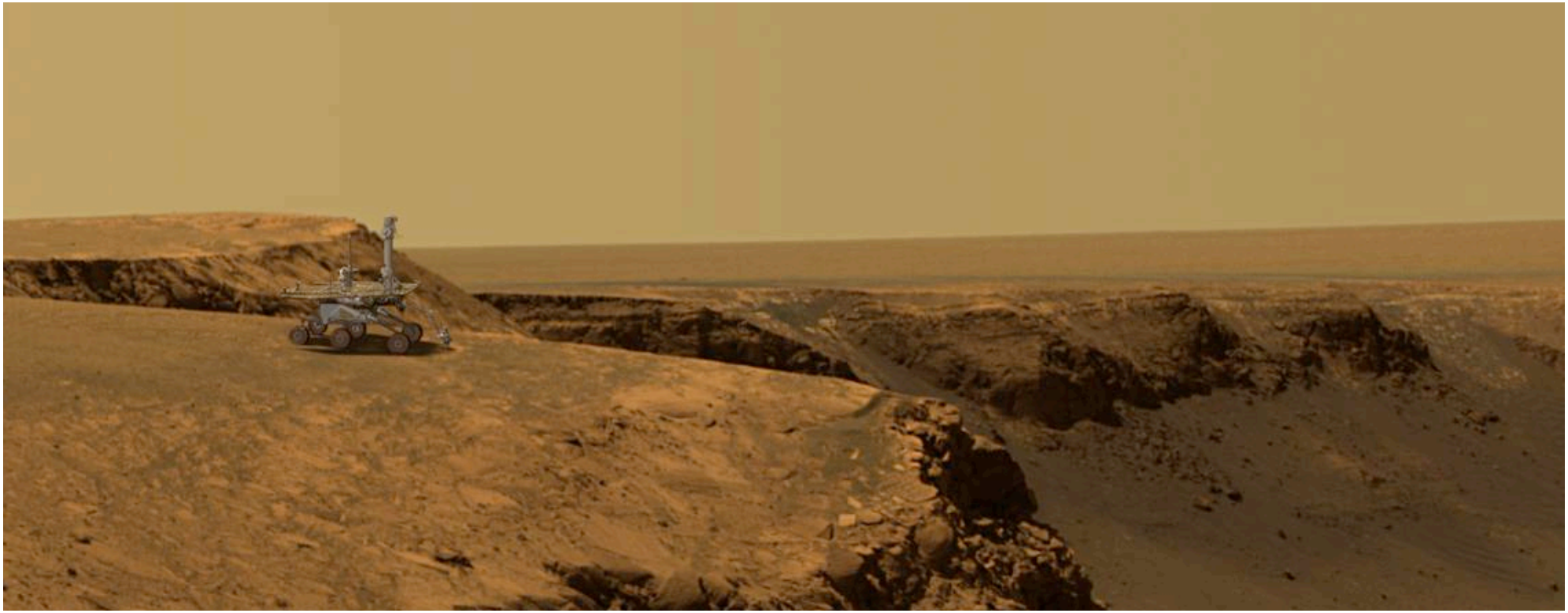
Robotics Mission Experience from Mars



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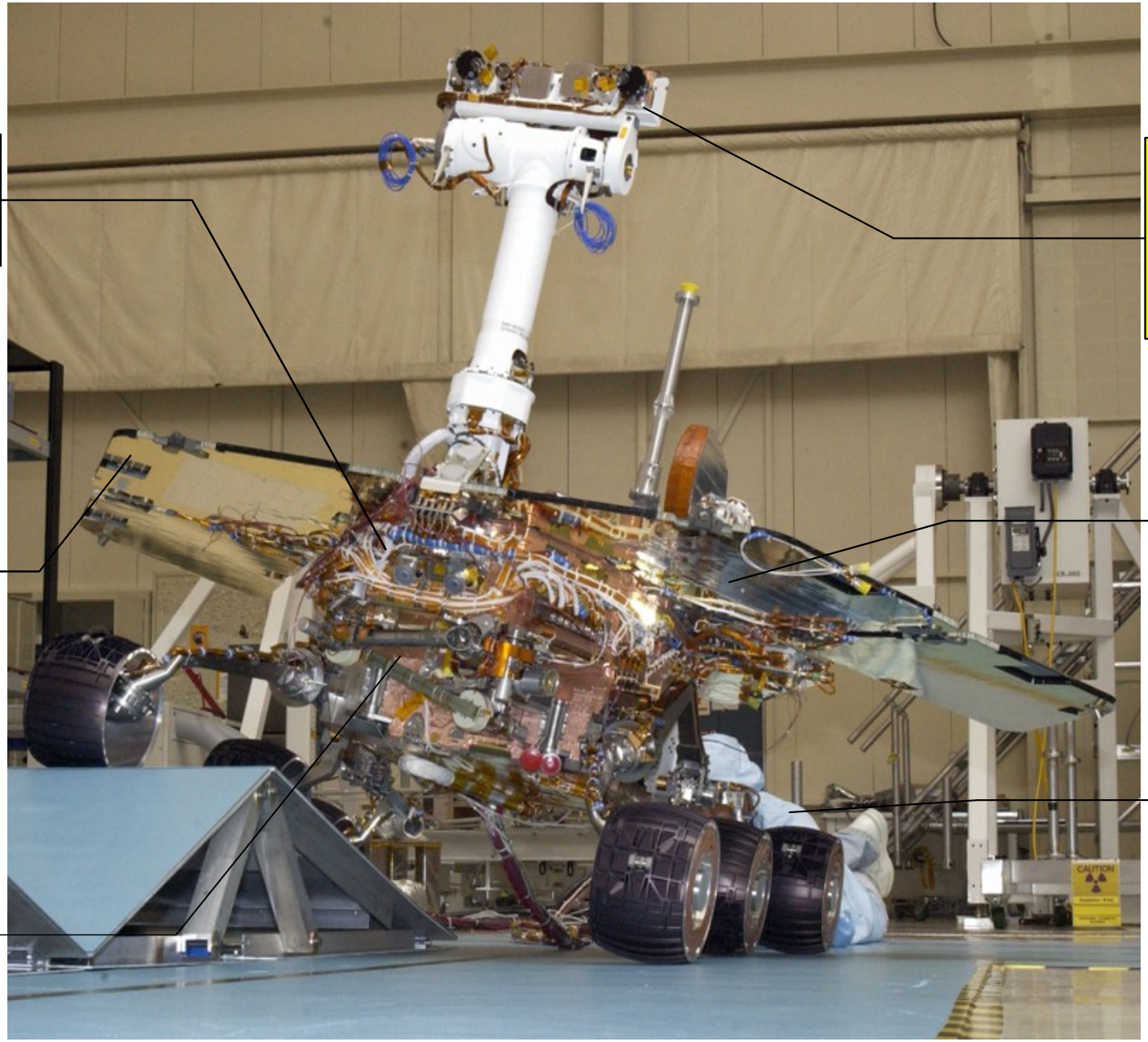
5 August 2009

MER Mobility Hardware



Wide FOV stereo HAZCAMs (front & rear) for on-board hazard detection

No bumpers/contact sensors on rover body or solar panels

IDD

Stereo NAVCAMS & PANCAMS used by ground team for planning. PANCAM used for sun based attitude update

IMU(internal) for attitude determination during motion

Six wheel rocker-bogie mobility system, steering at four corners

MER Driving Speeds

- Directed ("blind"): 120 m/hr. Gear ratios limit top mechanical speed to 5 cm/sec (180 m/hr), but nominally no more than 3.7 cm/sec (133 m/hr, less cool-off/re-steer periods).
- Hazard avoidance ("AutoNav"): 12-35 m/hr. Rover moves in 50 cm steps, but only images every 1.5 m (Spirit) or 2 m (Opportunity) in benign terrain. When obstacles are nearby, imaging occurs at each step.
- Visual Odometry ("VisOdom"): 12 m/hr. Desire is to have 60% image overlap; in NAVCAMs pointed nearby, that limits motions to at most 60cm forward or 18 degrees turning in place.

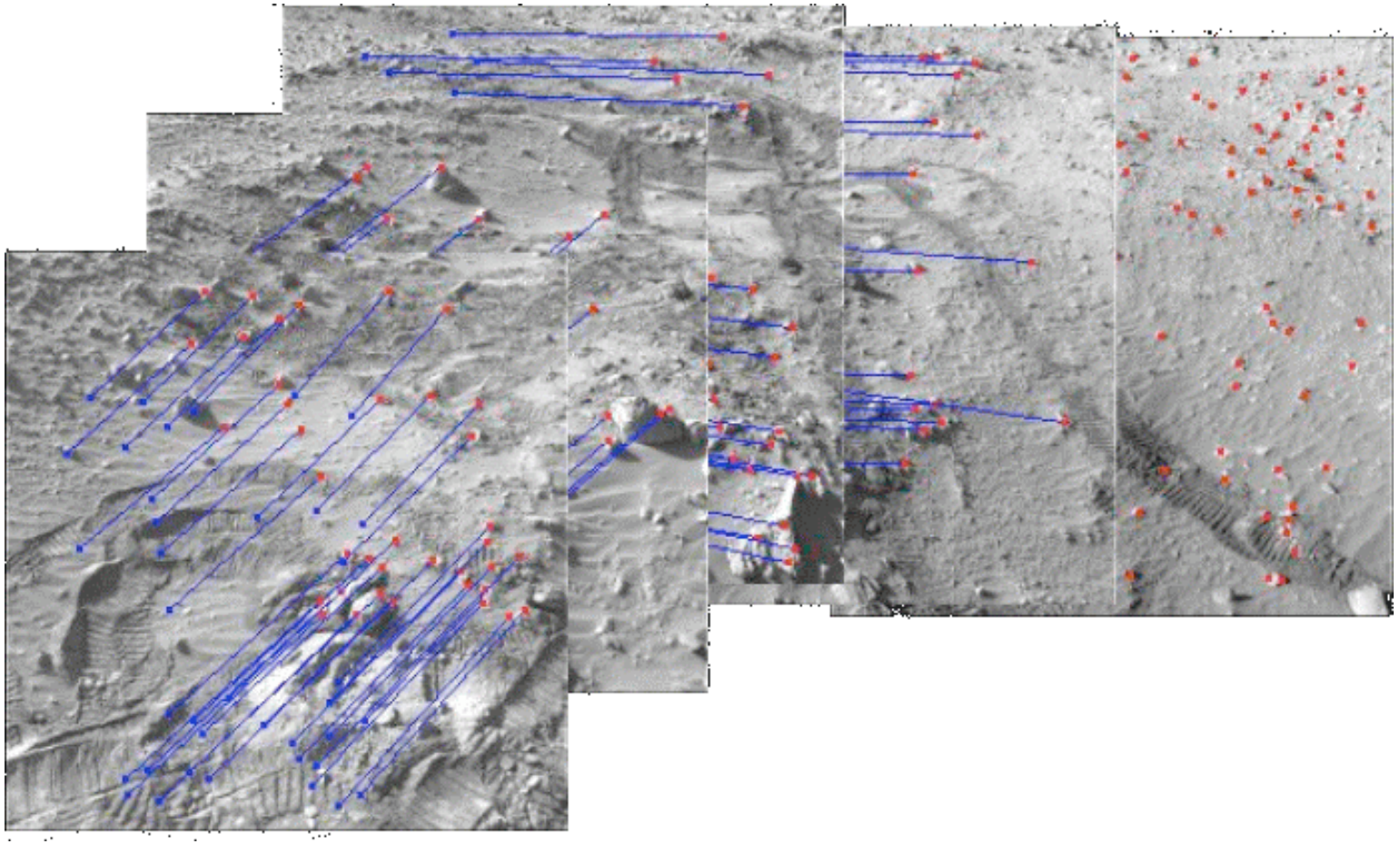
Drive Constraints

- Typically only enough power to drive 4 hours/day
- Rover generally sleeps from 1700 – 0900; humans plan next day's activities while it sleeps, e.g. human terrain assessment enables a blind drive
- A single VisOdom or AutoNav imaging step takes between 2 and 3 minutes (20MHz CPU, 90+ tasks)
- Onboard terrain analysis only performs geometric assessment; humans must decide when to use VisOdom instead of/in addition to AutoNav
- Placement of Arm requires O(10cm) precision vehicle positioning, often with heading constraint

Spirit Sol 106: Avoiding a 21cm rock

L - Caltech

Visual Odometry Processing



- VisOdom enables precise position estimates, even in the presence of slip, and enables Slip Checks and Keep-out zone reactive checks

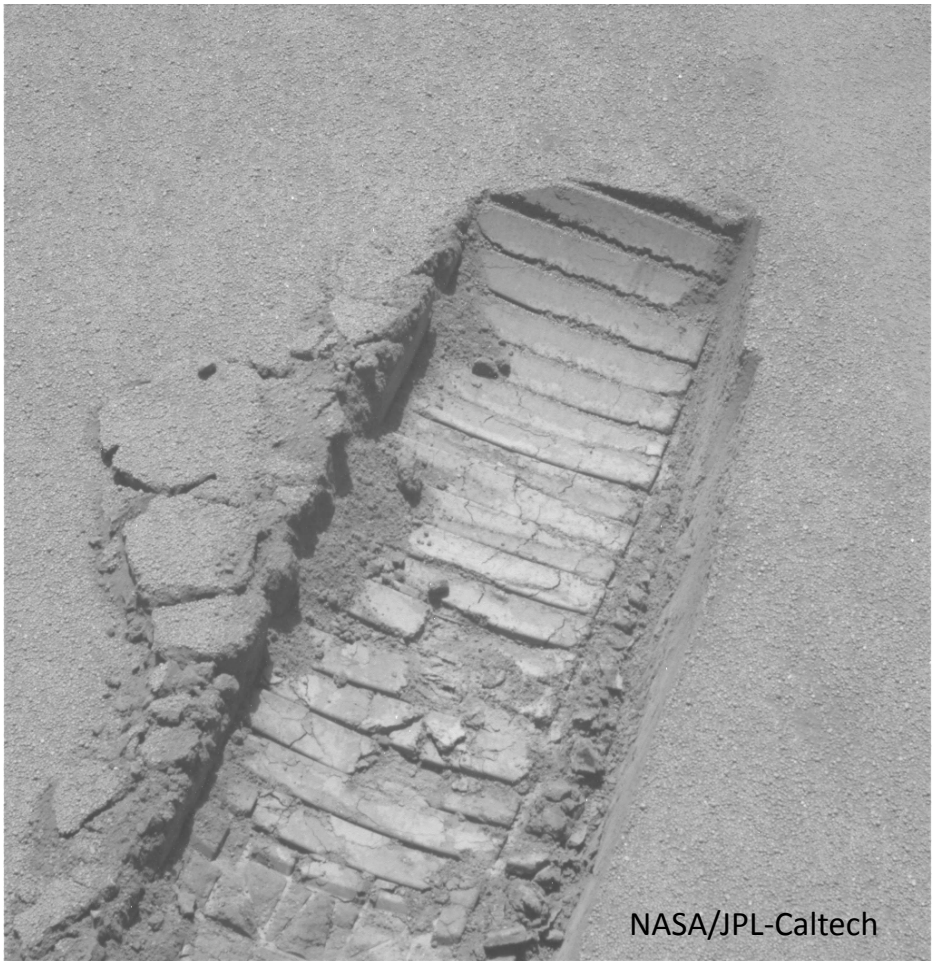
Lessons Learned: Opportunity Slip Check

On B-446, 50 meters of blind driving made only 2 meters progress, burying the wheels. Recovery time: 5 weeks.

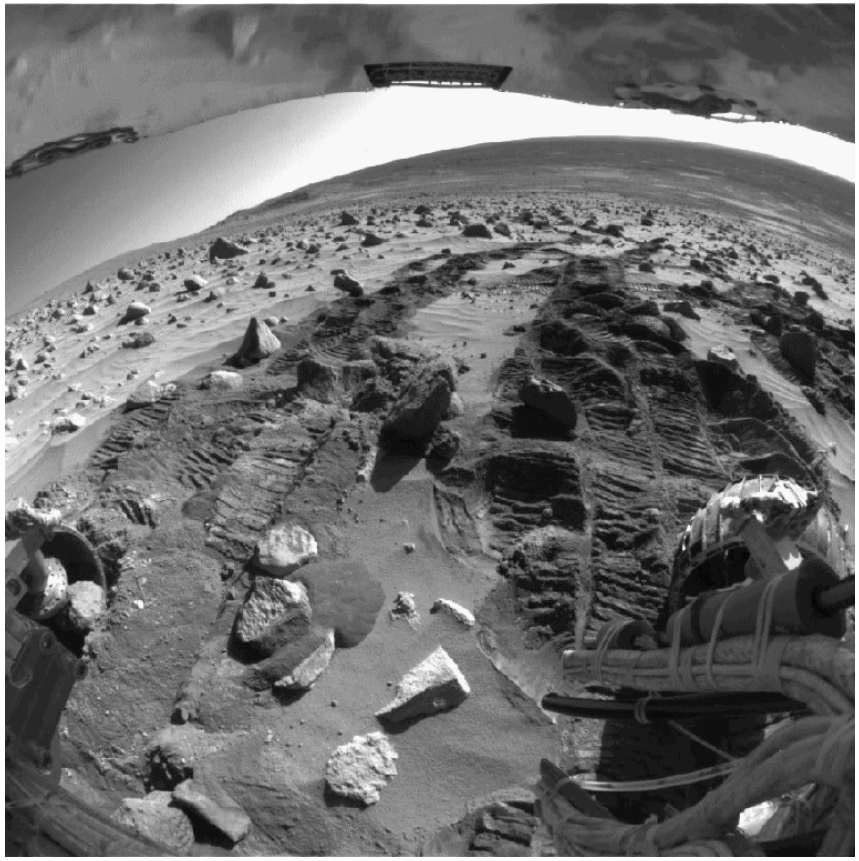
On B-603, 5 meters of blind driving made 4 meters progress (stopped by Visodom with 44% slip). Recovery time: 1 day.

Slip Check Prevents Digging In

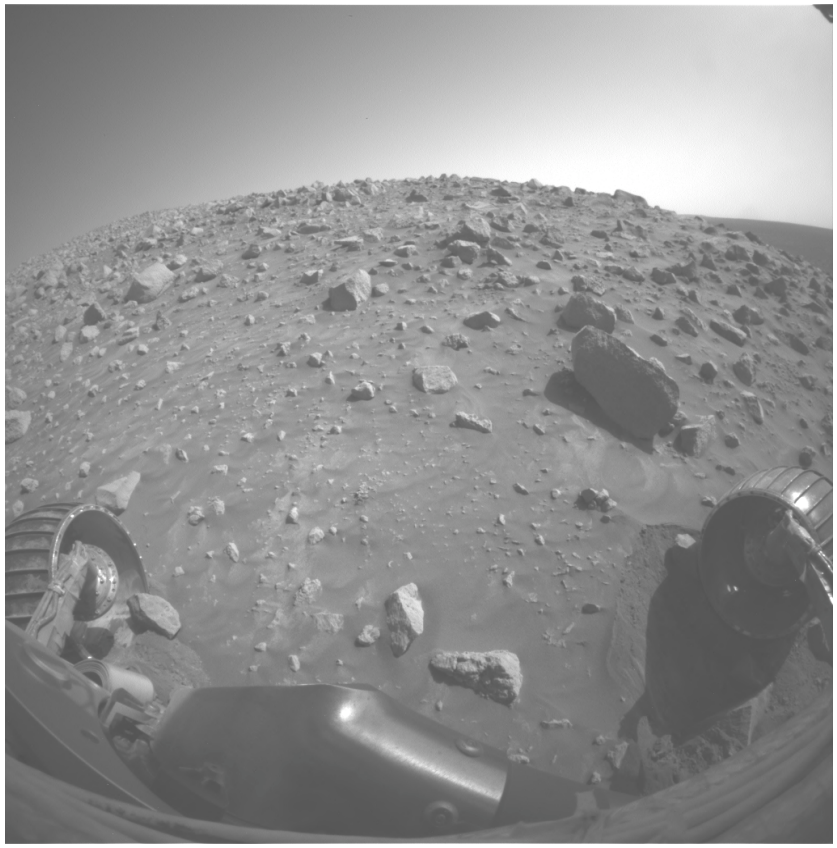
Next day Opportunity drove directly out of the sand ripple. A great improvement over the similar situation on Sol 446 (which, without VisOdom, took over a month to resolve)



Lessons Learned: Spirit Slip Check

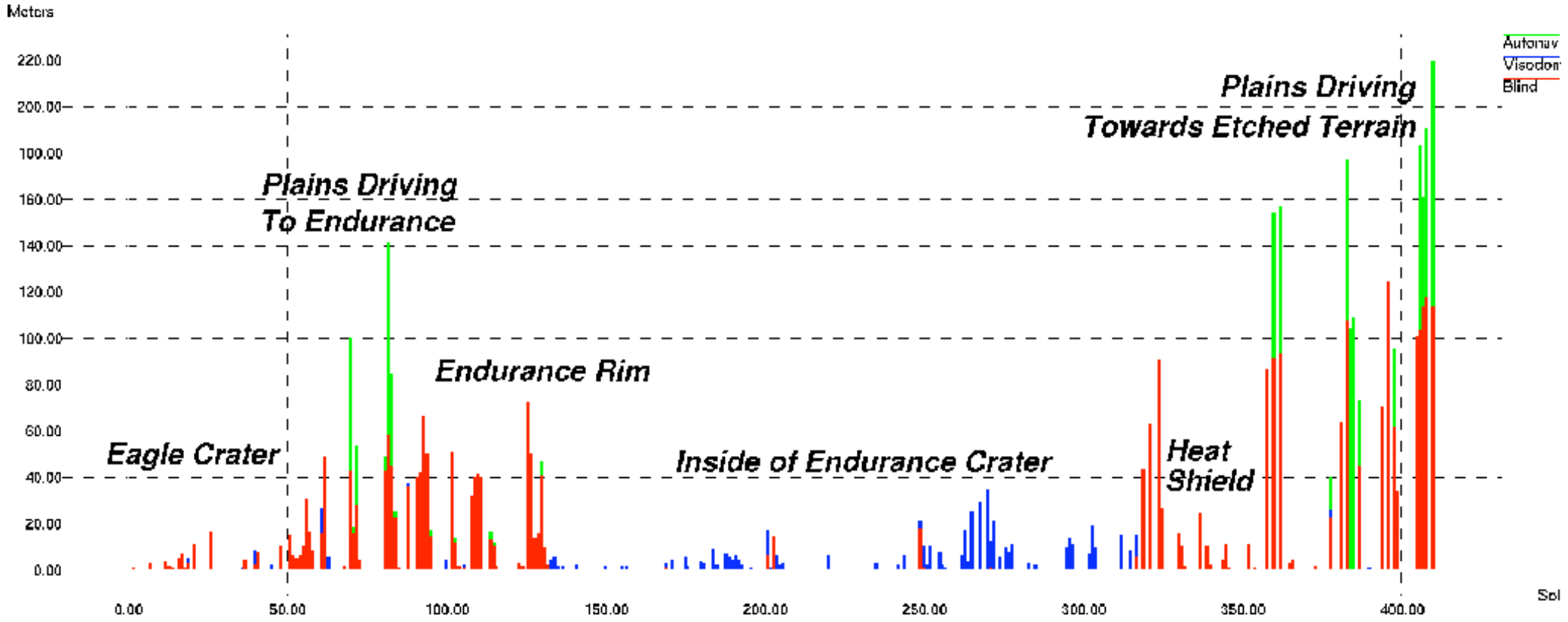


On A-345, Spirit stalled because a potato-sized rock had gotten wedged inside a wheel. Recovery time: 1 week.



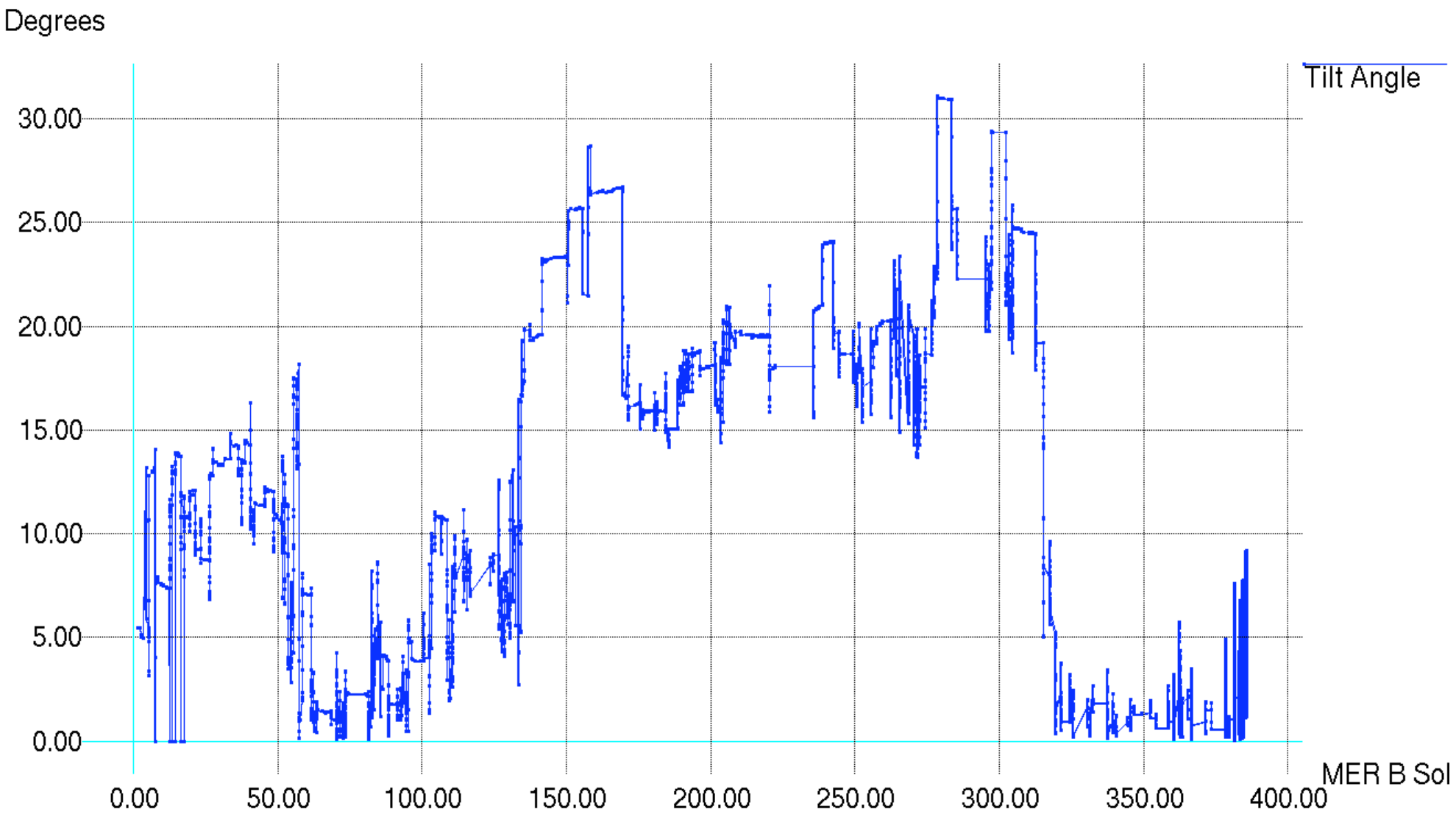
On A-454, Spirit detected 90% slip and stopped with rocks poised to enter the wheel. Recovery time: 1 day.

Opportunity Drive Modes in first 410 Sols

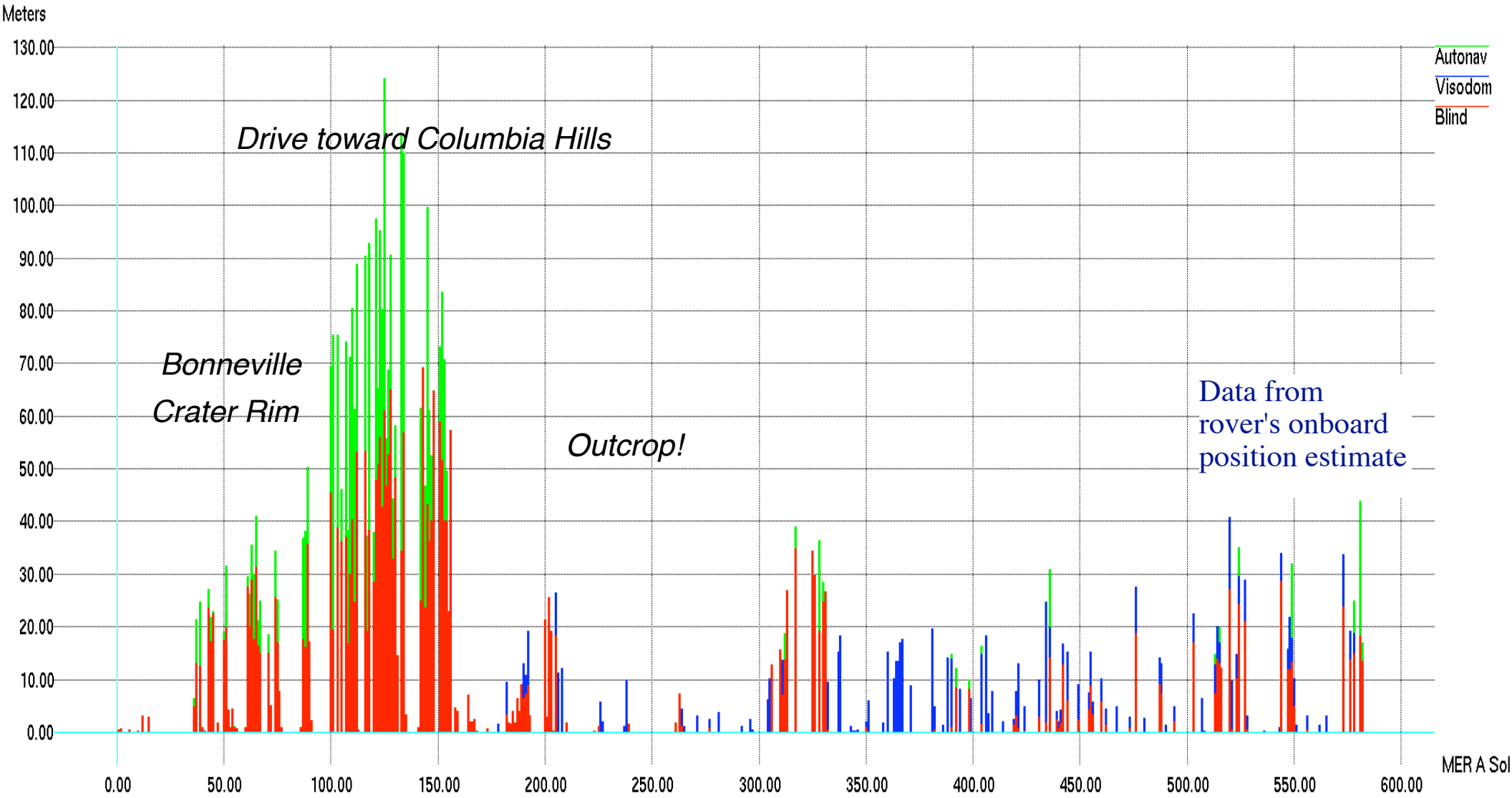


Data from rover's onboard position estimate

Opportunity Tilt History through Sol 380



Spirit Drive History through Sol 588



Benefits of Onboard Terrain Assessment

- Terrain Assessment Extends Drive Range *Safely*
  - **Human drivers plan directed drives as far as ground-based imagery and range data allow, (typically at most 50-100 meters at speeds up to 120 m/hr) then let the onboard system use the rest of the available drive time (12-35 m/hr)**
  - **Extra insurance against unexpected events**
  - **Faster to plan than directed drives**
- Optimistic IDD use
  - **Enabled by Guarded Arcs and Go and Touch stereo vision as of R9.2**

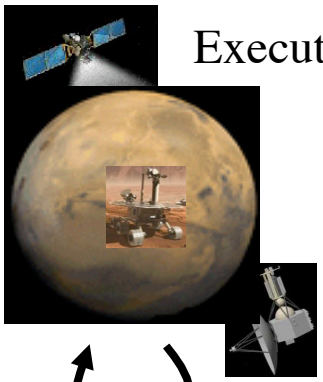
Benefits of Visual Odometry

- VisOdom Increases Science Return
  - **Provides robust mid-drive pointing; even if you slip, the proper target can still be imaged**
  - **Enables difficult approaches to targets in fewer Sols; drive sequences conditional on position**
- VisOdom improves Rover Safety
  - **Keep-out zones; if you slide too close to known hazards, abort the drive**
  - **Slip checks; if you're not making enough forward process, abort the drive**

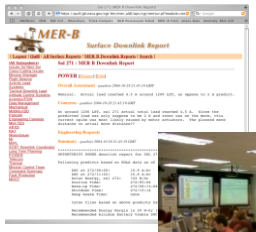
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

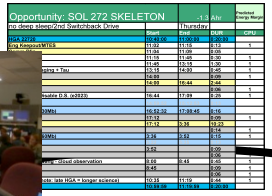
MER Daily Surface Ops Cycle (early prime mission)

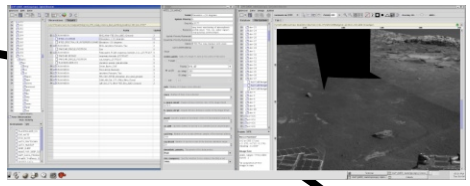


Execute



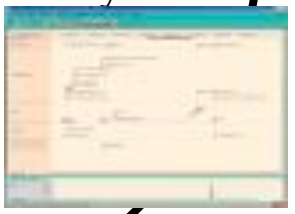
Assess & Analyze



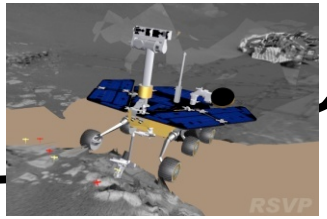


Plan Observations & Measurements

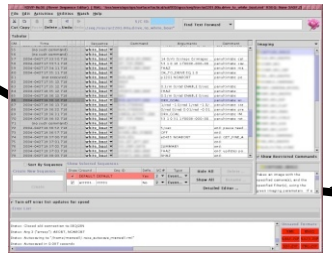
Integrate Activity Plan

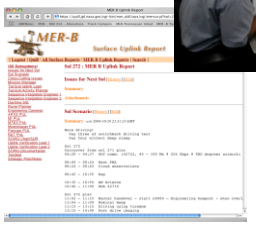


Test (if needed)

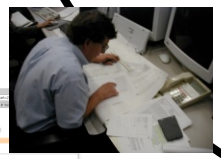


Sequence & Simulate





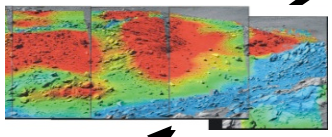
Prepare Command Products



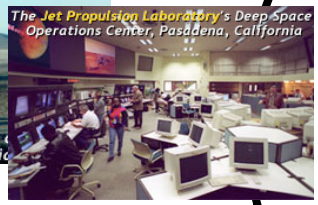
~18 hour planning cycle

7 days a week

Mars-time

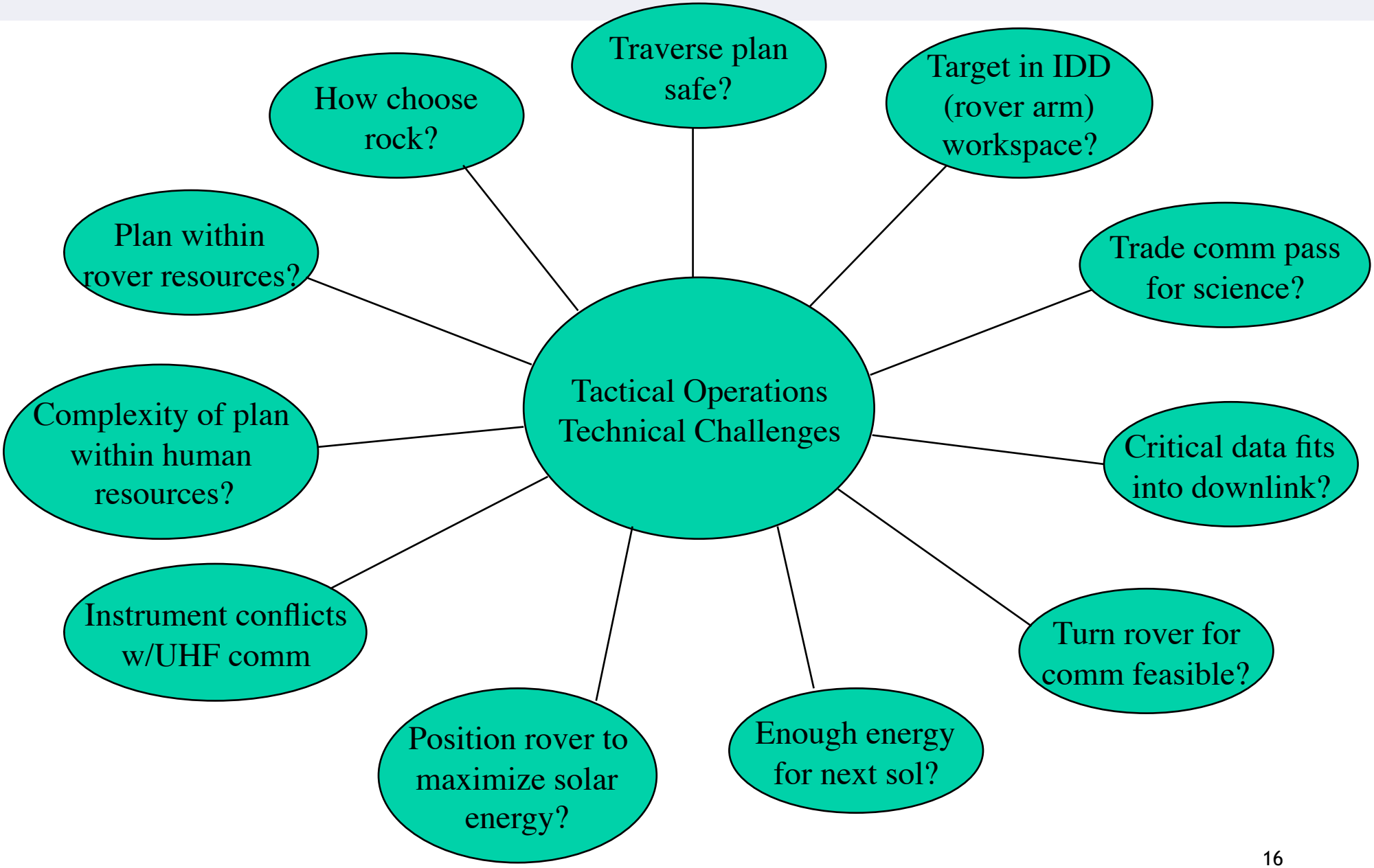


Generate Data Products



Communicate

Sample Issues for Planning a Sol



Drivers on the Original MER Operations Design

- Limited Lifetime
  - Dust accumulation on solar arrays and seasonal changes expected to end rovers' useful surface mission lives
- Reactive Operations
  - Rover plan for tomorrow depends on results from today
    - Traverse uncertainties (autonomous hazard avoidance, wheel slippage)
    - Science targets identified via telemetry from local rover observations
- Resource Constraints (energy, data, time)
- Communications Constraints
  - Limited uplink opportunities (~1/sol)
  - ~20Mbit per/sol direct-to-Earth downlink each Mars afternoon
- Time Delay
  - ~6 to 40-minute roundtrip communications time delays
  - No "joysticking" possible
- Every-sol Commanding
  - 7-day-a-week 18-hour command turnaround process
- Mars-Time
  - Rovers and operations team slaved to Mars day-night cycle
  - Workshifts begin 40 minutes later every day

Why Work Mars Time?

- Provides maximum number of usable workhours between afternoon downlink and morning uplink
  - Allows maximum resilience for teams in early surface mission (phase of maximum uncertainty)
  - Minimizes required level of cross-training across teams
- Key spacecraft and ground events are tightly coordinated
  - Sol n afternoon downlink triggers uplink planning process (downlink analysis, science planning meetings, activity plan approval, command and radiation approval) which must complete in time for sol n+1 uplink
  - Spacecraft and ground activities happen at a consistent time on the Mars clock
- Personnel have clear understanding of when spacecraft events will occur
  - Easy to know what's happening on Mars right now
- Contributes to team building

Extended Mission #1: Returning to Earth

- Mars-time not sustainable
  - Never intended to support long-duration mission
- How to get operations team off of Mars-time?
  - Reduce tactical process duration (produces time margin)
    - Additional automation for increased process efficiency
    - Increased team experience
    - Buildup of command sequence libraries
  - Spend time margin to eliminate night shifts
- Problem: Downlink now walks through Earth-day workshift
  - Solution: Sliding “Earth-time” schedule
    - Nominal sols: Downlink received before start of workday
      - Workday ~0800 to ~1700
    - Slide sols: Downlink received early in workday (<1300)
      - Start of workday shifts as late as 1300
    - Restricted sols:
      - Downlink received too late in day (>1300), or uplink is too early in day (<1600)
      - Plan using 1-sol-old telemetry
      - Restricts rover driving to every-other-sol
    - Tight sols: Uplink occurs near end of workshift (1600-1800)
      - Minimal or no time margin
      - Start workday at 0700 or 0800

Extended Mission #2: Distributed Operations

- Drivers on distributed operations for science team
  - Allows return of scientists to home institutions (and families)
  - Potential reductions in operations costs
  - Reduces facility requirements
- Enablers
  - Nearly “paperless” process for original fast tactical operations provided information distribution capability for distributed team
  - Webcams, open teleconference lines, web-based reports and online documentation all supported remote team participation
  - Workstations configured with key activity planning and command sequencing tools installed at remote sites
- Engineering team remains co-located at JPL

Fast Waypoint Designation

- In 1988, JPL modified a HMMWV for waypoint designation in a stereo display.
- Objective was to reduce designation time to 3-10 seconds.
- 10 seconds was achievable; 3 seconds was not.

Continuing Evolution

- Aging rovers
  - Process and software workarounds
  - Additional operations complexity
- New flight software
  - Fixes that simplify operations
  - New capabilities/technology experiments that increase risk and complexity
- Changing Martian seasons
  - Summer: Thermal constraints
  - Winter: Energy availability
    - Rover survivability
    - Additional consequence: Downlink data volume limitations, challenging onboard data management
- Changing operations environment at Mars
  - Competition for communications resources
    - Over-subscribed DSN
    - MRO mission frequently consumes Spirit rover communications opportunities on short notice
    - MER responses
      - Process for forward link commanding through Mars Odyssey orbiter
      - Multi-sol plans to make maximum use of available uplink opportunities