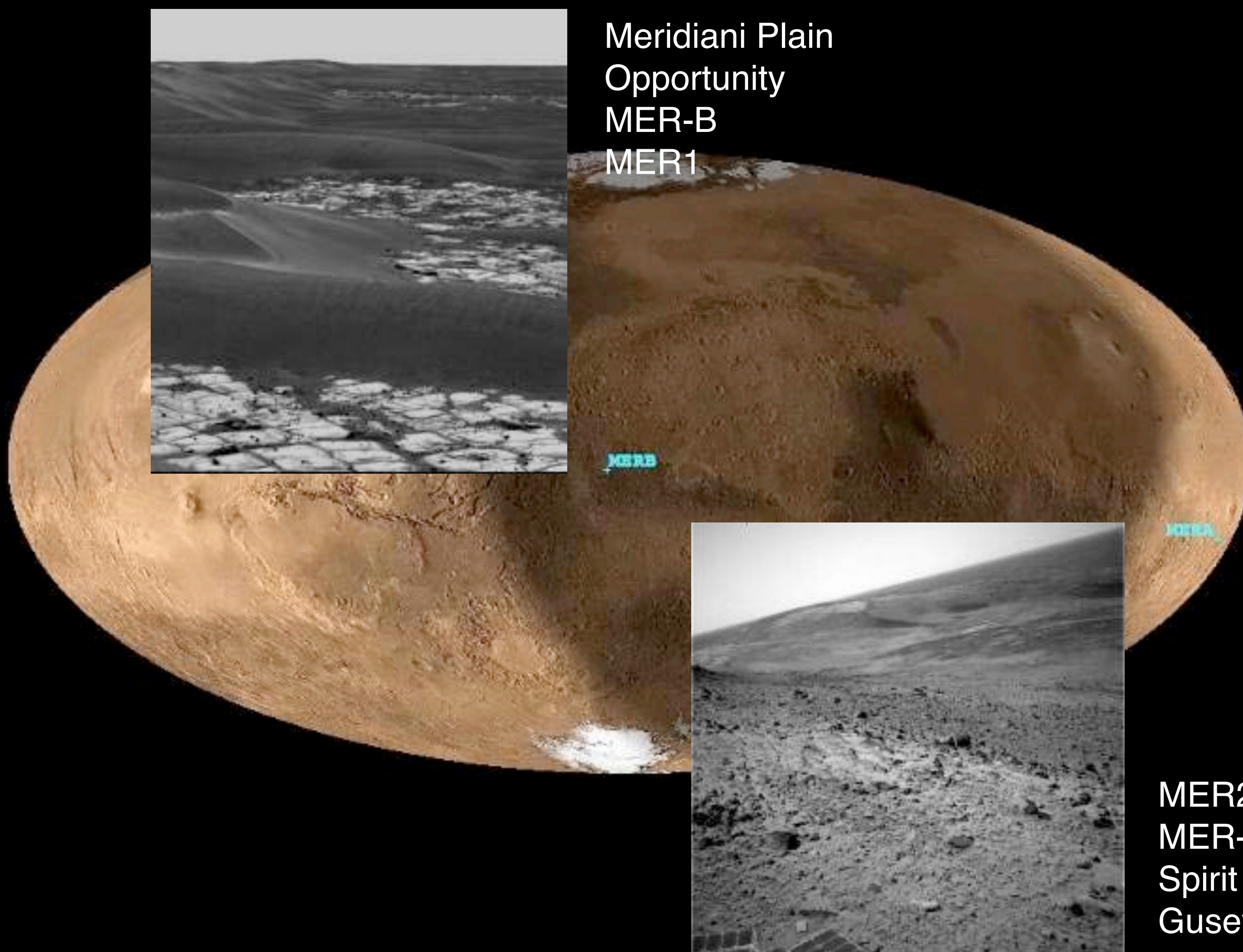
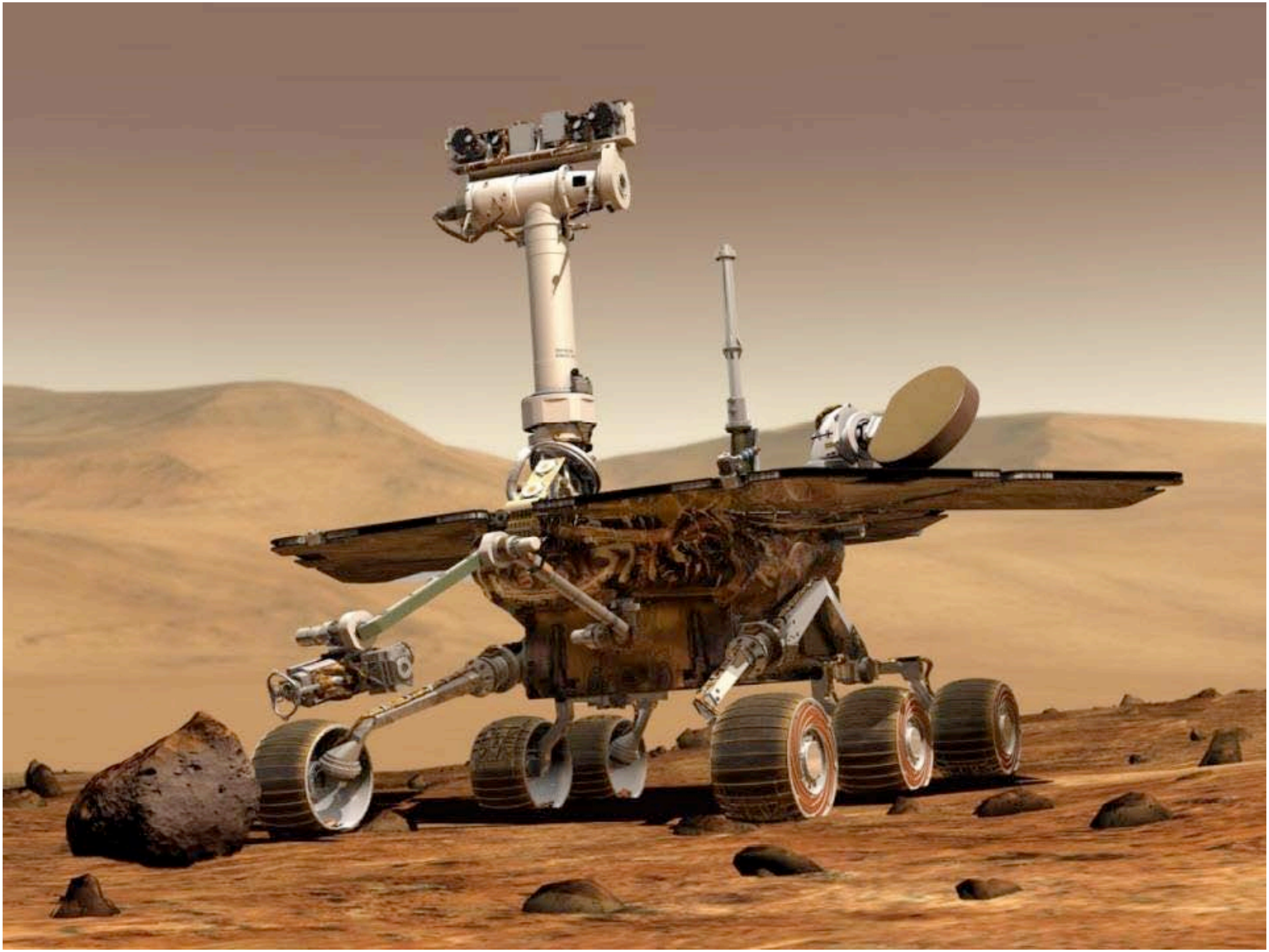
Mars Exploration Rovers Turning Three Months Into Five Years

J. Richard Morris
Caltech/JPL
NASA

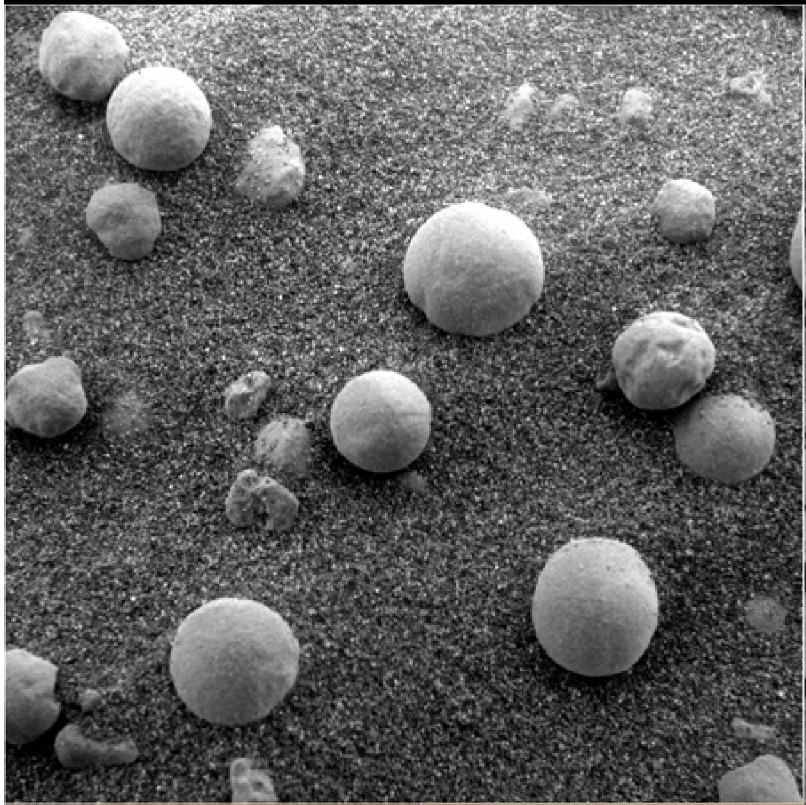
Agenda

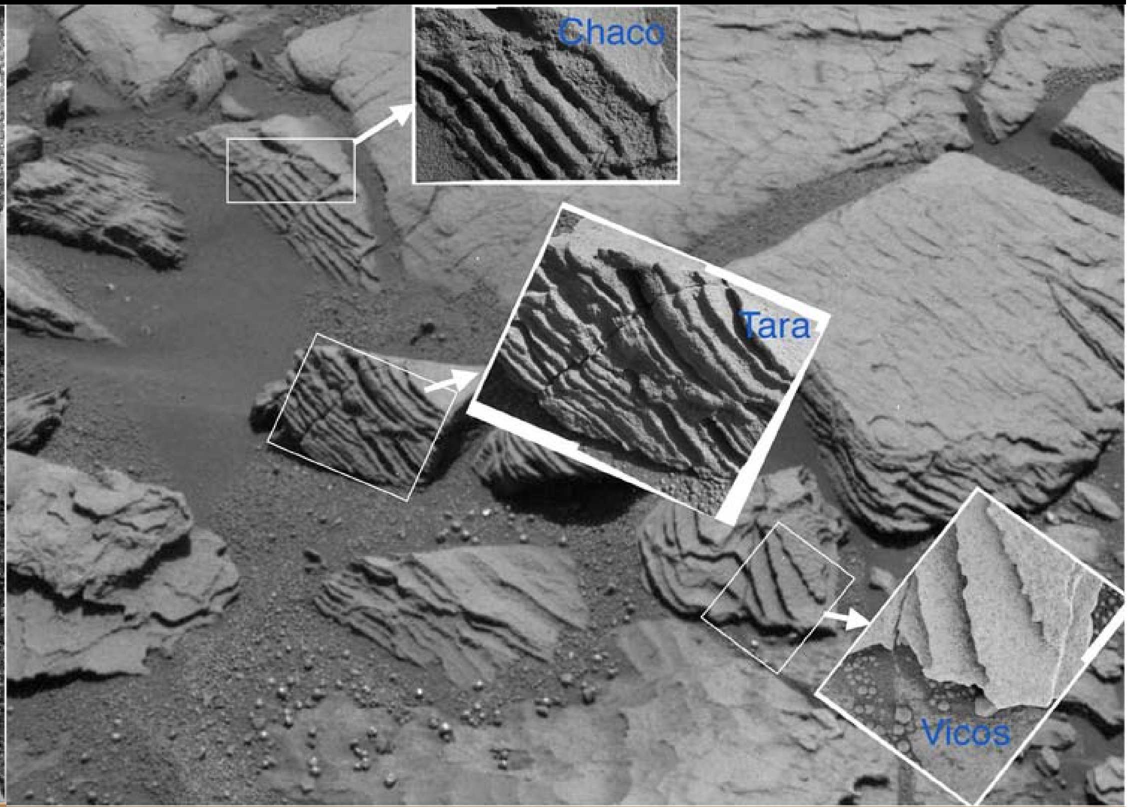
- Rovers
- Science
- Process
- Operations Stories
  - Conjunction versus Flight Software Load
  - Dust Storm
- Pictures

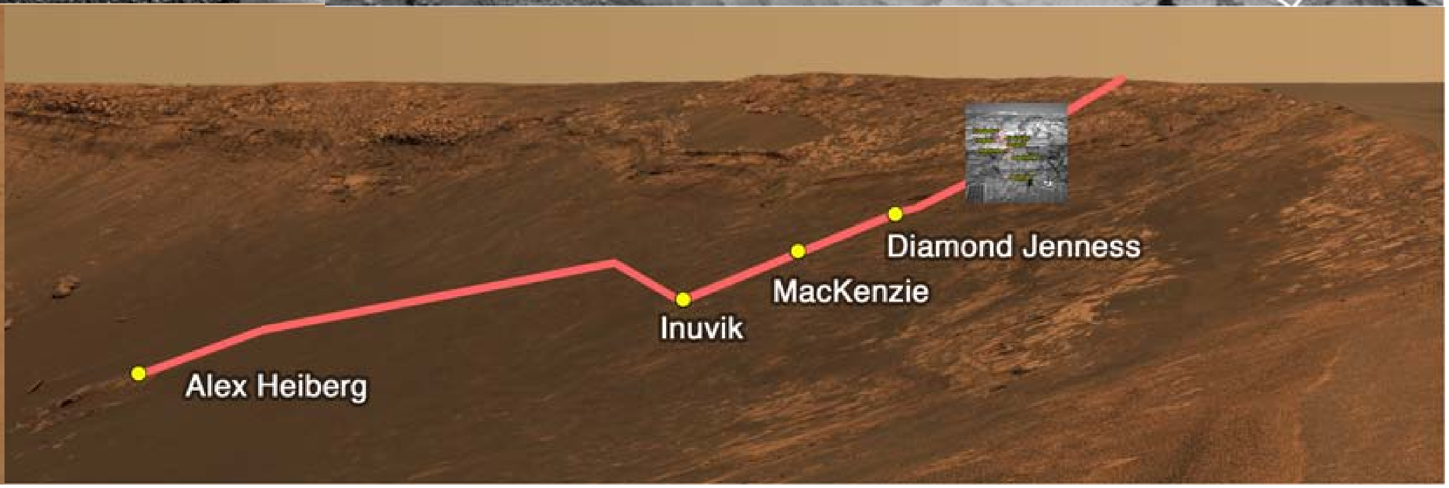

Meridiani Plain
Opportunity
MER-B
MER1
MER2
MER-A
Spirit
Gusev Crater



Science



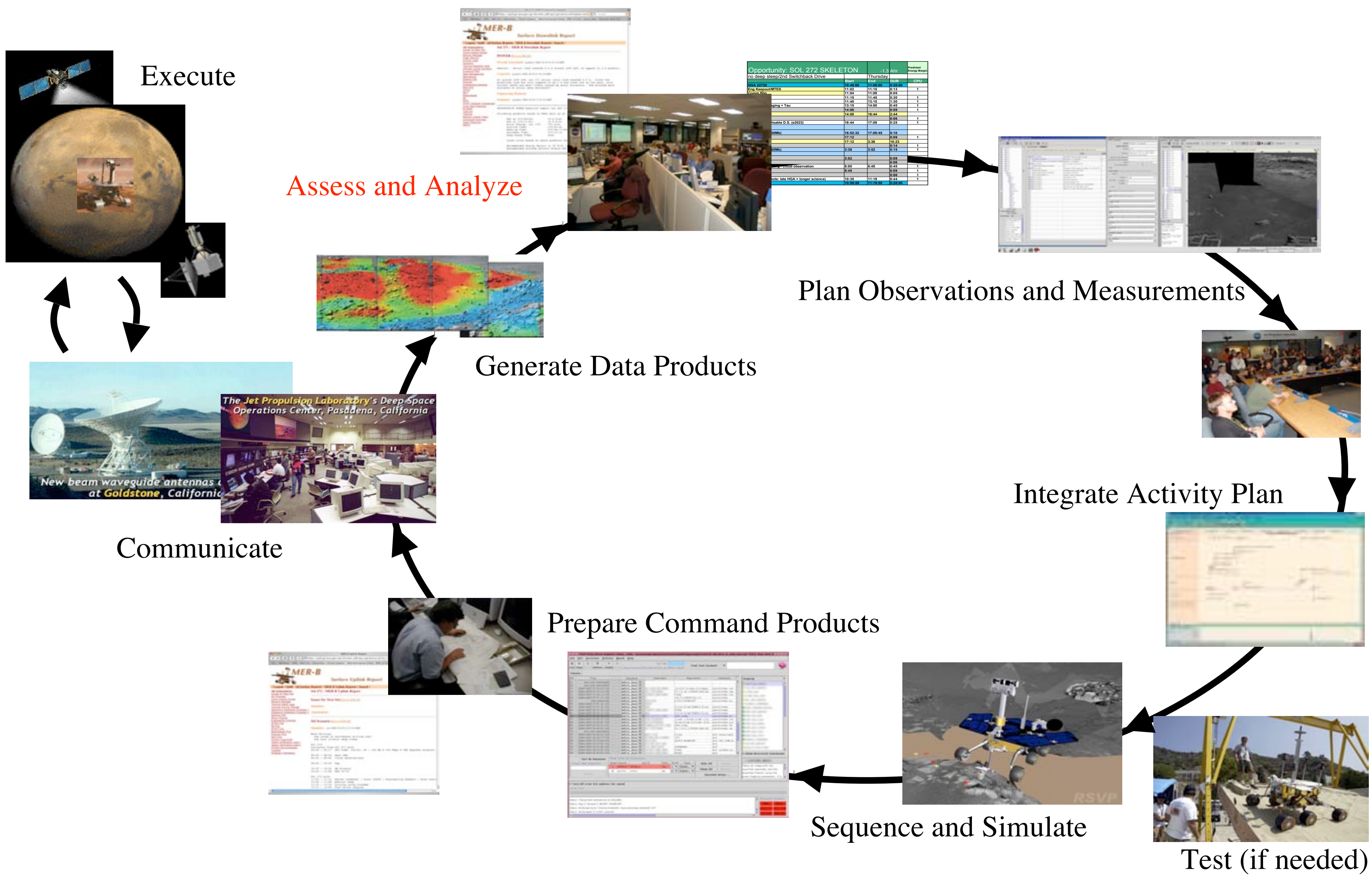

Chaco
Tara
Vicos


Diamond Jenness
MacKenzie
Inuvik
Alex Heiberg

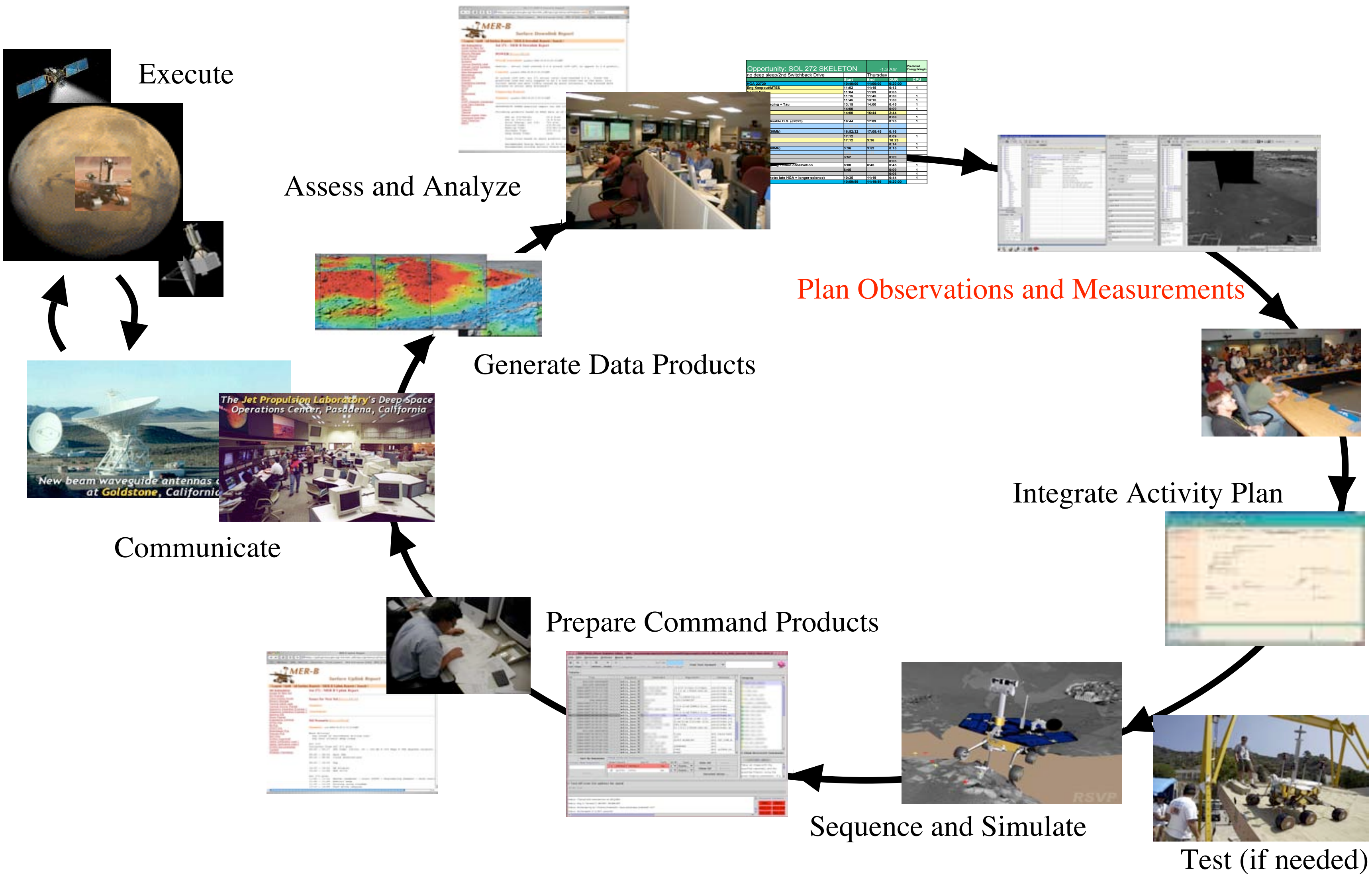
Science

- Spirit and Opportunity have allowed us, for the first time, to delve into the history of Mars using the tools and methods of a field geologist.
- They have found compelling chemical and physical evidence for the effects of water both on the surface and underground in Mars' past.
- Starting from each landing site, the rovers have been able to investigate many diverse locations with very different geological settings and histories, using the vertical access afforded by excavated craters and uplifted hills to study different rock levels corresponding to a range of geological ages.

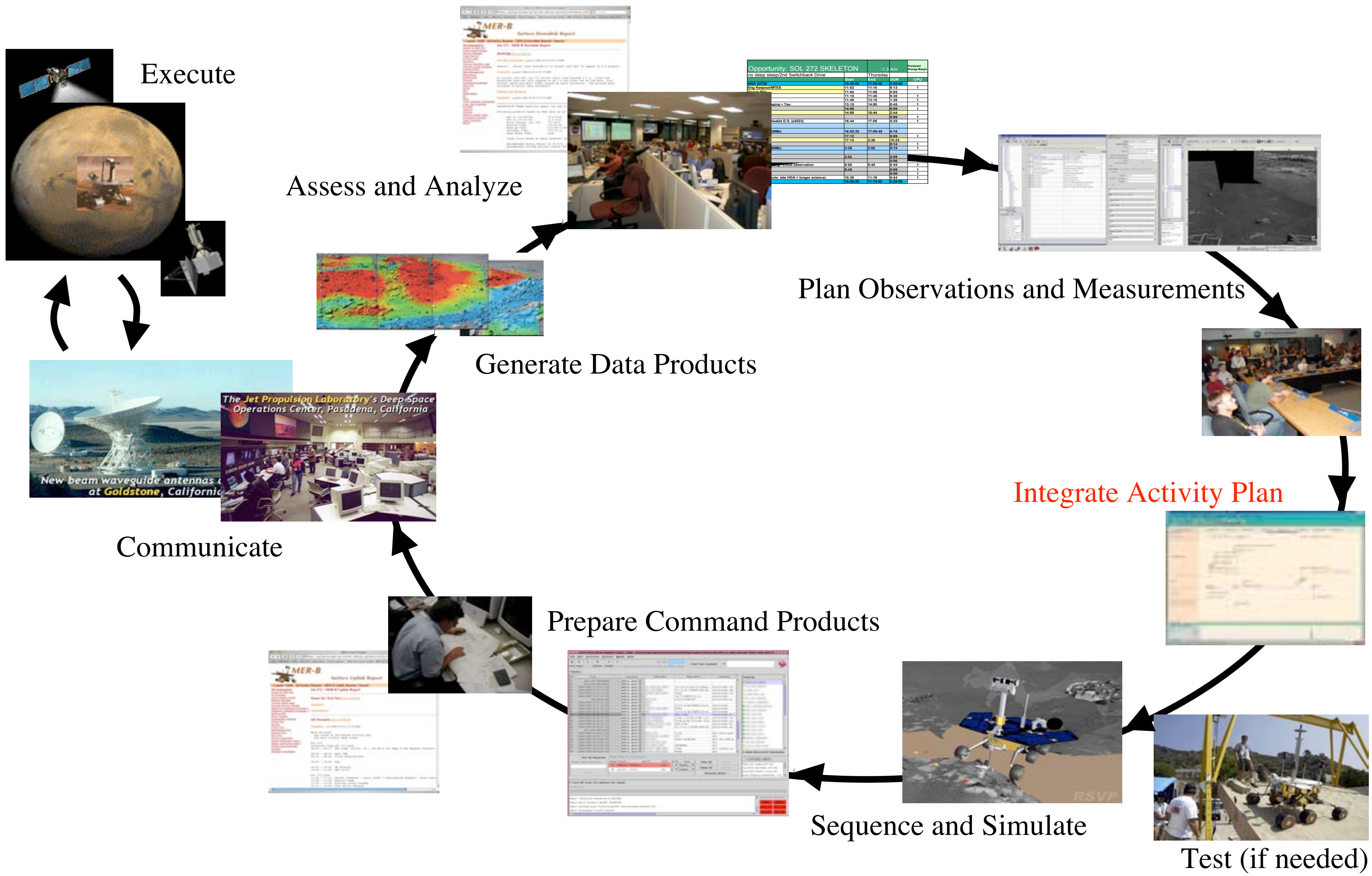
MER Surface Ops Cycle



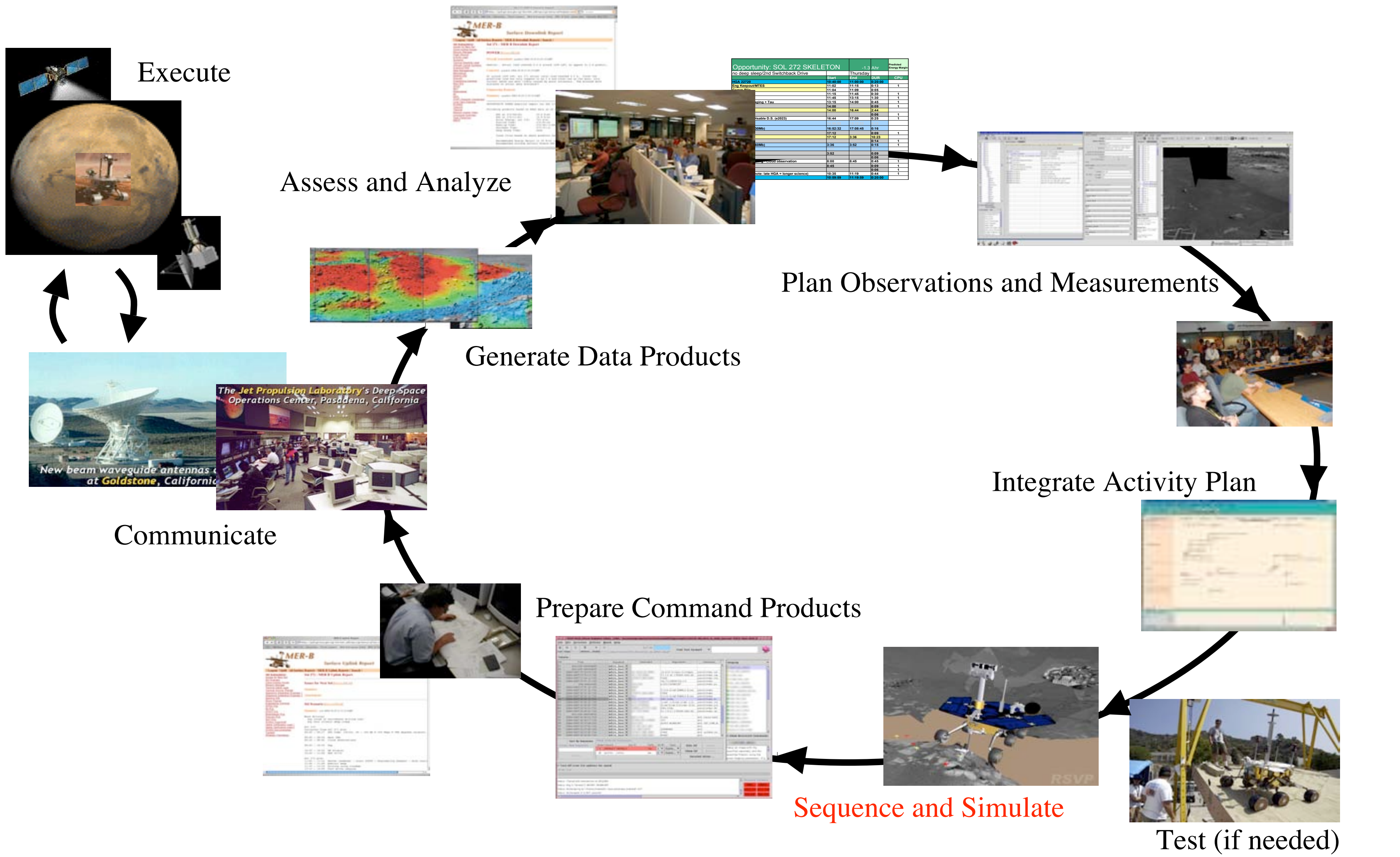
MER Surface Ops Cycle



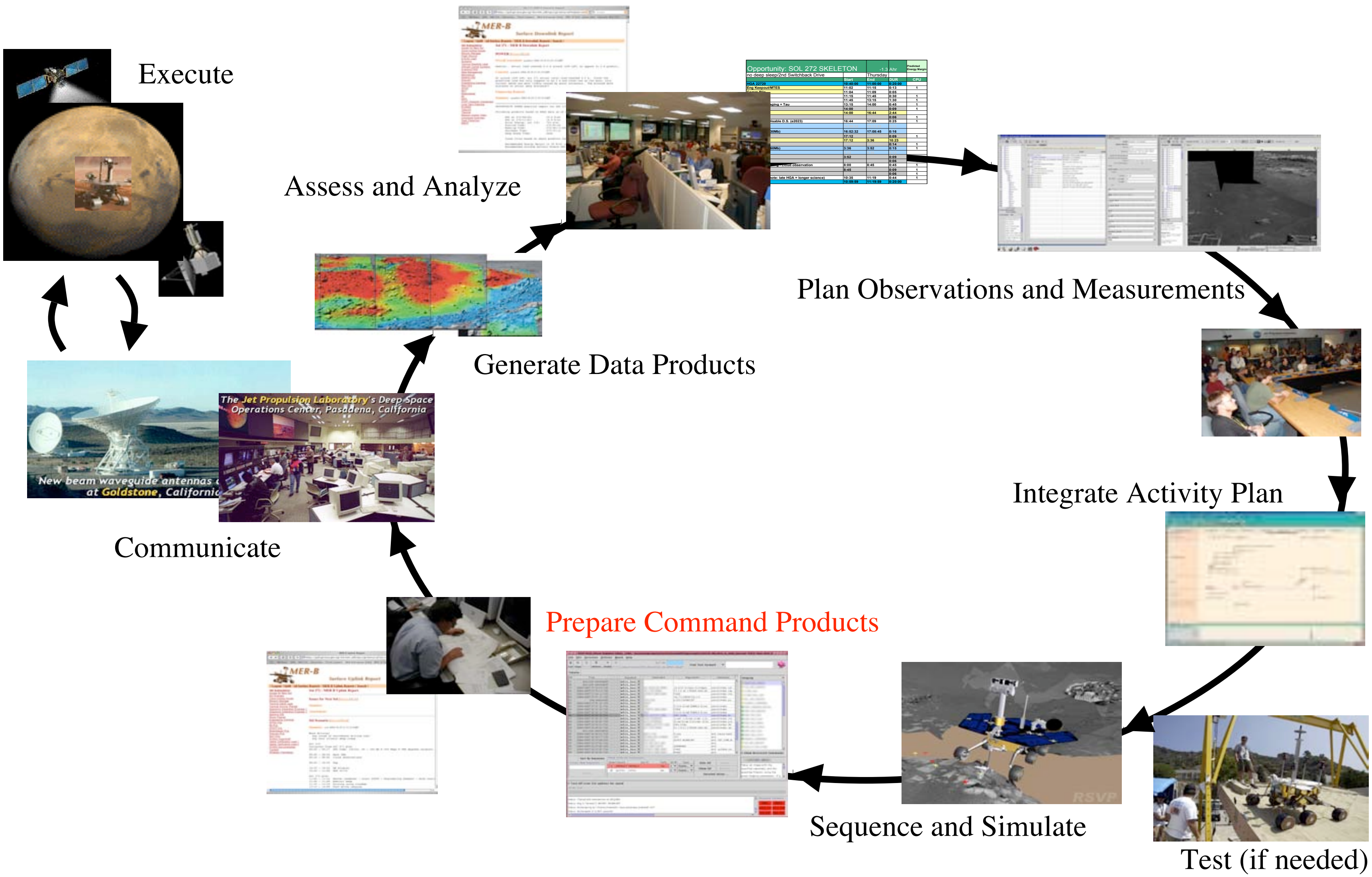
MER Surface Ops Cycle



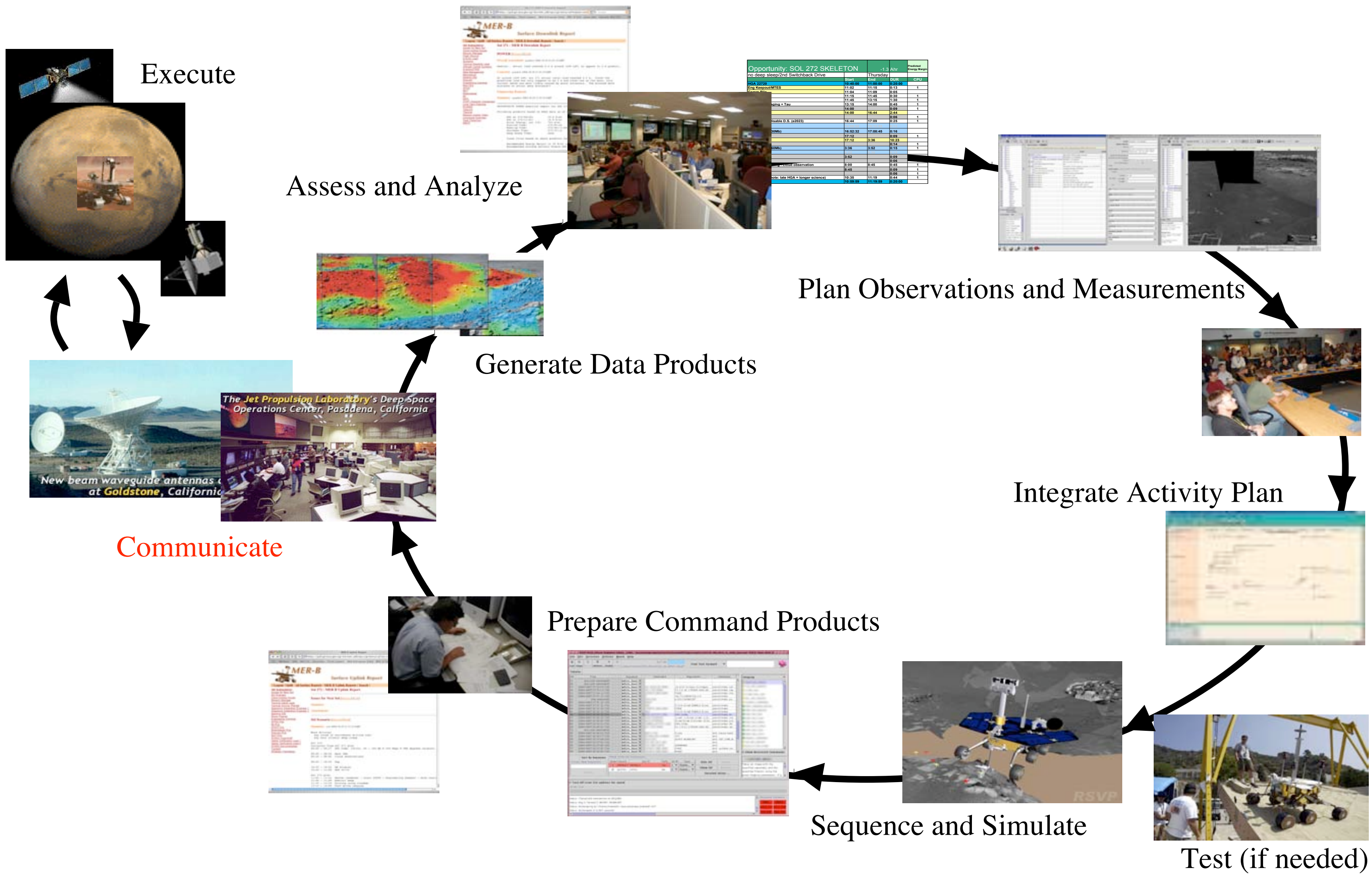
MER Surface Ops Cycle

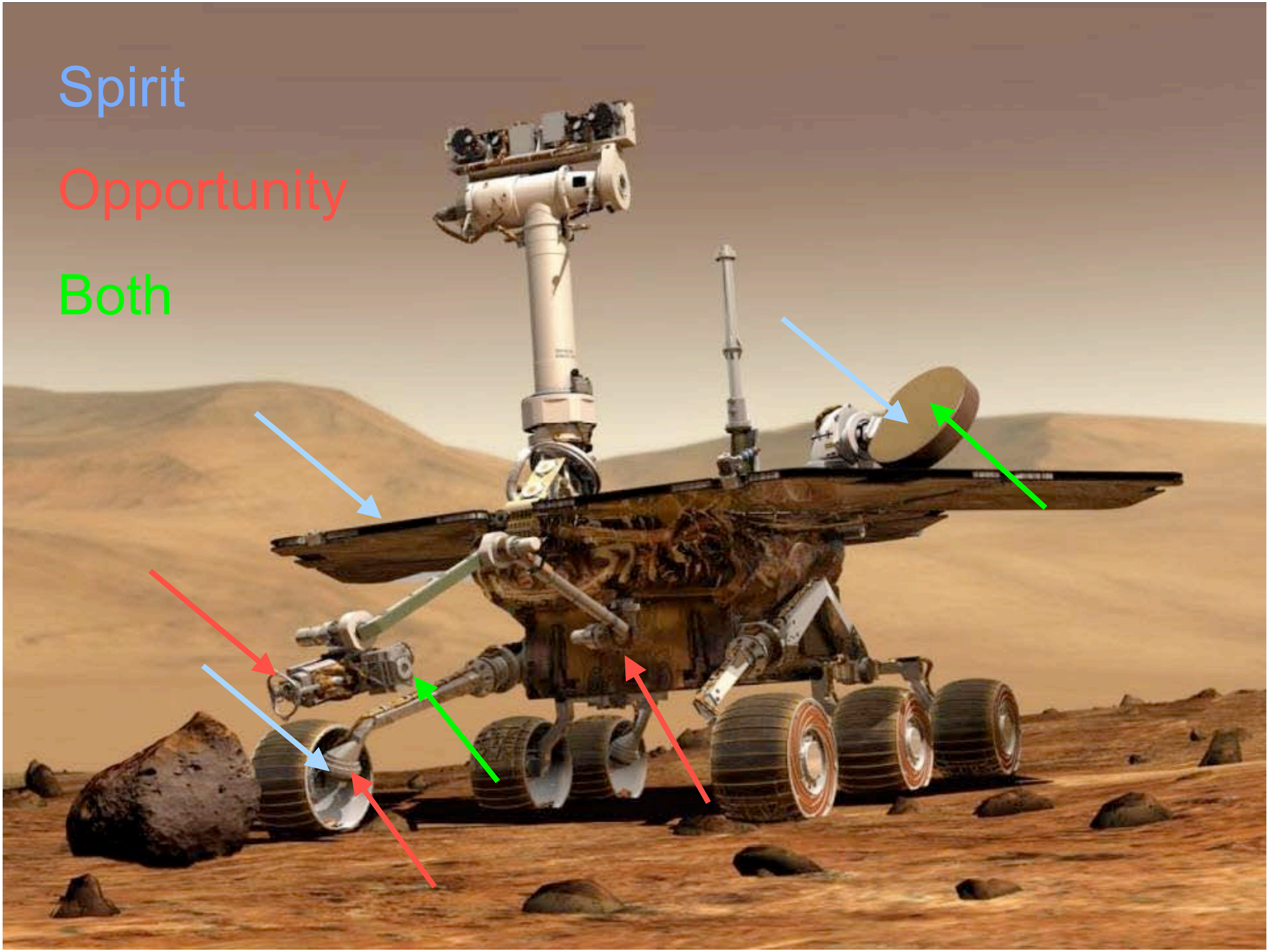


MER Surface Ops Cycle



MER Surface Ops Cycle




Spirit
Opportunity
Both

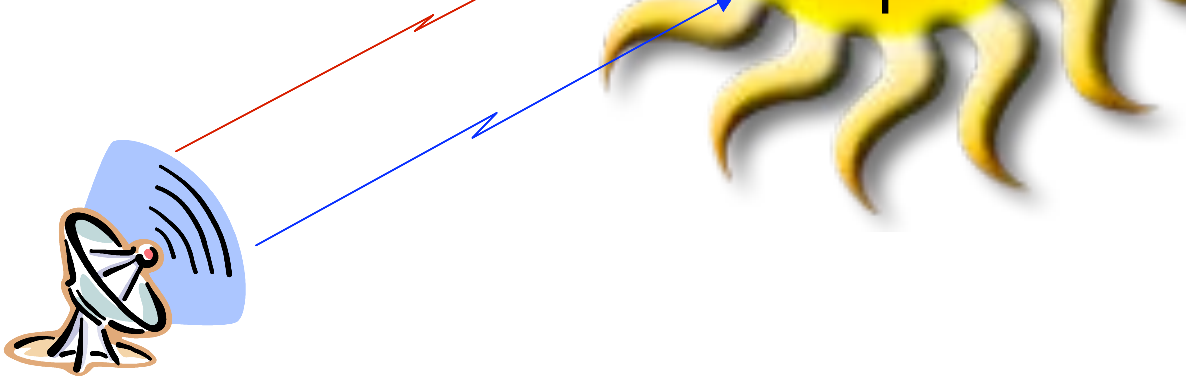
Challenges

- Spirit
  - Dust accumulation on solar arrays
  - Right front wheel drive motor failed
  - MRO frequency sharing
- Opportunity
  - Stuck heater
  - IDD shoulder azimuth motor stalls
  - Right front wheel steering motor failed
  - RAT encoder
- Both
  - Degradation of spectrometers’ radiation sources
  - Deep Space Network contention

Conjunction versus FSW load

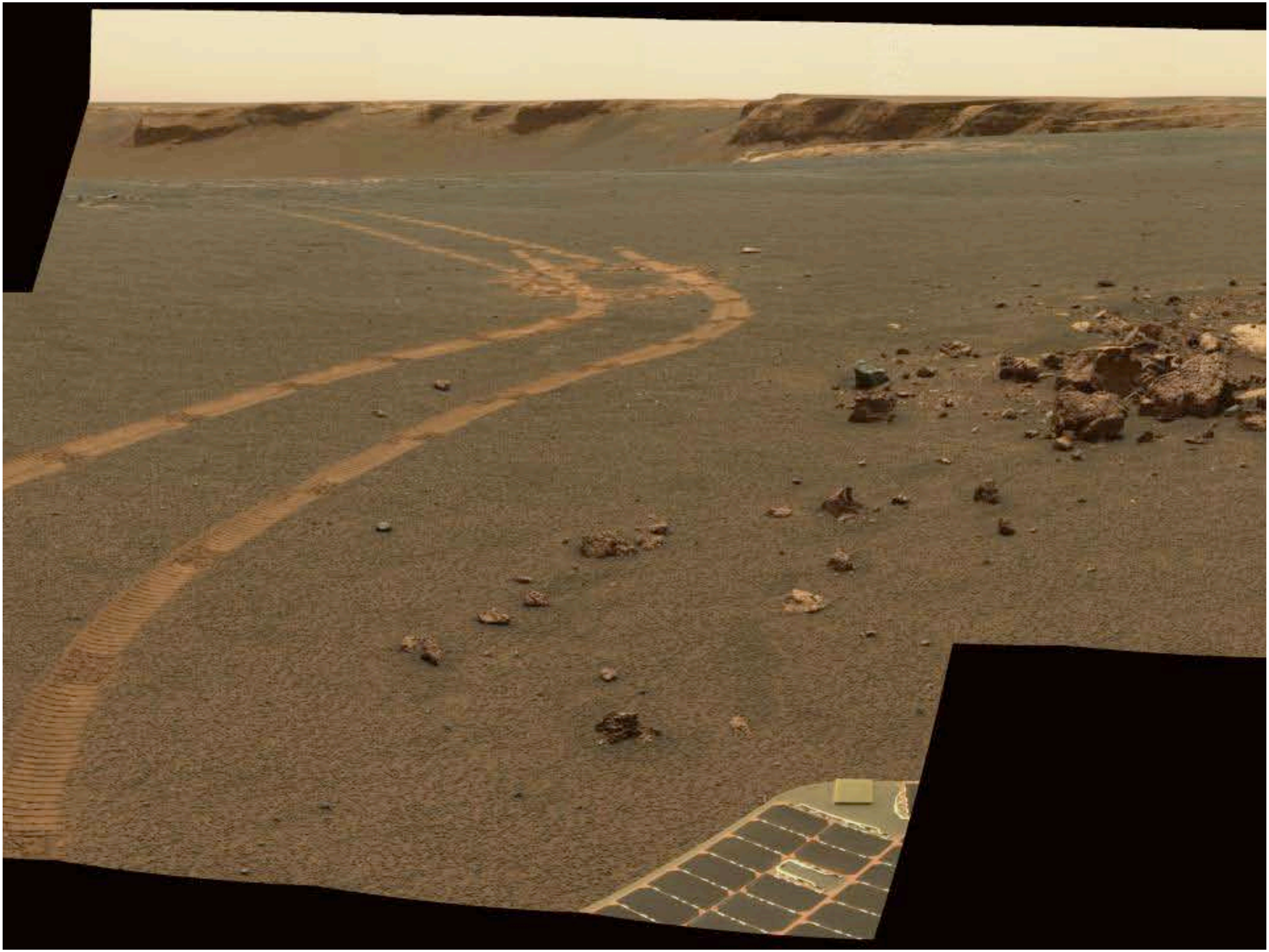
- Solar conjunction
  - 2 weeks without communications

- R9.2 Flight Software load
  - Two months of file uploads



Spirit and MRO

- Spirit's X-band frequency used for MRO
- Combination of X-band and UHF loads to get all 201 files on board each vehicle
- This was done during MRO late-stage aerobraking, a very critical and dangerous time for MRO



Constraints

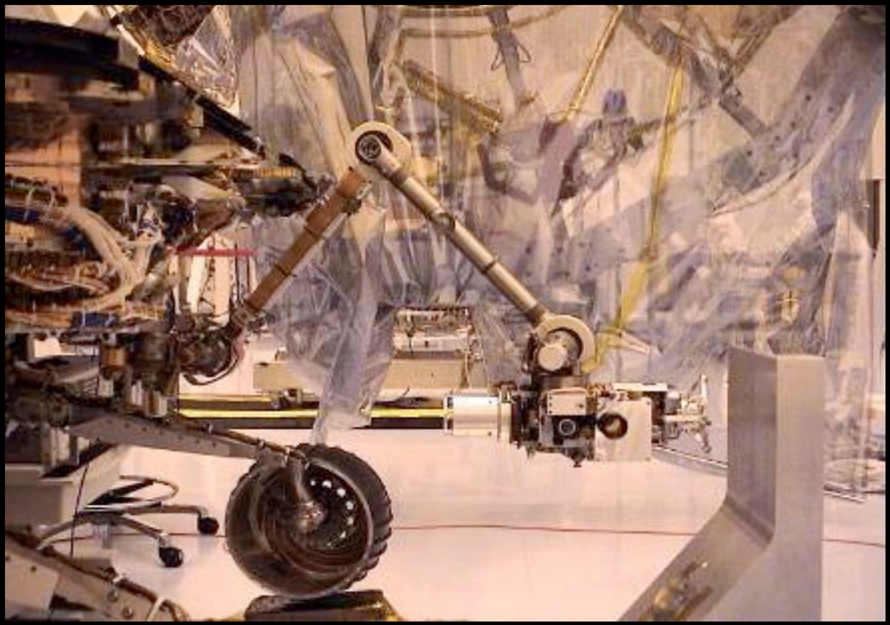
- Difficult to find time to boot both rovers.
  - MRO was finishing aerobraking
  - Launch of another spacecraft launch kept taking Deep Space Network coverage
  - A 70-meter DSN station was down.
- Since a single ground system controls both rovers, the boots must occur as close together in time as possible
- Sufficient time ahead of Conjunction was desired to boot to the new software, check it out, and have time to fix any problems


Y2K

Sol 1k

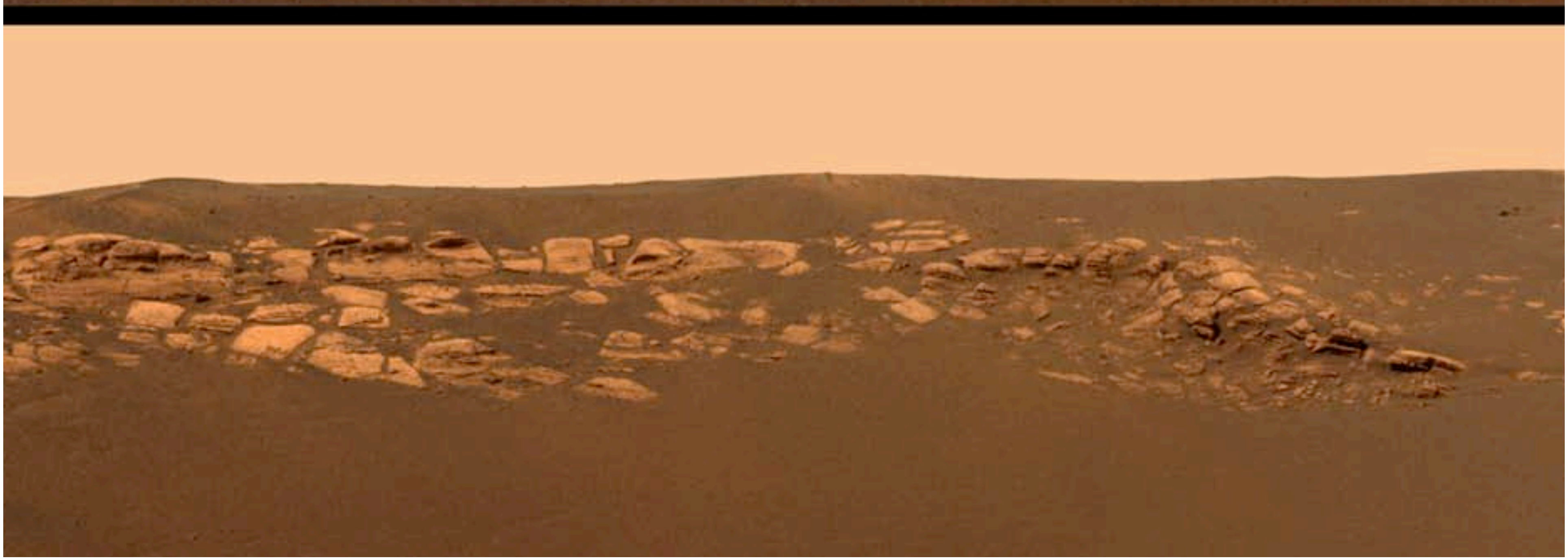
- The Sol 1000 (Sol 1 K) rollover for Spirit is during Solar Conjunction.
- With the early optimism that we would be comfortably under R9.2 control before now, the Sol 1K adaptions were made to the R9.2 version of our ground tools, not the R9.1 version.
- So the rovers and ground system must be Sol 1K compliant before entering the blackout period around Conjunction.
- This choice eliminated (or at least made very very difficult) the option of waiting until after Conjunction to perform the FSW boot.
- To add to the overall excitement, Opportunity is quickly approaching Victoria crater, with many waiting on her arrival there. So late last week, we thought we had a plan to get Opportunity to Victoria, collect that first look deep inside the crater, then boot R9.2 on both rovers.

Complications



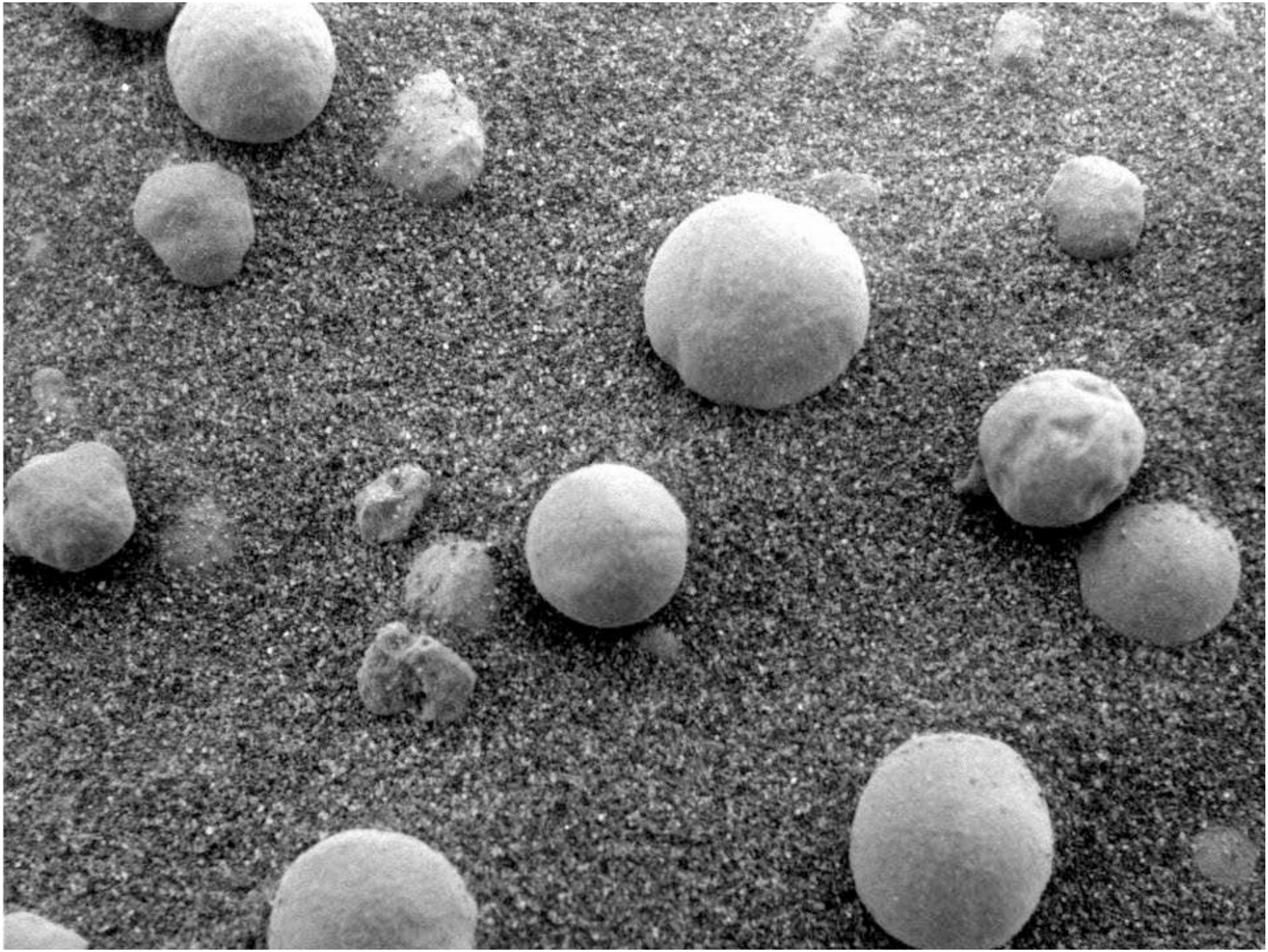
Complications

- Opportunity's IDD Joint 1 (Shoulder Azimuth) stalled during an IDD campaign, raising concerns about the health of the arm
- Eliminated the notion of arriving at Victoria before the scheduled boot
- MRO withdrew an essential X-band pass from Spirit that put into question conducting the boot as scheduled



The Shuffle

- Team developed a recovery strategy
  - For Opportunity to safely stow her arm for driving
  - To roughly maintain the timing of the R9.2 boot
- Spirit could be booted via UHF.
  - Only a 1-sol slip
  - Instead of 12 hours ahead of Opportunity Spirit would boot 12 hours after Opportunity
  - And there was enough time to build all the products and work the forward link details with Odyssey to make it happen.



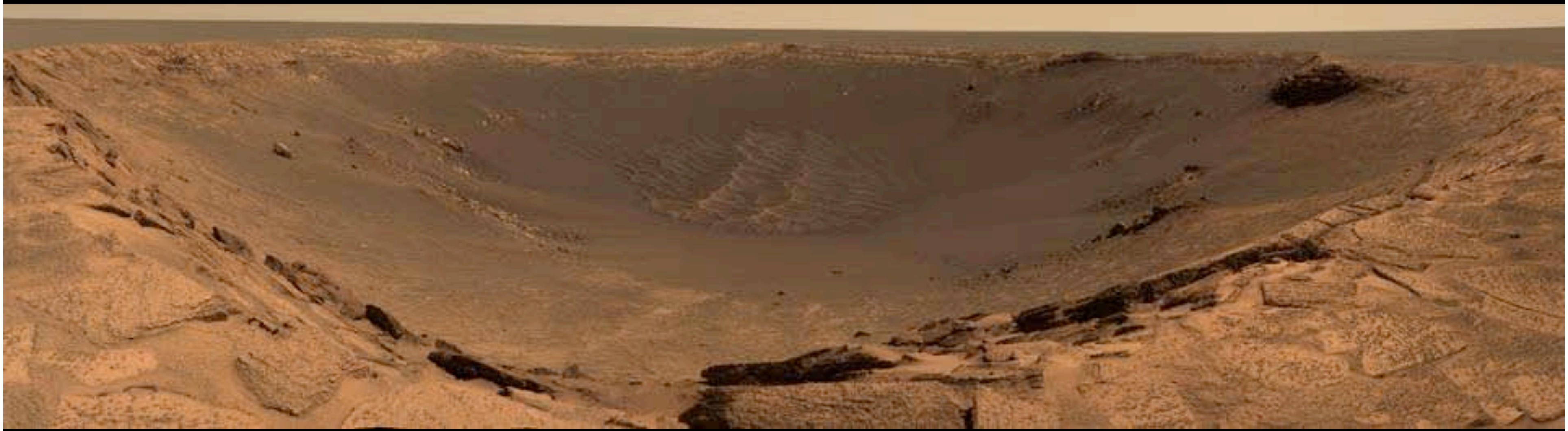
Implementation

- Opportunity drove to within about 50 meters of the rim of Victoria and waited there to receive the boot commands
- Boot commands for Spirit were on board Odyssey waiting to be relayed
- Began multi-step process of switching the ground system to R9.2
- The uplink ground tools were switched first. Now it was just a matter of waiting for the real-time commanding of the boot for Opportunity at around 5:00 PM PDT.

Disaster

- Early in the afternoon the JPL flight operations network goes down. Effectively all flight operations workstations on lab, including the MER ACE command console for Opportunity, are affected
- The Opportunity ACE could not access Opportunity's boot commands, nor have reliable contact with the DSN station in Australia for commanding.
- This level of network outage was unprecedented at JPL

A Chance

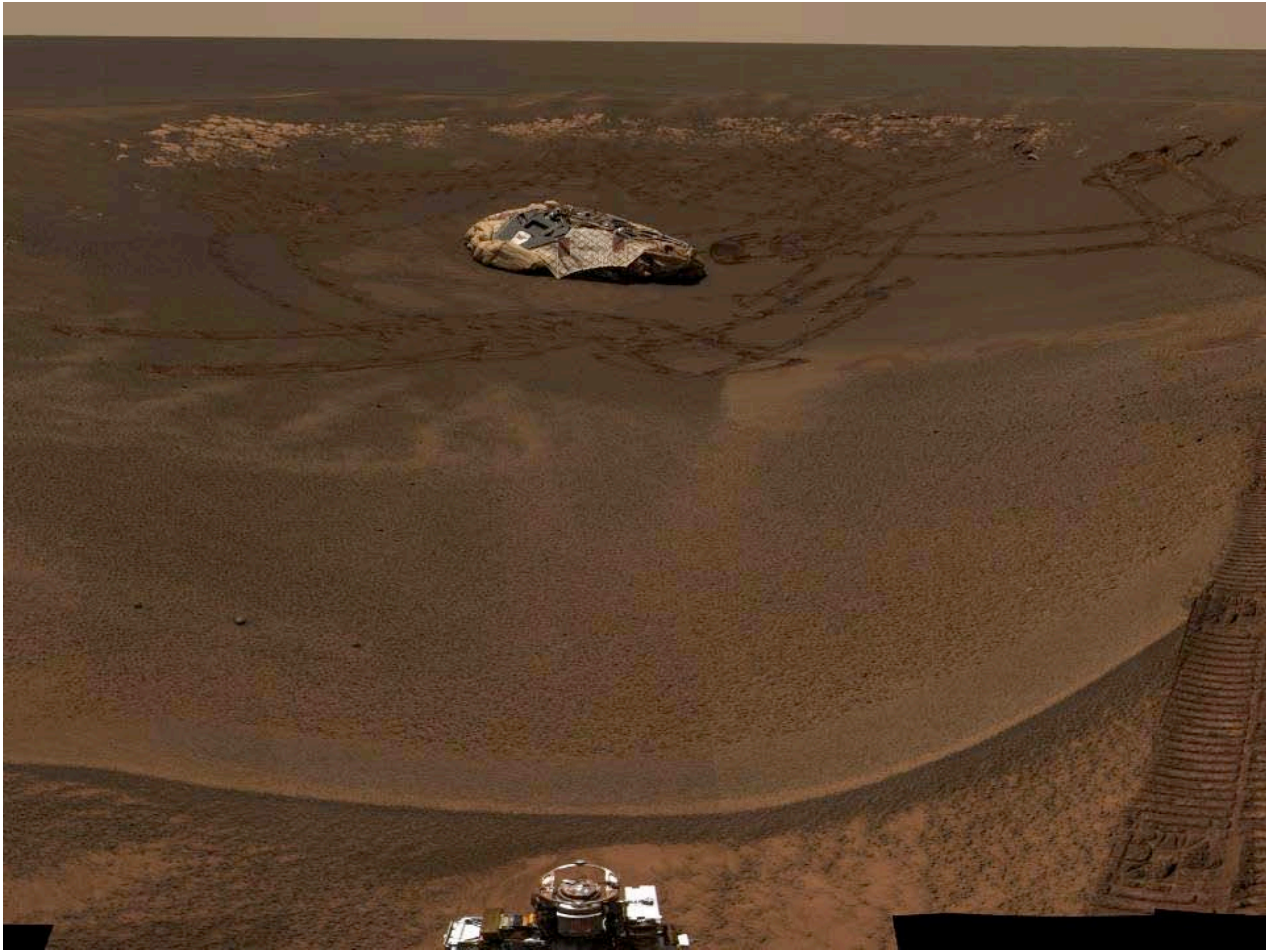


A Chance

- MER maintains a backup command workstation across the street
  - Must activate that backup system…time is quickly running out
- If we cannot get the commands out to Opportunity, we will be in a very difficult situation
  - Spirit proceeding and booting into R9.2
  - Opportunity stuck in R9.1
  - Ground system only partially in R9.2
  - It would be days of manually work getting both rovers to R9.2 and loosing many sols along the way

Floppy Disk

- Intermittent connectivity to the DSN station and no access to the server for the boot commands.
- Calls go out for a 3.25-in floppy diskette to copy the commands
- Miraculously, one is found
- Commands are copied onto the disk and the team sprints across the street



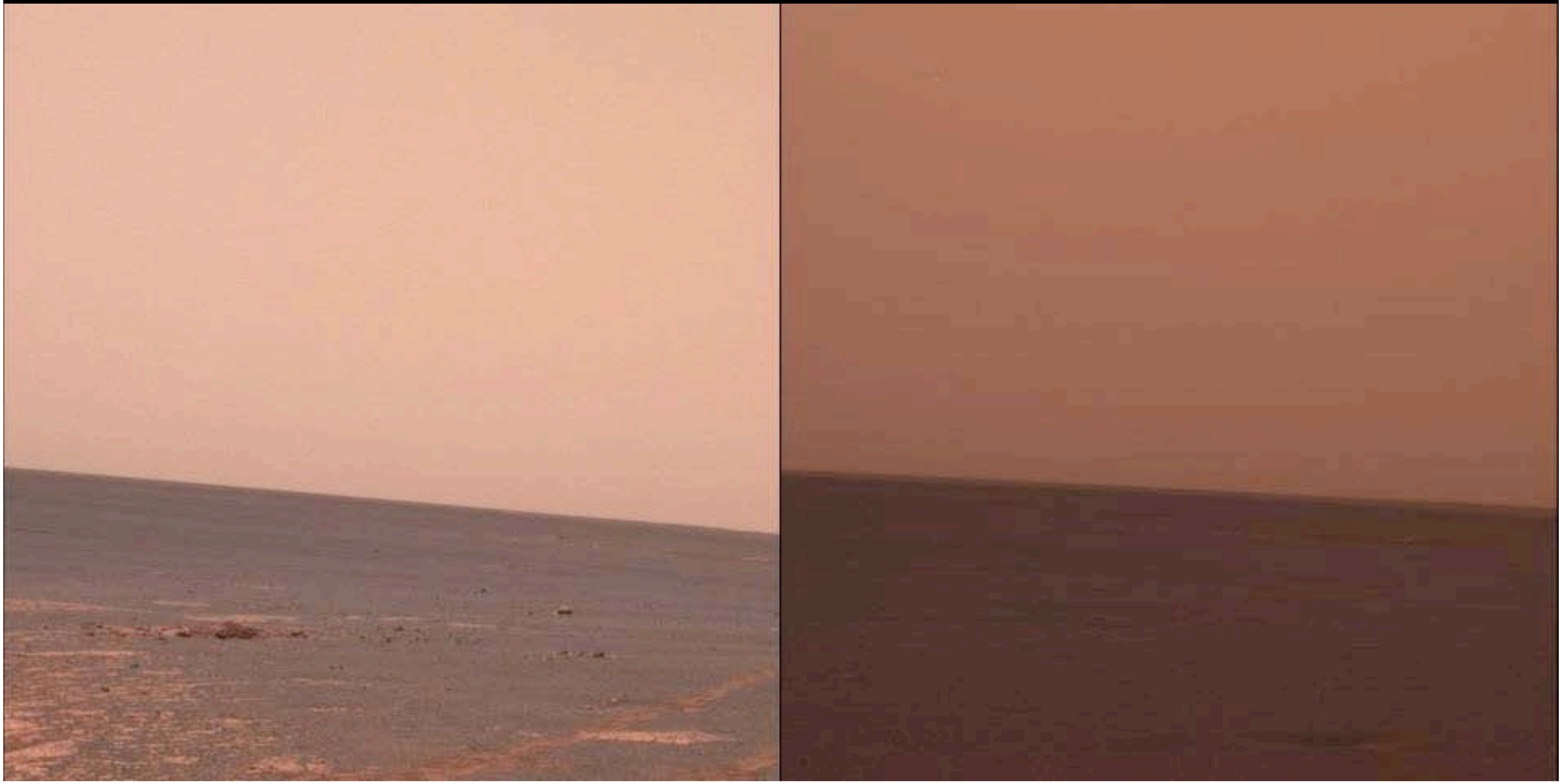
Commanding

- ACE on backup workstation maintains connectivity to DSN
- But must relay voice instructions via telephone to be communicated over the voice net to Australia
- The diskette is readable
- Checksums and the creation times confirmed
- With minutes left in the command window each file is sent 3 times to insure receipt by Opportunity
- The link to the station stays up and the station controller is able to confirm, through the voice net then via telephone, the error free transmission of each file
- The last file is sent with one minute to spare in the communications window!

In the End

- The network came back
- The R9.2 ground system deployment and checkout completed
- Both rover successfully booted to R9.2 without error

Sol 1220 Tau 2.99



Dust Storm 2007

- Tau
  - Atmospheric opacity
  - Measured with a Pancam observation of the Sun
- Dust Factor
  - Percentage of solar array power not lost from dust
- Array Energy
  - Total energy supplied by solar arrays per sol

Power

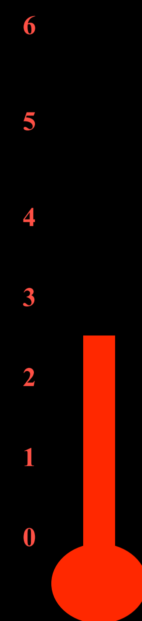
- Just the basics
  - 20 minute uplink
  - 15 minute downlink relay with Mars Odyssey
  - 10 minutes of science observations

  - ~220 WHrs

Rising Tau

- Week of 25/06/2007

Sol	Tau	Energy (WHrs)
1214	0.94	765
1215	1.33	670
1216	1.53	658
1217	1.75	605
1218	2.27	559



- Sol 1219 Tau = 2.64 Energy = 467

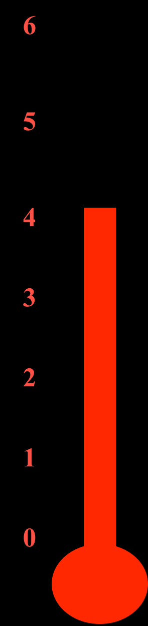
Late Changes

- Late Friday afternoon/evening 28/06
- Remove all activities from the sequences planned for the weekend
- Atmospheric dust monitoring only

Fluctuating Tau

- Week of 02/07/2007

Sol	Tau	Energy (WHrs)
1220	2.99	430
1221	3.31	402
1222	2.66	513
1223	3.06	413
1224	3.95	278



- Sol 1225 Tau = 4.12 Energy = 255

Weekend Changes

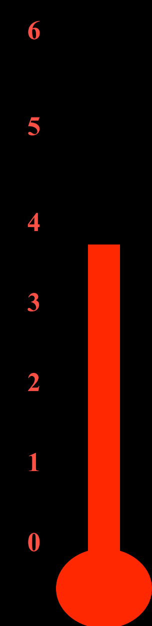
- Weekend staff instructed to NOT uplink mobility sequences
- Previous sol's sequence will continue to execute
- Previous sol's "run-out" is power conservative

Steady Tau

- Starting 07/07/2007

Sol	Tau	Energy (WHrs)
1226	3.70	321
1227	3.03	403
1228	2.93	444
1229	2.95	432
1230	2.92	452

- Sol 1231 Tau = 2.91 Energy = 426



Stay Alert

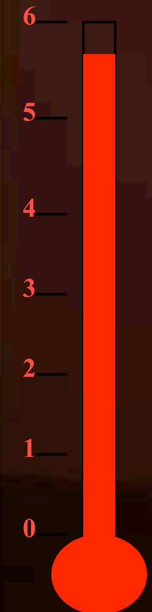
- Monitor atmosphere with Pancam Tau observations
- Communicate
- Sleep

Wild Tau

τ = 0.94 | 2.9 | 4.1 | 3.8 | 4.7

- Starting 13/07/2007

Sol	Tau	Energy (WHrs)
1232	3.31	383
1233	3.80	310
1234	4.25	299
1235	4.72	194
1236	5.30*	147



- Sol 1236 Tau = 5.60* Energy = 128

1205 11:14 | 1220 11:04 | 1225 11:30 | 1233 10:55 | 1235 10:53

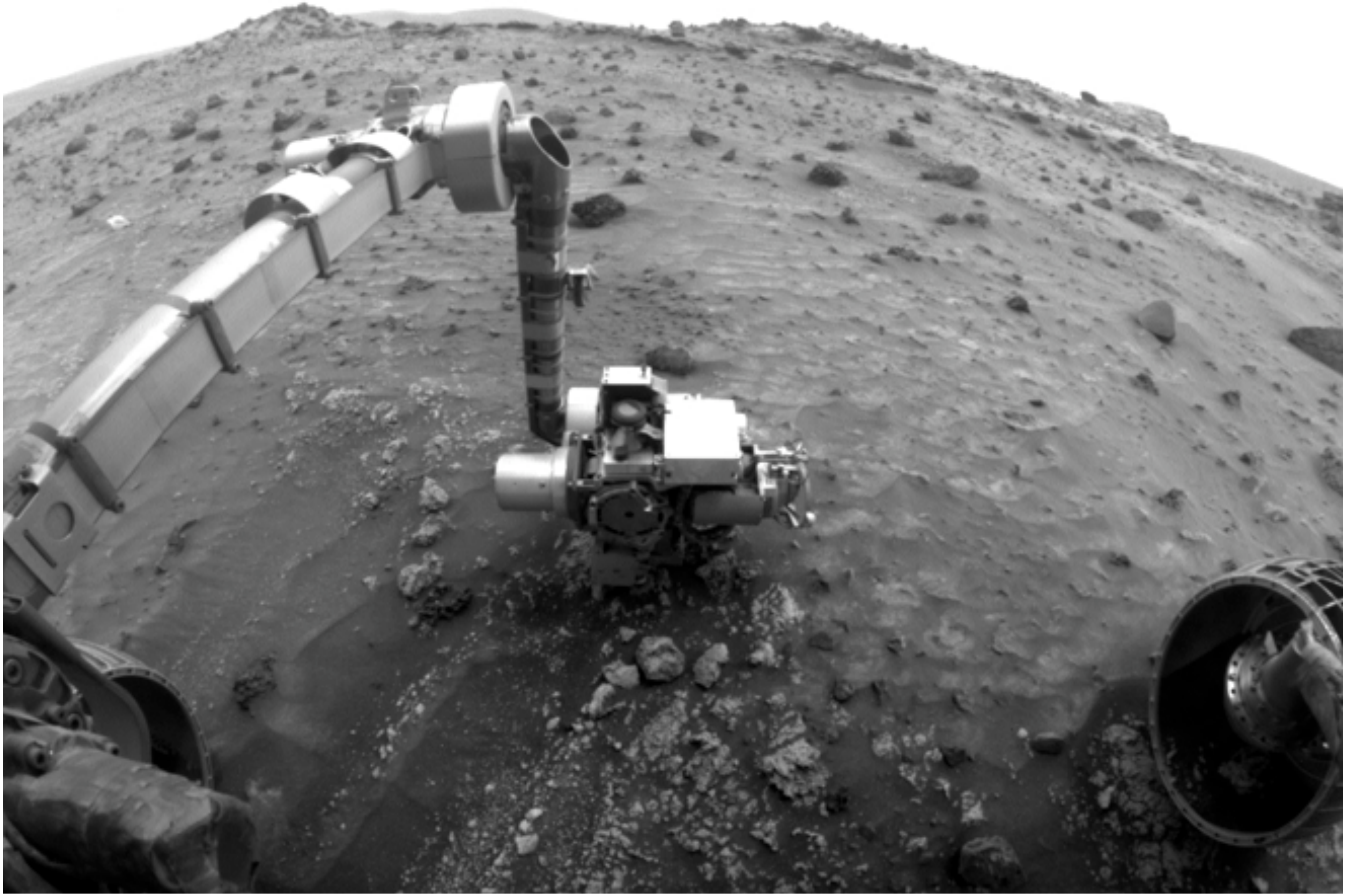
*Estimated

Opportunity Sol Number and Local True Solar Time

The Challenge

The Challenge

- Keep the electronics and batteries warm enough as to prevent damage
- Continue to receive downlinks to determine the health of Opportunity and state of the storm
- Maintain Opportunity under sequence control
- Maintain some energy margin in the batteries in case Mars has more storms in store
- Avoid tripping a Low Power fault condition



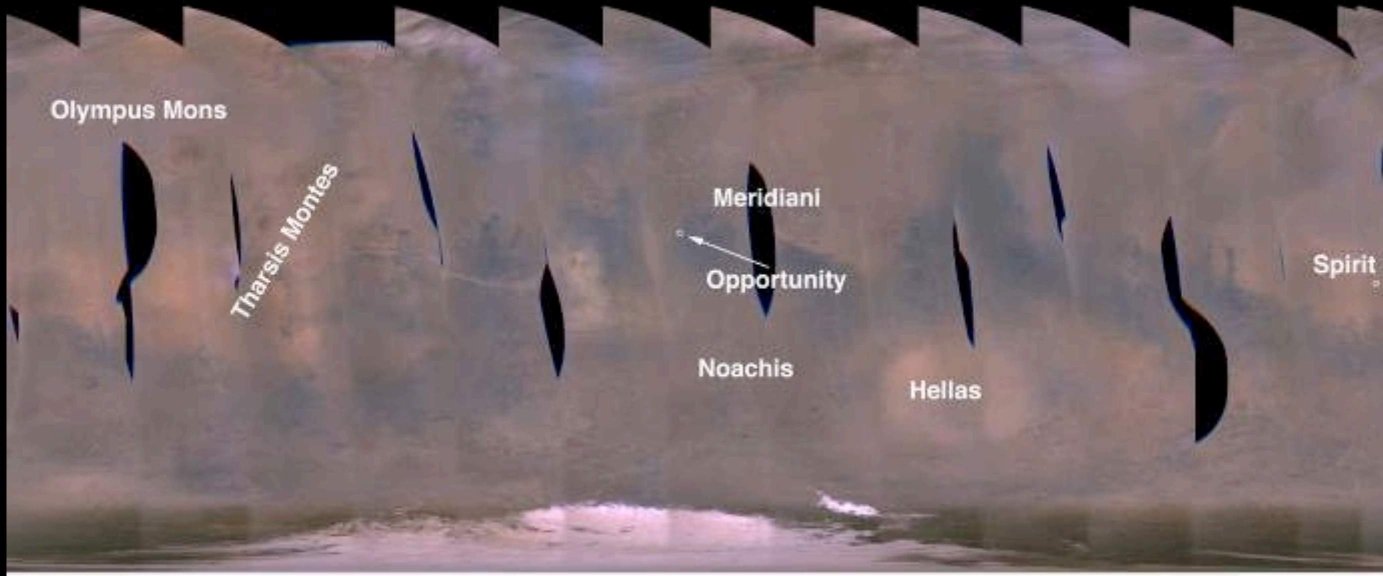
Heaters

- REM Heaters turn on at -38C
  - Temperatures approaching -36C
- Would draw ~114 WHrs extra and most likely trip low power fault
- Disable survival heaters and keep CPU on to maintain thermal inertia

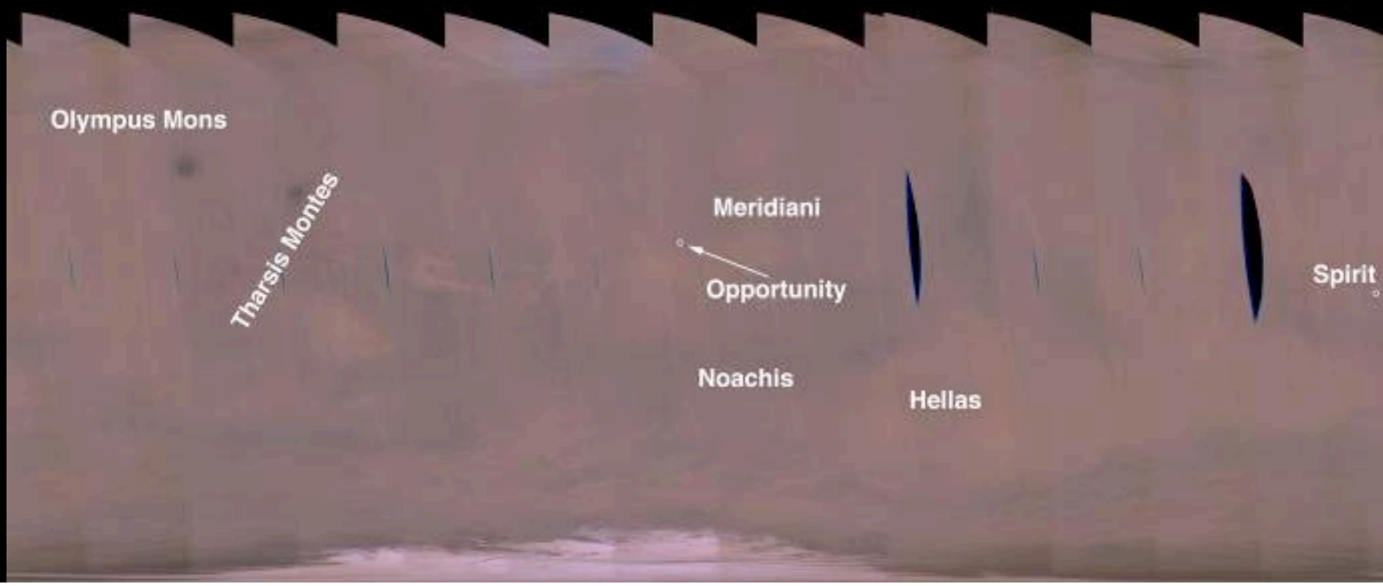
Low Power Fault

- When one cell of one battery reaches 2.9V
- Change fault protection parameters
  - Change X-band communications windows
    - from 40 minutes to 20 minutes per sol
    - From 2-way to receive only
- ~219 WHrs to ~116 WHrs

6/22/07

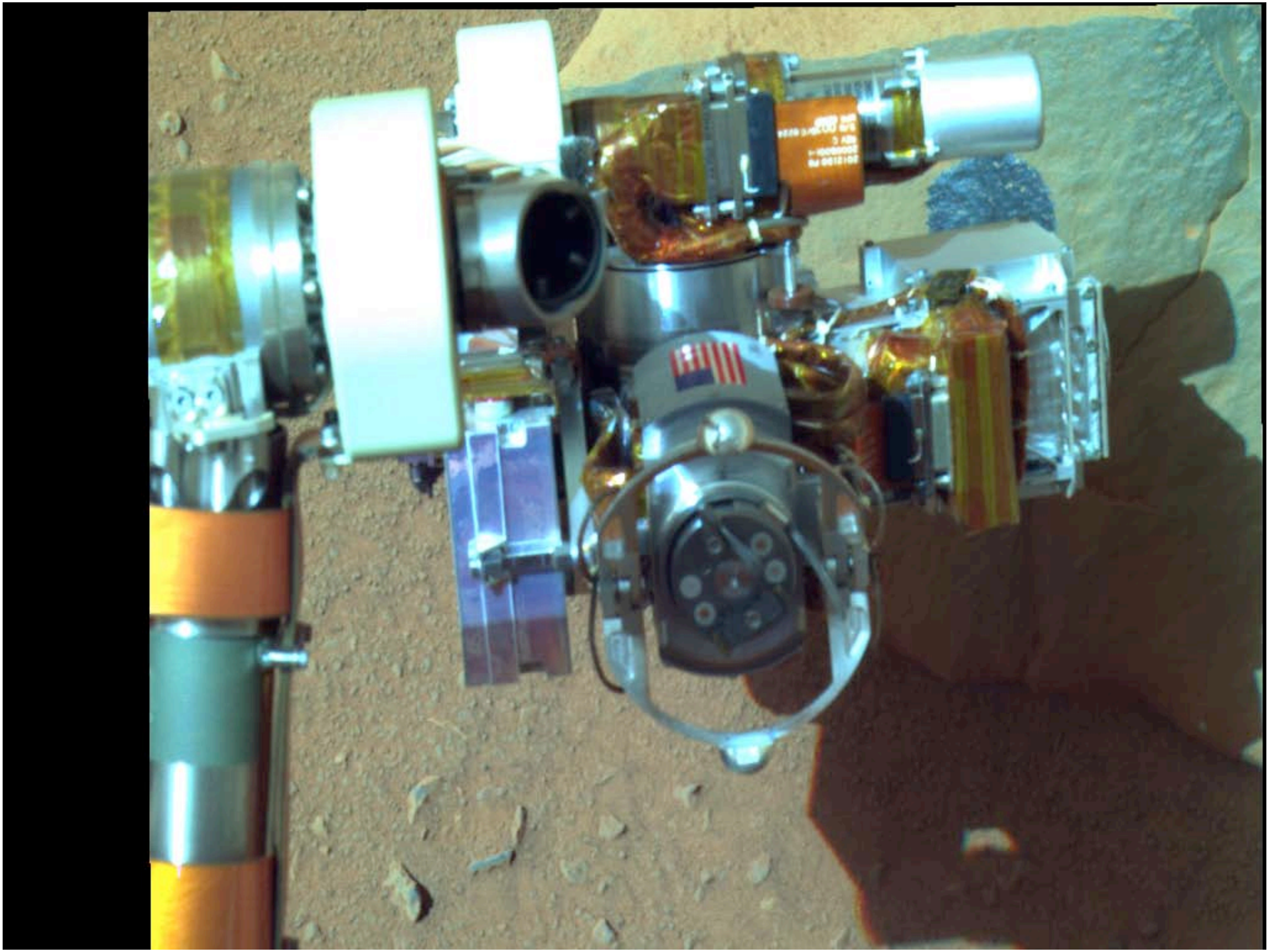

Olympus Mons
Tharsis Montes
Meridiani
Opportunity
Spirit
Noachis
Hellas

7/17/07

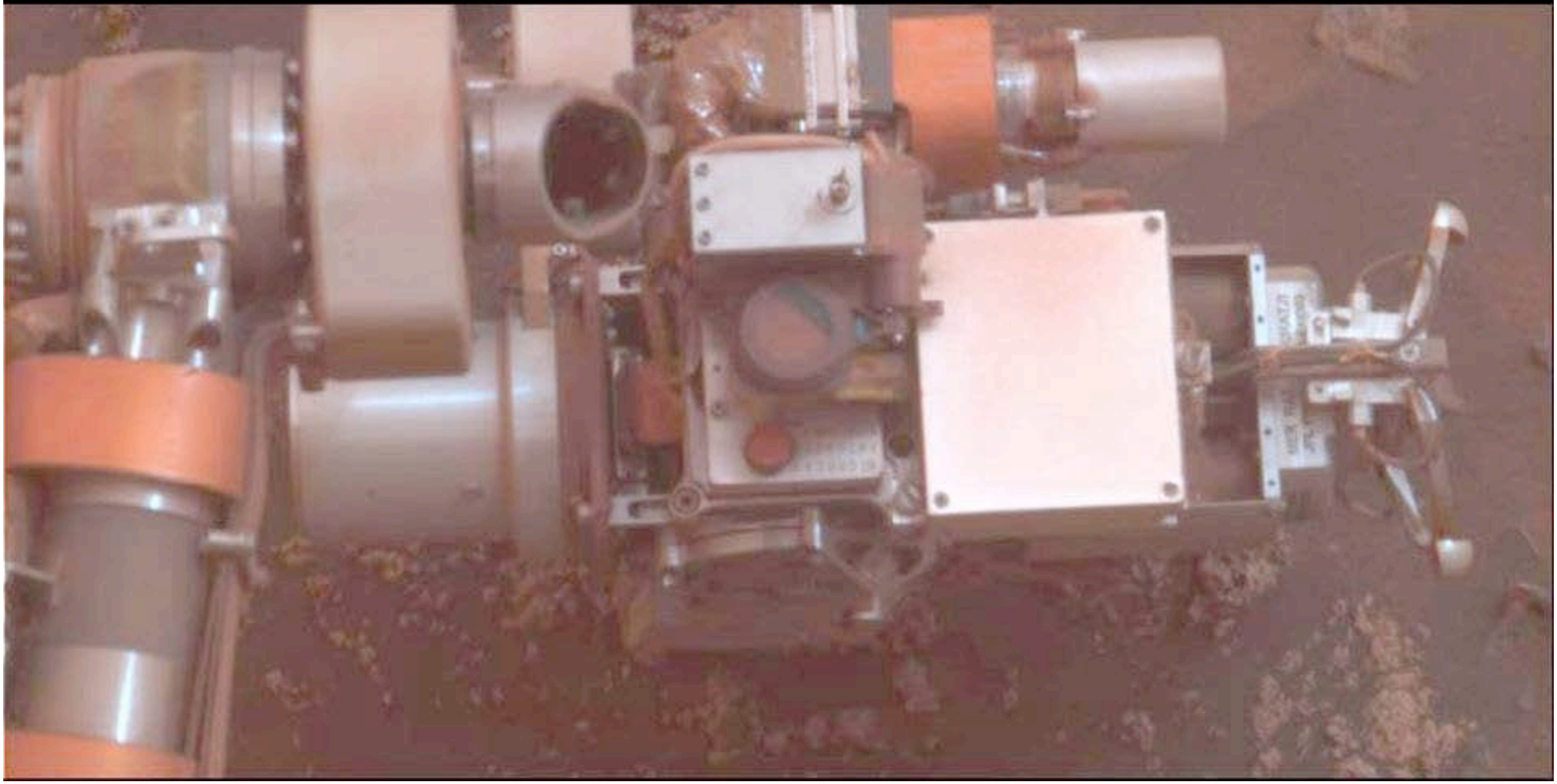

Olympus Mons
Tharsis Montes
Meridiani
Opportunity
Spirit
Noachis
Hellas

Stretch the Cycle

- Adopt a 3-sol pattern
  - Sol 1-Uplink plan, go to sleep (no downlink)
  - Sol 2-no uplink, no downlink, sleep all day
  - Sol 3-no uplink, sleep until downlink, go back to sleep
  - Sol 4-Uplink new plan, repeat cycle…
  - ~100 WHrs average

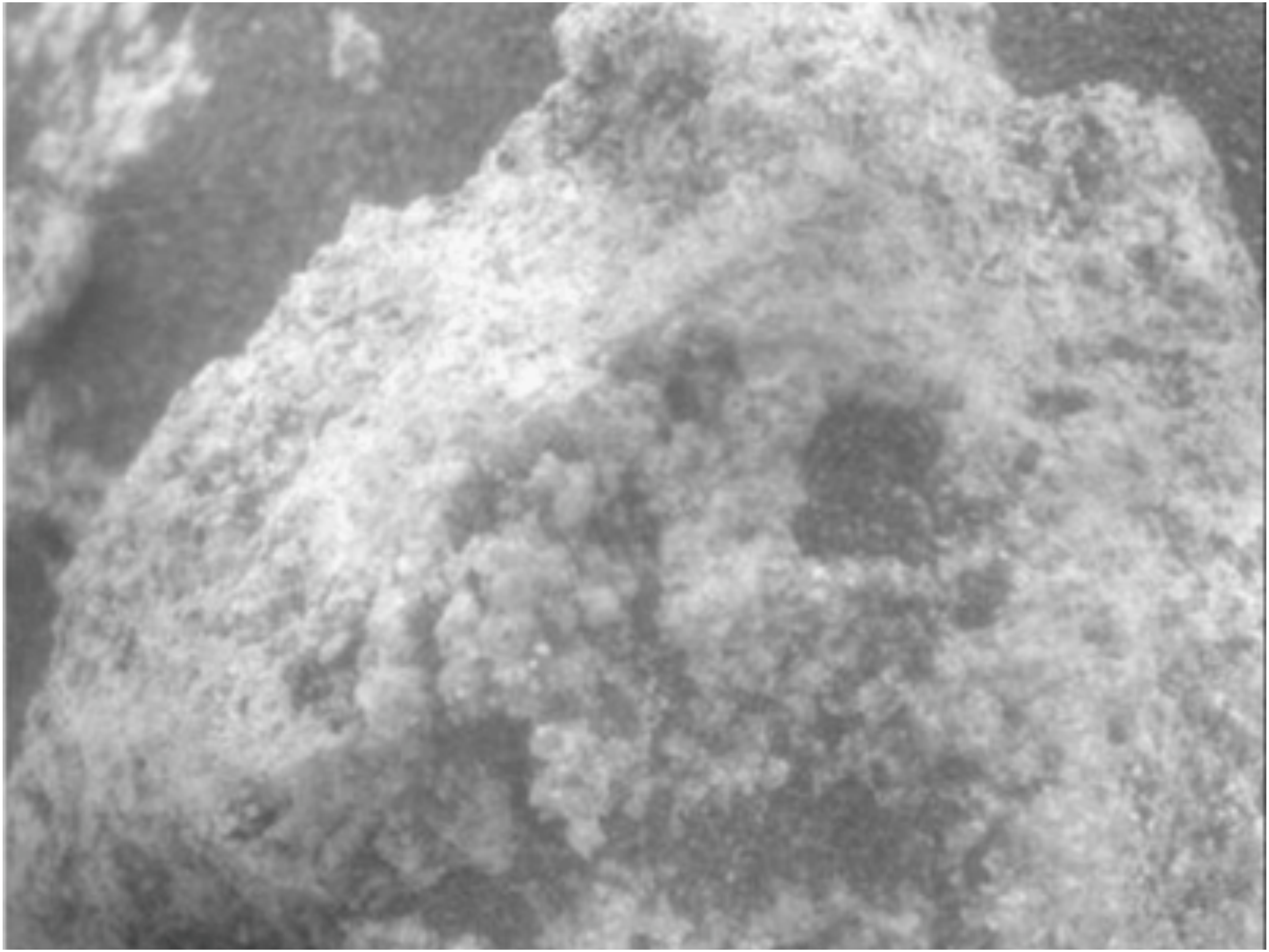


Dust on Microscopic Imager



If it’s not one thing…

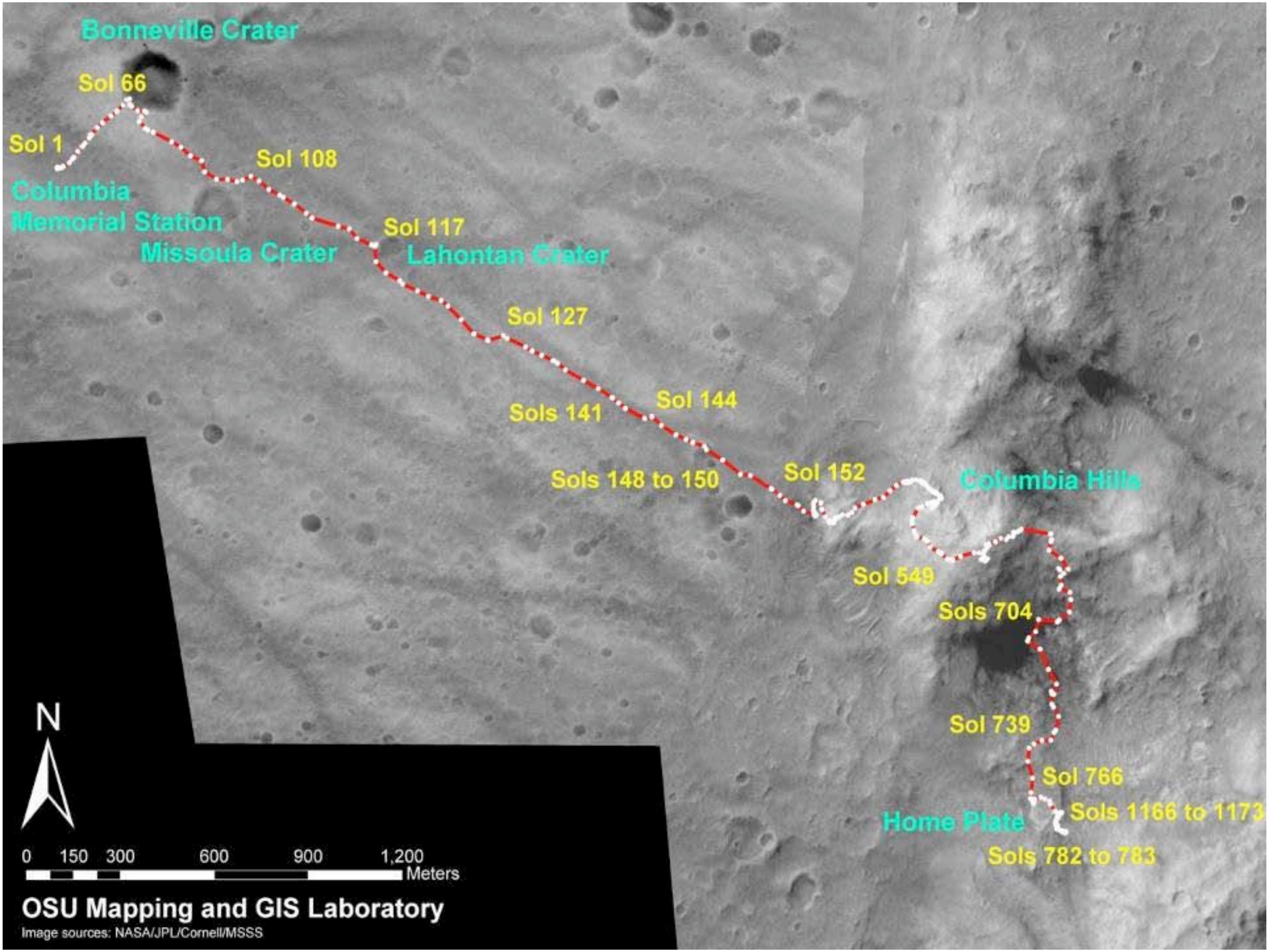
- Sol 1237 uplink lost
- Lower temperatures usually reached in winter (currently summer)
- Frequency offset results in successful uplink on sol 1238



Back to Business

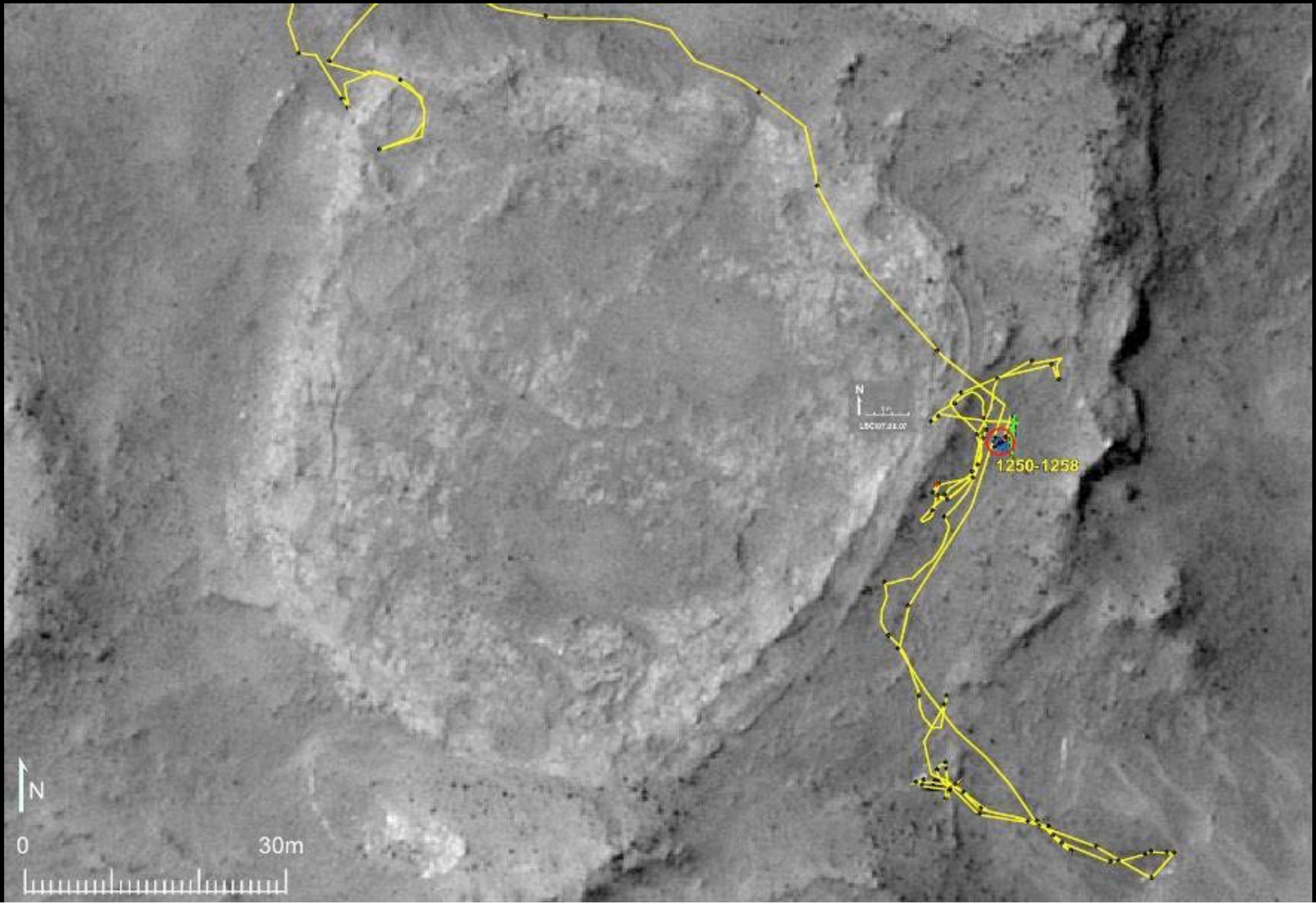
- Tau has returned to acceptable levels ~2.5
- Opportunity has entered Victoria Crater
- Spirit has climbed onto Home Plate
- Spirit dust accumulation

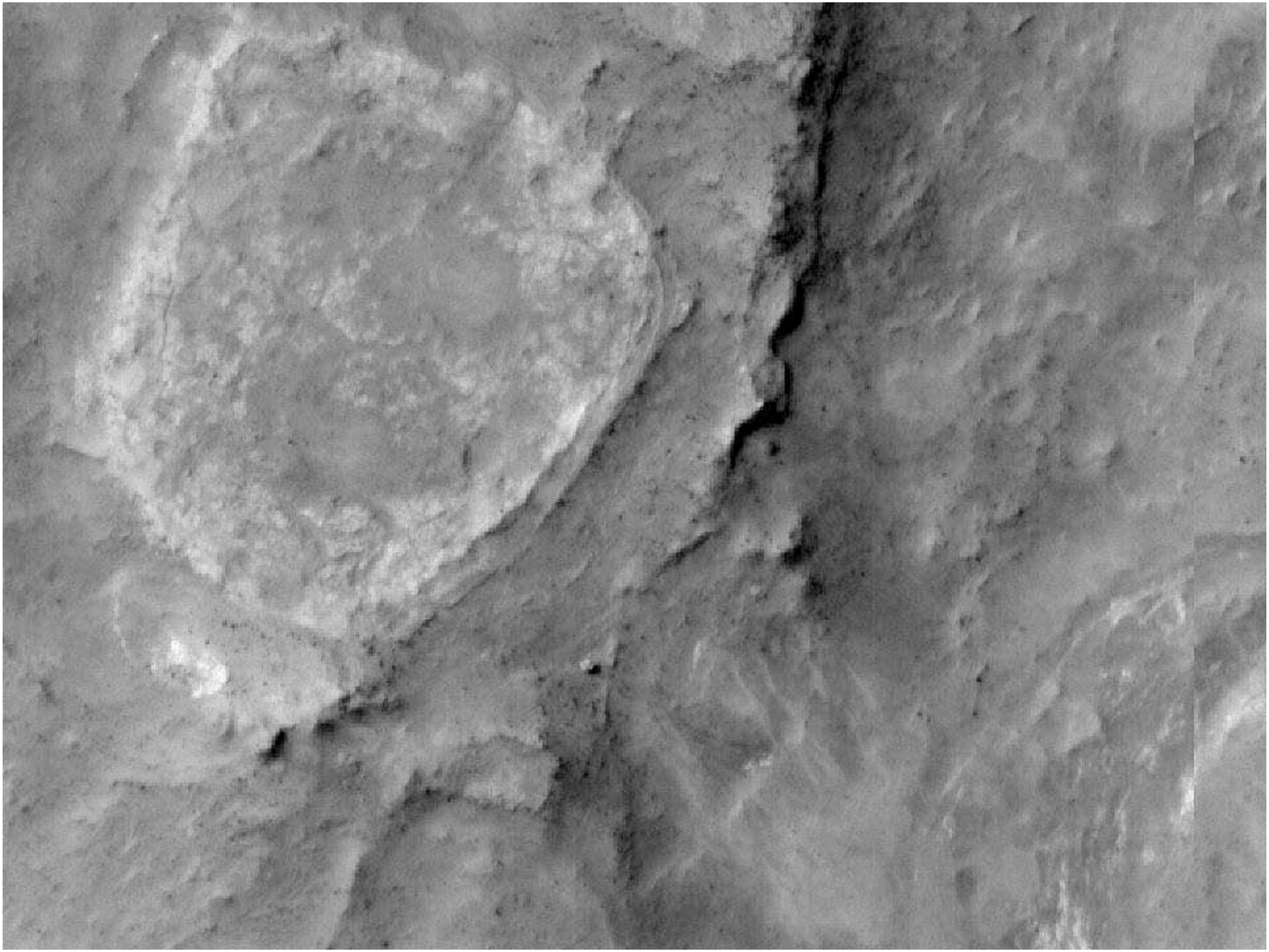
Pictures



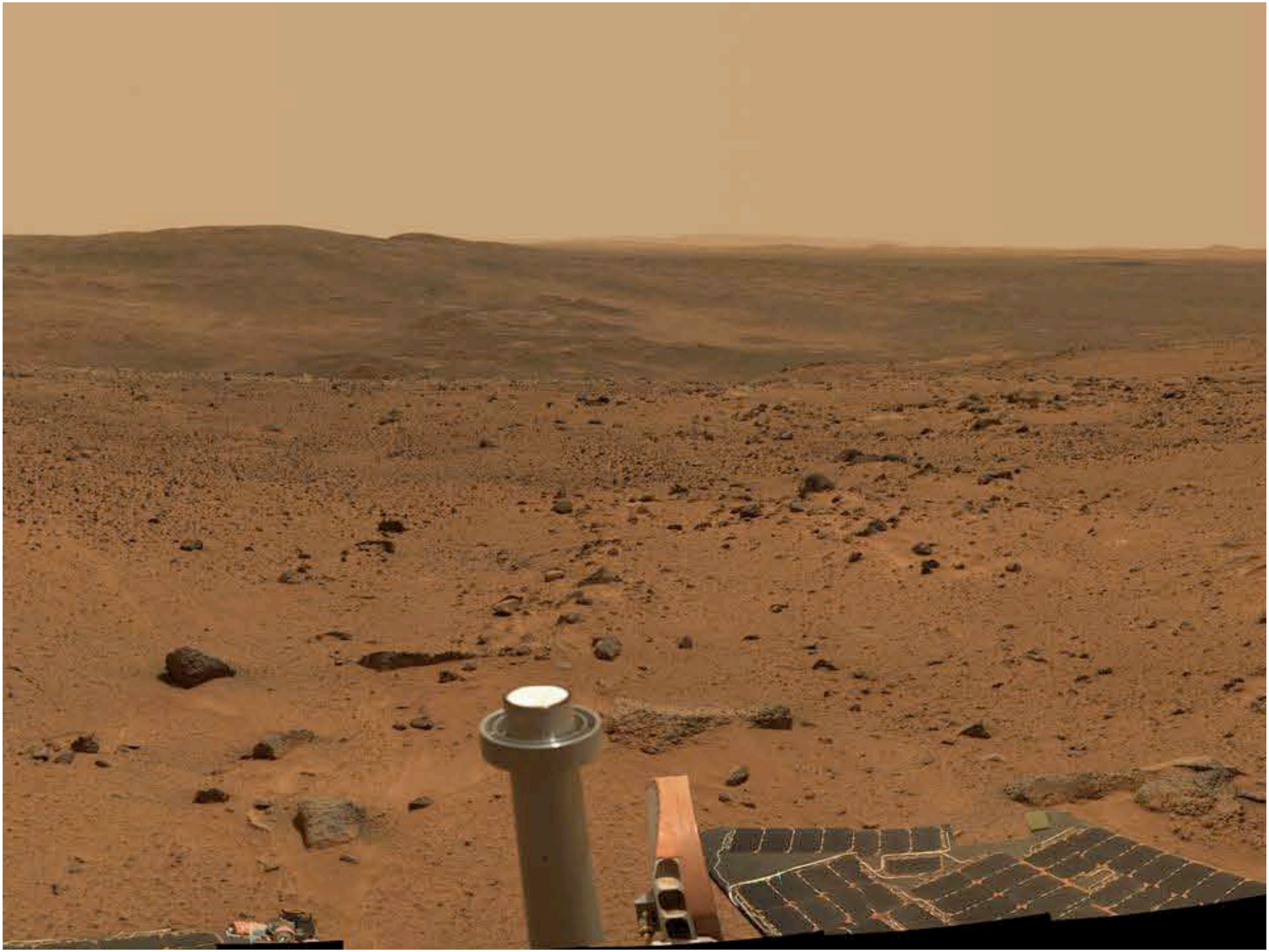
Bonneville Crater
Sol 66
Sol 1
Sol 108
Columbia
Memorial Station
Sol 117
Missoula Crater
Lahontan Crater
Sol 127
Sol 144
Sols 141
Sols 148 to 150
Sol 152
Columbia Hills
Sol 549
Sols 704
Sol 739
Sol 766
Sols 1166 to 1173
Home Plate
Sols 782 to 783
N
0 150 300 600 900 1,200
Meters
OSU Mapping and GIS Laboratory
Image sources: NASA/JPL/Cornell/MSSS

Spirit at Home Plate





Dust Devils at Gusev



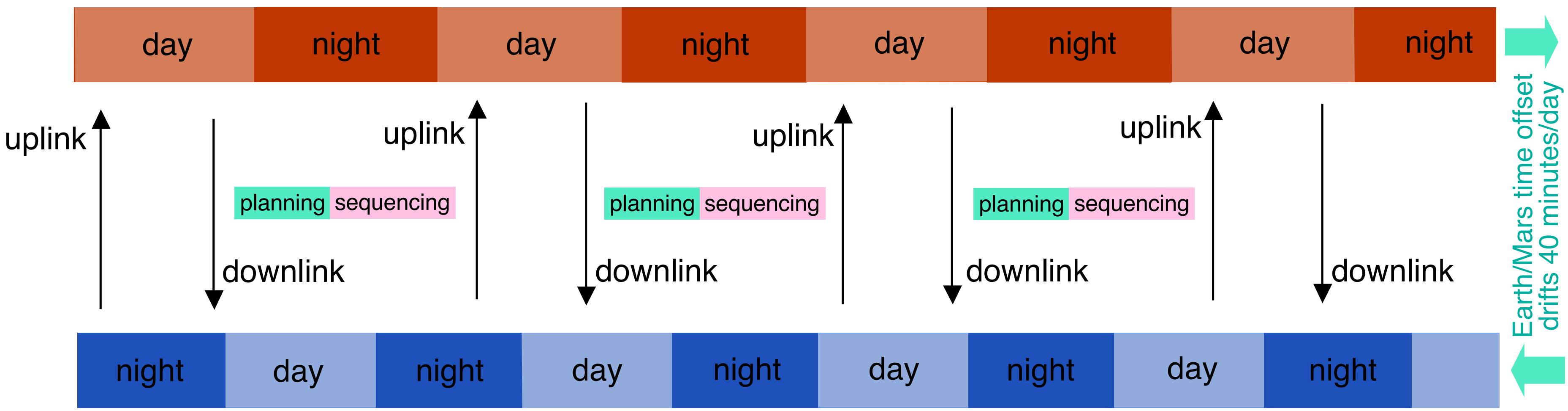

Thank You

Backup

Planning on Mars Time

A Martian day, or SOL, is 40 minutes longer than an Earth DAY.

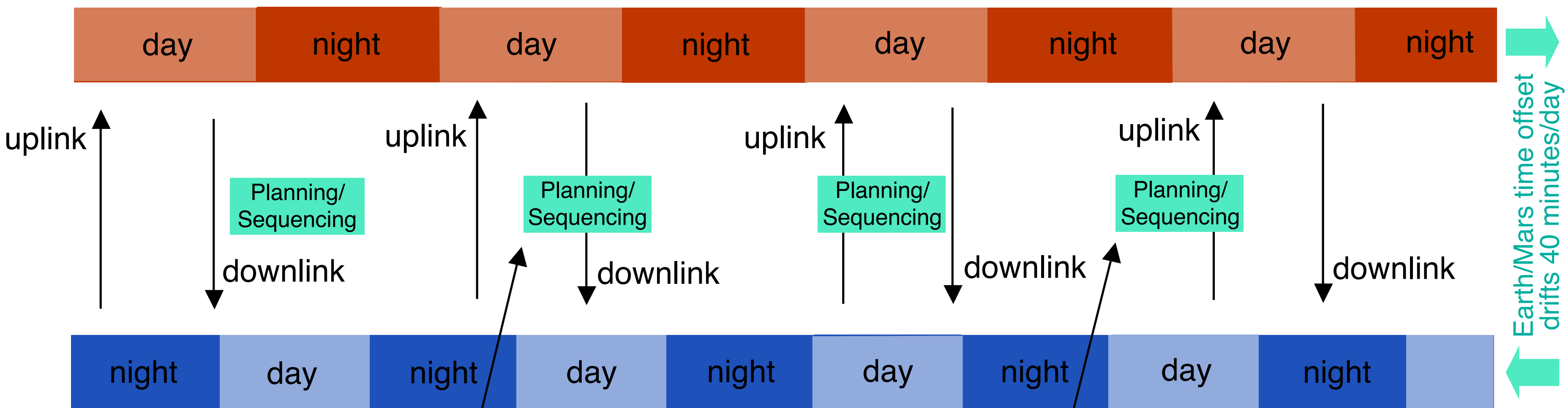
The downlink from Mars occurs at approximately the same time each SOL.



Planning on Earth begins 40 minutes later each DAY.

Planning on Earth Time

The downlink from Mars occurs at approximately the same time each SOL.



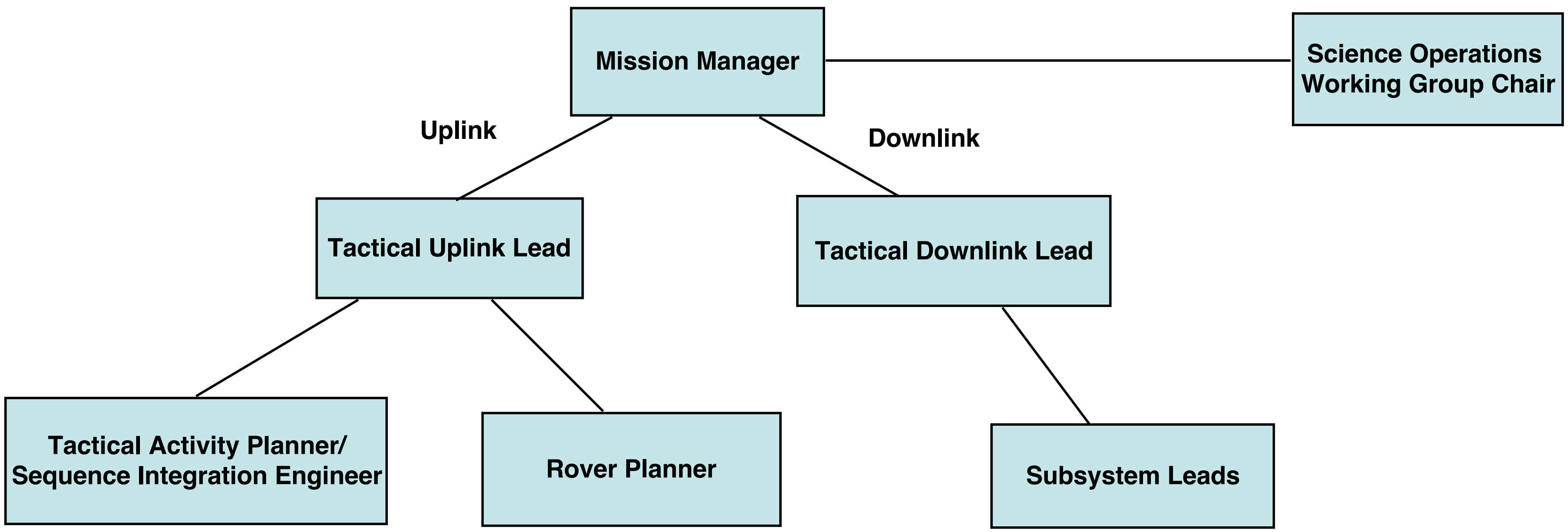
Planning begins at 8:00am each DAY.

When planning begins before the downlink occurs, this is called a RESTRICTED Sol.

It's the set of allowable ACTIVITIES that is restricted.

Because the results of the previous plan are UNKNOWN, activities which depend on those results cannot be planned.

Roles


Mission Manager
Science Operations Working Group Chair
Uplink
Downlink
Tactical Uplink Lead
Tactical Downlink Lead
Tactical Activity Planner/ Sequence Integration Engineer
Rover Planner
Subsystem Leads

Integrated Sequencing Team Tactical Roles (1)

- Mission Manager (MM)
  - Ultimate tactical responsibility for the health and safety of the rovers while maximizing the opportunities to conduct science. Specific responsibilities include:
  - Provides unbiased and independent review of Activity Plan and command sequences
  - Approves Activity Plan and command load
  - Works engineering issues having strategic impacts
  - Provides strategic-level view to tactical process
- Tactical Uplink Lead (TUL)
  - Responsible for maintaining the health and safety of the rovers while maximizing the opportunities to conduct science. Specific responsibilities include:
  - Ensuring that the tactical process progresses at an appropriate rate; that all tactical uplink positions have the information they require to progress with their tasks
  - Design of outlines for each Sol's daily rover activities; must ensure that all of the daily science objectives are met within power, time and data volume constraints
  - Leading the four post-Science Operations Working Group planning/review meetings during the planning day
  - Design of Sequence Plan structure in response to science and engineering objectives for the sol
  - Review and approval of command sequences
  - Generation of command radiation instructions for ACE
  - Documentation of overall tactical process
  - Preparation of planning products for next planning cycle

Integrated Sequencing Team Tactical Roles (2)

- Rover Planner (RP)

  Responsible for planning all MER rover motions, including traverse and IDD instrument placement. Specific responsibilities include:
  - Assessment of the safety and feasibility of reaching proposed terrain targets
  - Rover motion activity and command sequence planning and simulation
  - Rover motion command sequence generation
  - Review of rover motion command sequences
  - Documentation of tactical rover sequence development
- Tactical Activity Planner/Sequence Integration Engineer (TAP/SIE)

  Responsible for generating MER rover uplink and review products each planning cycle. Specific responsibilities include:
  - Planning and scheduling of all rover activities for a sol, including both engineering and science activities
  - Review and validation of the activity plan for compliance with flight rules and consistency with power, time and data volume constraints
  - Generation of the sol's Sequence Plan structure (master/submaster command sequences) implementing the validated activity plan
  - Integration of command sequences from all sequence providers (PULs, RPs, and TDLs)
  - Sequence management, including identification and resolution of duplicate sequence conflicts, and deletion of obsolete onboard sequences
  - Generation and delivery of command products for testing and uplink
  - Generation and delivery of review products
  - Generation of tools' input products for next planning cycle
  - Documentation of TAP/SIE tactical process results

Unknown Tau

Sol	Tau	Energy
1237	5.6*	128
1238	4.8*	191
1239	4.6*	209
1240	4.6*	214
1241	4.7*	207
1242	4.6*	213
1243	4.11	207
1244	4.0*	217
1245	4.2*	203
1246	4.33	177
1247	4.63	163
1248	4.69	152
1249	4.69	132
1250	4.66	142
1251	4.8*	139
1252	4.7*	148
1253	4.4*	183
1254	3.97	229

*Estimated