This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

xTerramechanics Canonical Case Discussion

The view from the JPL/NASA Flight Project Perspective

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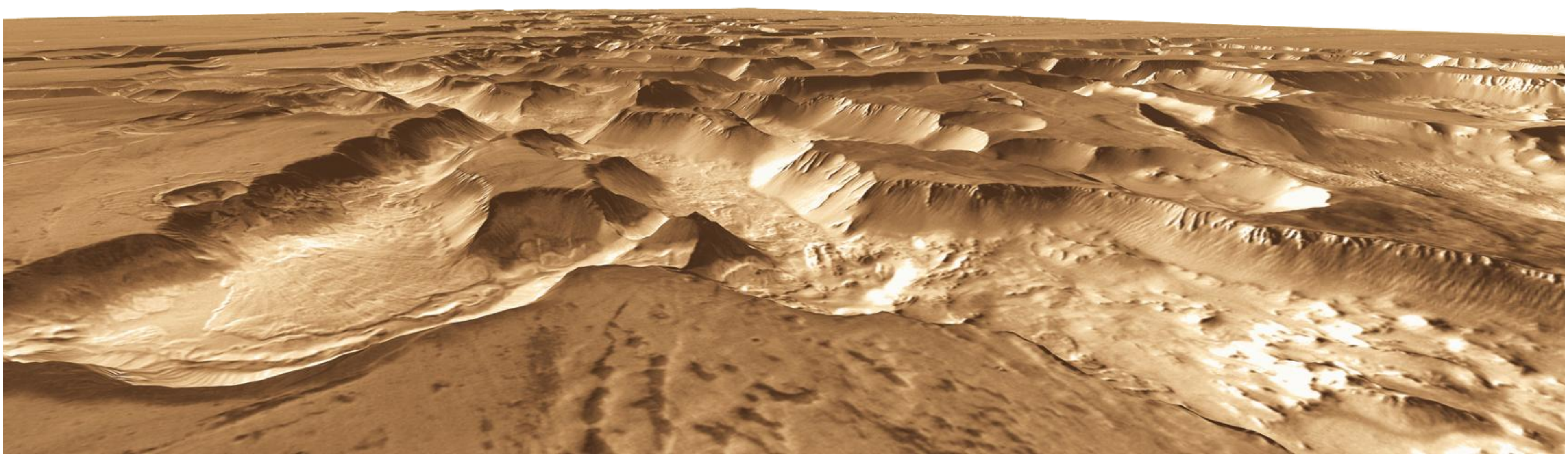
August 19, 2011

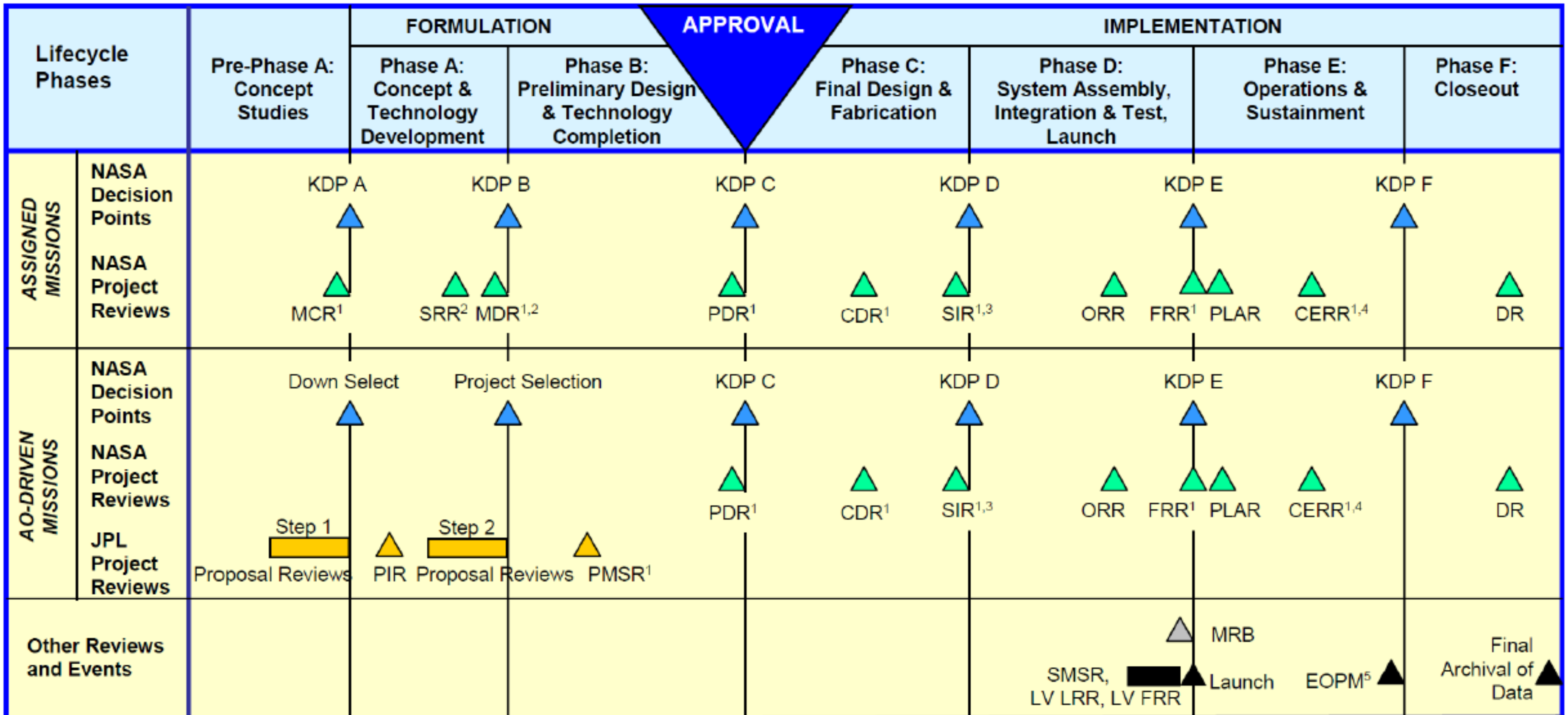


xTerramechanics:

A New Paradigm in Space Exploration, Terrain is No Obstacle

- NASA Project **L**ifecycle **I**ntegrated **T**esting, **M**odeling, and **S**imulation (LITMS) of Spacecraft and Extraterrestrial Terrains
- Increase Capabilities, Lower Risk, and Reduce Costs for Space Exploration by embracing a Structured Systems Approach to Design, Development, Verification, and Validation through **LITMS** for Planetary Surface Missions
- Proposing, Developing, and Demonstrating Extraordinary and Profound Advancements in NASA Planetary Exploration
    - Clearly Presented by both the KISS Management and the NASA Office of the Chief Engineer as the "**minimum level of their interest**"; otherwise we should go to the Program Directorates or actual Projects for funding
    - Unfortunately we cannot effectively market our **current** xTerramechanics to NASA Programs and Projects because firstly, they don't think they NEED it; and secondly, our technology is NOT flight ready (insufficient Technology Readiness Level)

NASA/JPL Project Lifecycle



Notes

(1) Review is followed by a JPL CMC. If the review immediately precedes a KDP, a Mission Directorate and/or Agency PMC/GPMC, as appropriate, are required prior to the KDP.
(2) The SRR and MDR may be combined
(3) SIR is a "soft gate", project may initiate Phase D work immediately upon completion of Phase C work products, absent a notice of discontinuance from the Program Manager
(4) CERRs are established at the discretion of Program Offices.
(5) At the end of the prime mission, if an extended mission is approved, the extended mission is still in Phase E.

Legend

CDR – Critical Design Review
CERR – Critical Events Readiness Review
CMC – Center Management Council
DR – Decommissioning Review
EOPM – End of Prime Mission
FRR – Flight Readiness Review
GPMC – Governing Program Management Council
KDP – Key Decision Point
LV FRR – Launch Vehicle Flight Readiness Review
LV LRR – Launch Vehicle Launch Readiness Review
MCR – Mission Concept Review
MDR – Mission Definition Review
MRB – Mission Readiness Briefing
ORR – Operations Readiness Review
PDR – Preliminary Design Review
PIR – Proposal Implementation Review
PLAR – Post Launch Assessment Review
PMC – Program Management Council
PMSR – Project Mission System Review
SIR – System Integration Review
SMSR – Safety and Mission Success Review
SRR – System Requirements Review

05.01.2007

xTerramechanics:

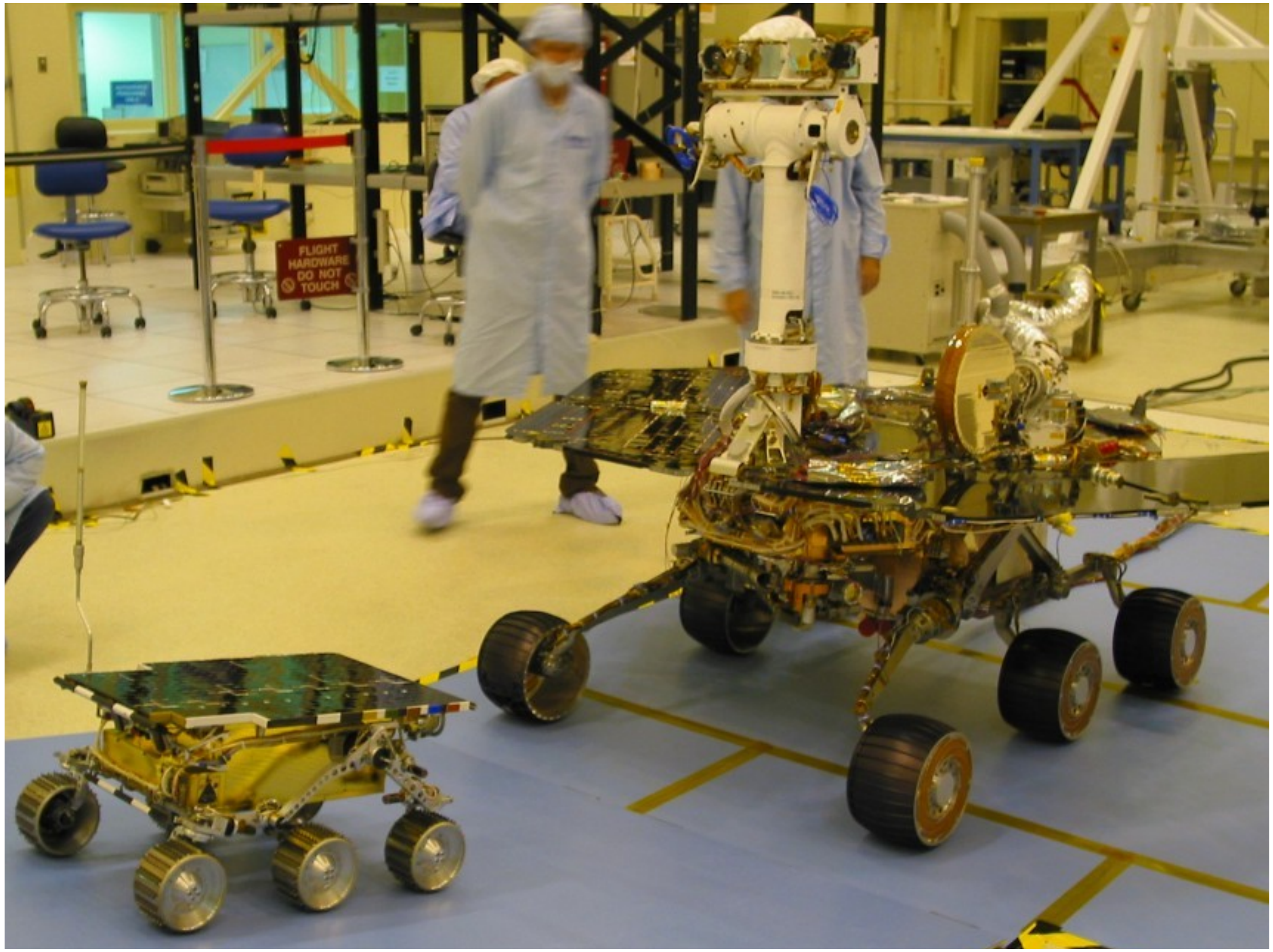
The Near Term, The Preliminaries

- **Mission Enhancing:** Evolutionary Contributions to NASA Missions already "On the Books" or likely to be chosen in the near future. This can be our avenue for near term development, demonstration, validation, proof-of-concept; as well as focusing the interests of other agencies like DARPA, the Army, the Construction Industry, etc.
    - **MER** (Martian Rover Mobility)
    - **MSL** (Martian Rover Mobility and Sample Transfer Functionality)
    - **OSIRIS-Rex** (Asteroid Sample Acquisition during a Touch-And-Go Encounter)

- **Our Canonical Case:** Martian Mobility
    - Starting with the *Bekker-Wong-Reece* Equations of Terramechanics in a fully functional Modeling and Simulation Environment of the MER rover on soft deformable Terrain
    - Modify, Improve, and Extend BWR with modern Soil Mechanics methodologies
    - Employ State-of-the-Art Physics-based modeling approaches at Multi-Scales via DEM, FEA, etc. to advance constitutive properties of Soil Functions and demonstrate improved predictive performance in simulations as compared to Testing and MER Telemetry

MER Mobility Design

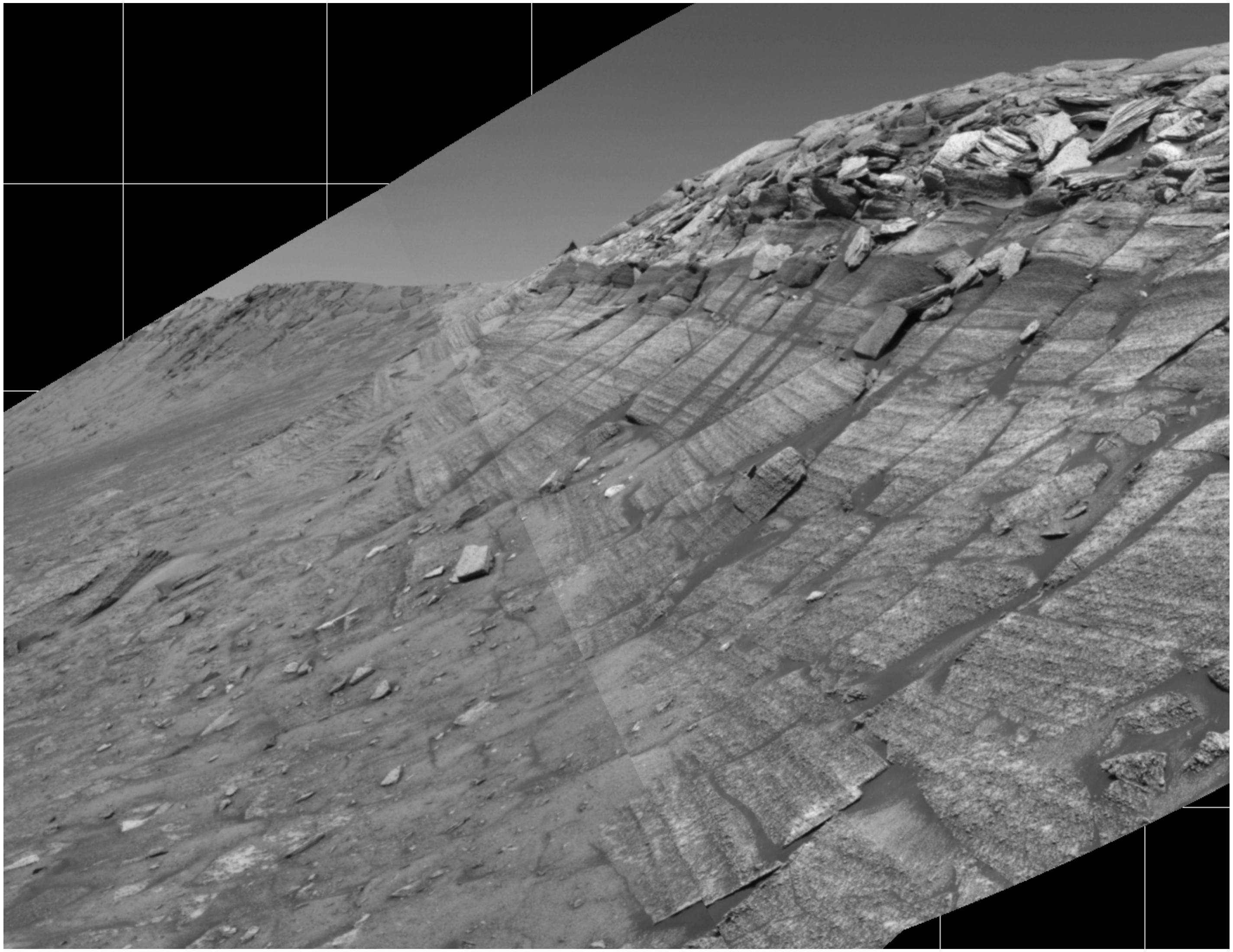
- The Rocker-Bogie mobility suspension is comprised of 6 driven wheels, with the outer 4 wheels steerable
- The Rocker-Bogie suspension utilizes a differential and linkages to effectively equilibrate the wheel loads during drives
- The first rover to Mars, Sojourner, also utilized a rocker bogie suspension



The rover *Spirit* shown behind *Marie Curie* from the Mars Pathfinder mission

MER Mobility Requirements

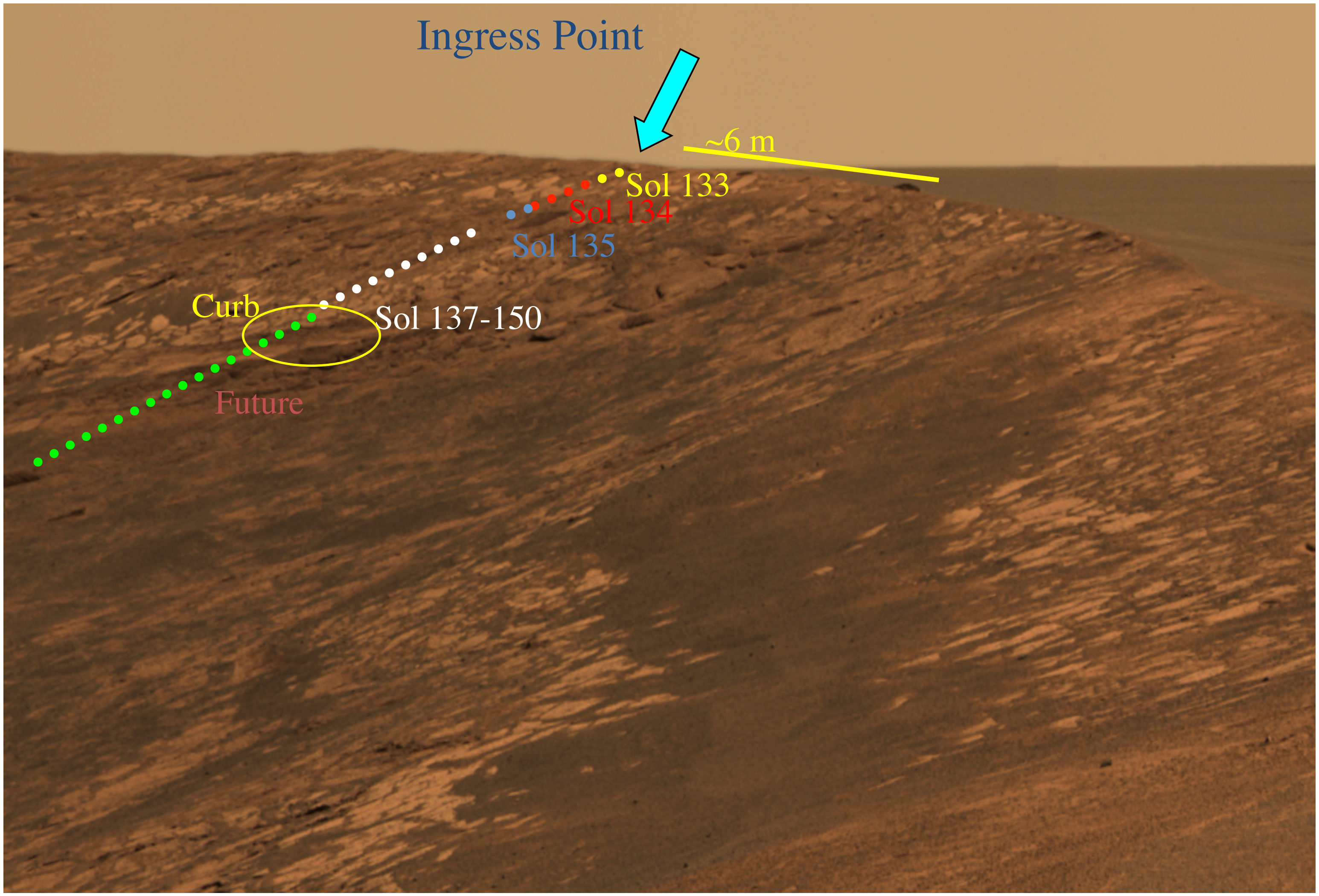
- Last 90 “sols” on Mars
- Drive up to 1 km
- Traverse obstacles up to 25 cm in height
- Traverse over very soft soils
- Be statically stable while tilted in any direction up to 45 degrees
- Not be “torque limited”,
- Perform precision drives to Science targets
- Wheels designed to achieve a low engineering ground pressure on soft terrain



View from the rover *Opportunity* of the Burns Cliff formation, Endurance crater

Opportunity Example: Karatepe Ingress

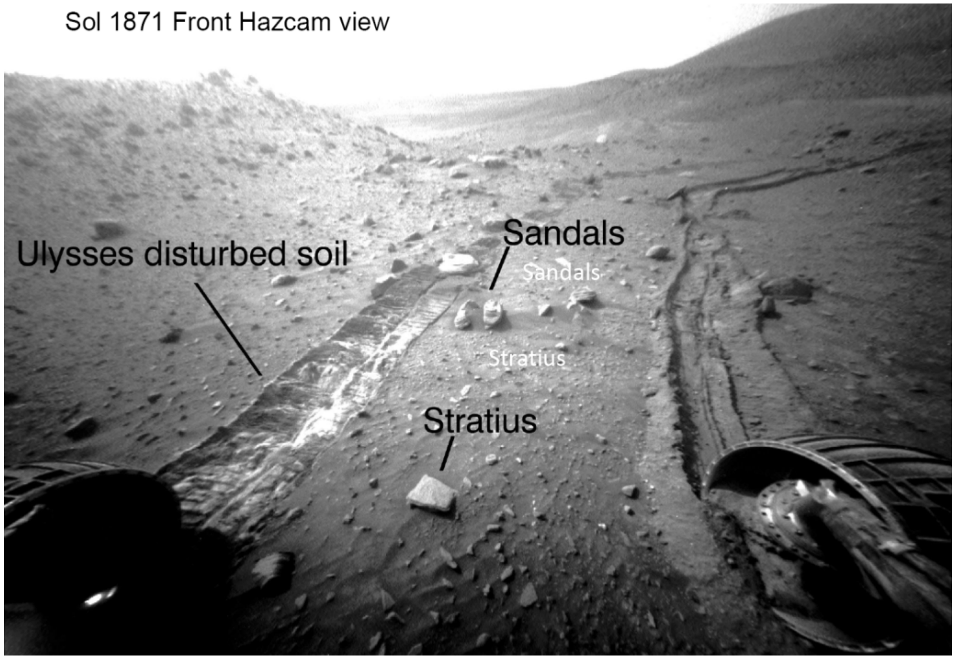
Crater Slopes exceeded all previous Testing and Analysis



Spirit's Predicament

Since Sol 1871

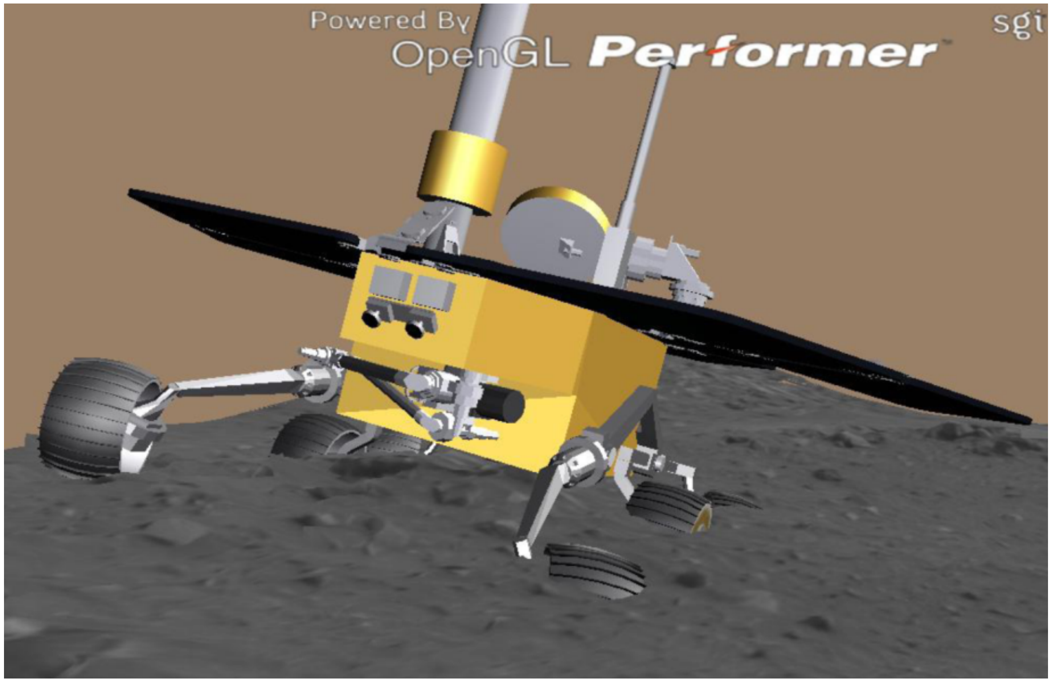
Sol 1871 Front Hazcam view



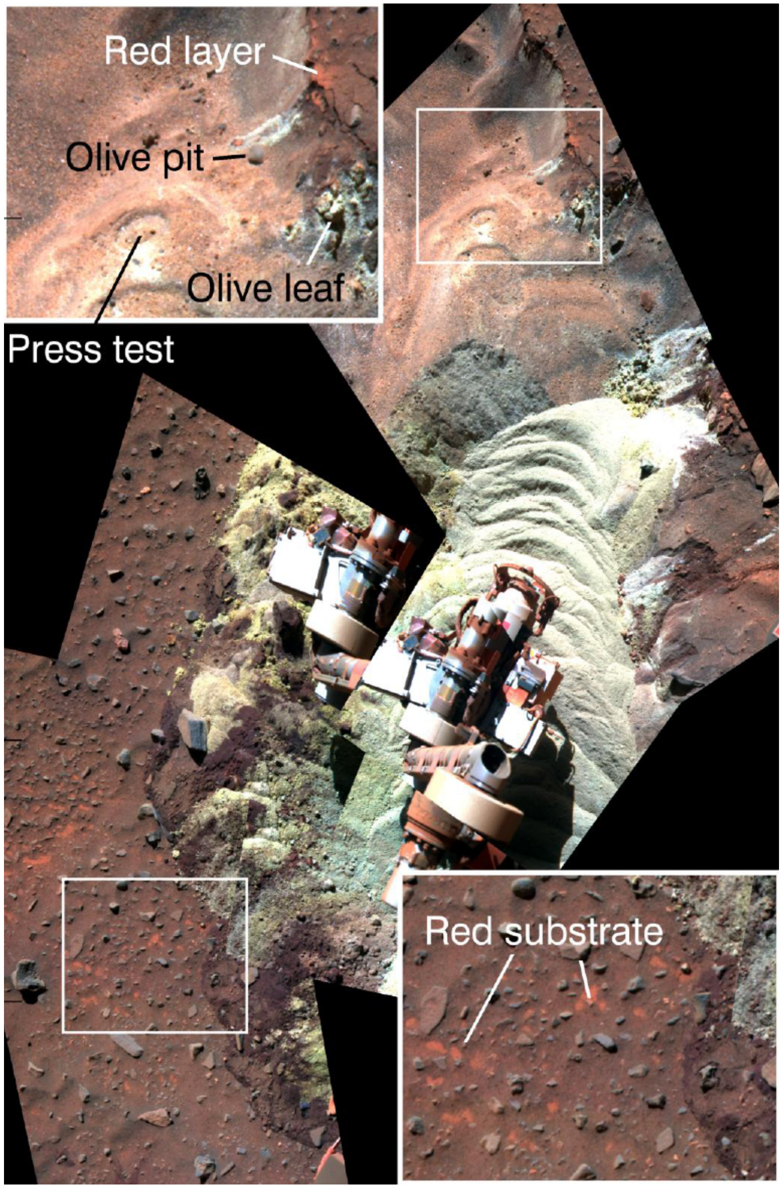
View from the Front Hazard Avoidance Camera on Sol 1871. Note that Spirit has been driving in reverse, dragging its right-front wheel behind it. The right-front wheel has been un-drivable since ~ Sol 1000.

View from the Rear Hazard Avoidance Camera on Sol 1871. This image shows the reverse driving direction of Spirit with the right-rear wheel nearly fully embedded, and with the left-rear wheel buried up to the radius of the wheel.

Details of Spirit's Embedding



Ground support software visualization of Spirit's embedding



Rover color images, generated on the ground, from the Panoramic Cameras, showing the deployment of the robotic arm and the science instruments to the disturbed soft soils that having caused Spirit's embedding

MER Mobility Testing
Ultra-Soft Deformable Soil, Simulating Embedding Event

SSTB Rover driving in Ferric Sulphate sand simulant, at a 12 deg slope, and covered with 20 cm of dry, loose Diatomaceous Earth and Fire Clay

MER Mobility Testing

Rigid, Frictional Terrain

- Testing under mobility conditions was performed on a 5 meter square tilt-able platform called the Variable Terrain Tilt Platform (VTTP)
- The slope of the VTTP could be set between 0 and 30 degrees
- The surface was initially bare, and later covered with dry and loose quartz sand
- Obstacles could also be attached to the platform

Dynamic Test Model rover driving up a 15 deg slope, climbing a 25 cm obstacle

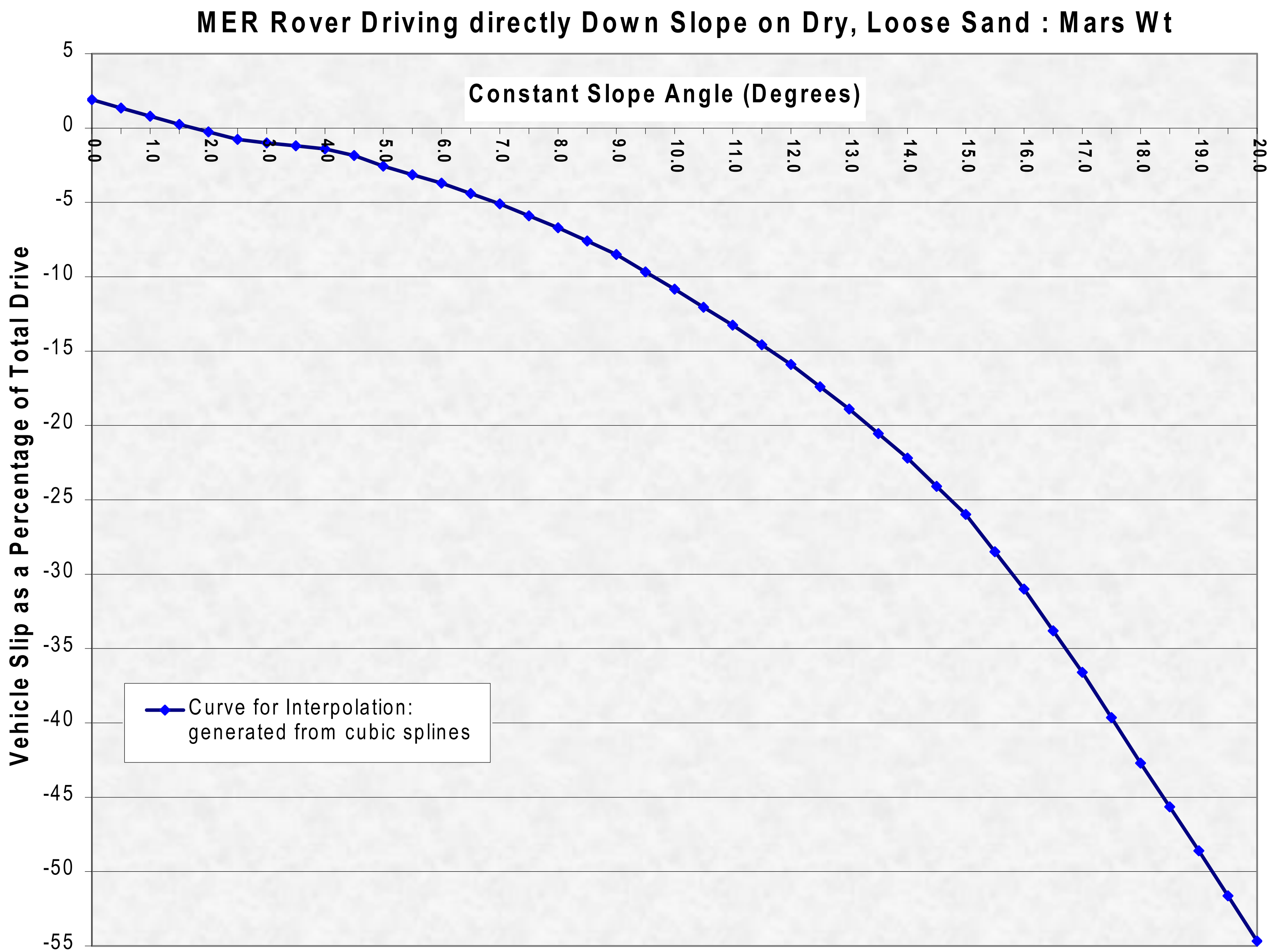
MER Mobility Testing

Soft Deformable Soil

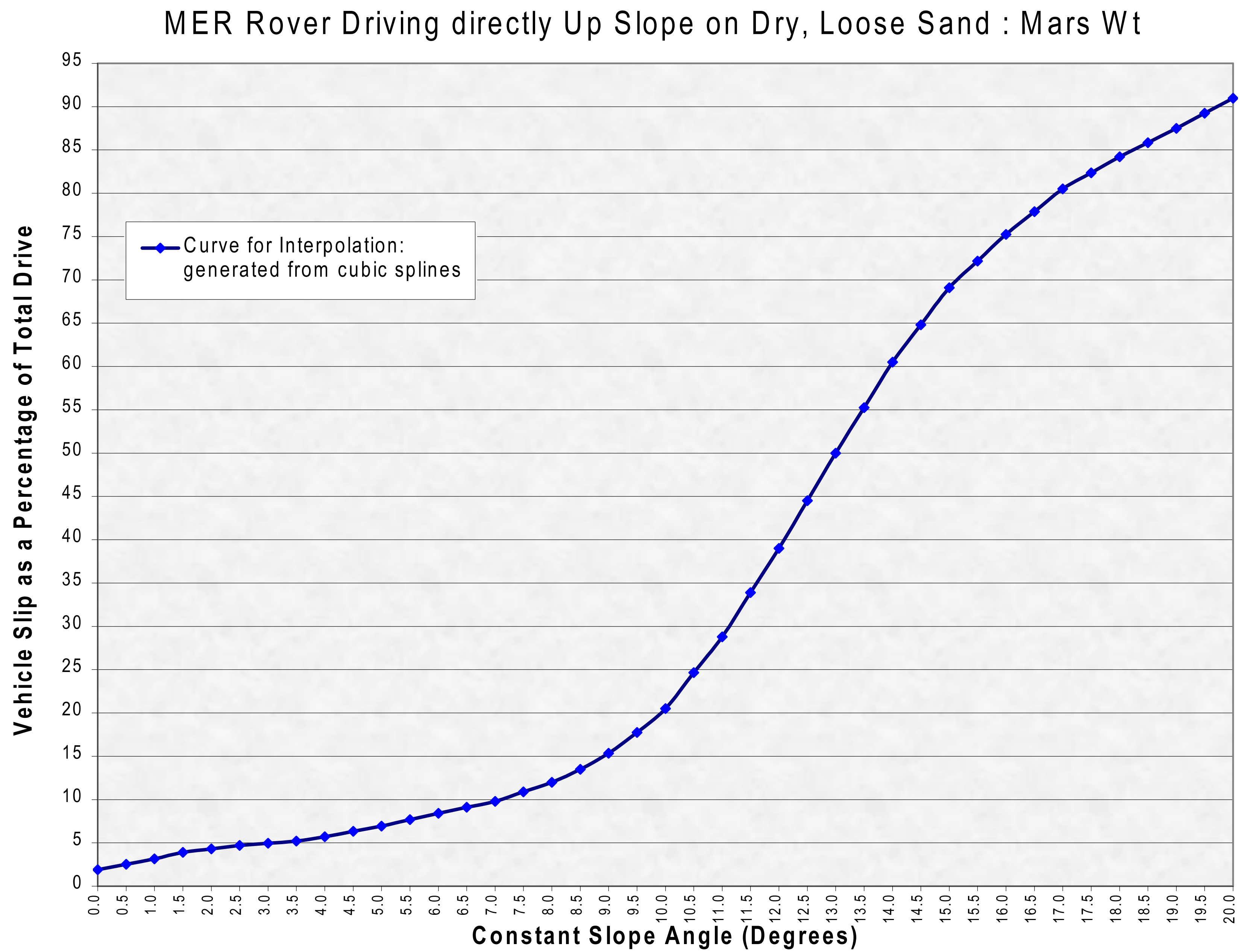
DTM Rover driving cross-slope on the VTTP, at a 20 deg slope, and covered with 20 cm of dry, loose quartz sand

Mocked Up Testing of the SSTB-Lite Rover in Pavers

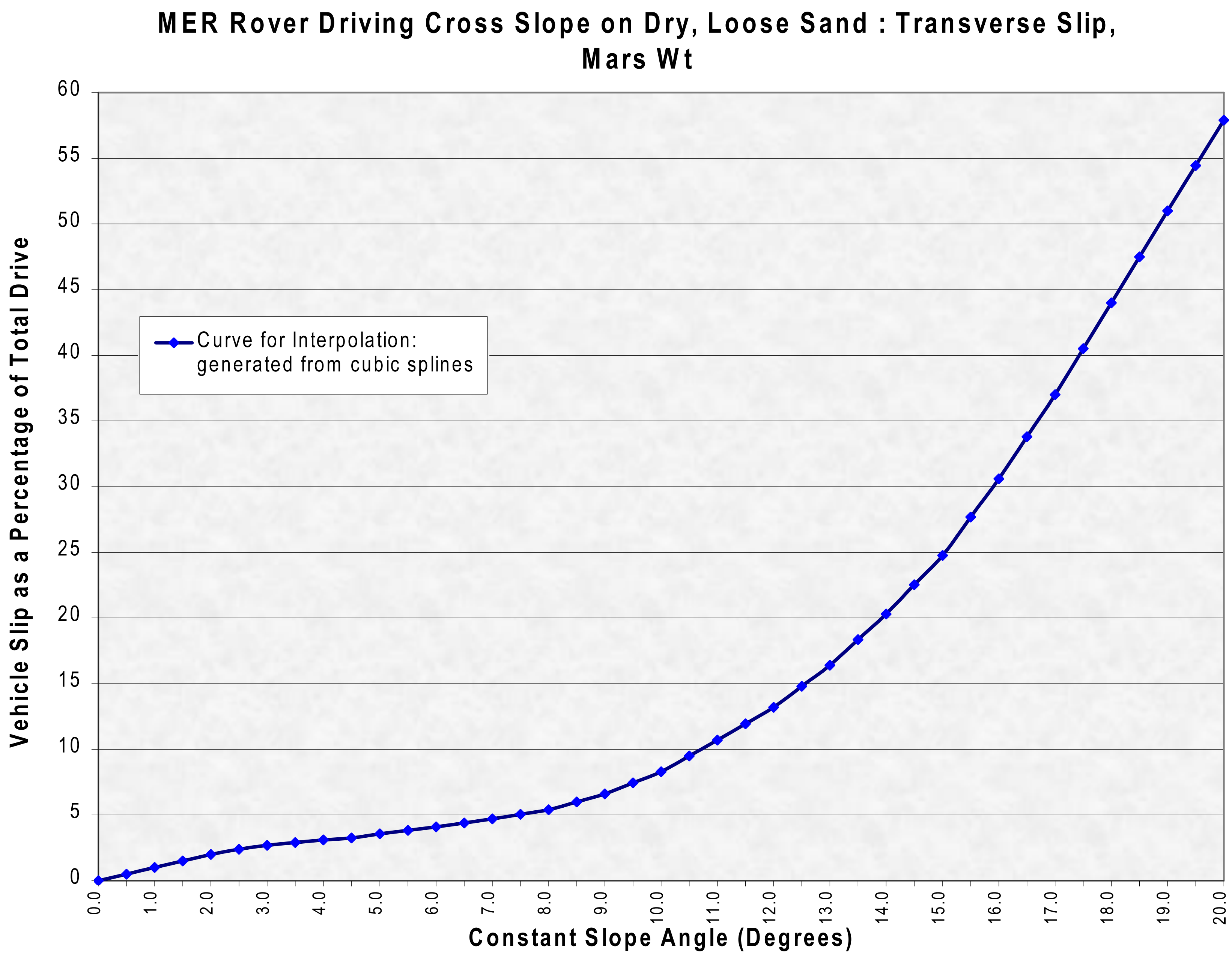
Rover Slip while driving Down Slope on Sand



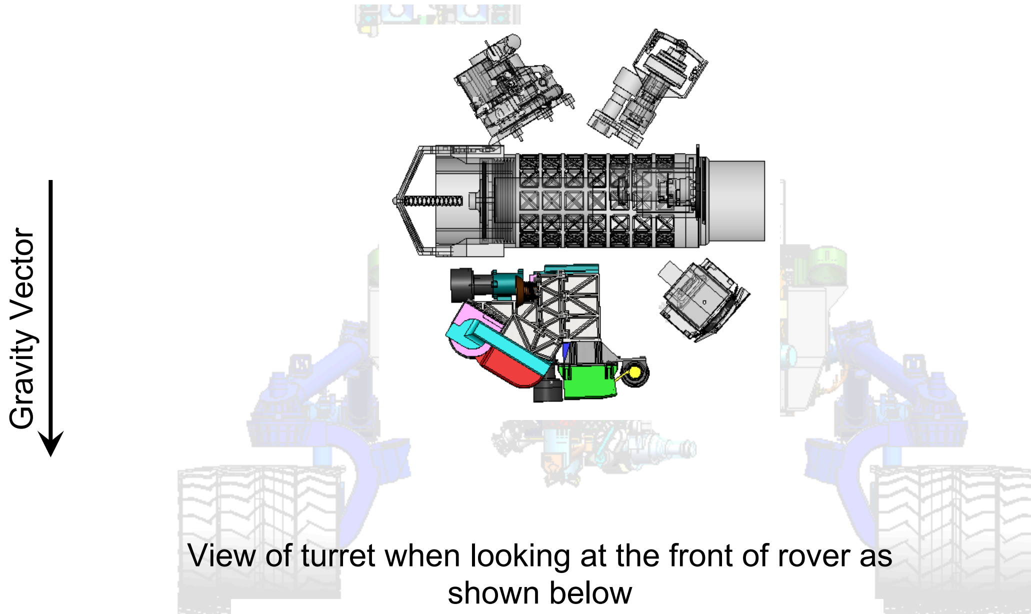
Rover Slip while driving Up Slope on Sand



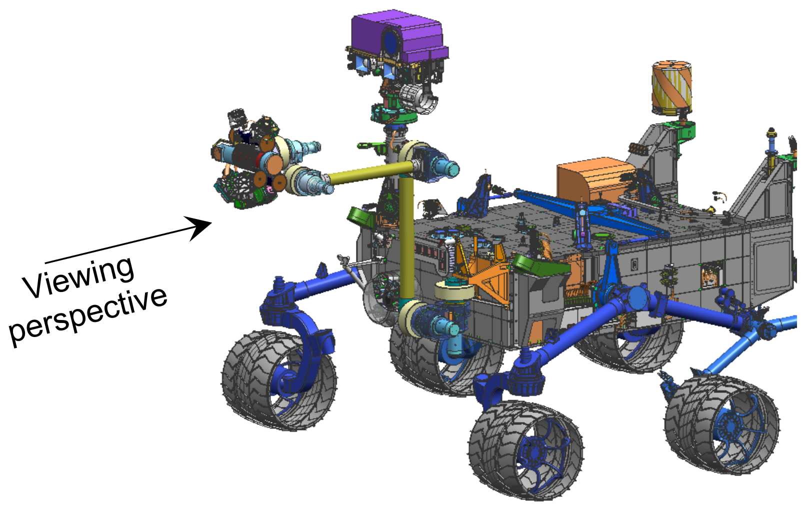
Rover Slip while driving Cross Slope on Sand

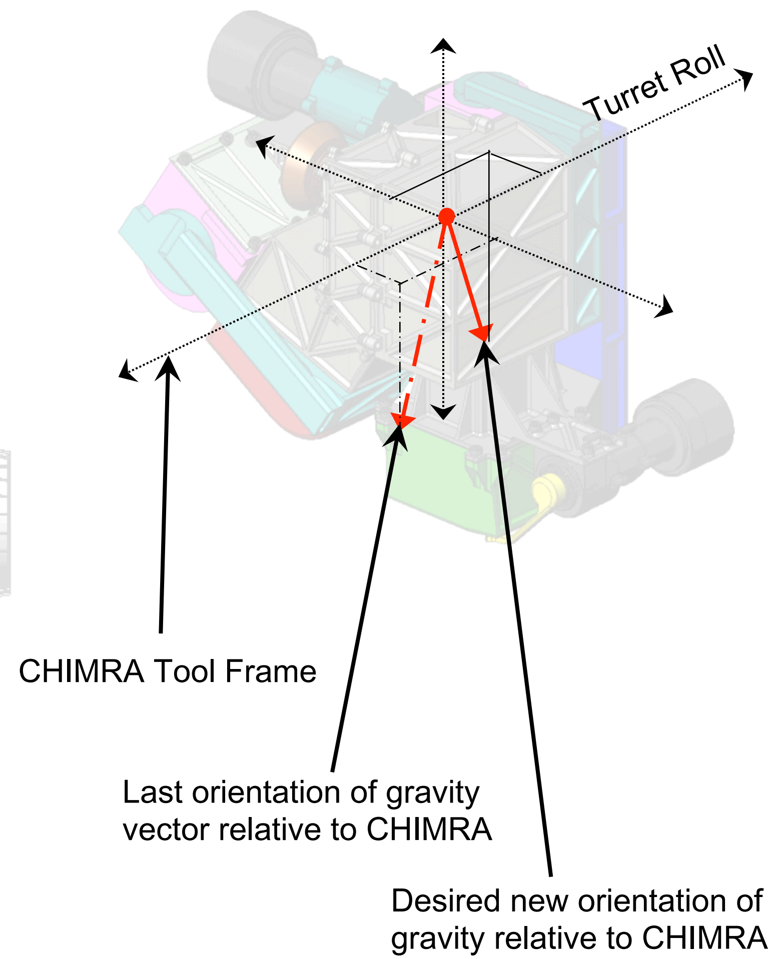


Overview of MSL/CHIMRA



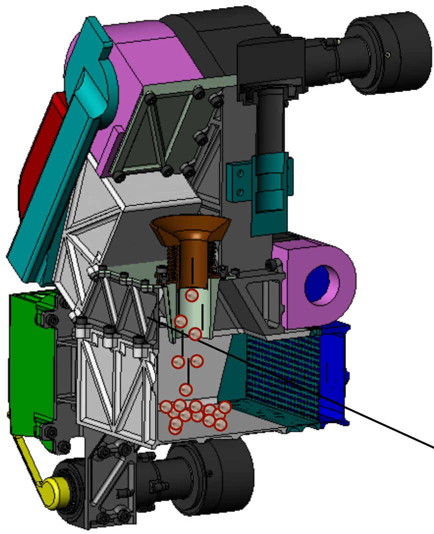
View of turret when looking at the front of rover as shown below





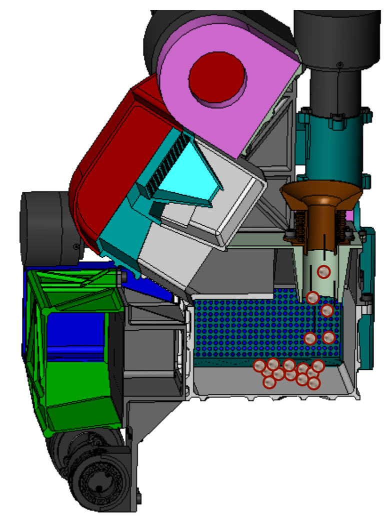
Path 1: Drilled sample sorted with 150um sieve

1)



Top Section View

- Drill percussion motivates sample through sample transfer tube into CHIMRA reservoir



Front Section View

Gravity Bias

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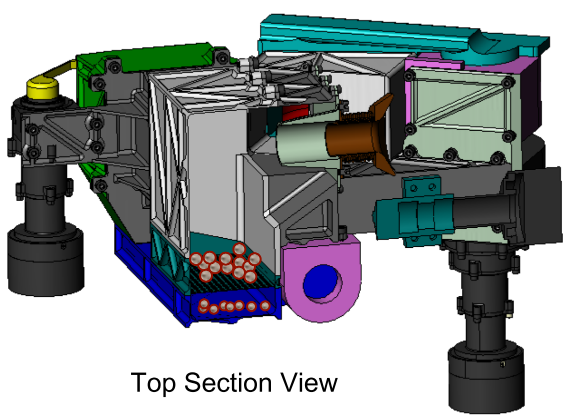
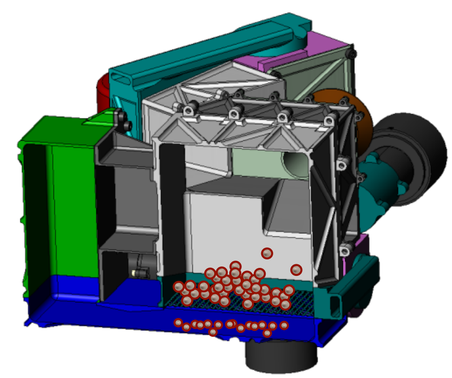
2)



Top Section View

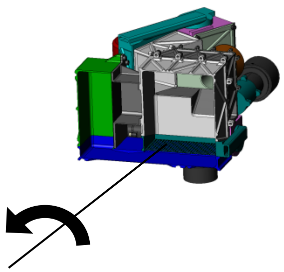
- 90° wrist rotation moves sample onto sieve
- Vibration Mechanism sorts sample through the 150um sieve

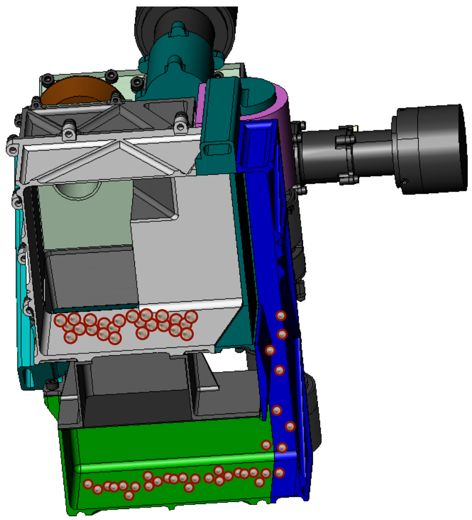


Side Section View

Path 1: Drilled sample sorted with 150um sieve

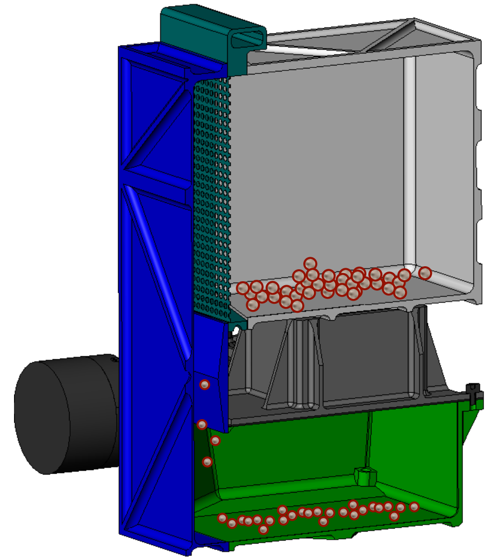
3)





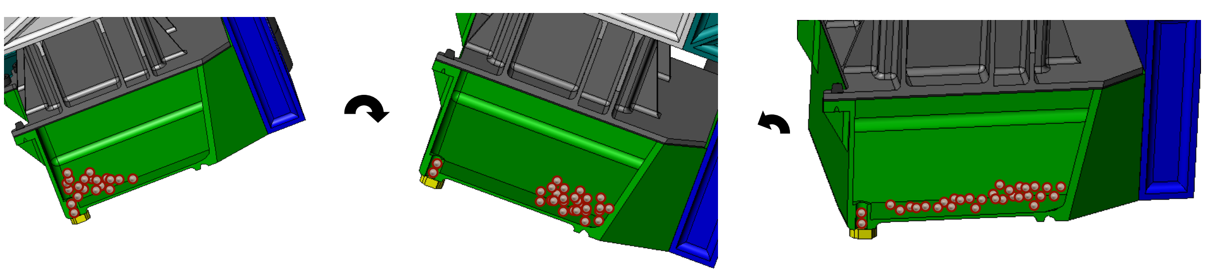
- Rotation of CHIMRA forward allows particles to flow through tunnel into mixing chamber

Side Section View



Opposite Side Section View

4)

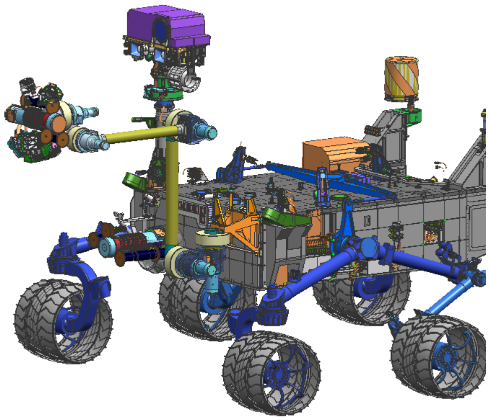


- Portion generated by motivating (through vibration) sample into portion tube, and then leveling off tube

Portion Generation Process

Path 1: Drilled sample sorted with 150um sieve

5)



- Portion generated away from rover while turret is in ready position
- Turret moved to deck inlets while keeping the axis of portion tube aligned with gravity vector

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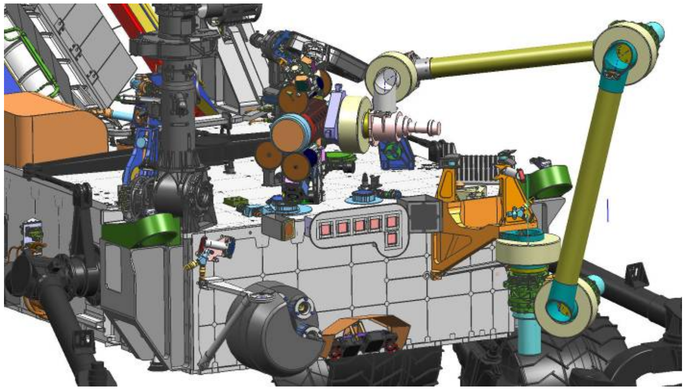
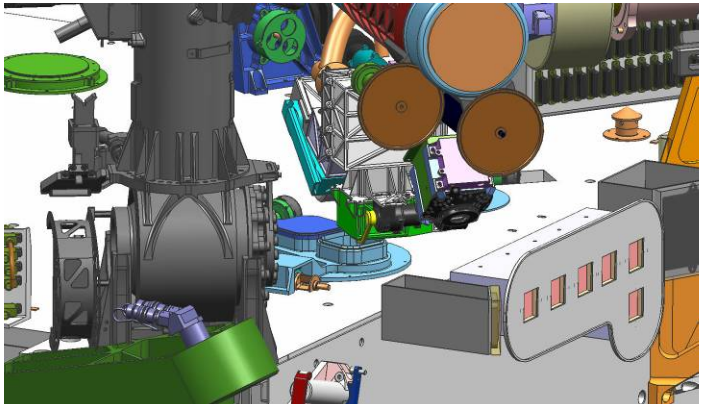
6)





ORIGINS • SPECTRAL INTERPRETATION • RESOURCE IDENTIFICATION • SECURITY • REGOLITH EXPLORER

Exploring Our Past, Securing Our Future Through Pioneering Asteroid Science

OSIRIS-REx will thoroughly characterize near-Earth asteroid (101955) 1999 RQ36. Asteroids are the direct remnants of the original building blocks of the terrestrial planets. Knowledge of their nature is fundamental to understanding planet formation and the origin of life. The return to Earth of pristine samples with known geologic context will enable precise analyses that cannot be duplicated by spacecraft-based instruments, revolutionizing our understanding of the early Solar System.

RQ36 is both the most accessible carbonaceous asteroid and the most potentially Earth-hazardous asteroid known. Its bulk properties have been well characterized by ground- and space-based telescopes, greatly reducing mission risk and providing strong evidence for the presence of regolith available for sampling.

Study of RQ36 addresses multiple NASA Solar System Exploration objectives to understand the origin of the Solar System and the origin of life, as well as fully addressing asteroid sample return objectives contained in the New Frontiers 2009 AO and NOSSE report. In addition, OSIRIS-REx will provide a greater understanding of both the hazards and resources in near-Earth space, serving as a precursor to future asteroid missions.

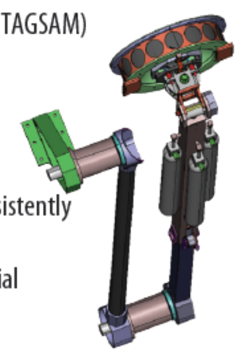
Science Objectives

1. Return and analyze a sample of pristine carbonaceous asteroid regolith in an amount sufficient to study the nature, history, and distribution of its constituent minerals and organic material.
2. Map the global properties, chemistry, and mineralogy of a primitive carbonaceous asteroid to characterize its geologic and dynamic history and provide context for the returned samples.
3. Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site *in situ* at scales down to the submillimeter.
4. Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.
5. Characterize the integrated global properties of a primitive carbonaceous asteroid to allow for direct comparison with ground-based telescopic data of the entire asteroid population.

Mission Overview

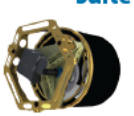
- Launch in September 2016, encountering asteroid (101955) 1999 RQ36 in October 2019
- Study RQ36 for up to 505 days, globally mapping the surface from a distance of 5 km to a distance of 0.7 km
- Obtain at least 60 g of pristine regolith and a surface material sample
- Return to Earth in September 2023 in a Stardust-heritage Sample Return Capsule (SRC)
- Deliver samples to JSC curation facility for world-wide distribution

TAGSAM



- Touch-And-Go Sample Acquisition Mechanism (TAGSAM)
  – Elegantly simple sampler head
  – Stardust heritage articulated arm
- On-board N_2 resources support up to three separate sampling attempts
- Vacuum and micro-*g* tests of sampler head consistently demonstrate collection of > 60 g of sample
- Surface contact pads collect fine-grained material

Instrument Suite



- **OSIRIS-REx Camera Suite (OCAMS)**
  Provides long-range acquisition of RQ36, along with global mapping, sample-site characterization, sample acquisition documentation, and sub-mm imaging

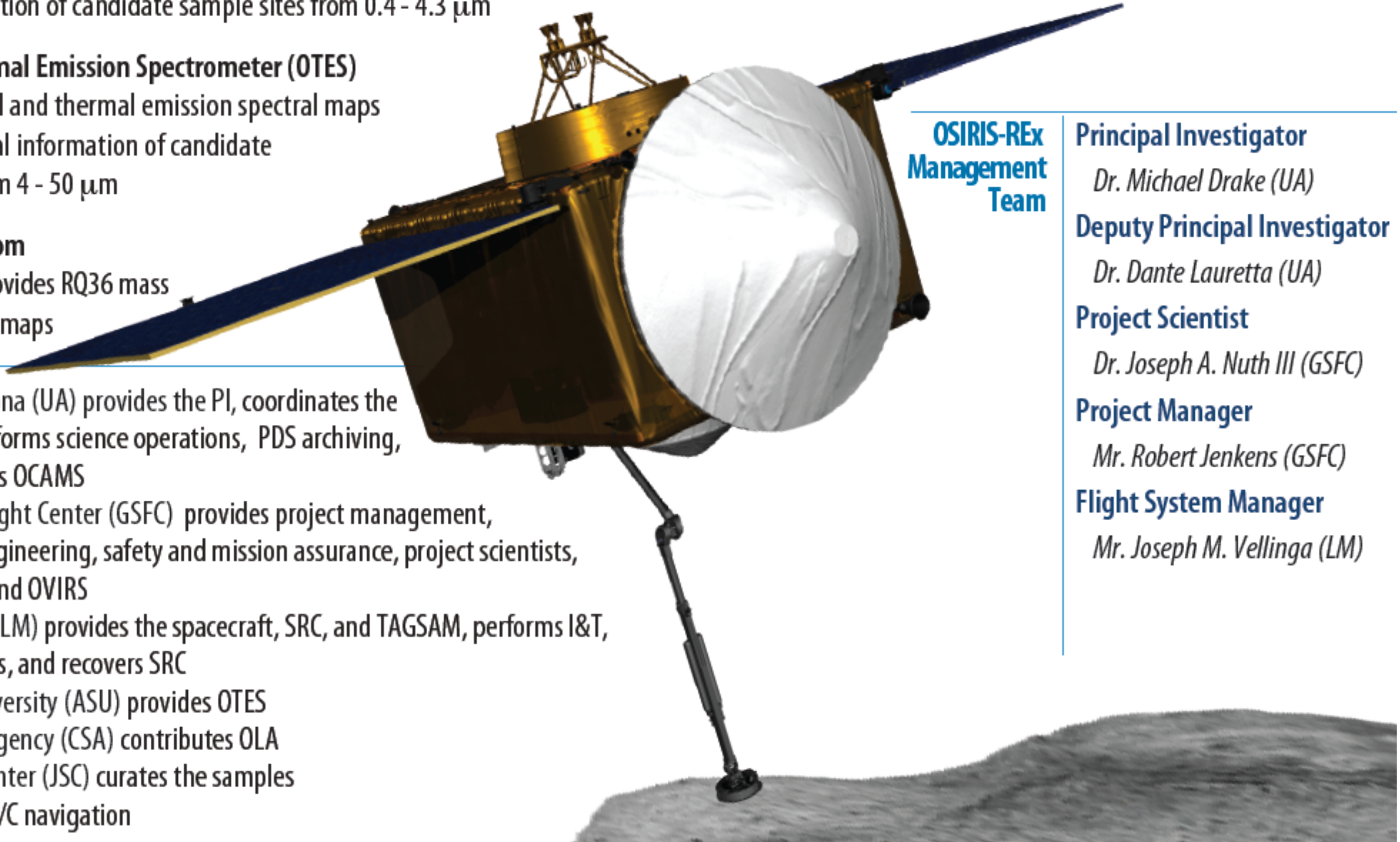
- **OSIRIS-REx Laser Altimeter (OLA)**
  Provides ranging data; global topographic mapping; and local topographic maps of candidate sample sites

Touch-and-Go Sampling

- Slowly approach surface at 0.1 m/sec
- Contact within 25 m of selected location
- OCAMS documents sampling at 1 Hz
- Collect samples in ~5 sec
  - Direct N_2 annular jet fluidizes regolith
  - Surface contact pad captures surface sample

- **OSIRIS-REx Visible and IR Spectrometer (OVIRS)**
  Provides mineral and organic spectral maps and local spectral information of candidate sample sites from 0.4 - 4.3 μm
- **OSIRIS-REx Thermal Emission Spectrometer (OTES)**
  Provides mineral and thermal emission spectral maps and local spectral information of candidate sample sites from 4 - 50 μm
- **Spacecraft Telecom**
  Radio science provides RQ36 mass and gravity field maps

- Verify bulk sample collection via spacecraft inertia change; surface sample by imaging sampler head
- Sampler head stored in Stardust-heritage SRC and returned to Earth



OSIRIS-REx Management Team

Principal Investigator
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Deputy Principal Investigator
Dr. Dante Lauretta (UA)

Project Scientist
Dr. Joseph A. Nuth III (GSFC)

Project Manager
Mr. Robert Jenkens (GSFC)

Flight System Manager
Mr. Joseph M. Vellinga (LM)

- University of Arizona (UA) provides the PI, coordinates the science team, performs science operations, PDS archiving, E/PO, and provides OCAMS
- Goddard Space Flight Center (GSFC) provides project management, project system engineering, safety and mission assurance, project scientists, flight dynamics, and OVIRS
- Lockheed Martin (LM) provides the spacecraft, SRC, and TAGSAM, performs I&T, mission operations, and recovers SRC
- Arizona State University (ASU) provides OTES
- Canadian Space Agency (CSA) contributes OLA
- Johnson Space Center (JSC) curates the samples
- KinetX performs S/C navigation

Competition sensitive information, this data is provided by OSIRIS-REx for the New Frontiers-3 CSR evaluation