Case Study: Lunar Mobility

- Overview of past lunar rover missions
- Design review of NASA Robotic Prospector (RP) rover for lunar exploration

Lunar Exploration Initiative

Briefing Topic:

Lunar Mobility Review

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Lunar Mobility

- **Robotic Vehicles**
  - **Lunokhod 1 (Luna 17)**
  - **Lunokhod 2 (Luna 21)**

- **Human Exploration Vehicles**
  - **MET (Apollo 14)**
  - **LRV (Apollo 15, 16, and 17)**
  - **Lunar Motorcycle (for Apollo 15, but not flown)**

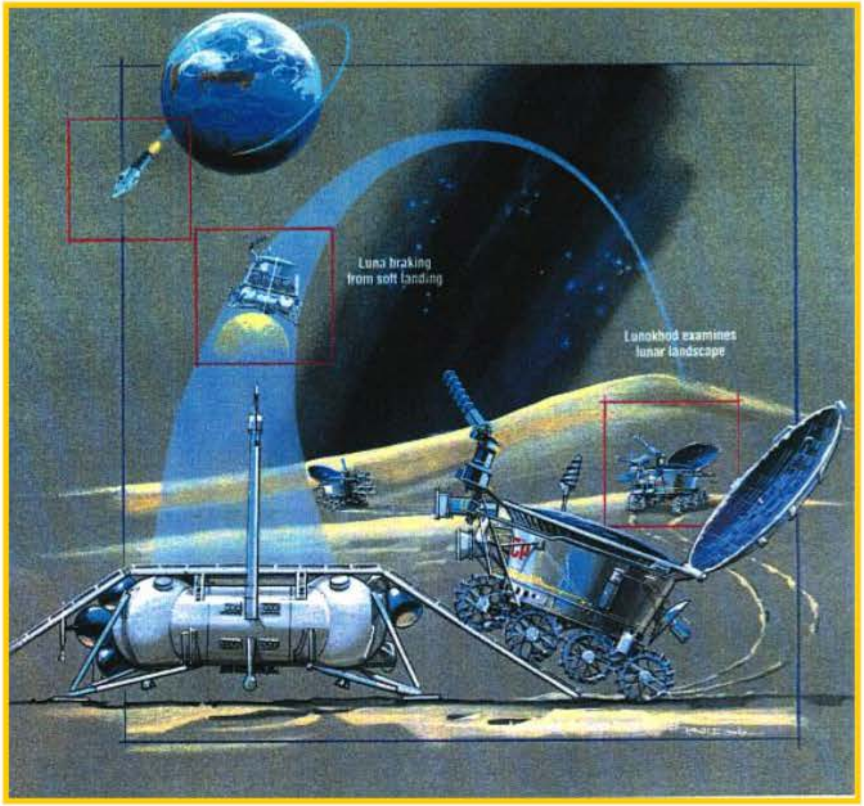
Lunar Robotic Vehicles

- **Robotic Rovers**
  - Lunokhod 1 (Luna 17, Nov 1970)
    - Explored Mare Imbrium
    - 756 kg
    - Rover had 1.7 m wheelbase and was ~1 m wide
    - Driven by 8 rigid spoked wheels with a wire mesh rim connected to three hoops
    - Wheel diameter ~51 cm and width ~20 cm
    - Operated on slopes up to 32°
    - 212-220 day lifetime (~7 lunar days) per Petrov (USSR, 1972) or 322 day lifetime (~11 lunar days) per National Space Science Data Center
    - Traversed 10.54 km

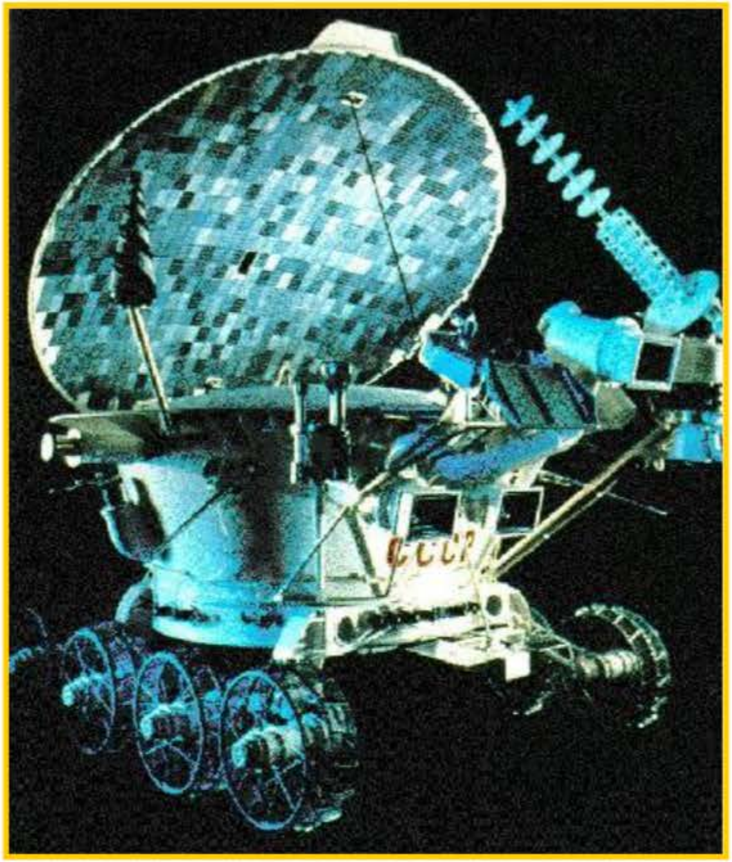
  - Lunokhod 2 (Luna 21, Jan 1973)
    - Explored Mare Serenitatis
    - 840 kg (1814 kg with lander)
    - 170 cm long, 160 cm wide, 135 cm high
    - Two-speeds: ~1 km/hr and ~2 km/hr
    - 139 day lifetime (~5 lunar days)
    - Traversed 37 km

NSSDC 1970-095A; 1973-001A

Lunokhod 2



Carried 3 TV cameras, one of which was high on rover for navigation, allowing real-time driving by 5-man team in USSR



Powered by batteries that were recharged by a solar panel on lid of payload bay & a Polonium-210 radiogenic heat source

Lunokhod 2 Mission Profile

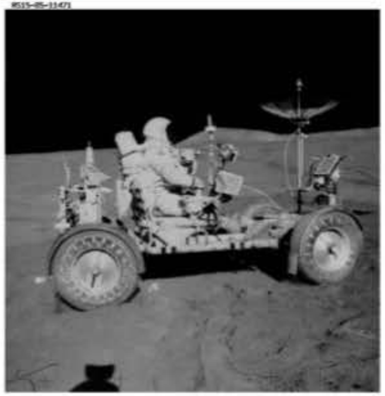
- Earth parking orbit
- Translunar injection
- 90 x 100 km parking orbit around Moon
- Perilune lowered to 16 km and stabilized for 40 orbits
- Braking rocket puts lander in free fall
- Main thrusters fire 750 m above surface
- Main thrusters shut down 22 m above surface and secondary thrusters ignited
- Secondary thrusters shut down 1.5 m above surface
- Landing occurs from a free fall height of 1.5 m

- Surface operations
  - Dual-ramp roll-off
  - Navigated while on battery
  - Stopped occasionally to recharge battery with solar panel
  - Hibernated during lunar night, remaining warm with radiogenic heater

Human Exploration Vehicles

- **Modular Equipment Transporter (MET) for Human Exploration**
  - Apollo 14 (Jan-Feb 1971)
    - 75 kg (with instruments and samples)
    - Hand-drawn
    - 2 pneumatic tires
    - 40 cm diameter tires, width of 10 cm

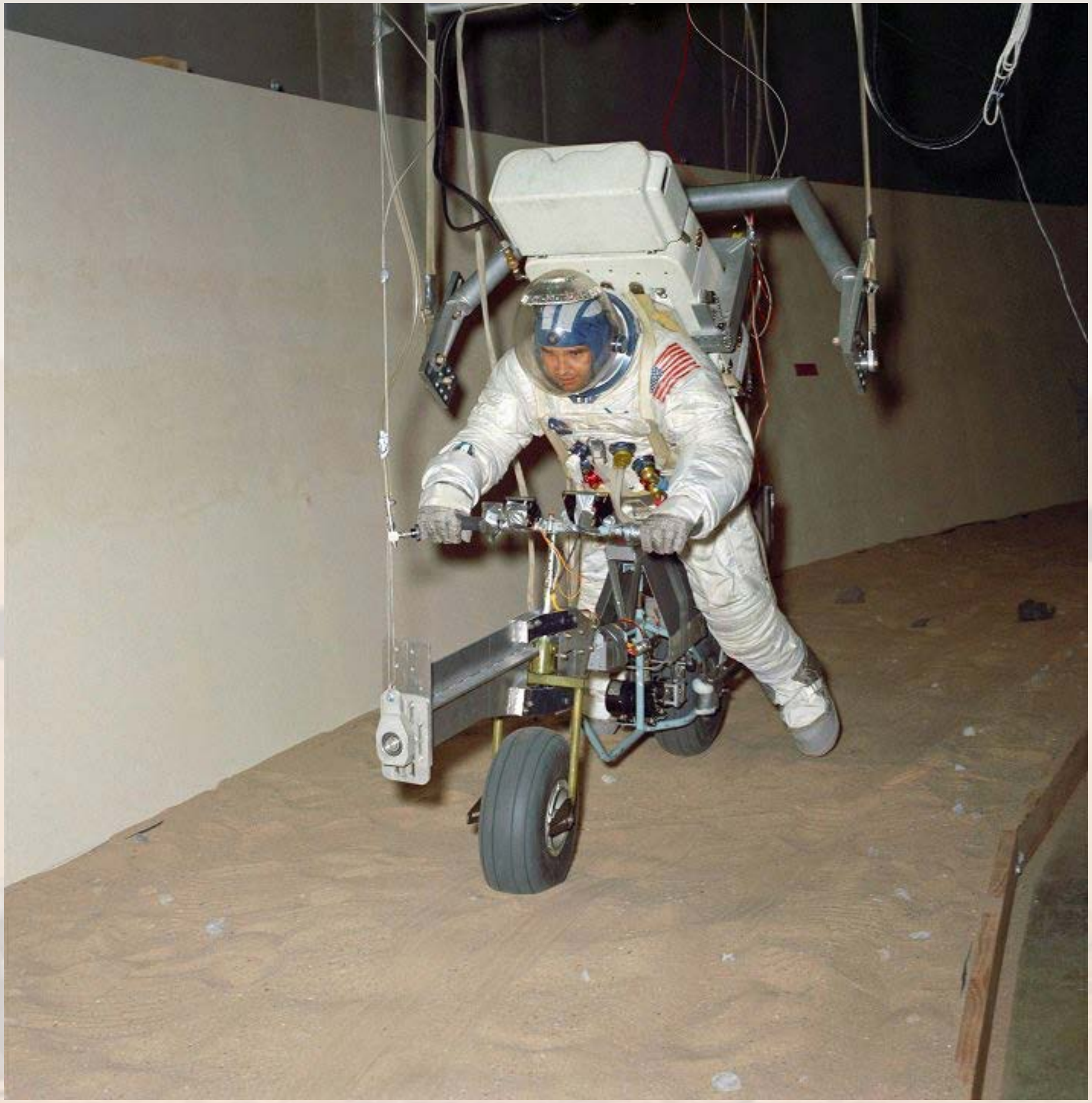
- **Apollo Lunar Roving Vehicle (LRV) for Human Exploration**
  - Apollo 15 (July-Aug 1971), Apollo 16 (April 1972), Apollo 17 (Dec 1972)
    - 708 kg (with astronauts, equipment, and samples; more than half of this mass was the astronauts and their life support systems)
    - 4 wheels composed of a flexible mesh of woven zinc-coated piano wire and chevron-shaped titanium treads
    - 82 cm wheel diameter and 23 cm width
    - Battery-powered



- **Lunar Motorcycle**
  - Designed for, but not flown on, Apollo 15
    - 2 pneumatic tires

Lunar Motorcycle in KC-135 Testing

Lunar Motorcycle in Suspension Testing



Apollo LRV

Empty mass	218 kg
Payload mass	490 kg
Two astronauts	363 kg
Experiments, tools, & samples	127 kg
Gross Mass	790 kg
Dimensions	
Length	310 cm
Wheelbase	229 cm
Overall width	206 cm
Height	114 cm
Power supply	2 parallel, non-rechargable Ag-Zn batteries (36 V)
Drive	Independent motors on each wheel
Steering	Front and rear independent steering
Minimum turning radius	305 cm
Wheels	Woven Zn-coated piano wire with Ti-treads in chevron pattern (50% coverage)
Maximum speed	13 km/hr
Normal cruise speed	6 to 7 km/hr
Maximum slope	19 to 23 deg
Energy consumption	35 to 56 W-hr/km 0.05 to 0.08 W-hr/km/kg

Mobility

- **Wheeled vehicles**
  - **Based on Apollo and Lunokhod mission results**
  - **Vehicles with round wheels work well on lunar surface if ground contact pressure does not exceed 7 to 10 kPa**
  - **Overcoming surface roughness and soil compaction consumes the energy equivalent to a 1 ½ degree climb up a smooth, rigid slope**
  - **Surface roughness, in a relatively low gravity situation, limits surface speed (otherwise, one bounces out of control)**
    - **The LRV was limited to 6-7 km/hr**
    - **Faster speeds require larger wheels, larger wheel base, greater mass, and/or softer suspension**

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Mobility

- **Soft soils**
  - The Apollo 15 LRV spun its wheels (and got stuck) in soft soil
  - The empty LRV weighed only 38 kg in lunar gravity, so the astronauts moved it to solve the problem. This solution is not possible in a completely robotic mission.
  - Lunokhod 2 encountered soft soils on the inside walls of craters; the soil was particularly soft at the base of slopes
    - Normal wheel sinkage was 2 cm
    - Wheel sinkage was >20 cm near impact craters

Maneuvering

- Cohesion varies as a function of geologic terrain
  - Cohesion on interior crater rims is less than that in intercrater areas
  - Cohesion in intercrater areas is less than that on crater rims

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Slope Requirements

- **LExSWG (1995) findings for rover mobility**
  - **Impact-cratered terrains**
    - **Old 100 m diameter crater (a common feature) has maximum slopes of 5 to 10°**
    - **Somewhat fresher craters have interior slopes of 15 to 20°**
    - **A very fresh crater, 500 m diameter South Ray Crater, has ejecta blanket and rim slopes of 7° or less; interior crater wall slopes can be as high as 35°, but routes to crater floors with slopes of 17 to 26° exist**
    - **Even large craters with diameters >10 km have average crater wall slopes <30°**
    - **Conclusion: capability to ascend and descend slopes of ~25° is sufficient**

Slope Requirements

- **LExSWG (1995) findings**
  - **Volcanic terrains**
    - **Near vertical walls will occur near rilles, but less steep routes to rille floors exist**
    - **Topographic study of Rima Prinz and Rima Mozart reveal numerous routes to rille floors with slopes of 15 to 20°; routes with slopes <15° also exist**
    - **Conclusion: capability to ascend and descend slopes of ~25° is sufficient**

Trafficability

- Empirical equations for the slope-climbing ability and energy consumed by a wheeled vehicle moving through lunar soil were determined for Apollo's LRV (Bekker, 1969):
  - Wheel sinkage
  - Soil compaction resistance per wheel
  - Gross pull per wheel
  - Maximum trafficable slope
- These equations failed, however, to represent the trafficability of small rovers in lunar soils, as simulated in 1/6 G conditions on NASA 930 (KC-135A) flights (Carrier, 1994, summarizing Scott)
- A computational method (WHEEL-E) was developed to evaluate small rover wheel performance in lunar soils (Carrier, 1995). These solutions are for flexible, elastic wheels on a flexible, elastic surface, so they may potentially be modified to assess the trafficability of tracks.

Summary

- Human and robotic rovers operated on the lunar surface in the past.
- The latter operated for several lunar days & nights, enduring cold conditions without solar power.
- The lunar surface is covered with a soft soil that varies in depth and cohesion; a wheeled vehicle has been stuck in this soil.
- LExSWG (1995) recommended future rovers have the ability to climb slopes up to 25° for operations in both impact-cratered and volcanic terrains.

References

- Bekker M. G. (1969) Introduction to Terrain-Vehicle Systems, University of Michigan, Ann Arbor.
- Carrier W.D. III (1994) Trafficability of lunar microrovers, part 1. Lunar Geotechnical Institute document LGI TR94-02.
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- LExSWG (1995) Lunar Surface Exploration Strategy, Final Report.
- NASA Space Science Data Center, document 1970-095A.
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- Petrov G.I. (1972) Investigation of the Moon with the Lunokhod 1 space vehicle, In *COSPAR Space Research XII*, Akademie-Verlag, Berlin.

RP Rover Tiger Team

Mission Overview

The Lunar Resource Prospector (RP) rover was an earlier version of what became Volatiles Investigating Polar Exploration Rover (VIPER), which will be launched to the Moon in 2023. The technical details are not necessarily representative of the final VIPER design.

Level-1 Mission Requirements

1.1 RP SHALL LAND AT A LUNAR POLAR REGION TO ENABLE PROSPECTING FOR VOLATILES

- Full Success Criteria: Land at a polar location that maximizes the combined potential for obtaining a high volatile (hydrogen) concentration signature and mission duration within traverse capabilities
- Minimum Success Criteria: Land at a polar location that maximizes the potential for obtaining a high volatile (hydrogen) concentration signature

1.2 RP SHALL BE CAPABLE OF OBTAINING KNOWLEDGE ABOUT THE LUNAR SURFACE AND SUBSURFACE VOLATILES AND MATERIALS

- Full Success Criteria: Take both *sub-surface measurements of volatile constituents via excavation and processing* and *surface measurements*, at multiple locations
- Minimum Success Criteria: Take either sub-surface measurements of volatile constituents via excavation and processing or surface measurements, at multiple locations

Simplified view of RP

Get there…

- Launch
- Lunar Transfer
- Lunar Orbit
- Descent & Landing
- Quick Checkout
- Roll-off Lander
- Quick Checkout
- Begin Surface Ops

Find & Excavate Volatiles…

Map surface	Use the Neutron Spec & Near-IR Spec to look for Hydrogen-rich materials
Enter permanent shadows	Go to the areas with highest concentrations of volatiles, Permanently Shadowed Regions (PSRs)
Expose regolith	Use the Drill Subsystem to expose material from 1[m] depth to examine with Near-IR Spec

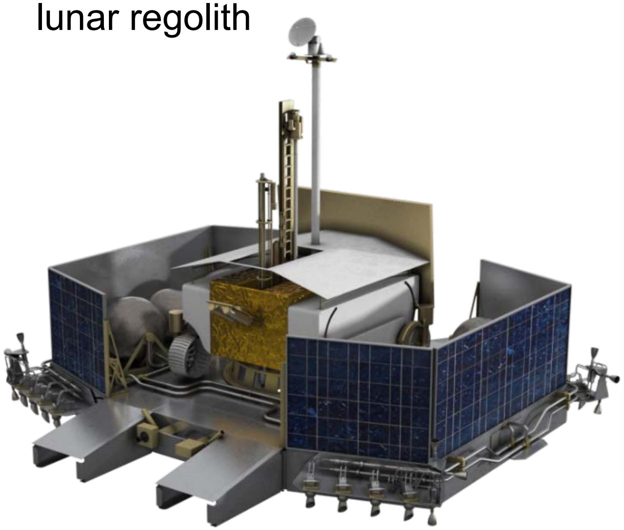
Collect and Process the volatiles…

Capture regolith	Use the Drill Subsystem to capture samples from up to 1[m] depth
Heat regolith	Heat samples (150-450 degC) in the OVEN Subsystem
Identify Volatiles	Determine type and quantity of volatiles in the LAVA Subsystem, (H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2)
Show me the water!	Image and quantify the water created using the LAVA Subsystem

Resource Prospector (RP) Overview

Mission:

- Characterize the nature and distribution of water/volatiles in lunar polar sub-surface materials
- Demonstrate ISRU processing of lunar regolith



Project Timeline:

✓ FY13: Pre-Phase A: MCR (Pre-Formulation)
✓ FY14: Phase A (Formulation)
✓ FY15: Phase A (Demonstration: RP15)
- FY16: Phase A (Risk Reduction)
- FY17: Phase B: SRR/MDR
- FY18: PDR (Implementation)
- FY19: CDR (Critical design)
- FY20: I&T
- FY21: RP launch

RP Specs:

Mission Life: 6-14 earth days
(extended missions being studied)
Rover + Payload Mass: 300 kg
Total system wet mass (on LV): 5000 kg
Rover Dimensions: 1.4m x 1.4m x 2m
Rover Power (nom): 300W
Customer: HEOMD/AES
Cost: ~$300M (excl LV)
Mission Class: D-Cat3
Launch Vehicle: Falcon 9 v1.1

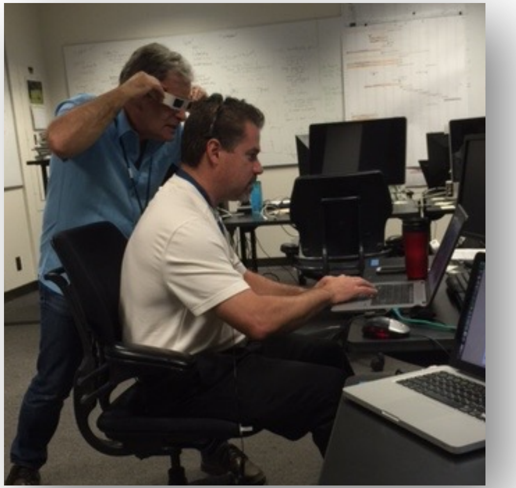
Distributed Operations Test

NASA-ARC Mission Control room driving RP15 rover @ NASA-JSC

NASA-JSC Rock Yard from the rover (left) stereo camera

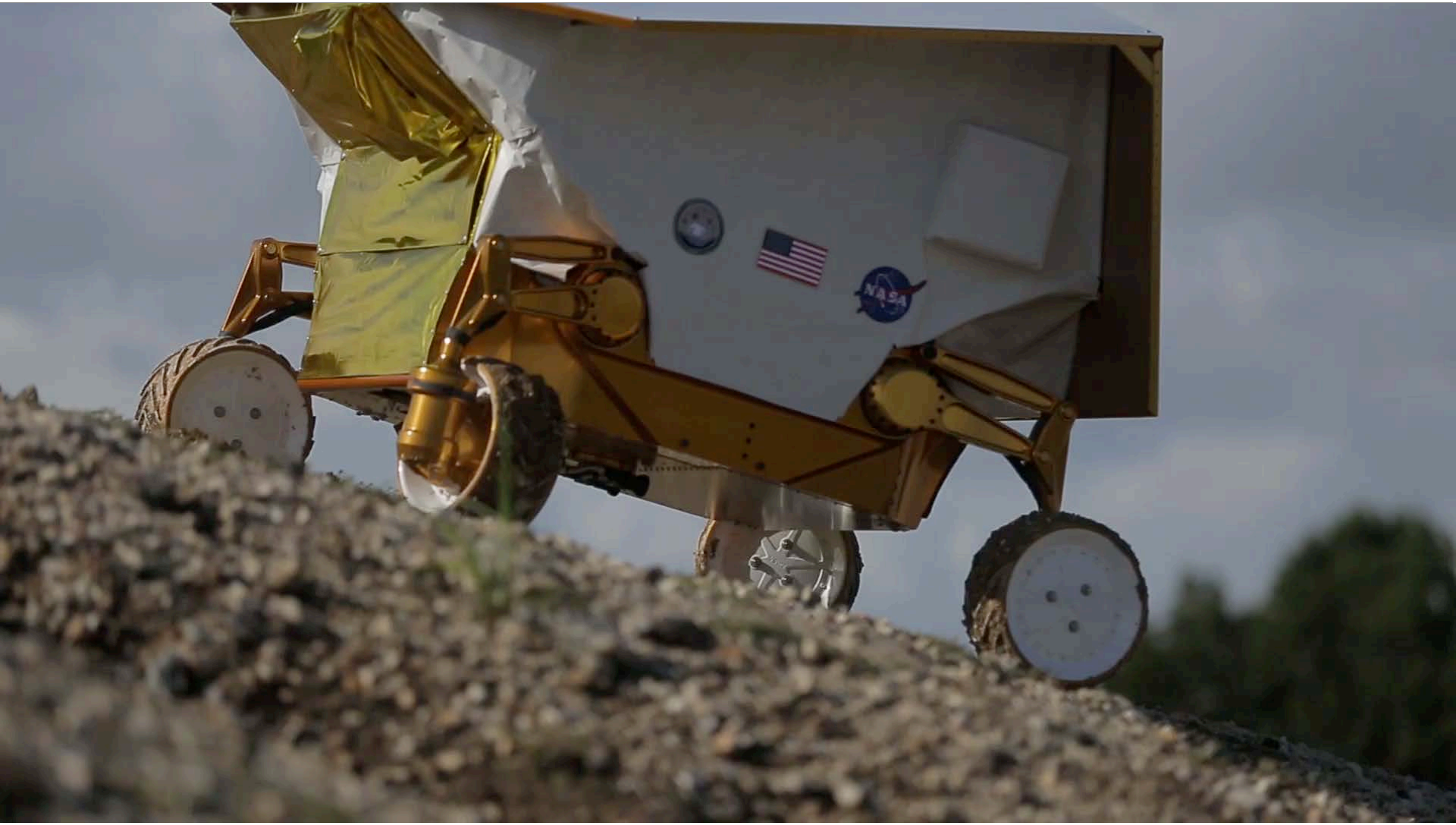
NASA-KSC Payload Control room

3-D Image Viewing of NIRVSS Camera Images During DOT

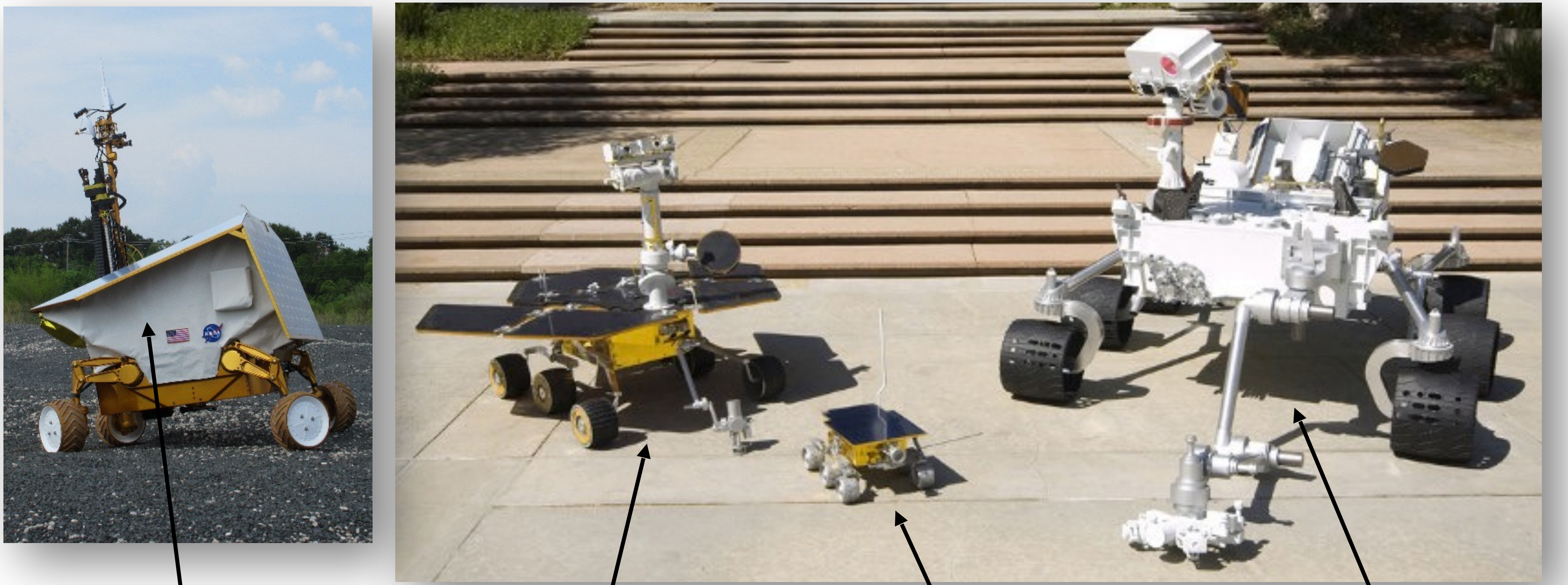


RP15 In the Dirt

2015-08-15



Rover Dimensional Comparison (approx.)



RP/RP15 (2015):
- 1.5m x 1.5m x 2.0m (LxWxH)
- Weighs about 300kg

Spirit/Opportunity (2004):
- 1.6m x 2.3m x 1.5m (LxWxH)
- Weighs about 180kg

Sojourner (1996):
- 0.6m x 0.5m x 0.3m (LxWxH)
- Weighs about 11kg

Curiosity (1996):
- 3.0m x 2.8m x 2.1m (LxWxH)
- Weighs about 900kg

RP Rover team makeup and background

Horizon line is shown in green in these Basalt Hills images.
Results are obtained in real time 2 fps and are robust to variations in illumination conditions, clouds, shadows and fast movements of the rover.

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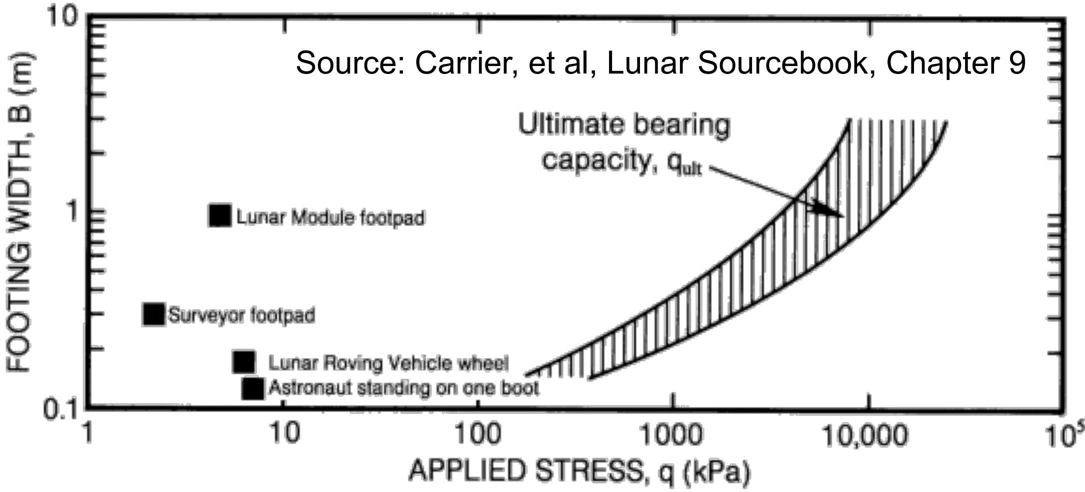
Resource Prospector Rover Overview

- Design tensions between the lunar poles complexities with Class D sensibilities
  - Lunar complexities
    - Uncertain terrain; soft soils, size and frequency of rocks
    - Stark lighting conditions
    - Short duration
    - Operations in permanently shadowed regions; very cold regions
    - Severe radiation
    - Sun and earth very low to the horizon
  - Class D sensibilities
    - Robustness under constrained resources (mass, power, schedule, budget, …)
    - Single string, with limited redundancy
    - Risk tolerant, but risk informed
    - Use heritage designs when possible

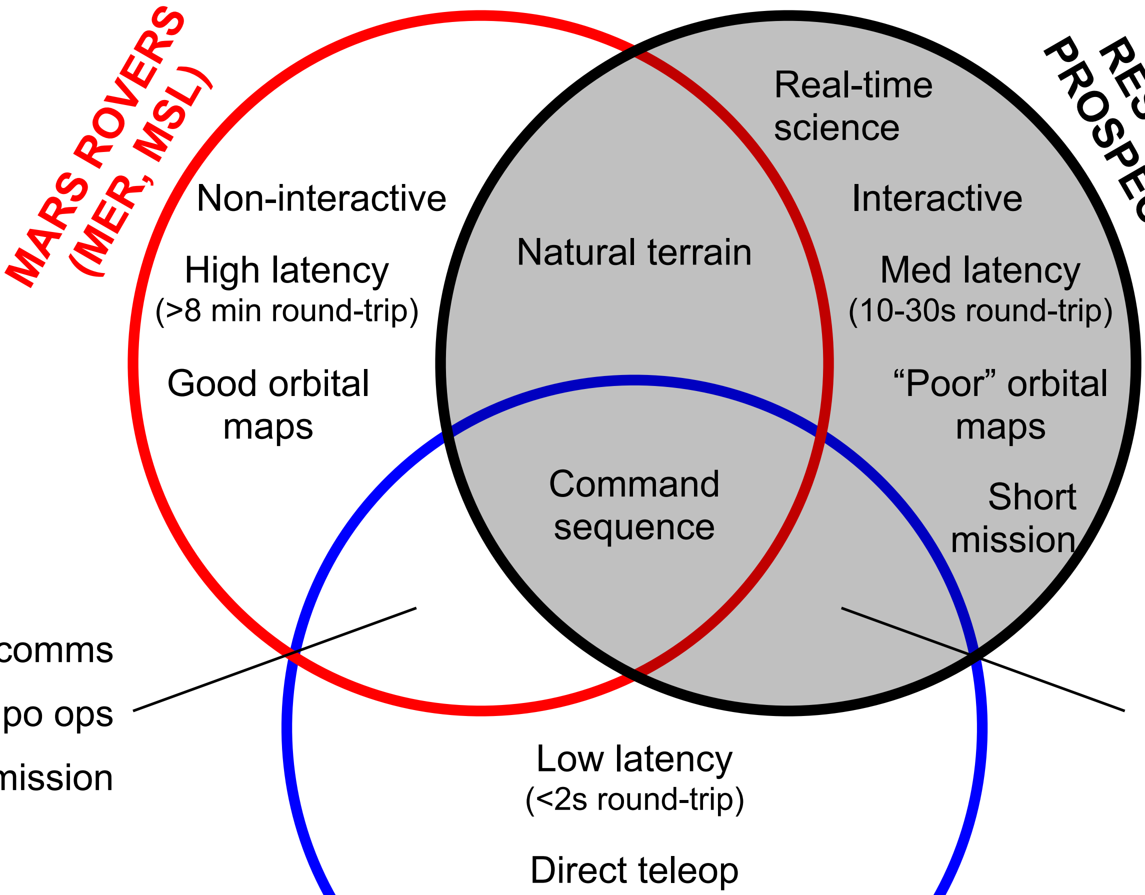


Source: Carrier, et al, Lunar Sourcebook, Chapter 9

Resource Prospector Rover Overview

- Rover is science payload delivery device
- Short duration mission; could be as short as a 6 day mission
  - 1 km distance target leading to high paced operations
  - Not designing to survive the night
- Design reference mission is currently JAXA designed lander
  - Options for NASA designed pallet lander being considered
  - While lander does effect rover, it’s not a significant driver
- Rover is operated through direct-to-earth communications using waypoint commanding
  - Expect waypoints to be on the order of 4-6 meters
- Rover is minimally autonomous;
  - Short time delay calls for a different operating approach than Mars

RP vs. ISS vs. Mars Rovers



MARS ROVERS (MER, MSL)

Non-interactive

High latency
(>8 min round-trip)

Good orbital maps

Natural terrain

Command sequence

RESOURCE PROSPECTOR

Real-time science

Interactive

Med latency
(10-30s round-trip)

“Poor” orbital maps

Short mission

Intermittent comms

Low-tempo ops

Long mission

Continuous comms

Extreme lighting

High-tempo ops

Med latency RP, ISS SPDM

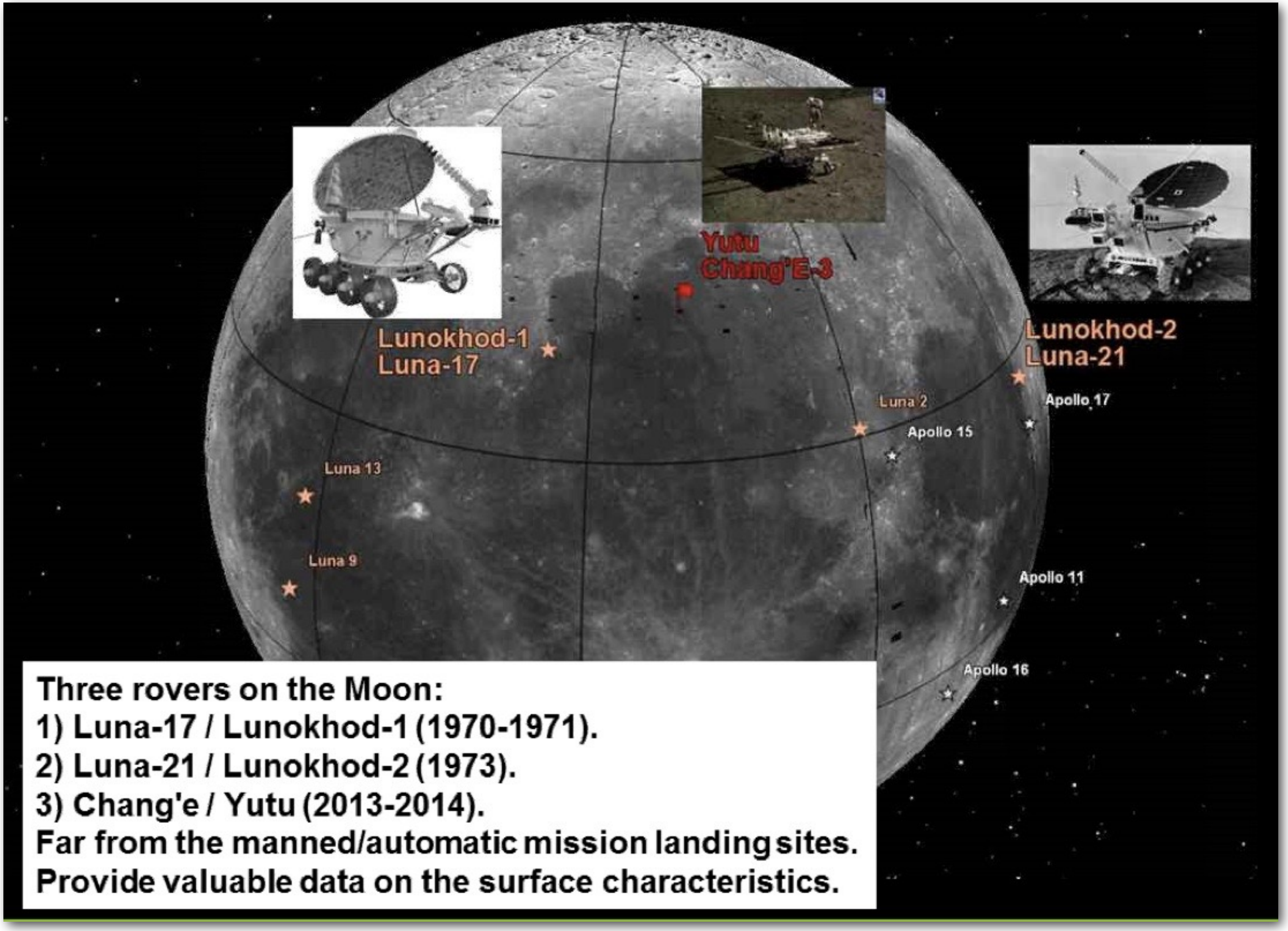
Low latency
(<2s round-trip)

Direct teleop SSRMS

Structured environment

ISS EVA ROBOTICS

Prior Lunar Rover Missions



Three rovers on the Moon:

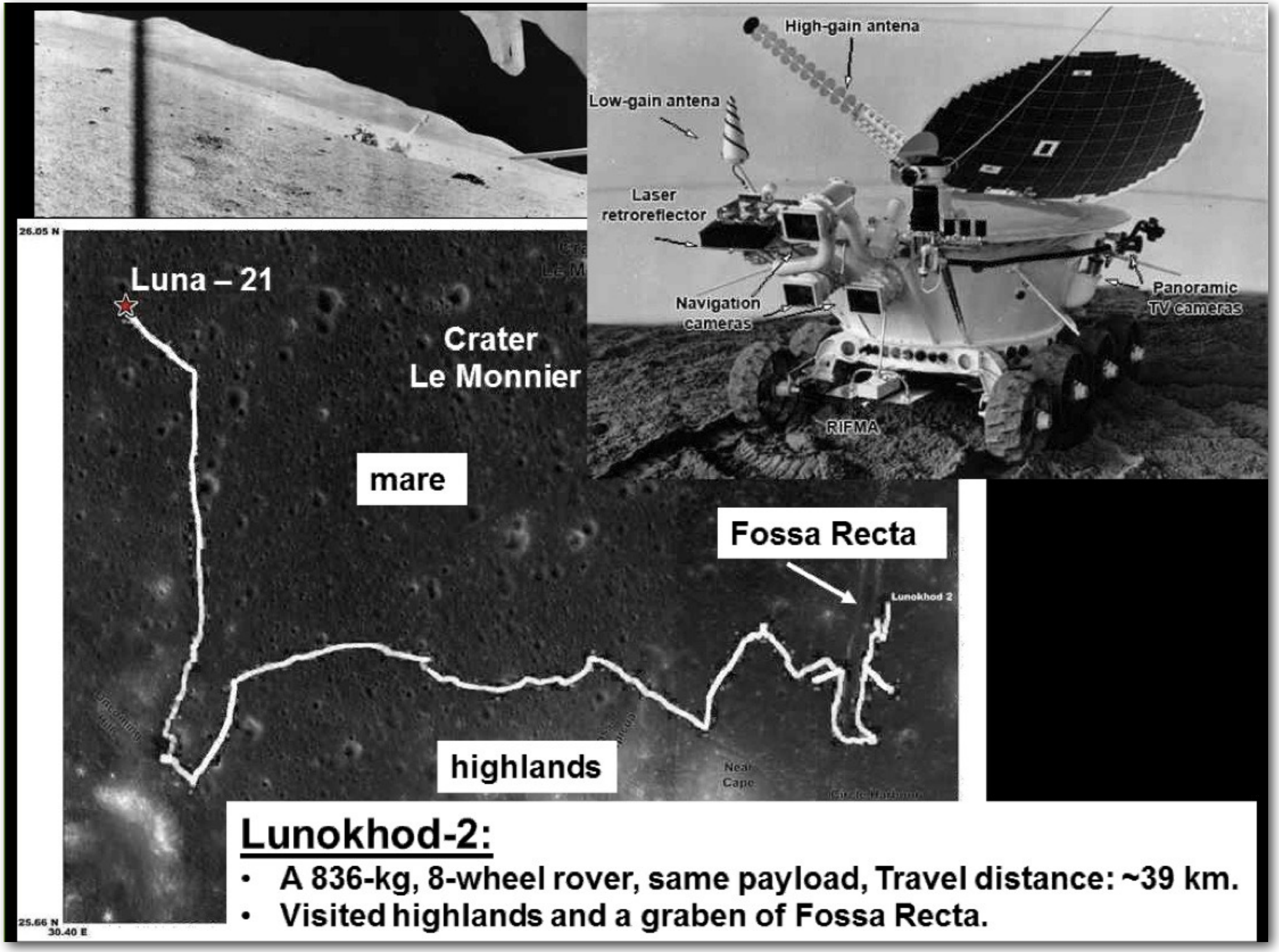
1) Luna-17 / Lunokhod-1 (1970-1971).
2) Luna-21 / Lunokhod-2 (1973).
3) Chang'e / Yutu (2013-2014).

Far from the manned/automatic mission landing sites.

Provide valuable data on the surface characteristics.

Image from Abdrakhimov, Basilevsky, Ivanov, Head, Scott, and Xiao (2015)

Lunakhod 2



Lunokhod-2:

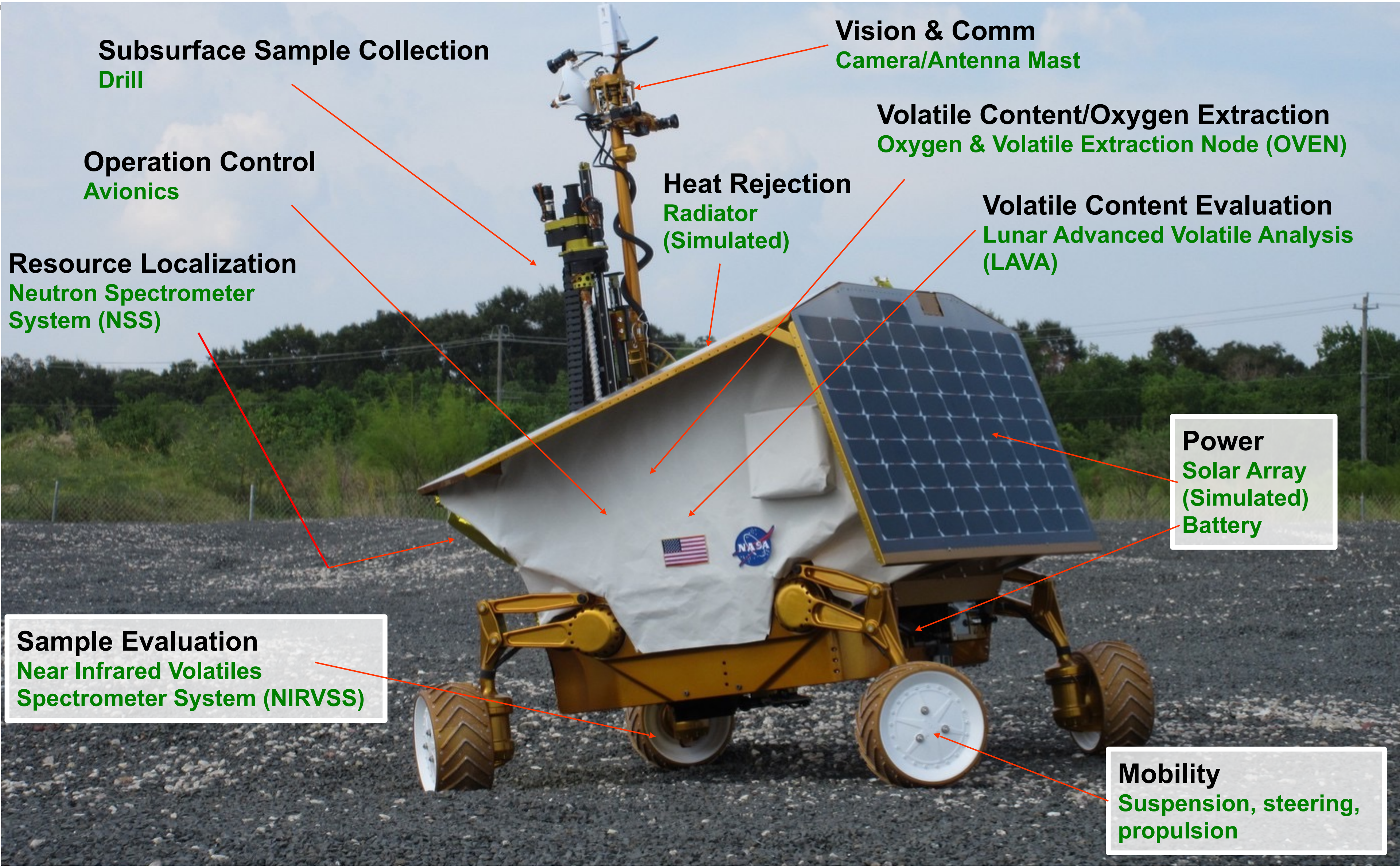
- A 836-kg, 8-wheel rover, same payload, Travel distance: ~39 km.
- Visited highlands and a graben of Fossa Recta.

Image from Abdrakhimov, Basilevsky, Ivanov, Head, Scott, and Xiao (2015)

RP vs. Lunakhod

	RP (as planned)	Lunokhod 2
Lunar location	High latitude (polar)	Equatorial
Terrain type	Highlands	Mare (+ some highlands)
Mission duration (surface)	6 days	139 days
Total drive distance	3 km	39 km
Illumination	Oblique	Overhead
Downlink latency	10-30 sec (via DSN)	3 sec (analog)
Footprint (width x length)	1.5 x 1.5 m	1.6 x 1.7 m
Mass	300 kg	836 kg
Wheels (# x diameter)	4 x 30 (TBD) cm	8 x 51 cm
Steering	Explicit (independent 4 wheels)	Skid-steered
Power	Solar + battery	Solar + battery (+ Polonium-210 heater)
Drive speed (max)	10 cm/s (prospecting mode)	28 cm/s (low), 55 cm/s (high)
Surface activities	Prospecting, drilling, ISRU processing	Surface imaging, solar x-rays, magnetic fields, penetrometer

RP Engineering Prototype



Subsurface Sample Collection
Drill

Operation Control
Avionics

Resource Localization
Neutron Spectrometer System (NSS)

Vision & Comm
Camera/Antenna Mast

Volatile Content/Oxygen Extraction
Oxygen & Volatile Extraction Node (OVEN)

Heat Rejection
Radiator (Simulated)

Volatile Content Evaluation
Lunar Advanced Volatile Analysis (LAVA)

Power
Solar Array (Simulated)
Battery

Sample Evaluation
Near Infrared Volatiles Spectrometer System (NIRVSS)

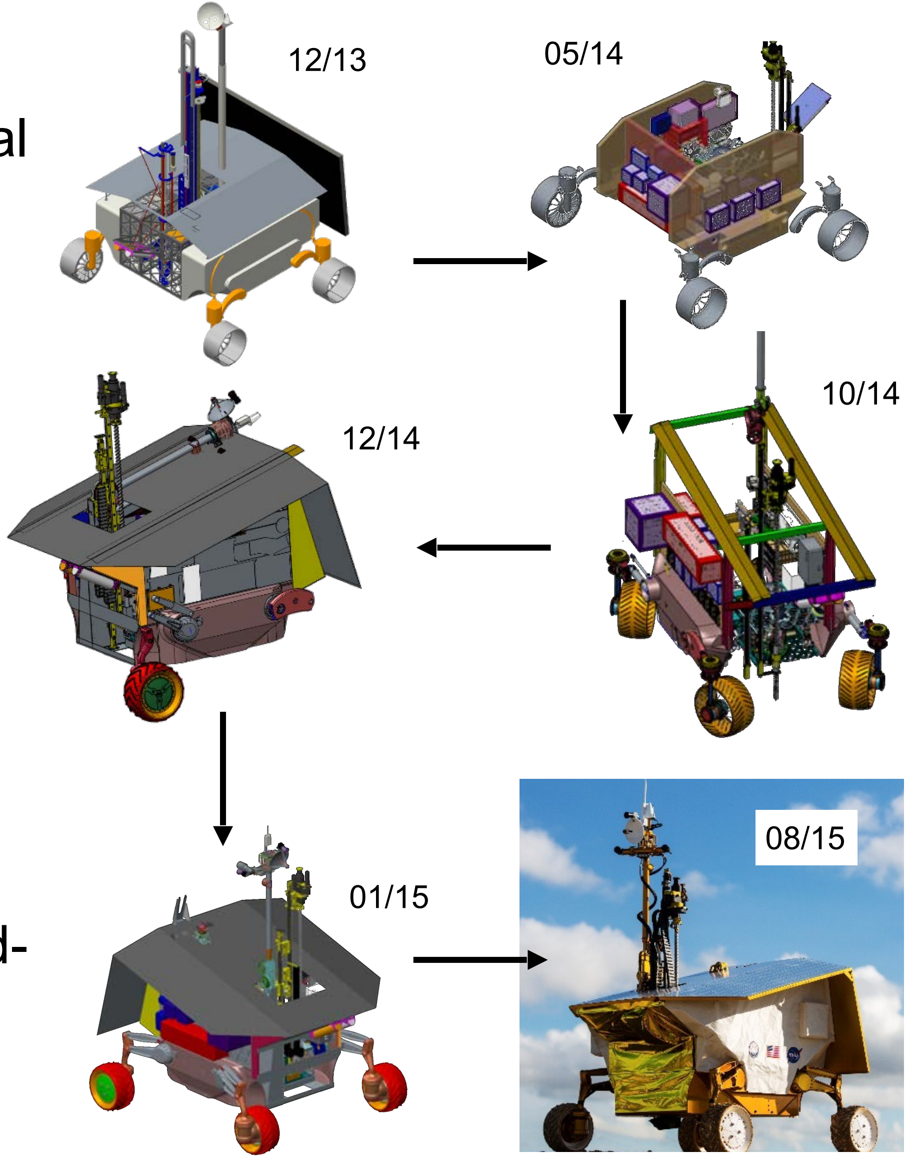
Mobility
Suspension, steering, propulsion

Rover Baseline Design

- Mobility
  - 4 wheel explicit steering and propulsion
  - Independent active suspension
  - Ability to crab; getting out of trouble, sun tracking
- Structure
  - Integrated rover and payload systems
  - Combined billet/sheet metal approach
- Power
  - Lithium Ion battery (5.5 kw-hr)
  - Charged by solar array (350 W)
  - Active trade about battery voltage
- Communications
  - Direct-to-earth 600 kbps directional X-band (400 kbps for roving)
  - 2 kbps omni-directional
- Navigation
  - Stereo camera pair on the mast
  - Wide angle hazard camera on each side of the rover for virtual bumper
  - Fish-eye-lens under the rover to view rover wheels
- Thermal
  - Five temperature controlled zones
  - Cooled by radiator
- Software
  - GSFC Core Flight Executive/Core Flight Software using Simulink model based development
  - Ground software providing localization
- Avionics
  - RAD750; options being explored
  - Robonaut heritage motor control

FY15: The year of build

- During FY15, the RP team built and performed initial testing of a functional prototype system
  - – Approach following flight flow, with project owned gate reviews
  - – Flexibility granted given schedule and budgetary constraints
  - – Integrated functional payload components
  - – Capable of 1G operations
    - Heavier than flight design
  - – Look and feel of flight rover
    - Wheels are small for 1G operations
- Rover was virtually a blank sheet mid-October 2014

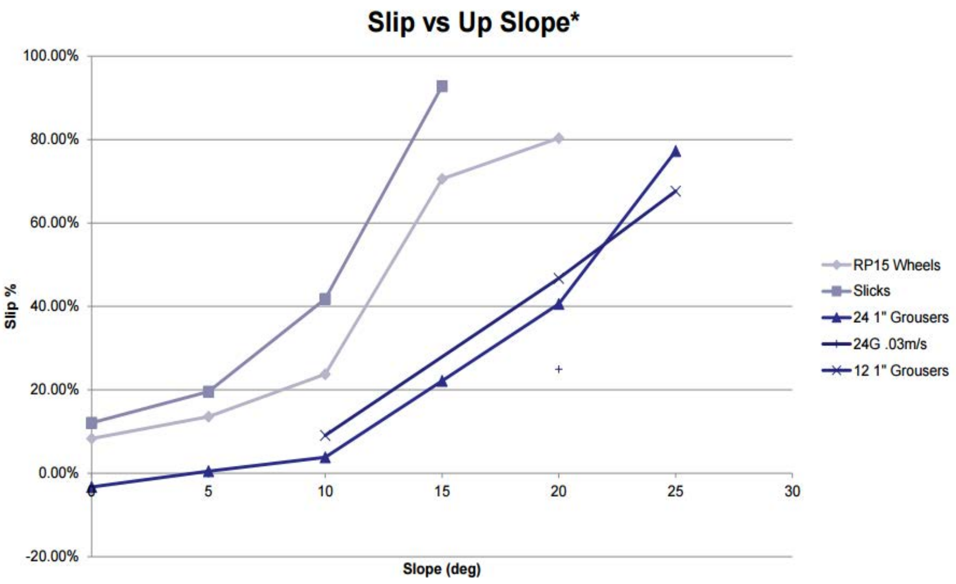


FY16: Gravity Offload testing

Mobility, Lander Egress, Drilling

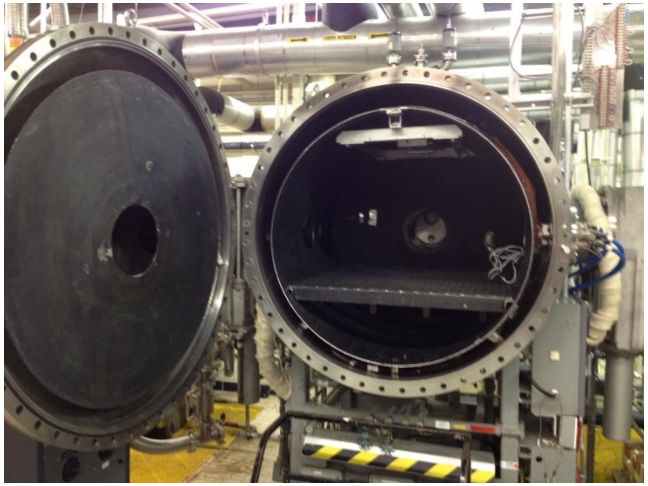
FY16: Gravity Offload lessons learned

- RP15 wheels were able to drive up 15º slopes, but with >50% slip.
- 12 1” grousers worked best at 25º slopes, similar to RP15 at 15º.
- Reducing speed (.03cm/s) on 20º slopes reduced slip (~45%<), but speed made good was lower.
- RP15 wheels could climb a 10cm rock but not the 15cm rock on 0º and 15º slopes.
- The 24 1” Grouser wheels could climb all rocks on all slopes
- JAXA Lander egress was feasible at worst test cases: 35º pitch; 20º pitch+15º roll.
- Pallet Lander egress was feasible at worst test case: 30cm step.
- Drilling was stable at worst test case: 20º slope, wheels straight, mobility off, percussive drilling
- Lower efficiency harmonic gears reduce static loads on steering and suspension during normal driving. Good for low duty cycle operations.

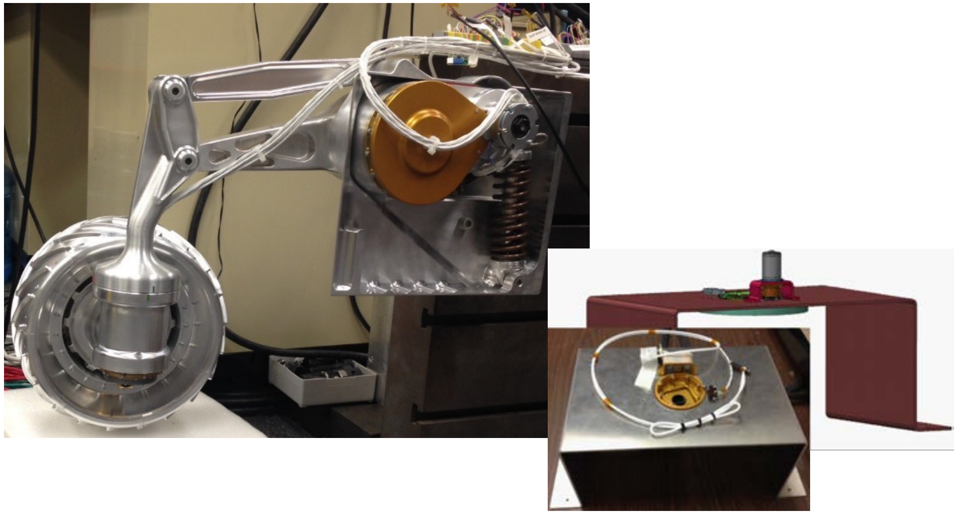


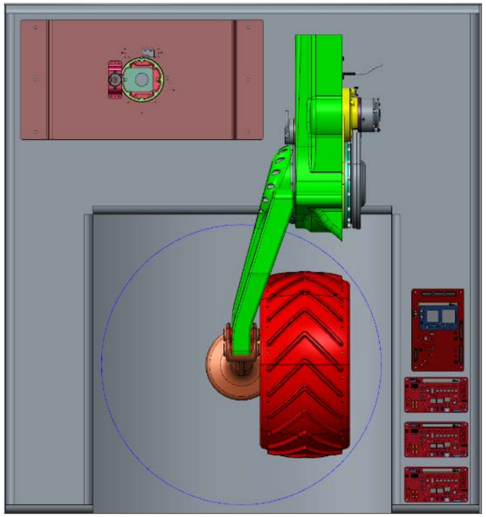
FY16: Thermal vacuum testing

- Objective is engineering testing to validate design approaches
- Use the RP15 wheel module, mobility/gimble drivers and single gimbal axis
- Scheduled to begin March 7
- Use results to drive flight design iteration



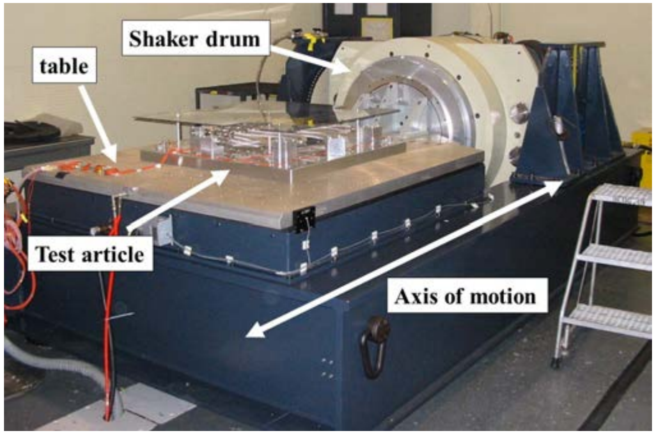
JSC Chamber N

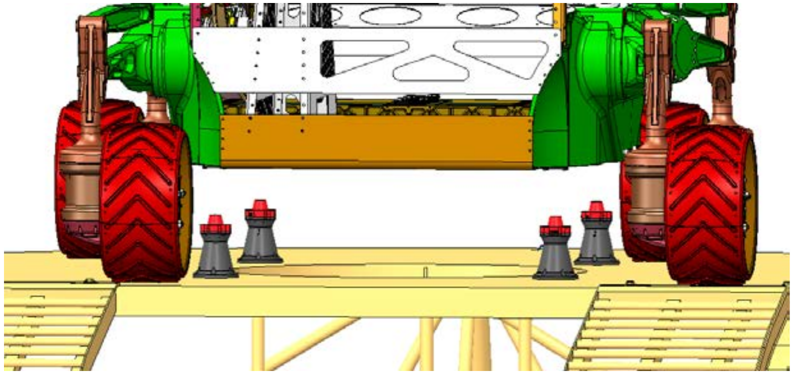


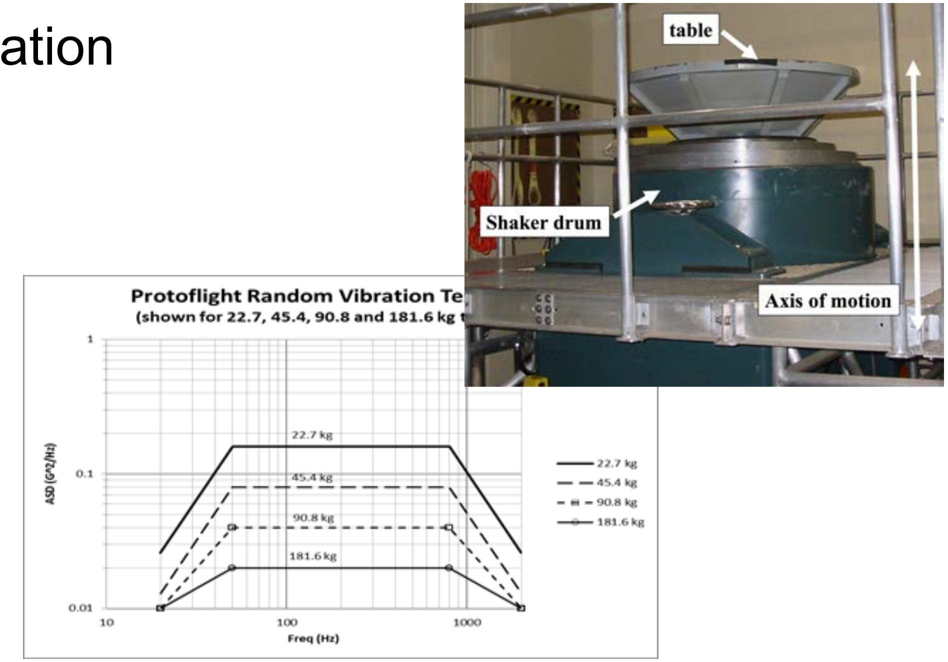


FY16: Vibration testing

- Objective is engineering testing to gauge design approaches, investigate lander mounting options
- RP15 rover with select payload components (OVEN and drill)
- Mass simulators on items that were mocked up on RP15 rover
- Use results to drive flight design iteration
- Scheduled to begin March 7 or 21







Rover Systems: Enabling Technologies

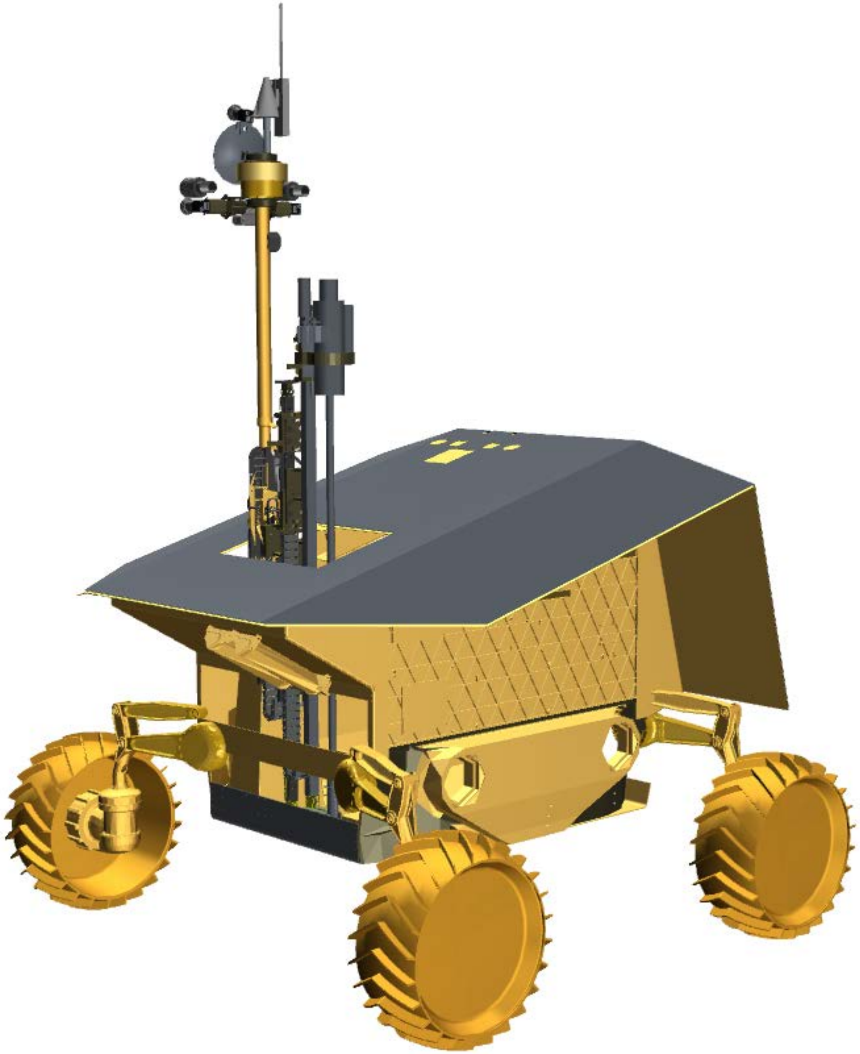
- All wheel active steering
  - Crabbing: Decouples drive vector and solar pointing to maximize solar power and science return for short duration mission; minimizes sun exposure on radiator.
  - Offset axis kinematic coupling with propulsion: Provides no-scrub turning; decreases power while steering; Low soil disturbance from steering.
  - Star (or X) pattern: Stable configuration for wheels when drilling.
  - One non-direct SWaP downside to crab steering is hazard avoidance requires coverage on all 4 sides of the vehicle.

Rover Systems: Enabling Technologies

- Active suspension:
  - Independent impedance control:
    - Provides even wheel force distribution to maximize traction
    - Allows climbing over rocks with more stable pose (helpful for DTE comm)
    - Potential assist in relieving built-up drill forces.
  - Kinematic control:
    - Provides simple stow/deploy capability
    - Allows drill height and angle adjustment;
    - Allows greater ground clearance in rockier terrain;
    - Allows pitch and roll adjustment for improved CG on slopes and sun angle.

Rover Systems: Large wheels and Crab Steer

- Larger wheels are not inherent to skid steer vehicles.
- A simple alteration was developed from the RP15 model to demonstrate one option for a crab vehicle with 0.5m wheels.
- This configuration would have a +-90º steering range.
- The footprint changed from ~1.5mx1.5m to ~1.6mx1.6m
- We are confident a crab steer rover with a larger steering angle (if desired) is possible without changing the existing footprint.



Rover Systems: Ground Pressure

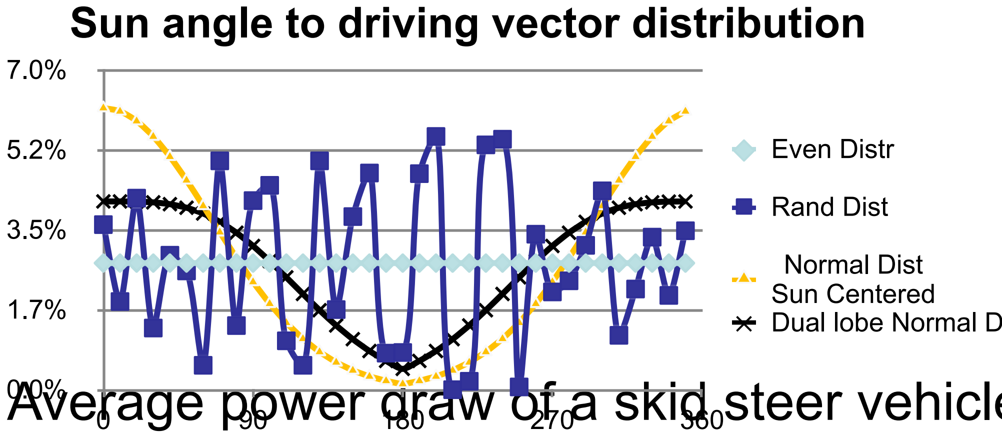
- Comparing Equivalent Ground Pressure for various planetary rovers
  - Where EGP(kPa) = Weight/(radius*width*#wheels)/1000 [1]

Equivalent ground pressure							
	MET Apollo 14[2]	LRV[2]	Lunakhod 2[2]	MER[1]	MSL[1]	RP15	RP
mass (kg)	75	708	756	177	899	300	300
gravity (m/s/s)	1.622	1.622	1.622	3.711	3.711	1.622	1.622
weight (N)	122	1148	1226	655	3336	487	486.6
# wheels	2	4	8	6	6	4	4
radius (m)	0.20	0.41	0.26	0.12	0.24	0.15	0.25
width (m)	0.10	0.23	0.20	0.16	0.40	0.15	0.20
EGP (kPA)	3.04	3.04	3.01	5.50	5.72	5.24	2.43
EGP (psi)	0.44	0.44	0.44	0.80	0.83	0.76	0.35

- RP15 wheels are in the same grouping as MER and MSL
- The baseline RP wheels have a lower EGP than any previous rovers
- 1, Heverly, et al, “Traverse Performance Characterization for the Mars Science Laboratory Rover”, Journal of Field Robotics 30(6), 835–846 (2013)
- 2, Kring, “Lunar Mobility Review”, http://www.lpi.usra.edu/science/kring/lunar_exploration/briefings/lunar_mobility_review.pdf

Rover Systems: Solar power without Crabbing

- Using a variety of trajectory distributions the average solar power collected for a skid steer vehicle (all other systems fixed) is ~30-50% (100-150W) of a crab steer vehicle.


Sun angle to driving vector distribution

	% Solar Power				
	Crab	Skid Normal	Skid Dual Lobe	Skid Rand	Skid Even
Rear Panel	100%	60%	46%	31%	32%
Rear and Side Panels		90%	79%	63%	63%

- Average power draw of a skid steer vehicle is estimated to be ~25-50W less on average (considering lower static power, higher steering power)
- Options for increasing solar power:
  - Larger deployable or gimbal solar panel
  - Solar panels on 3 sides of vehicle (should recapture ~50% of lost power)
  - Mission Trajectory planning to maximize sun normal driving (limited in real-time by terrain resolution, can possibly capture another ~10%)

Driving Requirements, per RP SRD/ERD, Rev J

- Overall System
  - The **System** should investigate the geotechnical characteristics of cold traps.
  - The **System** shall have a total mass of no greater than 5,000 kg <TBR>.
  - The **System** shall have the capability to function under modes of operations facilitating safe operations and autonomous fault recovery.
- I&T
  - The **System/Rover** shall provide access to critical components and payloads during the I&T phase.
- Landing/Egress
  - The **System/Rover** shall provide for a Rover Egress within 6 <TBR> hours of lunar landing.
  - The **Rover** shall release itself for egress upon command from MOS.

Driving Requirements, per RP SRD/ERD, Rev J

- Mobility
  - The **Rover** shall traverse the lunar surface with a minimum range of 1 km (point to point).
  - The **Rover** shall provide a "Prospecting" traverse speed of 10 cm/sec or less
  - The **Rover** shall operate on the lunar surface on slopes up to 15 degrees relative to lunar gravity.
  - The **Rover** shall traverse lunar terrain as specified in the RP-SPEC-0001 Environmental Specification Document.
  - The **Rover** shall be remotely driven by a ground based operations team per the <TBD> Surface Segment Operations document.
  - The **Rover** shall enable Science Payload measurements while traversing within a region without direct solar illumination.

Driving Requirements, per RP SRD/ERD, Rev J

- Localization/Navigation
  - The **System/Rover/MOS** shall determine its horizontal location within the pre-launch defined lunar surface operating area to at least +/- 20 meters at any time from 3 <TBR> hours **post egress through decommissioning**. (paraphrased from SRD and ERD)
  - The **Rover** shall provide rover sensor telemetry, images, and payload data of surrounding lunar environment to MOS for surface segment position estimation to within +/- 10 meters <TBR> in the predifined landing DEM with respect to coordinate frame <TBD> **post mission**.
  - The **Rover** shall, with ground commanded assistance, return from any location to a previously identified "Area of Interest" to within 5 <TBR> meters.

RP Rover Tiger Team Review

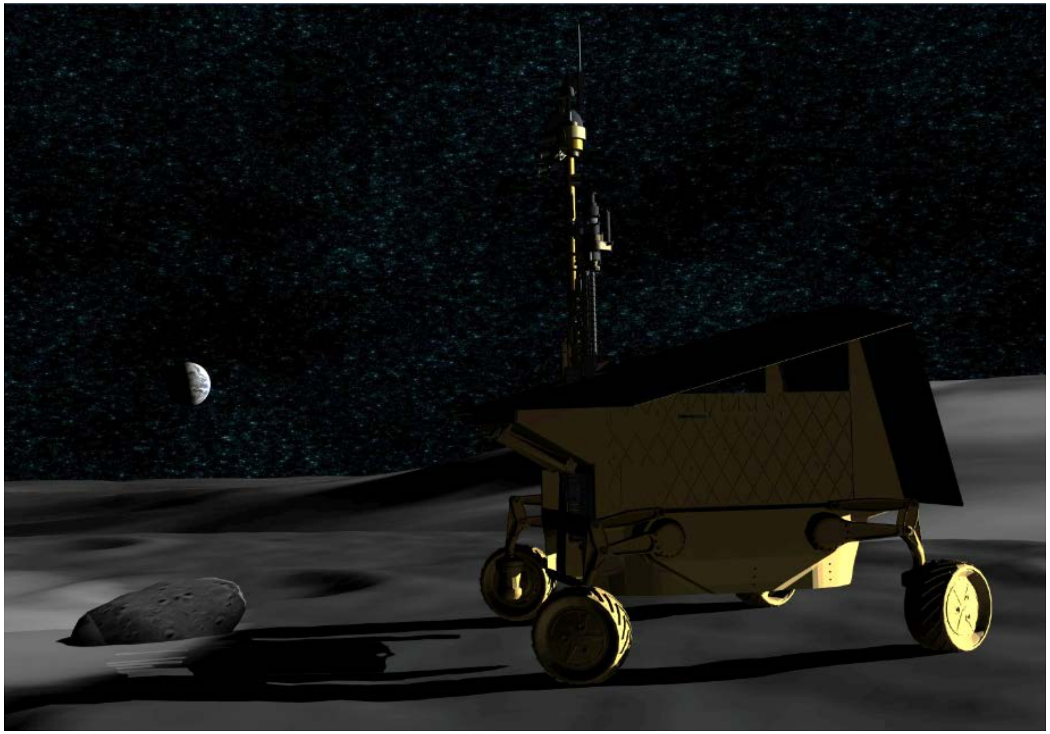
March 2016

Rover Mobility

Ed Herrera, Colin Creager, Josh Figuered, Anthony Lapp

Mobility System Outline

- Baseline Design
  - Architecture options
  - Baseline architecture drivers
  - Baseline architecture
    - Wheels
    - Propulsion
    - Steering
    - Suspension
  - Rover functionality benefits
  - Make vs Buy
  - Technology Maturation
- Mobility trade/discussion

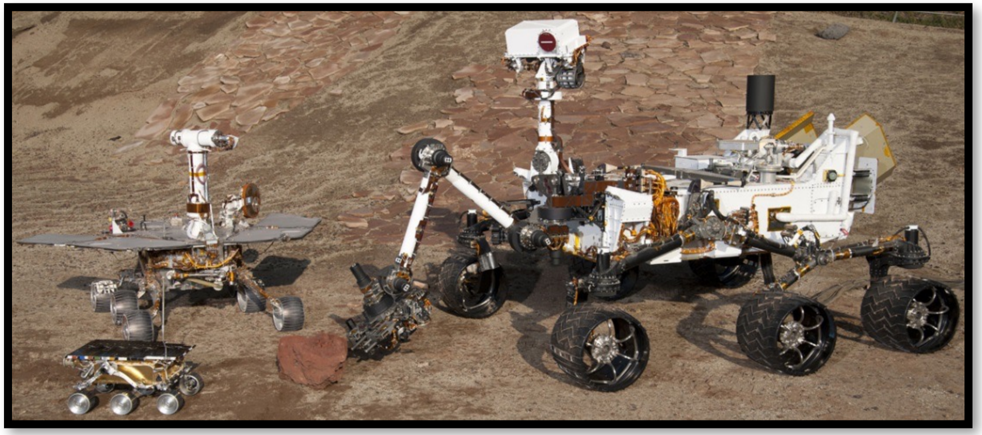


Mobility Architecture Options

Skid Steer With Four Bar Suspension

*Lunokhod

6 Wheel/4Wheel Steer with Rocker Bogie Suspension



*Sojourner, Spirit/Opportunity, MSL

All Wheel Steer With Four Bar Active Suspension

*Chariot, RP15

Mobility Architecture Options

- Skid steer with passive four bar suspension (Lunokhod)
  - Pros
    - Simplest solution for mobility (1 actuator/wheel for propulsion)
    - In comparison to steered designs, wheel size can be maximized for improved flotation and tractive efficiency in soft soil as steering volume is eliminated
    - Capable of lander egress without requiring folding or additional actuators
  - Cons
    - Steering requires more power than steered wheel designs
    - Skid steering imparts increased side loads on wheels in comparison to steered wheel architecture increasing size/weight of structure
    - Unable to track sun during mission operations
- Skid Steer With Active Four Bar Suspension
  - Pros vs Passive System
    - Increased mobility
      - Traverse larger obstacles
      - Increased traction
    - Load leveling capability
    - Greater versatility in lander packaging and egress options
  - Cons vs Passive System
    - Increased complexity, cost, mass, and power demands

Mobility Architecture

- 6 Wheels/4 Wheel Steer With Rocker Bogie Suspension (Sojourner, Spirit, Opportunity, MSL)
  - Wheels: 6
  - Steered Wheels: 4 (Corners)
  - Total Mobility Actuators: 10 (4 Steering, 6 Propulsion)
  - Pros
    - Improved traction and reduced body pitch in comparison to passive four bar suspension
    - Passive suspension does not require power
    - Suspension enables rover to traverse larger obstacles in comparison to passive 4 bar suspensions
    - Corner steer reduces power demands of steering compared to skid steer
  - Cons
    - More complex than skid steer
    - The necessity of 6 wheels results in a reduction of wheel diameter when compared to 4 wheeled rovers given a fixed volume. Reduction of wheel diameter means reduced draw bar pull.
    - Increased weight compared to 4 wheeled designs
    - Requires differential mechanism across rover body
    - May require foldable components or additional/specialized actuators for stowing and lander egress
    - Lack of active suspension and all wheel steer increases risk of getting stuck
    - Inability to track sun during mission operations
    - No ability to actively control force on individual wheels/cannot actively load level rover chassis

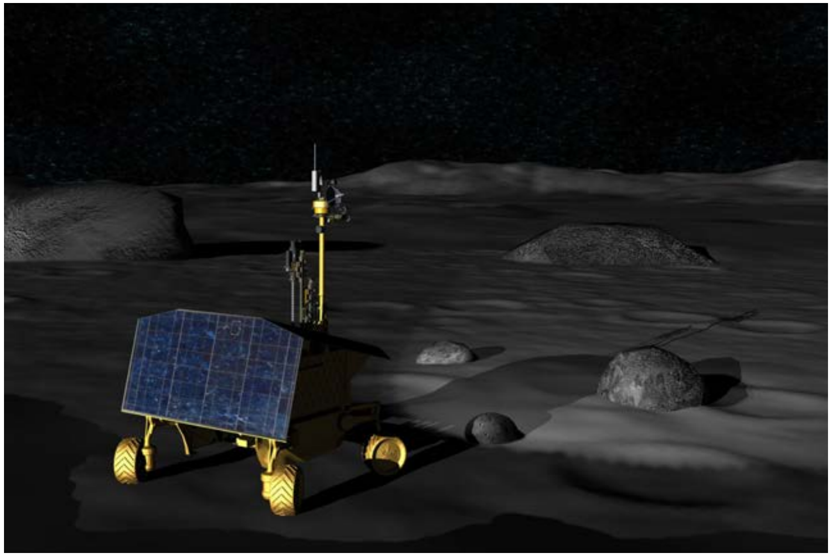
Mobility Architecture

- All Wheel Steer With Active Four Bar Suspension (RP)
  - Total Mobility Actuators: 12 (4 Steering, 4 Propulsion, 4 Suspension)
  - Pros
    - Ability to track sun during mission operations (2 DOF sun tracking w/active suspension)
    - Active suspension can change angle of vehicle during recharge periods for increased solar charging performance
    - Ability to stow and egress from lander without additional actuators/specialized actuation
    - Active suspension maximizes traction with control of force at each wheel
    - Active suspension enables rover to traverse larger obstacles
    - Active suspension allows for adjustment of drill angle (load leveling) and provides increased ability to dislodge the drill in the event it gets stuck
    - Greater ability to get unstuck from soft soil
    - All wheel steer reduces power demands of steering compared to skid steer
  - Cons
    - More complex than skid steer
    - Increases requirements for hazard avoidance
    - Complexity vs rocker bogie is design specific based on stowing egress requirements of rocker bogie rover aboard lander
    - Active suspension requires power (when on) and additional mass compared to passive

Mobility Architecture Drivers

Drivers for All Wheel drive and steer with Active Suspension

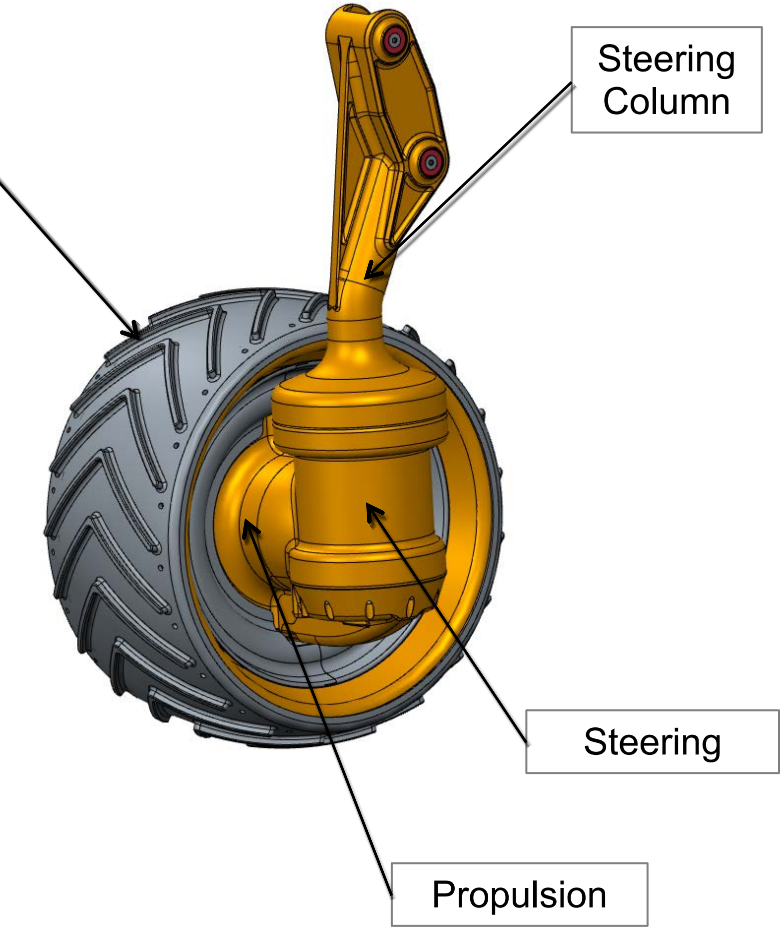
- Coordinated DOF improve performance in soft soils
  - Valuable in uncertain terrain
- All Wheel Steering
  - Sun tracking for max charging
    - Polar mission not equatorial
    - Low sun angle, long shadows
    - Boulder distribution
  - Area of Interest Mapping
    - Raster/spiral scanning for volatiles
- Active Suspension
  - Lander
    - Provides most design flexibility and options for stow and egress
    - Stow against hardstops for launch vibe
    - Egress extreme ramp or step
  - Adds a DOF for sun tracking and DTE comm.
  - Traverse timelines
  - Uncertainty in terrain
  - Passive suspension even when active is off



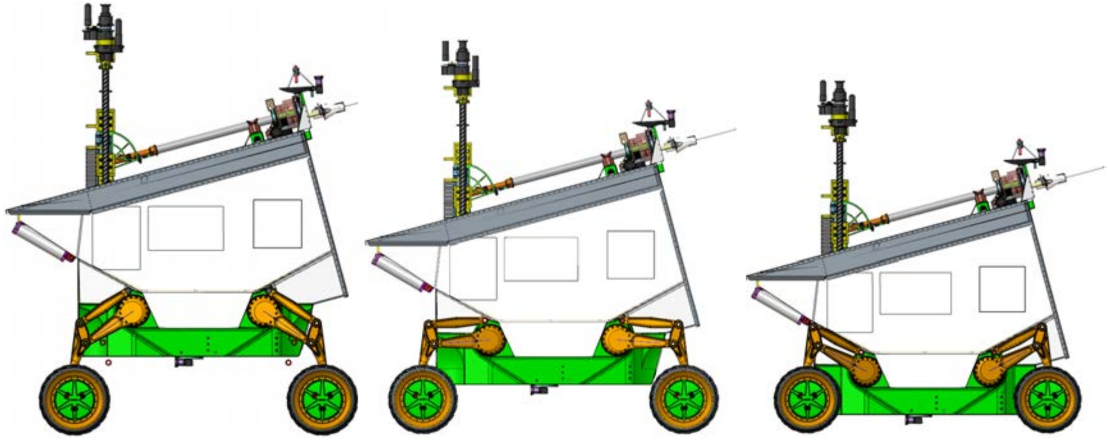
Mobility Baseline Architecture

- Baseline mobility subsystems
  - Wheel (Colin Creager)
  - Propulsion (Josh Figuered)
  - Steering (Anthony Lapp)
  - Suspension (Ed Herrera)

Wheel Module



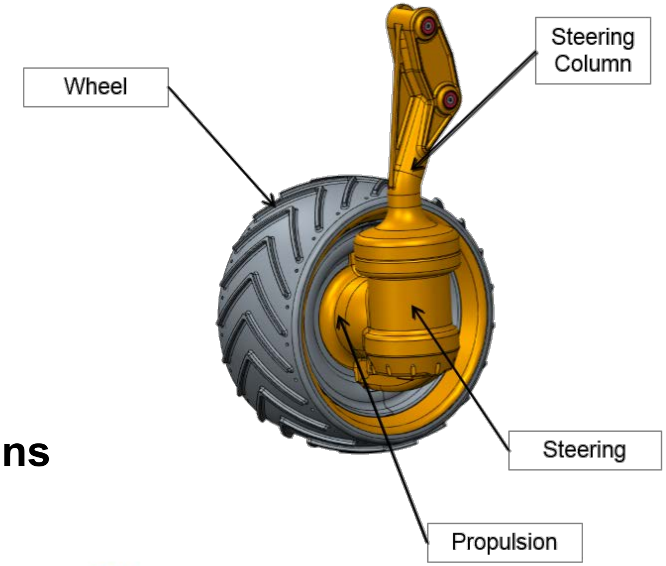
Suspension


Max Nominal Min/Stowed

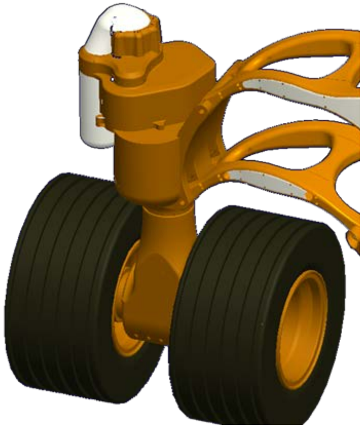
Mobility Baseline Architecture

- Baseline mobility subsystems
  - Wheel (Colin Creager)
  - Propulsion (Josh Figuered)
  - Steering (Anthony Lapp)
  - Suspension (Ed Herrera)

Wheel Module



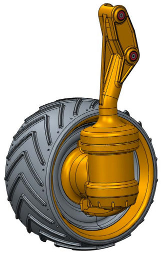
Wheel Module Configurations



Chariot

Centaur 2

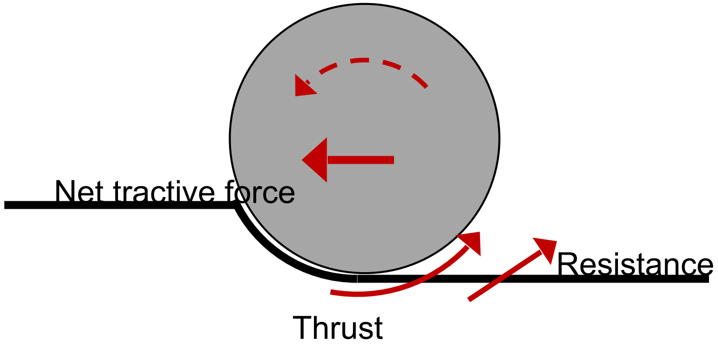
MRV



RP15

Mobility Baseline Architecture

How to optimize traction in soft soil?



Net tractive force =
Thrust - Resistance

Increasing Thrust

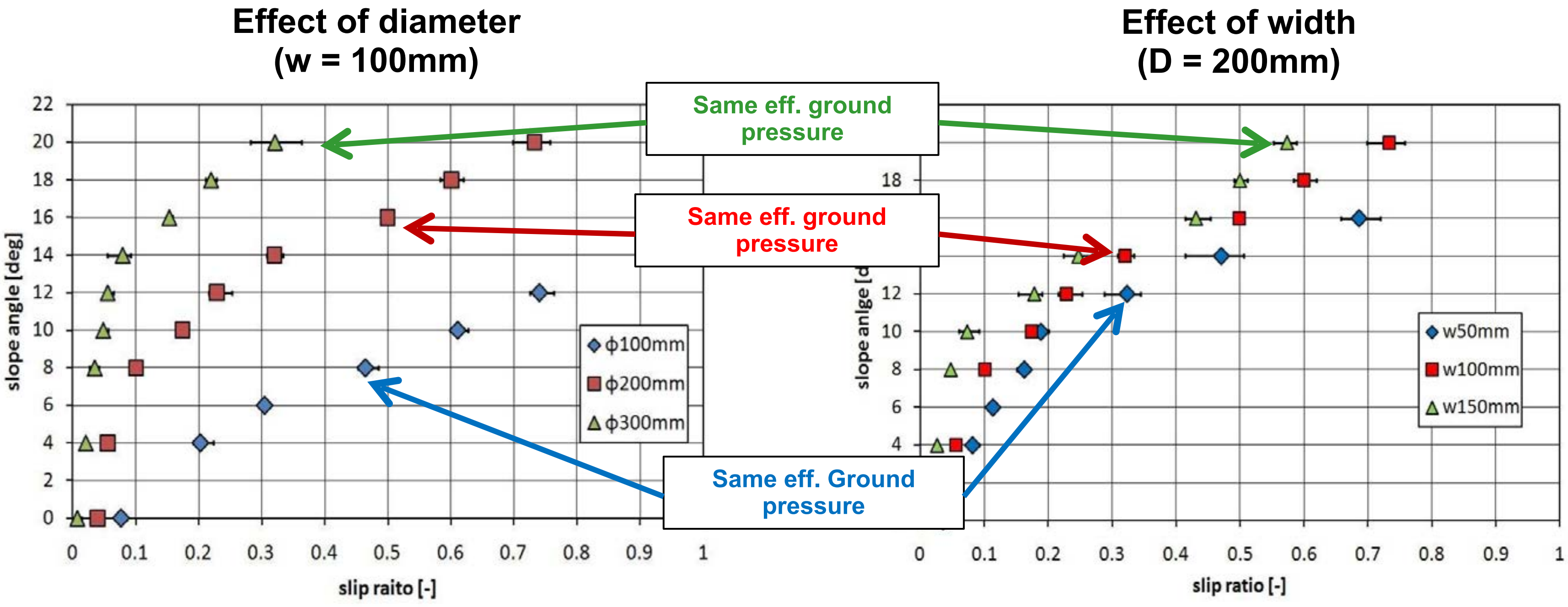
- Maximize wheel-soil contact area
  - ➢ Increase **diameter** and **width**
- Maximize horizontal component of thrust
  - ➢ Add compliance to tire or increase **diameter**

Decreasing Resistance

- Reduce ground pressure to minimize sinkage
  - ➢ Increase **diameter** and **width**
- Reduce wheel/soil entrance angle
  - ➢ Increase **diameter**
- Use **grousers** to excavate soil in front of wheel

Mobility Baseline Architecture

Wheel diameter has the greatest impact on traction in soil



Effect of diameter
(w = 100mm)

Effect of width
(D = 200mm)

Same eff. ground pressure

Same eff. ground pressure

Same eff. Ground pressure

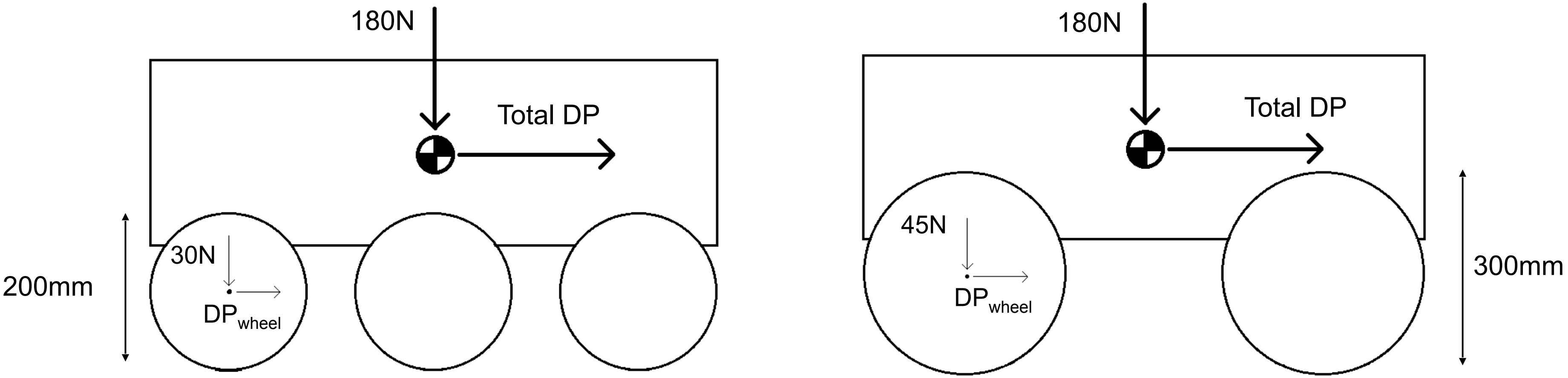
Plots courtesy of Sutoh et. al., “Traveling performance evaluation of planetary rovers on loose soil.” Journal of Field Robotics, Vol. 29, Issue 4, 2012

- Width can be cut down to save on mass, as long as the sinkage doesn’t become too great

Mobility Baseline Architecture

Total net tractive force (drawbar pull, DP) of 4 large wheels vs. 6 small wheels

- Constant total wheel mass and effective ground pressure (3kPa / 0.44psi)



Tire load = 30N

DP coefficient = 0.19 (@20% slip)

Individual DP force = 0.19(30N) = 5.7N

Total DP force = 6(5.7N) = **34.2N**

Tire load = 45N

DP coefficient = 0.29 (@20% slip)

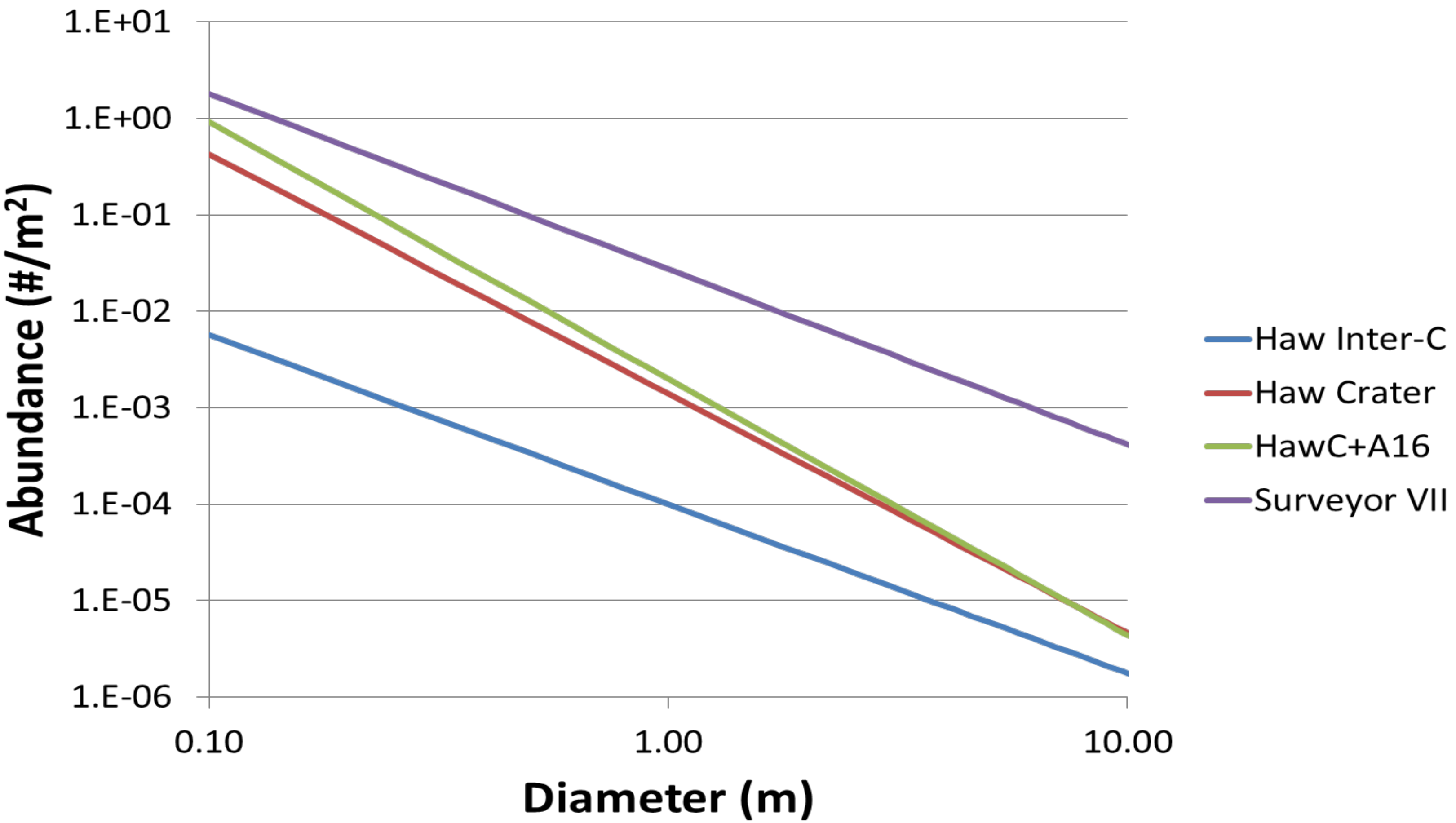
Individual DP force = 0.29(30N) = 13.1N

Total DP force = 4(13.1N) = **52.4N**

Drawbar pull coefficient data courtesy of Sutoh et. al., “Traveling performance evaluation of planetary rovers on loose soil.” Journal of Field Robotics, Vol. 29, Issue 4, 2012

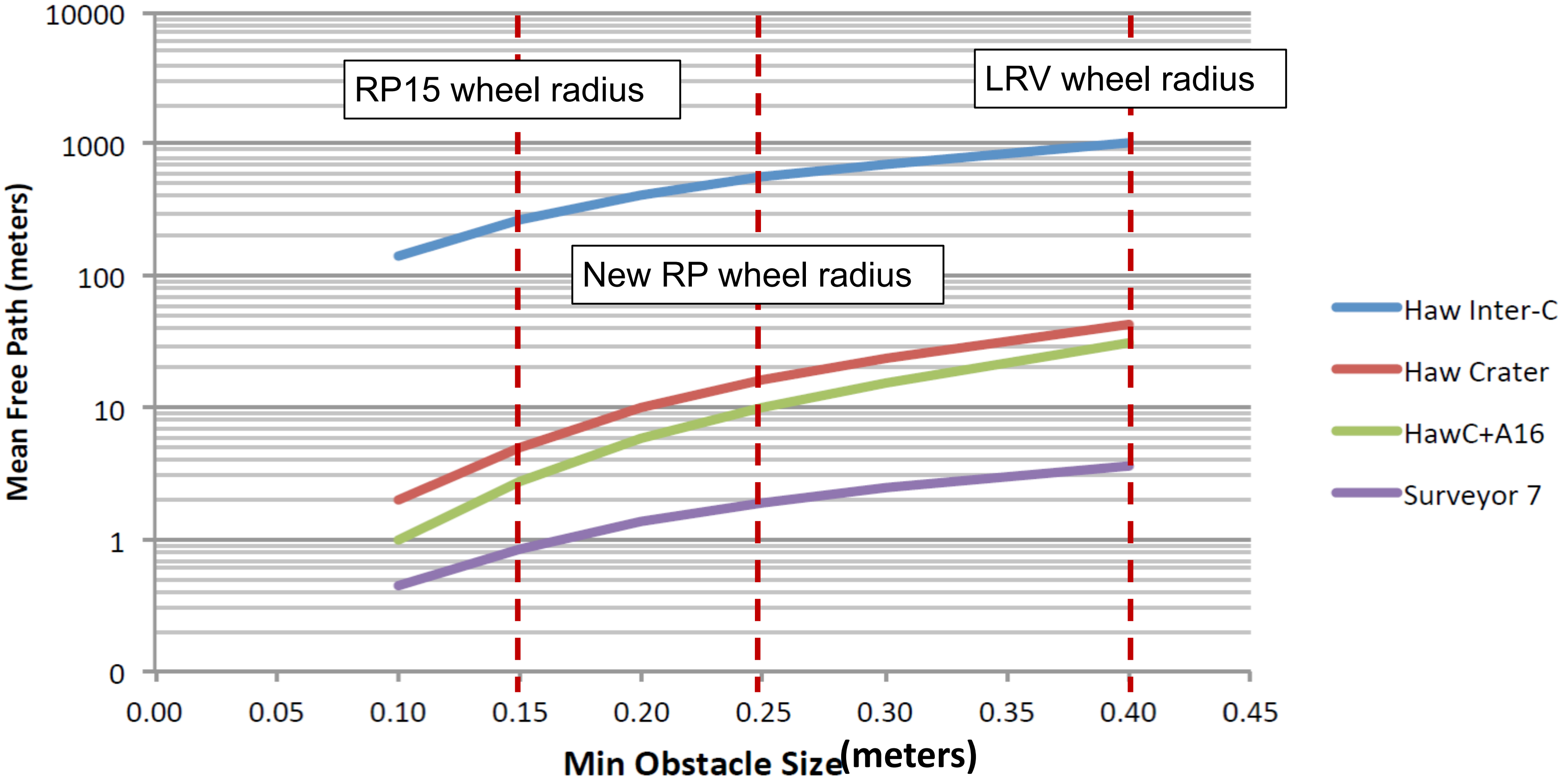
Mobility Baseline Architecture

Predicted rock size distribution



Mobility Baseline Architecture

Mean free path: effect of diameter on rock traversal
(assuming vehicle width ~ 1m)

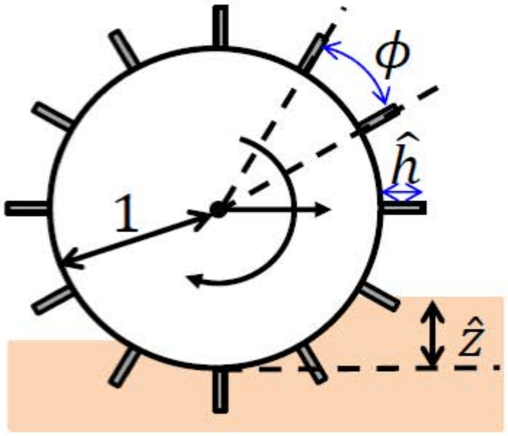


A 67% increase in diameter = 200-400% increase in mean free path

Mean free path graph courtesy of Matt Deans, ARC

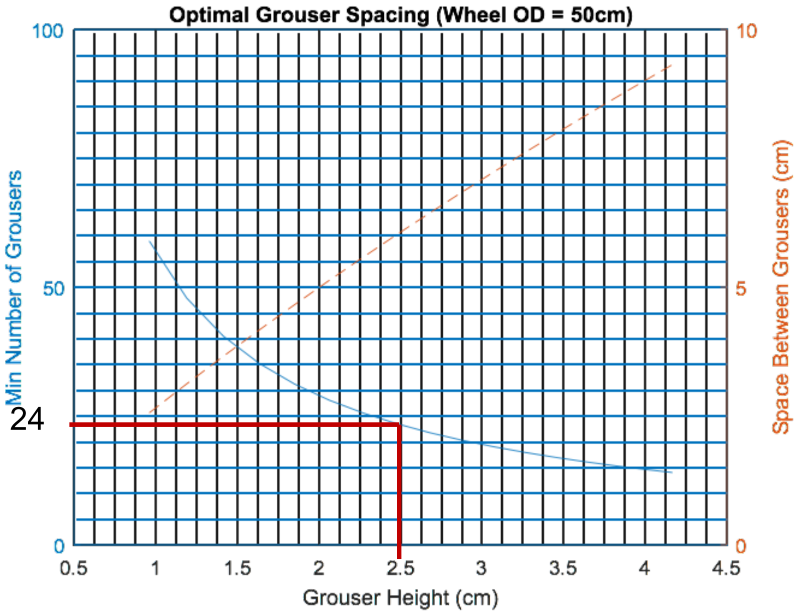
Mobility Baseline Architecture

Grouser height and spacing are based on theory of excavating soil in front of wheel



Φ = Angular grouser spacing
n = Number of grousers
$\hat{h}$ = Normalized grouser height
$\hat{z}$ = Normalized wheel sinkage
i = Wheel slip

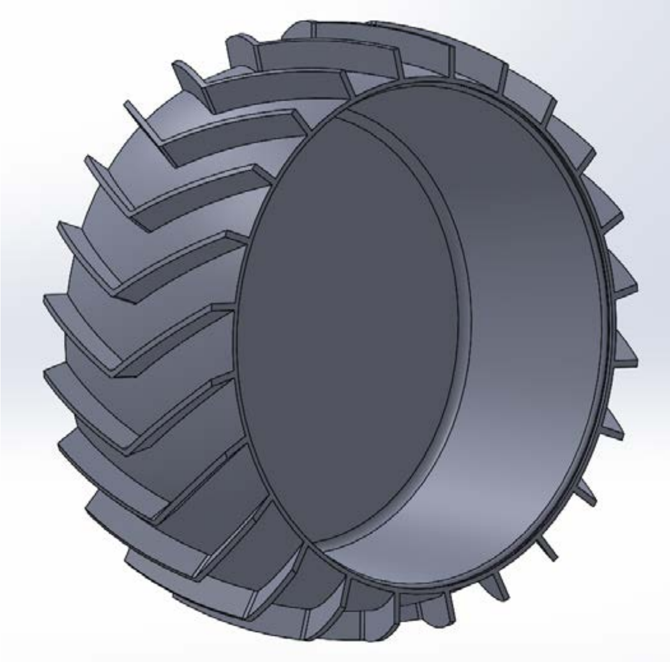
$$n > \frac{2\pi(1-i)}{\left(\sqrt{(1+\hat{h})^2-(1-\hat{z})^2}-\sqrt{1-(1-\hat{z})^2}\right)}$$



Equation courtesy of K. Skonieczny, S. J. Moreland and D. S. Wettergreen, "A Grouser Spacing Equation for Determining Appropriate Geometry of Planetary Rover Wheels," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012.

Mobility Baseline Architecture

New wheel design



For tire load = 134N (30lbs),
Effective ground pressure = 2.68kPa (0.39psi)

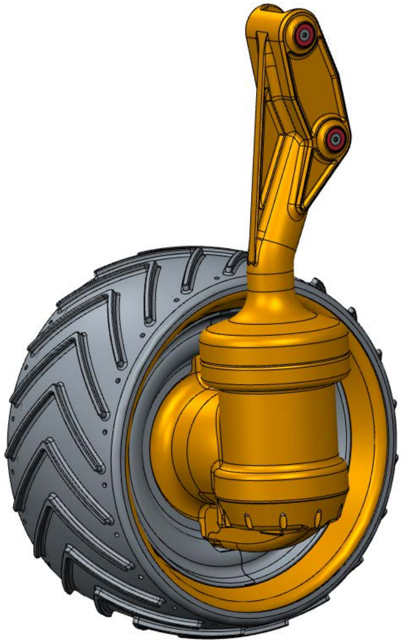
Parameter	Design Choice	Justification
Outer diameter	50cm (RP15 ~ 30cm)	Largest possible based on predicted mass/volume/system constraints
Width	20cm	Minimize sinkage (secondary to diameter)
Grouser height	2.5cm	Largest possible while structurally sound
Number of grousers	24	Excavate soil in front of wheel (grouser design equation)
Crown radius	30cm	Add lateral support while maximizing contact with the soil
Chevron angle of grousers	30deg	Allows for constant rolling radius on hard ground

Mobility Baseline Architecture

- Propulsion:
  - Purpose: Provide required torques and speeds to traverse lunar terrain
  - Design Drivers:
    - Path planning
      - Terrain slopes
      - Range of operating speeds
    - Wheel
      - Diameter
      - Rolling resistance
    - Volume
      - Wheel internal volume
      - Steering interface
    - Mass
    - Power

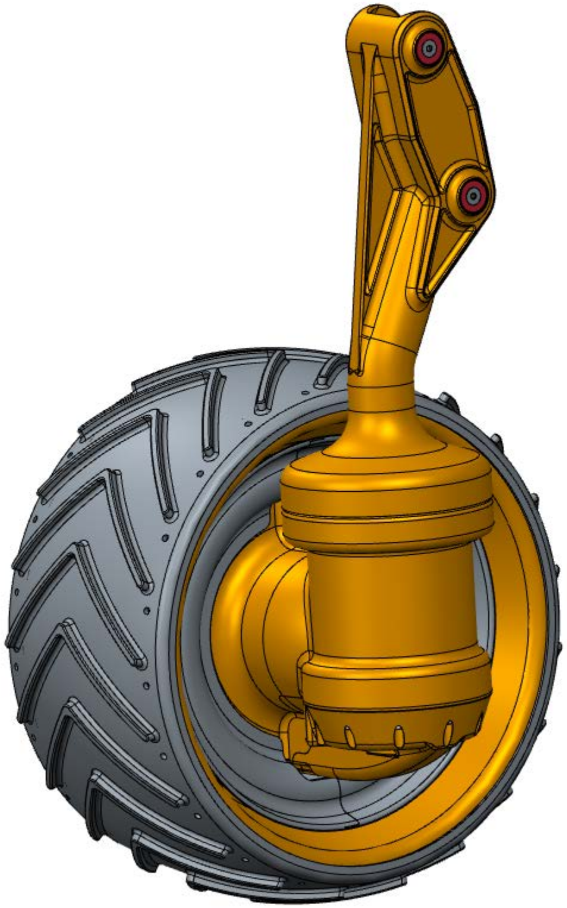
Mobility Baseline Architecture

- Propulsion: (Cont...)
  - Design approach to drivers:
    - Path planning
      - Design for rim force adequate to traverse expected slopes with margin for extreme cases
      - Optimize design to be efficient at nominal speed with capability to sprint
    - Wheel
      - Wheel diameter effects actuator design in respect to speed and torque
      - Wheel diameter is proportional to actuator torque requirement
      - Wheel diameter is inversely proportional to actuator speed requirement
    - Volume/Mass
      - Custom integration of components
    - Power
      - Voltage available from power system effects max motor speed
      - Higher voltage provides more options for motor and increased speed capability for sprinting
      - For efficiency and rim force capability the actuator will likely need a gear ratio greater than 100:1



Mobility Baseline Architecture

- Propulsion: (Cont...)
  - Baseline Propulsion Design:
    - In-wheel hub actuator
    - Actuator components:
      - Brushless, frameless kit motor (rotor/stator)
      - Planetary gear set
      - Incremental position sensor
      - Bearings
      - Seals
      - Heater?
  - Benefits:
    - Independent propulsion provides redundancy with limited loss of functionality
    - Independent propulsion provides greatest traction
    - Custom housing allows for compact package/ weight reduction
    - Planetary gear set is more efficient and robust than harmonic drive



*RP15 Configuration

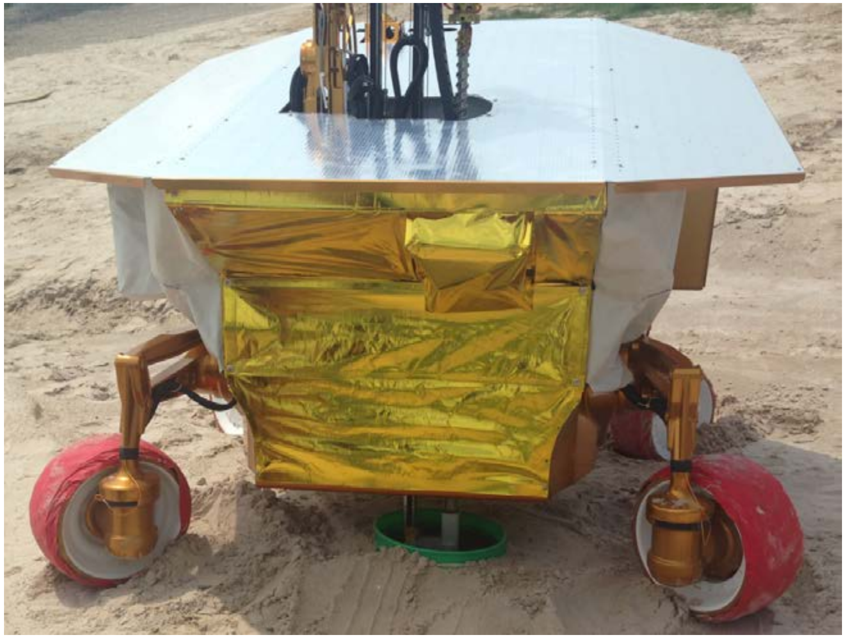
Mobility Baseline Architecture

- Propulsion: current design assumptions:
  - 300 kg (660lb) Vehicle, Coefficient of Rolling Resistance = 0.4
  - Nominal Operating Point (Design for efficiency)
    - 5 Degree slope
    - 10 cm/s
    - Assume ground force capability equal to 31% of vehicle weight
  - Sprint Capability (Design for capability)
    - 5 Degree slope
    - 25 cm/s
    - Assume ground force capability equal to 31% of vehicle weight
  - Peak Operating Point (Design for capability)
    - 15 Degree slope
    - 10 cm/s
    - Assume ground force capability equal to 34% of vehicle weight
  - Peak Output (Time Limited)
    - Assume ground force capability equal to 40% of vehicle weight and coefficient of friction =1

Mobility Baseline Architecture

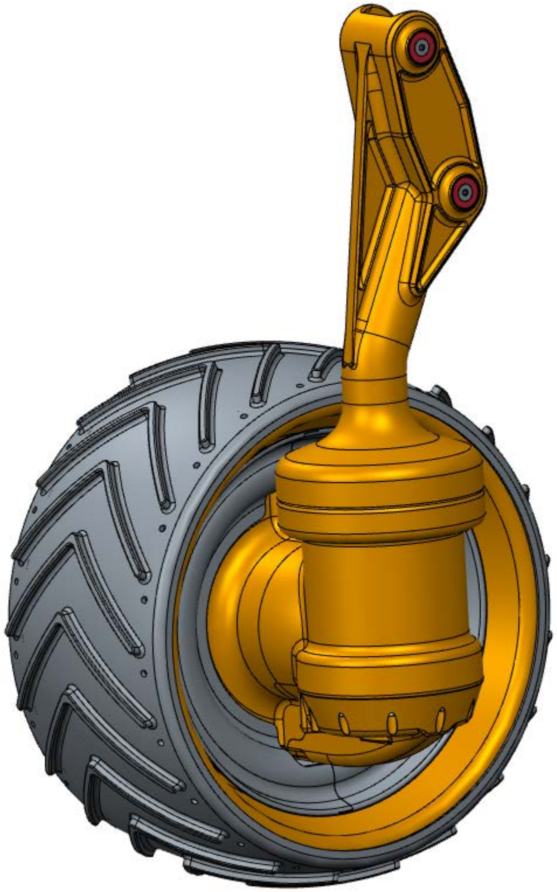
- Steering:
  - Purpose: Provide maneuverability and pointing

  - Design Drivers:
    - Path planning
      - Solar tracking independent of trajectory
      - Polar mission not equatorial
        - Slow moving, low sun angle requires dexterity
      - Hazard avoidance
      - Boulder distribution
    - Drilling operations
      - Location accuracy
    - Wheel
      - Diameter
    - Volume
      - Multi-turn hard stop
    - Mass
    - Power



Mobility Baseline Architecture

- Steering: (Cont...)
  - Design approach to drivers:
    - Path planning
      - Provide a wide steering range to allow for continuous solar tracking independent of path
      - Offset wheel steering axis to allow for advanced maneuverability
    - Wheel
      - Maintain ideal wheel diameter and wide range of steering motion
        - » Larger wheels may require kinematic limits with respect to suspension posing
    - Volume
      - Custom integration of components
    - Mass
      - Custom integration of components
    - Power
      - Select an zero backlash drivetrain and optimize actuator for predominant driving condition
      - Ability steering through locked propulsion joint



Mobility Baseline Architecture

- Steering: (Cont...)
  - Baseline Steering Design:
    - Actuator components:
      - Harmonic Drive
      - Parker Brushless Motor
      - US Digital Incremental Encoder
      - Zettlex Incoder Absolute Position Sensor
      - Kaydon Output Bearings
      - Locking Heli-coils
      - Dust Seals
      - Multi-Turn Hardstop
      - Internal wire routing
  - Benefits:
    - Can use coordinated motions to climb out of holes, stuck wheels, high centers, etc.
    - Continuous solar tracking independent of path
    - Rover can continue to navigate and steer around locked steering joint
    - Could assists gimbal with DTE communication
    - Track adjustment, inch worming, 3 DOF maneuvers
      - Steering geometry when combined with 3DOF kinematic control allows rover to navigate into and out of places that other machines cannot

Mobility Baseline Architecture

Steering: current design assumptions: (Cont…)

- Light Load Case:
  - Primary force supplied by propulsion
  - 14 RPM max @ 54.5 Nm (482.5 in-lbs) @ 88v-2.3A

- Nominal Load Case:
  - Track propulsion kinematics
  - 5 RPM @ 109.0 Nm (965 in-lbs) @ 38v-5.3A

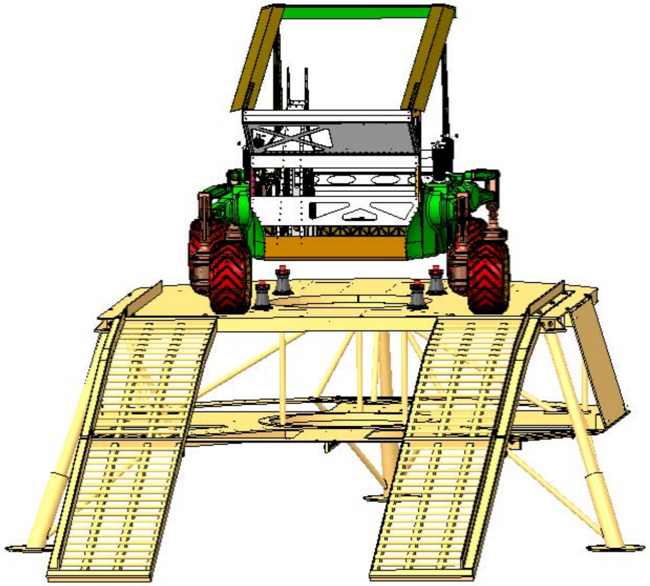
- Peak Load Case:
  - **Locked wheel steering**
  - 1 RPM @ 369.9 Nm (3273.9 in-lbs) @ 20.3v-16.7A

- Launch Load Case: TBD, pending 3/2016 vibe test results

- Actuator Requirements (303 kg Rover in 1/6G and 15° max slope)
  - Max Output Speed: 14 RPM (1.47 rad/s)
  - Max Output Torque: 34.22 Nm (302.8 in-lbs)

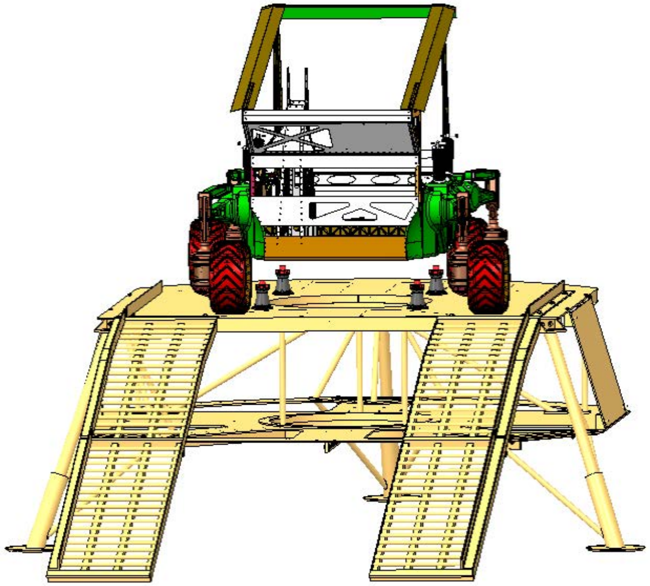
Mobility Baseline Architecture

- Suspension:
  - Purpose: Provide required ground clearance, terrain holding/handling, and ride quality
  - Design Drivers:
    - Lander
      - Stow configuration
      - Release/deploy mechanisms
      - Duration
      - Ramp angle
    - Path planning
      - Boulder distribution
      - Boulder height traverse requirement
      - Ground speeds through boulder fields
    - Drilling operations
      - Leveling on sloped terrain
      - Stuck drill recovery assist
    - Volume
      - Available Lander footprint - Payload
    - Mass
    - Power



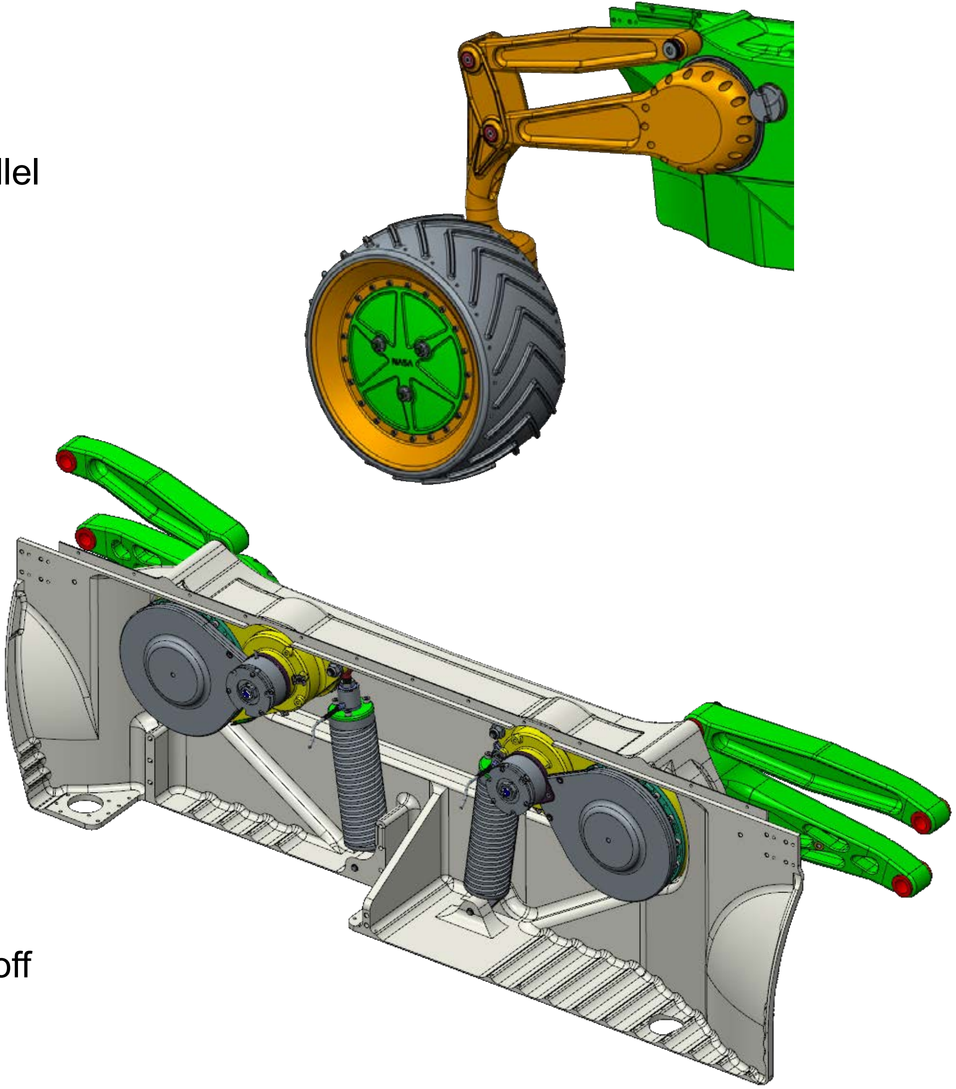
Mobility Baseline Architecture

- Suspension: (Cont...)
  - Design approach to drivers:
    - Lander
      - Preload wheel module against suspension hardstop for launch vibe
      - Minimize deploy actuations
      - Extend functionality of deploy mechanisms to rest of mission
    - Path planning
      - Maximize functionality within limits to address unknowns
    - Drilling operations
      - Select functionality that benefits Drill
    - Volume
      - Custom integration of components
    - Mass
      - Custom integration of components
    - Power
      - Select components that minimize static load (e.g. bi-stable brake, back-drivability of actuator)



Mobility Baseline Architecture

- Suspension: (Cont...)
  - Baseline Suspension Design:
    - Series-elastic actuator w/ equal length parallel 4-bar geometry
    - Actuator components:
      - Brushless, frameless kit motor (rotor/stator)
      - Harmonic gear component set
      - Incremental position sensor
      - Absolute position sensor
      - Single axis load cell
      - Bearings
      - Seals
      - Bi-stable brake
  - Benefits:
    - Kinematic control of all DOF
      - Lander stow and egress
      - Sun tracking
      - Load leveling
      - Ground force sensing
      - Steering assist
    - Maintains passive suspension with system off
    - Functions with either all wheel or skid steer architectures

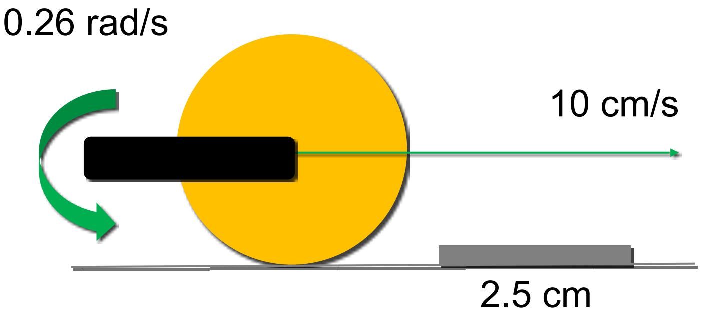


*RP15 Configuration

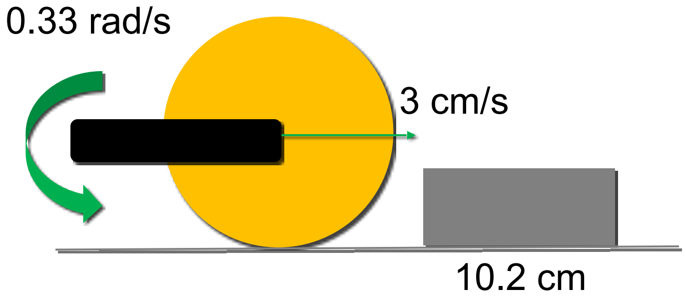
Mobility Baseline Architecture

- Suspension: current design assumptions:
  - Ride Height:
    - Nominal: 20.32 cm (8 in)
    - Active vertical range:
      - Min: 10.16 cm (4 in)
      - Max: 30.48 cm (12 in)
  - Active Response:
    - Response to boulder size is vehicle speed dependent
    - 2.5cm (1in) obstacles at prospecting vehicle speed, 10cm/s
      - Actuator Output Speed: 0.26 rad/s (2.5 rpm)
    - 10.2cm (4in) obstacles at reduced vehicle speed, 3cm/s
      - Actuator Output Speed: 0.33 rad/s (3.2 rpm)
    - Scenario B sets max actuator speed
    - Other actuator speed dependencies
      - Control arm length: inversely proportional
      - Wheel Diameter: inversely proportional (e.g. 50 vs. 30.5 cm wheel, 0.19 rad/s)

Scenario A



Scenario B



Mobility Baseline Architecture

- Suspension: current design assumptions: (Cont…)
  - Nominal Load Case:
    - Traverse 5˚ slope
    - Rim-force equal to 40% vehicle wheel rolling resistance
    - 31% vehicle mass on wheel
    - (TBD) Duty Cycle
  - Peak Load Case:
    - Traverse 15˚ slope
    - Rim-force equal to 40% vehicle wheel rolling resistance
    - 34% vehicle mass on wheel
    - (TBD) Duty Cycle
  - Launch Load Case: TBD, pending 3/2016 vibe test results
  - Actuator Requirements (303 kg Rover in 1/6G and 15˚ max slope)
    - Max Output Speed: 0.33 rad/s (3.2 rpm)
    - Output Torque: 116 Nm (85 ft-lbf) Nominal; 194 Nm (143 ft-lbf) Peak

Baseline Rover Functionality Benefits

- Active Suspension
  - Ability to fold
    - Tuck wheels for transit and deploy for operations
  - Ability to change height
    - Stand up from lander
    - Avoid obstacles
    - Lower CG
    - Control sensor height
    - Change skirt height
  - Ability to adjust vehicle angle
    - Drill placement
    - Solar alignment
    - Load leveling
  - Ability to package easier
    - Eliminates linkages
    - Compact
  - Ability to traverse more severe terrain
    - Keep 4 wheels on ground
    - Rim transition
- Offset Crab Steering
  - Ability to change vehicle driving angle
    - Point assets
      - Solar arrays
      - Sensors
  - Point turn
  - Ability to get "out of trouble"
    - Change tracking to a different direction
    - Shift wheel tracking
- Independent Propulsion
  - 4 motors allows for 2 failures with limited loss of functionality

Mobility Technology Maturation

- Mobility Technology after RP15 at TRL 5
  - "The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment."
  - RP15 components successfully integrated with functional testing in field (JSC rockyard) and reduced gravity environment (ARGOS)
  - Plan to raise to TRL 6 prior to PDR
    - Vibe, Radiation, Thermal Vacuum testing
      - Individual components such as motors and sensors
      - Complete mobility unit
    - Lubrication and Sealing decisions
      - Selection of appropriate lubricant for harmonics and bearings. Will leverage flight heritage
      - Design of dust sealing systems are still TBD
    - Design mass reduction.
      - Utilize RP15 architecture, but design components for 1/6G.
      - Leverage design work done prior to RP15.
      - Functional testing of 1/6G components likely necessary.