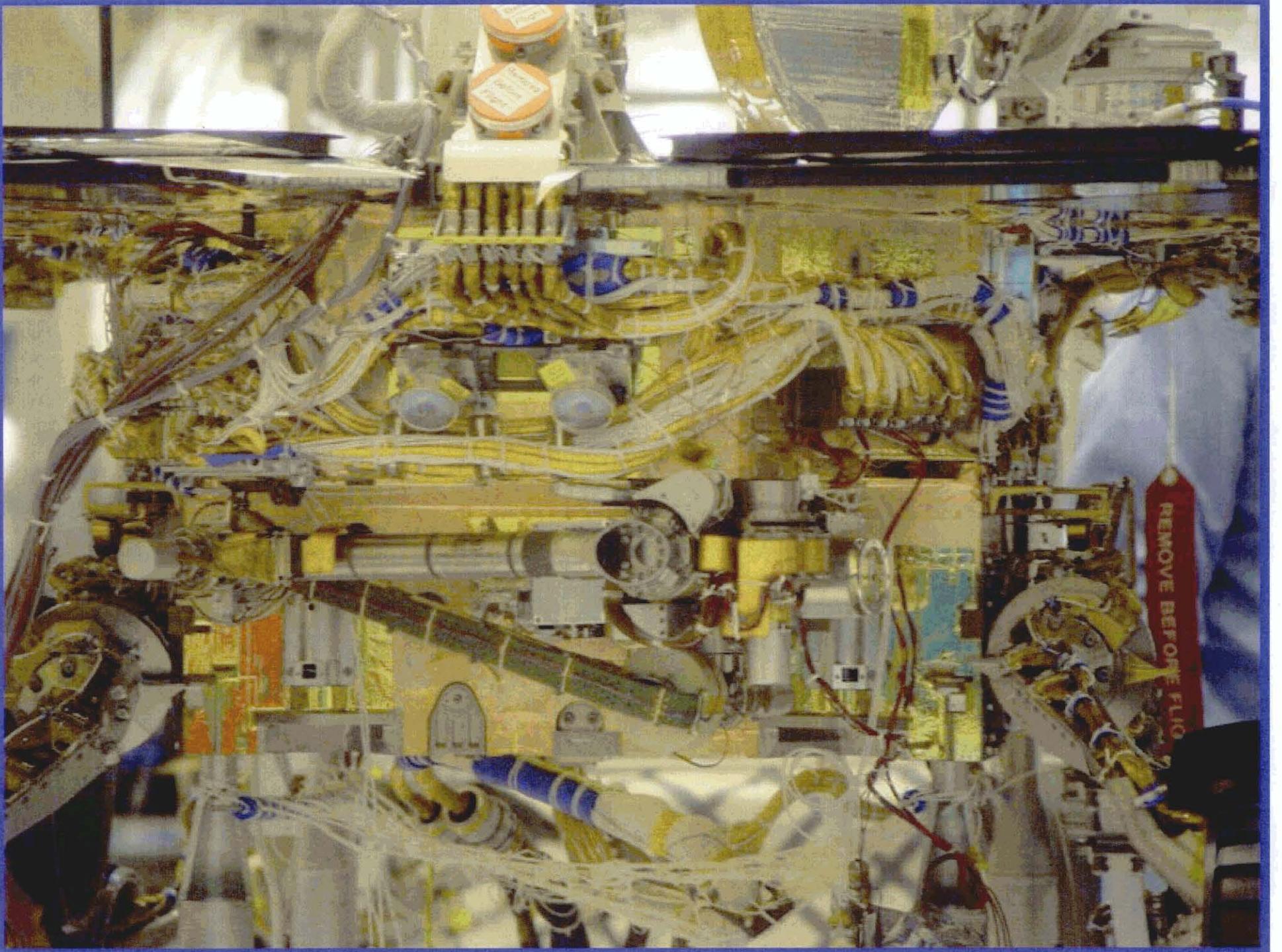
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Phases of Sol 18 Anomaly Response



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- Discovery
- Determination of Vehicle State
- Regaining Control of the Vehicle
- Diagnosis
- Repair and Restoration of Normal Operations
- Follow-up Mitigations
- Lessons Learned



Discovery



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- 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)



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- 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)



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- 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



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- 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



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- 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 Normal Ops



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- 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



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- 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
- Sols 95-98
 - Loaded new version of the flight software that eliminated problem entirely



Lessons Learned (1)



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- 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)



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- 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



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- 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 ...