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Dynamic Radioisotope Power System (DRPS) Permanently Shadowed Region (PSR) Demonstrator Rover

Steven Oleson
Glenn Research Center, Cleveland, Ohio

Paul C. Schmitz
Power Computing Solutions, Avon Lake, Ohio

Kirby Runyon, Ben Bussey, and Paul Ostdiek
Johns Hopkins University Applied Physics Lab, Laurel, Maryland

Anthony J. Colozza, Thomas W. Packard, and John Z. Gyekenyesi
HX5, LLC, Brook Park, Ohio

Elizabeth R. Turnbull, Brent F. Faller, Natalie J. Weckesser, Brandon T. Klefman,
Onoufrios Theofylaktos, Christine L. Schmid, Christopher R. Heldman, and Cassandra Chang
Glenn Research Center, Cleveland, Ohio

James E. Fittje
Science Applications International Corporation, Brunswick, Ohio

August 2021

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James E. Fittje
Science Applications International Corporation, Brunswick, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Acknowledgments

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

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National Aeronautics and Space Administration
Glenn Research Center
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Avon Lake, Ohio 44012

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Johns Hopkins University Applied Physics Lab
Laurel, Maryland 20723

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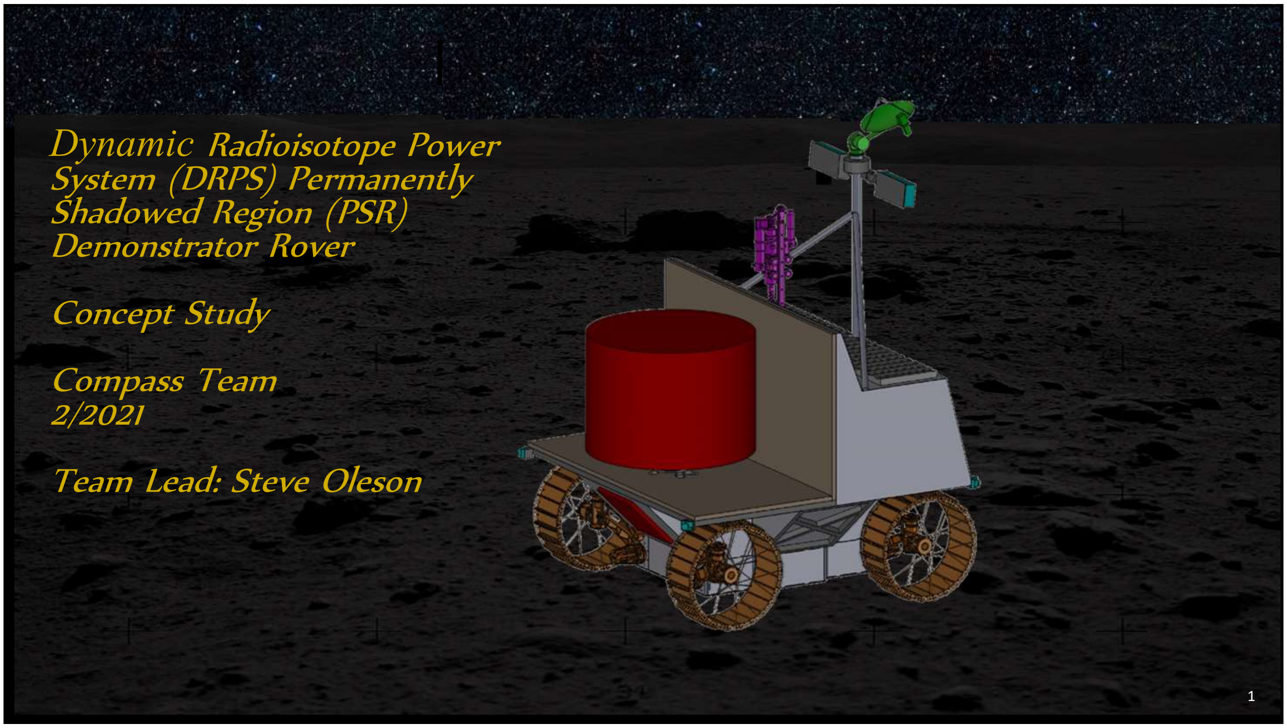
HX5, LLC
Brook Park, Ohio 44142

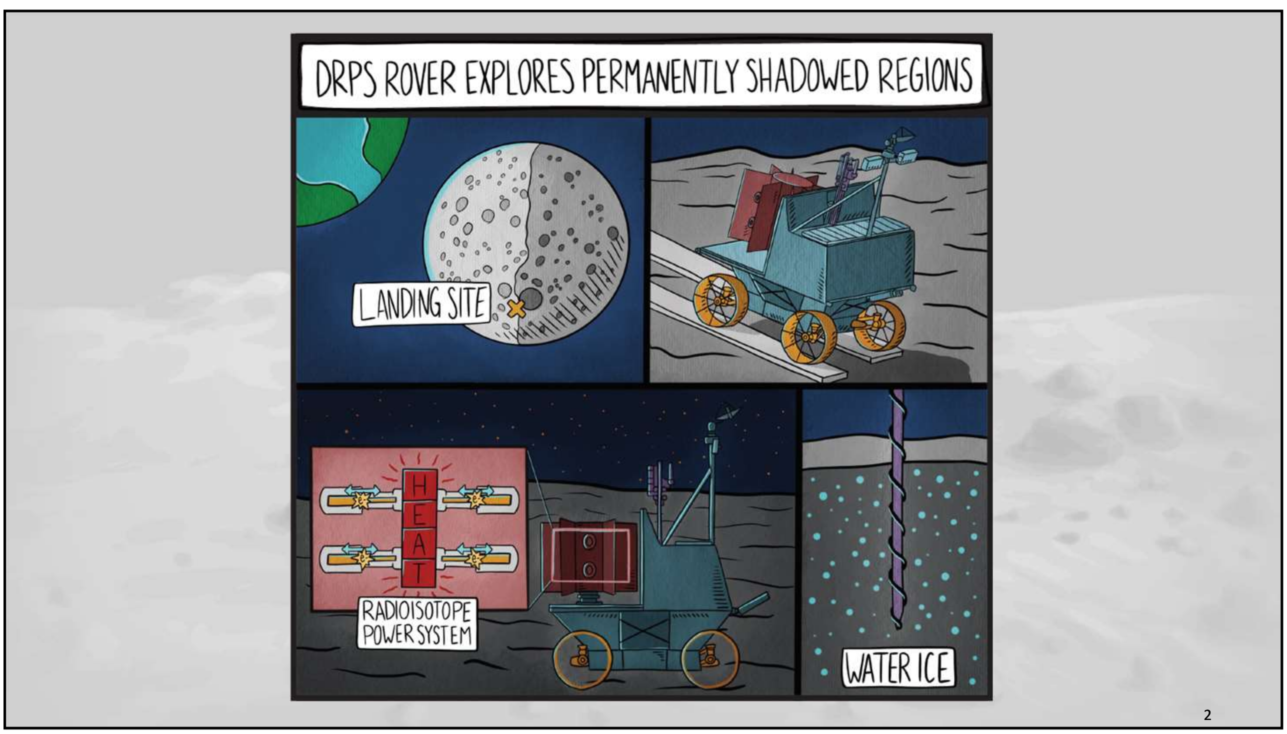
Elizabeth R. Turnbull, Brent F. Faller, Natalie J. Weckesser, Brandon T. Klefman, Onoufrios Theofylaktos, Christine L. Schmid, Christopher R. Heldman, and Cassandra Chang
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

James E. Fittje
Science Applications International Corporation
Brunswick, Ohio 44212

Abstract

This conceptual design study investigated trading several Dynamic Radioisotope Power Systems (DRPS) in development to supply power to a lunar science rover which operates for long periods (months) in permanently shadowed regions (PSR) over many years. The design was conducted by the Compass team and relied heavily on the planned VIPER rover design, which is limited to only a few hours of operations in PSRs and less than a month near the south pole. As such this conceptual design shows what a DRPS can do for a follow-on type VIPER rover. In addition to the long duration, go anywhere DRPS power system, the Compass team added a communications system that utilizes the Gateway spacecraft as a relay node for nearly 24/7 communications link to the DRPS rover in lunar craters not visible from the earth. The Compass design includes a notional conops, launch and delivery, subsystem designs of power, mobility, structures, science, command and data handling, communications, guidance and control, and thermal. The thermal design was especially important due the low temperatures in PSRs where the science environment needs to be shielded from the waste heat from the DRPS.


Dynamic Radioisotope Power System (DRPS) Permanently Shadowed Region (PSR) Demonstrator Rover
Concept Study
Compass Team
2/2021
Team Lead: Steve Oleson
1


DRPS ROVER EXPLORES PERMANENTLY SHADOWED REGIONS
LANDING SITE
HEAT
RADIOISOTOPE POWER SYSTEM
WATER ICE
2

Team Roster

- Customer – June Zakrajsek
- Lead – Steve Oleson
- Science – Paul Ostdiek, Ben Bussey, Kirby Runyon
- System Integration, MEL – Betsy Turnbull
- Structures – John Gyekenyesi
- Environmental – Tony Colozza
- Power – Paul Schmitz, Brandon Klefman
- Mobility – James Fittje
- C&DH/Software – Christopher Heldman
- Communications – Noulie Theofylaktos
- GN&C/Mission – Brent Faller, Christy Schmid
- Configuration – Tom Packard
- Cost – Natalie Weckesser, Cassandra Chang

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Purpose

- Develop a strong Class D, lunar design reference mission for the DRPS system demonstrator
  - Science and moon/mars architecture drives the options
    - Build support with science, commercial, moon/mars community for DRPS
  - Carry options for other tech demos (ISRU, comms…)
  - Preferred locations: Lunar Polar regions including permanently shadowed areas
  - Combine interests of many users
    - Long duration lunar science
    - Crew support aux power
    - Terrain reconnaissance in advance of human crews

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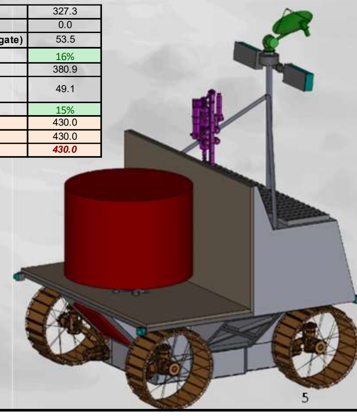
DRPS Rover for PSRs: Executive Summary

- Overview: Rover will demonstrate a Dynamic Radioisotope Power System (DRPS) while providing long duration, 18 month exploration of Permanently Shadowed Regions (PSR) on the south pole of the moon
- Mission:
  - Launch, lander, rover equipment/science using Astrobotics/VIPER solar rover, assume that reuse of VIPER components will reduce costs
  - Install DRPS vertically through fairing door using beam/crane, switch to rover installed controller, cool in fairing
- Science: Drill and three spectrometers, search for water
  - DRPS will heat up areas behind the rover in DRPS so science focus needs to stay in front of thermally shielded part of rover
- Power: Representative ~330 We, 6 GPHS DRPS, batteries for peak loads (roving and drilling)
- Mobility: same wheel/motors as VIPER ~10 cm/s avg speed, up to 25° slope
- Thermal: Adiabatic walls and struts to isolate waste heat from DRPS, Rover bus insulated and heated using avionics waste heat, louvered radiator during sunlit operations
- Comms: Ka band (high gain: 250 kbps and omni) up to Gateway for relay with earth, option for DTE when in sight
- C&DH: Control of all mobility/science, 1 TB data storage, performs waypoint driving based on earth commands
- AD&CS: IMU, star tracker, Gateway tracking, surface recognition
- Structures: Al bus with low conductivity materials to keep heat in rover, 5 g launch loads

MEL Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	Basic Mass (kg)
Radioisotope Power	96.4
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	13.4
Thermal Control (Non-Propellant)	34.8
Science	40.0
Mobility	67.0
Structures and Mechanisms	42.1
Element Total	327.3

Element Dry Mass (no prop,consum)	327.3
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	53.5
MGA as a %'age	16%
Predicted Mass (Basic + MGA)	380.9
Recommended Mass Margin (Additional System Level Growth) 15%	49.1
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	430.0
Element Inert Mass (Basic+MGA+Margin)	430.0
Total Wet Mass (Allowable Mass)	430.0



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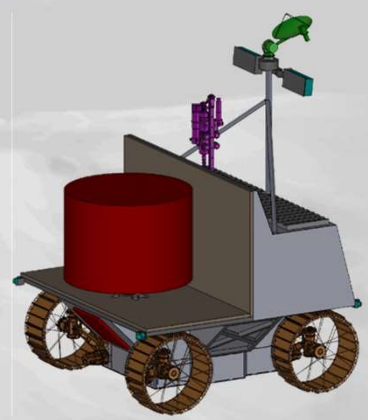
Lessons Learned

- With Stirling DRPS option mass is within the planned VIPER lander capability and is very close to VIPER mass and size (DRPS replaces large battery pack/solar arrays)
- But replacing solar/battery power with radioisotope power allows 24/7 presence (instead of 6 hrs) in a PSR and over 18 months of operations with minimal science impact (rearward surface heating)
  - Use of a dynamic system reduces the heat impact on science environment 2-3X
  - Roving for 8 hrs per day possible, range >100 km in 18 months!
- Using the exposed DRPS approach eases installation and saves mass
- Preliminary costs may fit in Class D (assuming launch, lander, operations, nuclear specific costs (NEPA, PCP, fueling, transport, LSP, etc.), DRPS not included, and VIPER heritage)



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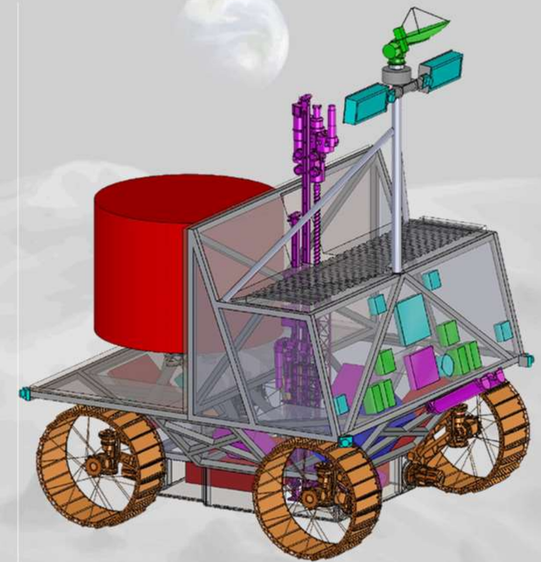
Next Steps

- Re-evaluate performance as DRPS are designed
  - Reduction in power performance easily handled by reducing daily drive time
- Explore PSR areas to be explored
- Evaluate long term science in a PSR
- Trade other science instruments – more active ones given power available
- More in-depth assessment of use of VIPER components for a DRPS rover
- Use available lander margin to add additional science instruments (may increase charge time or frequency for batteries)
- Investigate sample caching



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DRPS Lunar Demo Compass Run

- Purpose: Options
  - Lander (evaluate use of CLPS)
  - ✓Rover
    - Put a demo DRPS on a 'copy' of VIPER to perform science in a PSR for targeted cost between \$150 and \$250 M (Class D, less launch and lander, DRPS GFE protoflight)
- Requirements
  - Launch date: 2029-30
  - Duration: ~18 months (initial)
  - Location (PSR or lunar poles)
  - Cost: Class D (~\$150 to 250 M launch/lander/DRPS/operations not included)
    - Class D risk – but single fault tolerant for DRPS
      - Single fault tolerant except for mobility and science instruments
- Figures of Merit: DRPS Operation, Science Gathered (# drillings, distance traveled/surface mapped), cost
- Some Lunar science goals
  - Hydrogen search
  - Magnetic anomalies
  - Ice search, drill, spectrometer

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Secondary DRPS Demo Objectives

- Primary
  - Full power electrical output for at least 18 months (option for >10 yrs)
  - Under launch, landing, roving loads
  - Degradation rates
  - Survival in lunar environments (sun, shadowed, PSR..)
- Secondary
  - Attitude of DRPS (horizontal, vertical, inclined) open but vertical and open preferred
  - Demonstrate DRPS exposed to environment (dust, heat sink, sunlight…
  - Be careful of exposure to surface (heating, sublimation…)
    - Need 'MLI dog collar' to shield surface?
  - Be near science instruments (radiation, neutron impacts?)

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Science Goals

- Replicates VIPER's high priority goals but at many more locations, including terrain that VIPER cannot sample
  - Can travel further into permanently shadowed regions
  - Can travel over 100 km during an 18-month mission
- From VIPER: (3 spectrometers and 1 m drill).
  - Volatile Distribution (concentration, including lateral and vertical extent and variability)
  - Volatile Physical State (H_2, OH, H_2O, CO_2, Ice vs. bound, etc.).
  - The Context and Correlation, including:
    - Accessibility/Overburden: How much and type of material needing to be removed to get to ore?
    - Environment: Sun/Shadow fraction, soil mechanics, trafficability, temperatures
    - Distribution and Form vs. Environment
    - Extrapolates small scale distributions to global data sets, critical for developing "mineral/resource models"
    - Provide information to help plan ISRU operations
- Added science benefits
  - Deposition rate of volatiles in shadowed craters
  - Understand volatile transport and sequestration
  - Mapping of surface frost
  - Information on traceability and geotechnical properties of permanently shadowed regolith
  - Opportunistic examination of geology in PSRs
- ISRU demonstrations of components and mapping of mining operations
- Possible Extended Missions:
  - Continue mapping
  - Provide a navigation/comm link node for future missions

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Requirements, Assumptions, Trades

Item	Requirements/Assumptions	Trades
Top-Level/Science	Flight Demonstration of a ~300 We DRPS on a telerobotically operated VIPER based lunar rover for long term operation in PSRs. Rover Scans and drills multiple craters for volatiles using three spectrometers. >30 km in 18 months TBR FOMs: DRPS demo, science returned/#drillings/distance traversed, cost Able to survive 24/7 in a PSR. Class D, $250 M cost cap (less lander/launch, RPS GFE), 18-month primary mission, Single fault tolerant except for science and mobility	Land on Spudis ridge or directly in a PSR, Science suite, craters to be explored, Rover platform/launcher, Extended mission: provide long term science in crater, become a relay navigation node. Trade impact of Pu238 decay neutron products on neutron detector
System	Minimize? new technologies, TRL 6 cutoff 2026, as early as 2029 launch year (Mass Growth per ANSI/AIAA)	Rover dimensions, wheelbase, science locations, COM
Mission, Ops, GN&C	Launched and landed similar to VIPER TBR. Assume launcher nuclear material approved. Lands/deploys during sunlit period at lunar south pole, Spudis ridge. Scans for volatiles in multiple PSRs, 20 cm/s top speed, 10 cm/ scan speed up to 15° slopes, traverse <10 cm TBR rocks, cameras/lights for navigation. Data uplink (250 kbps) for waypoint (driving) and science, drives 8 hrs a day or does 1 hour of drilling – rest of time charging. Can spend time indefinately in a PSR.	Other CLPS landers other launcher, other landing sites, C.O.M.
Launch Vehicle	Various Launch Loads: Axial SS +/- up to 5.5 g, Lateral +/- 2 g	Other launchers/rover platforms
Mobility	Motor brushless pancake driven, 4 independent wheels, ~60 W avg, ~300 W max, 24 DCV, COM <1 m high for 30° slope	Trade: wheel, chassis length/width, motors
Power	~380 We (4 K) or 350 We (50 K) Dynamic Radioisotope Power System (DRPS) demonstrator, 800 Whr battery, 28 VDC batteries charged by DRPS during an 18 hr charge period/day	Battery type, bus voltage, investigate DRPS radiation impact on science (esp emitted neutrons on NSS instrument), higher sink temp (50 K) lowers the power
Avionics/Communications	All operations run thru Gateway to/from earth (backup DTE at ~ same data rate or future relay sats), 128 GB data storage, 250 kbps, small, up looking Ka antenna, 0.2 m antenna (5° BW), helix for constant contact, option for relay thru other assets	Computer type, DTE or other lower relay satellites Use of 20 cm antenna to earth 20 m antenna, up to 1 TB data storage
Thermal and Environment	Body mounted radiator (main loads ~1200 Wth), Shared heat from DRPS and electrical heaters, MLI covering, (South pole Sink Temps: daytime 150 to 210 K, nightime/craters 50 to 60 K seasonally dependent), use single vertical and single horizon (bottom) insulated walls to keep DRPS heat from radiating forward into science area, use low conductivity struts to limit heat conduction into the chassis	Evaluate impact of DRPS radiated heat on surface Traded heater power vs. thermal link Trade: encapsulated vs. shielded DRPS fins to prevent heat radiation into the science (ice) surface <6.5 W/m^2
Mechanisms	4 wheel, four motor, independent steering /suspension	Tracks, # wheels, legs…
Structures	~5 g axial loads, 2 g limit for operation, aluminum spaceframe for chassis, titanium wheels	Longer/wider wheelbase
Cost	<$250 M, not including launch/lander/operations, DRPS GFE	
Risk	Major Risks: mechanisms, unknown surface features, thermal	

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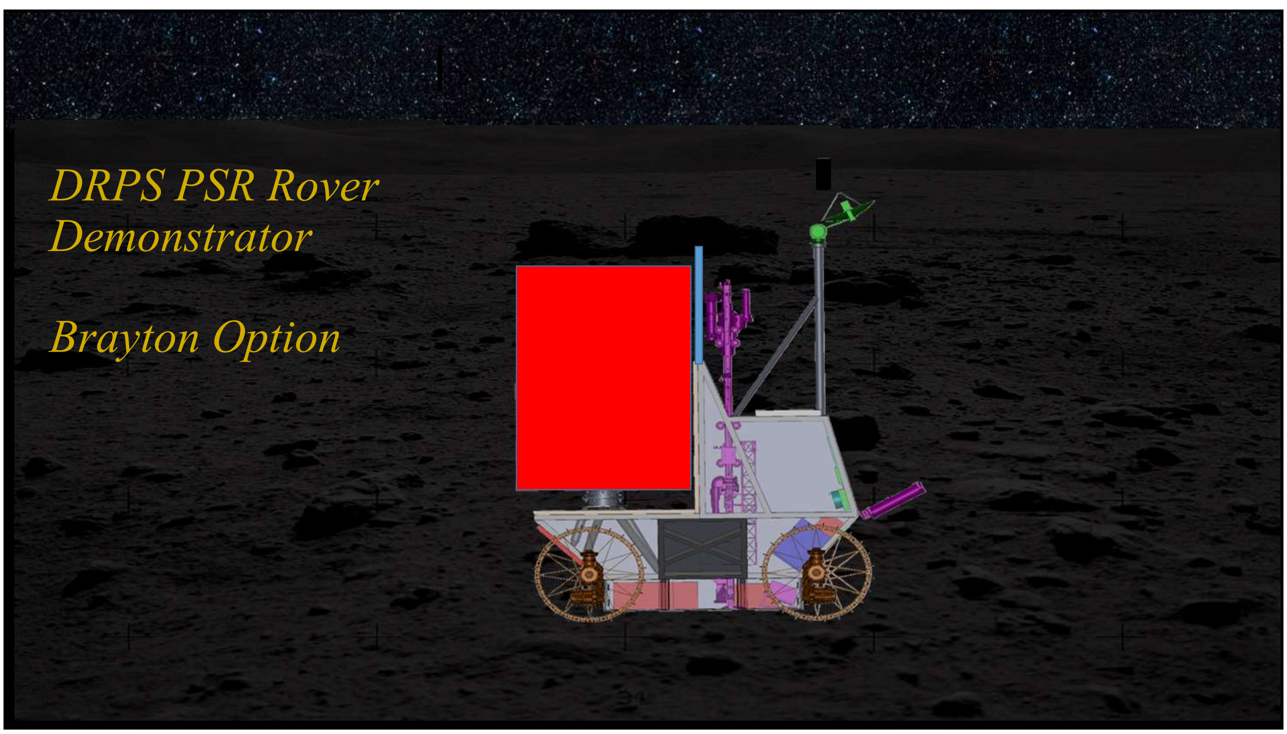

Other Cases

- Phase 2 lower Carnot efficiency (4.5 yr power from DRPS reduced from 333 We down to 260 We)
  - Impact on batteries and/or conops (e.g., reduced driving time)
    - Lower power increases charge time by 2x
    - Better option – keep battery same and halve drive time to 4 hrs a day (20 hrs charge time)
- DRPS Brayton option (see next page)

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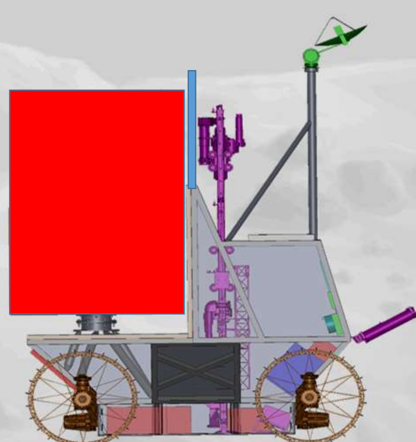
Brayton Option

- DRPS Brayton option
  - Heavier (135 kg CBE) and bigger. (0.78 m diameter x 1 m tall)
  - BOL 318W, 4.5 yr EOL 299W
  - Need taller wall to block waste heat
  - Changes
    - Power
      - Heavier DRPS, lower power (~10's of W)
      - Lower power adds ~3 kg battery mass
    - Structures
      - More installations
      - Increase vertical wall by ~50%, longer diagonals
    - Thermal
      - 0.5 m x 1.5 m added insulation
    - C.O.M – higher – reduced max slope
    - Mobility: a 20% heavier rover will lose 20% speed? (8 cm/s instead of 10 cm/s)
    - Bigger door in fairing?
    - Comms, Avionics, ACDS, science the same
- Requires a margin/growth launch mass of 513 kg
  - Higher than Astrobotics lander stated 475 kg
  - >80 kg heavier than Stirling options



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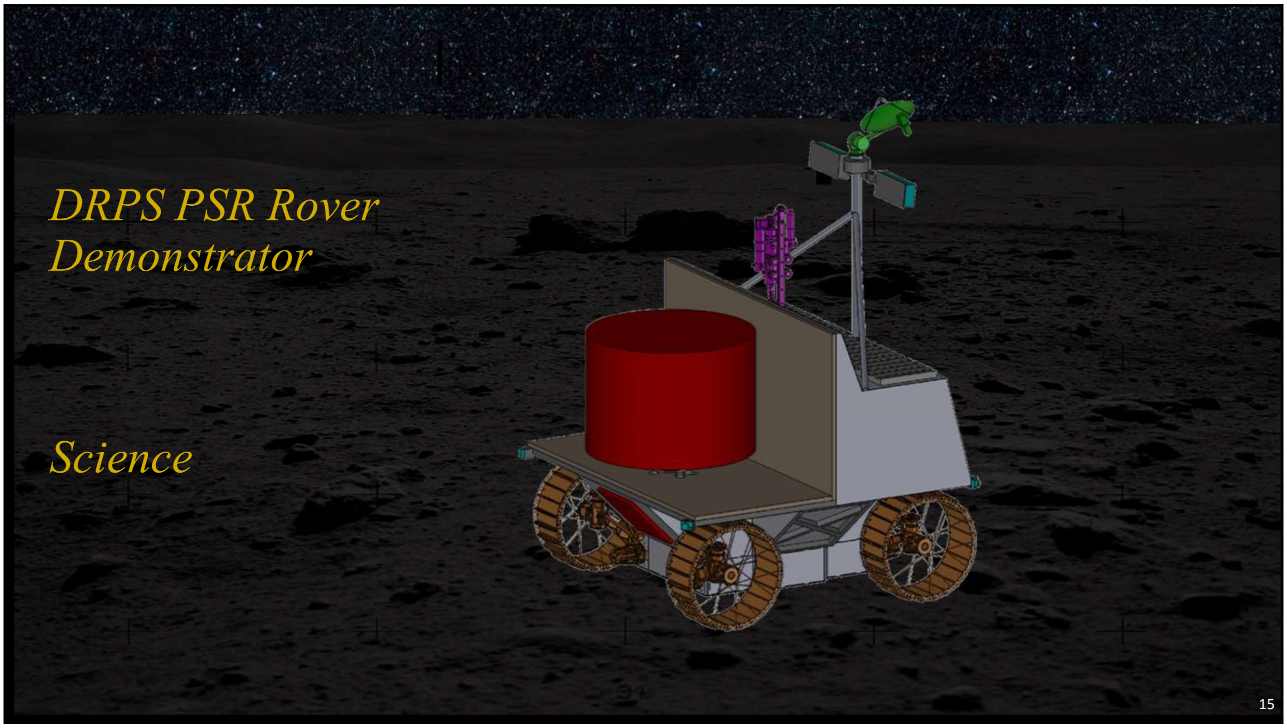

Impact of DRPS on Mission

- VIPER greatly limited by both sun and Earth visibility competing with the need to get to PSRs
  - VIPER solves problem by using mobility and 1 m drill to reach areas that rarely do see sunlight
  - VIPER must transit continuously to survive AND reach PSR areas
    - Moving in and out of PSRs may require transiting difficult/steep slopes
- DRPS and a comm link through Gateway allows
  - Constant power and communications for constant driving in the dark
  - Can land in a PSR IF the lander can survive long enough to deploy ramps and detach rover
    - Eliminates need for rover to transit difficult/steep slopes
- Extended mission possible, but may require longer life components (e.g., wheels)

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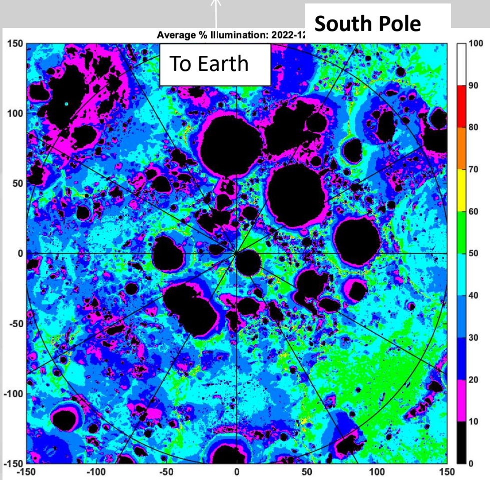
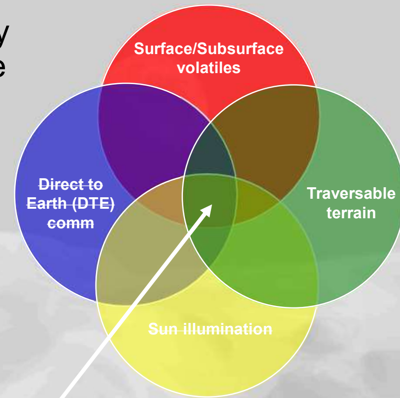
Where to Land?
DRPS and Gateway Commlink Simplify Operations: increase Places to Explore





Candidate polar landing sites meet these four criteria:

1. Plausible surface/subsurface volatiles
2. Reasonable terrain for landing and traverse
3. ~~Direct view to Earth for communication~~
4. ~~Maximize sunlight for power *(including safe havens)*~~

R. Vaughan, "VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview," in *International Small Satellite Conference*, Virtual, 2020.

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Science thoughts

- Rover 10 s of Km
- Shackleton direct landing possibility
  - Power the lander
    - Adds a second RPS- lander has a mass spec too – for comparison with the mass spec on the rover
    - OR– use as a relay/base/recharge station?
  - Pristine crater
  - Extended mission: climb out of Shackleton
- Shadowcam (on a Korea Pathfinder Lunar Orbiter)… 200x more sensitive than NAC

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Landing Site Selection

- **Option 1 Different Class of PSR** (Deep and Dark, surface ice?): Shackleton or other crater
  - Pros:
    - Would show the difference between the shallower PSRs that VIPER will investigate (more ice? Easier to get? Ice on the surface?)
    - DRPS enabling
  - Cons:
    - Need to land in crater (impacts on CLPS lander landing systems and power–deploy ramps)
    - Even with lots of ice in the crater how would one get it out with the high walls (hopper?)
- **Option 2 VIPER 2.0**: Longer/in depth exploration of VIPER sites: Explore PSRs that VIPER explored quickly (<6 hrs) spending a longer time/more in-depth science at those promising locations
  - Pros: Same landing site and conops as VIPER, could be an asset for follow-on crew
  - Cons:
    - A case for long duration science in the PSR will need to be made to say that DRPS is enabling
- **Option 3: VIPER 2.1: Longer/more in-depth exploration of Spudis Ridge AND do many more craters**
  - **Stay inside a PSR for up to a month to detect volatile migration (from a nearby lander too?)**

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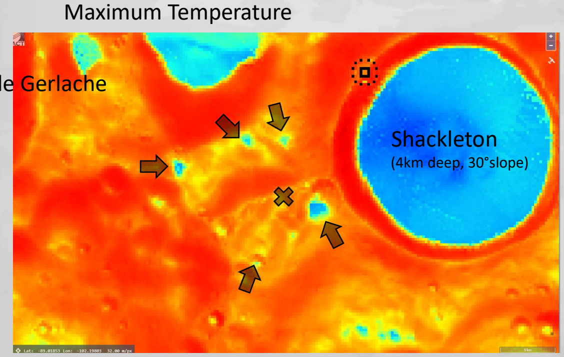
Selection of PSR sites

In order to select potential water bearing sites, the area around Spudis Ridge was analyzed using temperature and ice stability maps available in Quickmaps. Below are the maps with the ISRU propellant plant site marked by the “X”.

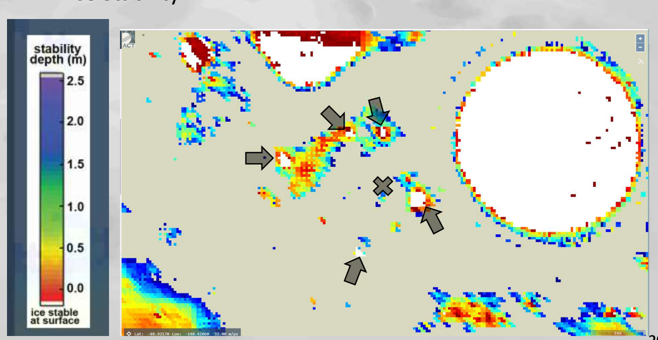
- There were 5 ‘shallow’ PSRs in the area that had shallow ice stability and low temperatures that indicate good access to ice indicated by the arrows.
- Mission could land in sunlit areas, then proceed to small PSRs
- Next explore De Gerlache

Maximum Temperature

de Gerlache



Ice Stability



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Lander

- Astrobotics Griffin Lander for VIPER (launcher TBD)
- Can we reuse?
  - Can it carry nuclear materials (can launcher carry them too?)
  - Can it land in a dark crater?
- Comes with ramps
- 475 kg stated payload

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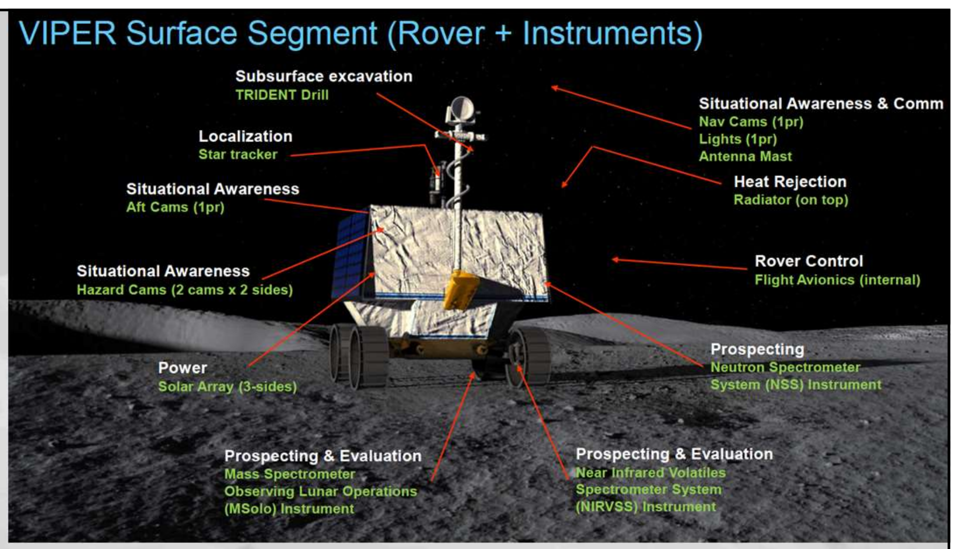

R. Vaughan, "VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview," in *International Small Satellite Conference*, Virtual, 2020.

The science objectives of the VIPER mission are to:

- Characterize the distribution and physical state of lunar polar water and other volatiles in lunar cold traps and regolith to understand their origin
- Provide the data necessary for NASA to evaluate the potential return of In-Situ Resource Utilization (ISRU) from the lunar polar regions

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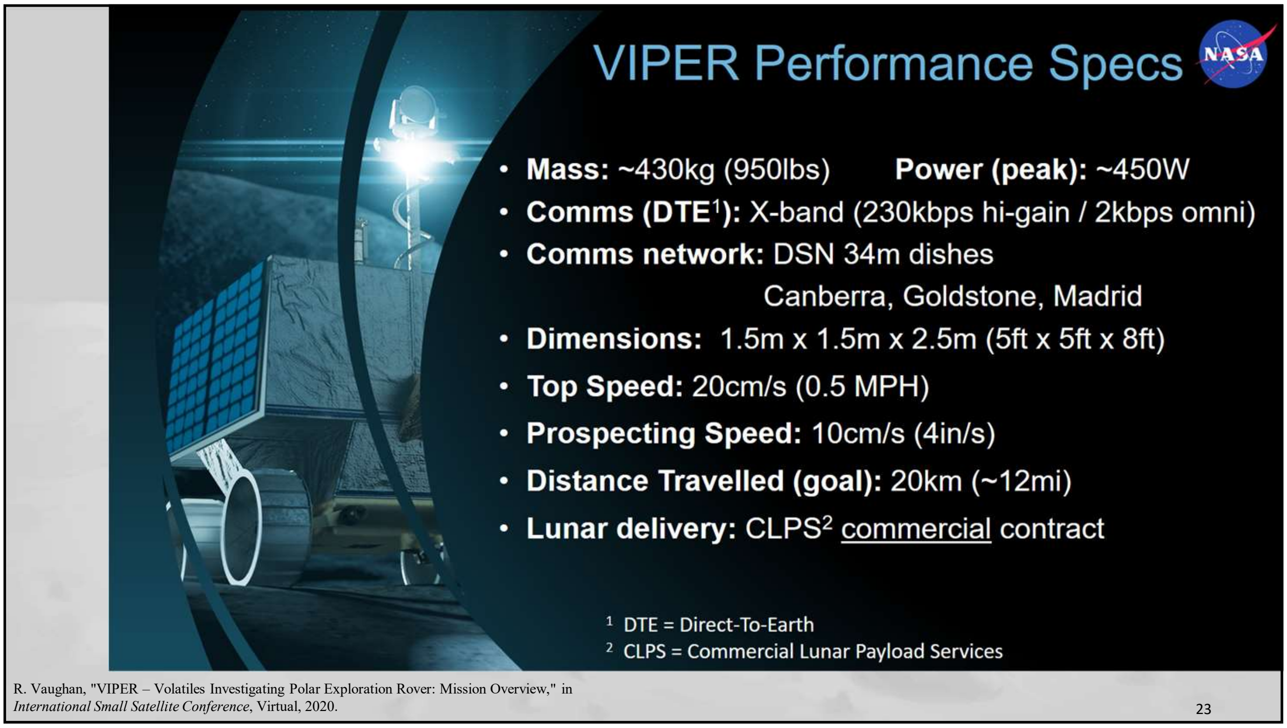
VIPER Performance Specs
• Mass: ~430kg (950lbs) Power (peak): ~450W
• Comms (DTE1): X-band (230kbps hi-gain / 2kbps omni)
• Comms network: DSN 34m dishes
Canberra, Goldstone, Madrid
• Dimensions: 1.5m x 1.5m x 2.5m (5ft x 5ft x 8ft)
• Top Speed: 20cm/s (0.5 MPH)
• Prospecting Speed: 10cm/s (4in/s)
• Distance Travelled (goal): 20km (~12mi)
• Lunar delivery: CLPS2 commercial contract
1 DTE = Direct-To-Earth
2 CLPS = Commercial Lunar Payload Services
R. Vaughan, "VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview," in International Small Satellite Conference, Virtual, 2020.
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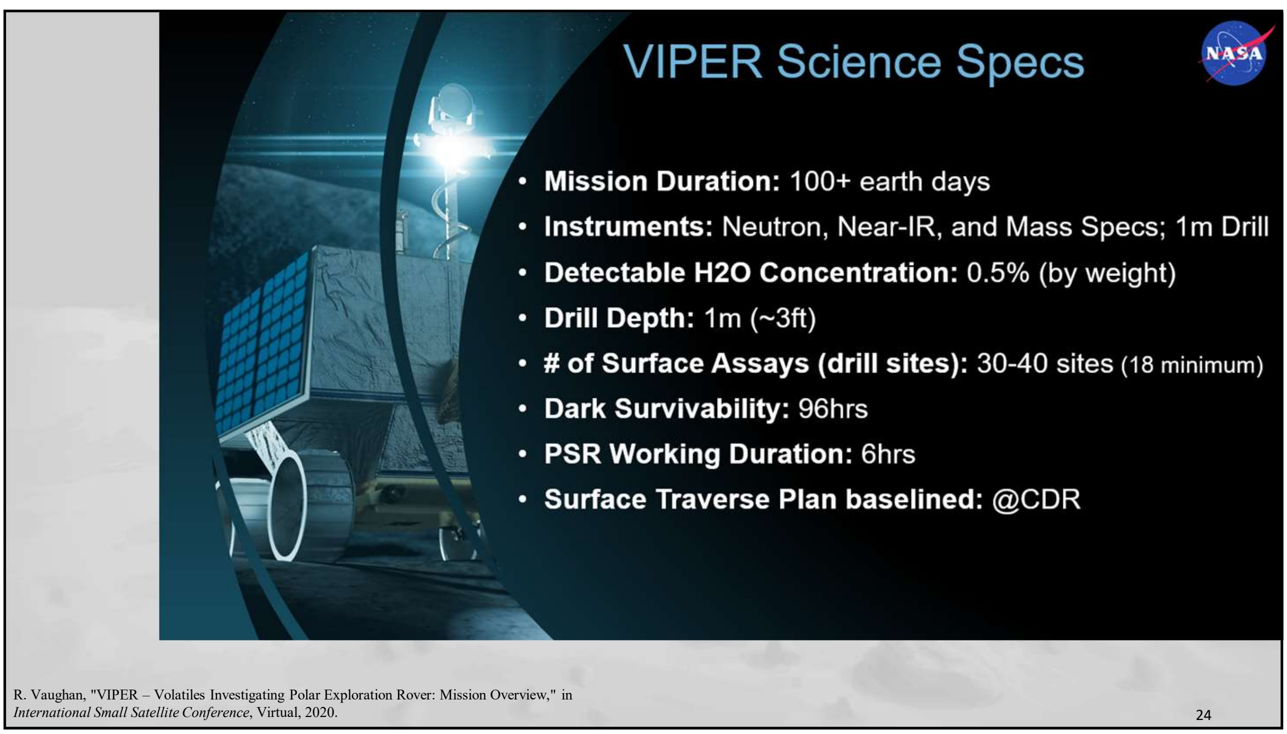
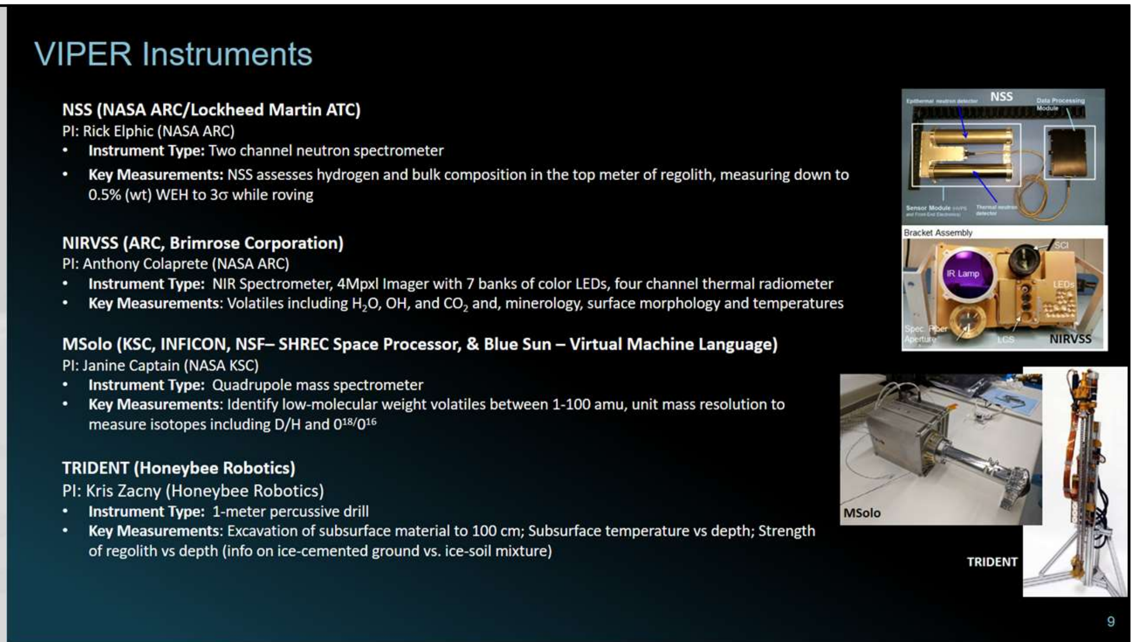
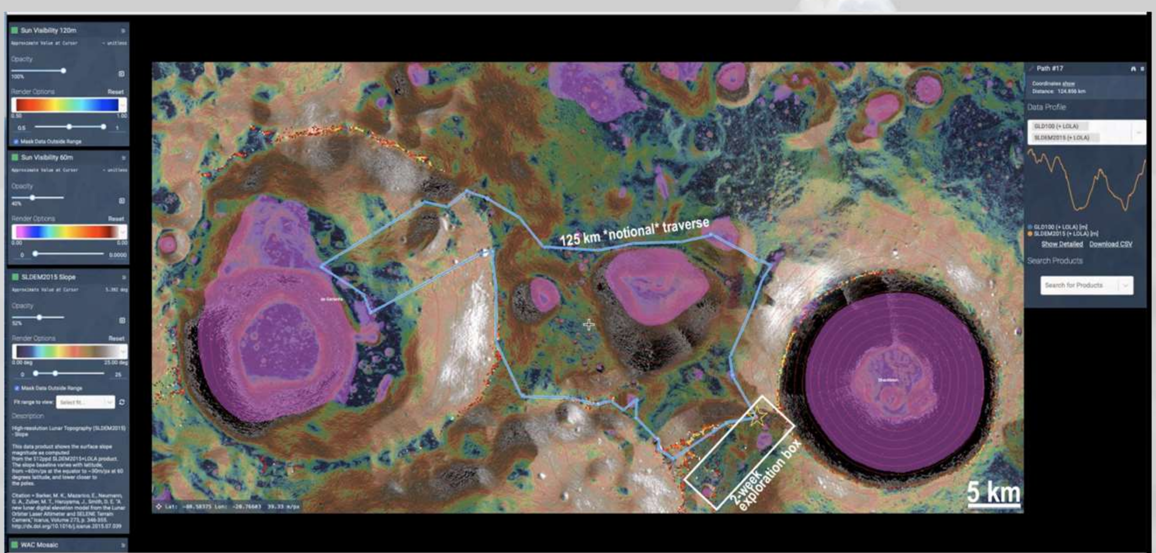

VIPER Science Specs
• Mission Duration: 100+ earth days
• Instruments: Neutron, Near-IR, and Mass Specs; 1m Drill
• Detectable H2O Concentration: 0.5% (by weight)
• Drill Depth: 1m (~3ft)
• # of Surface Assays (drill sites): 30-40 sites (18 minimum)
• Dark Survivability: 96hrs
• PSR Working Duration: 6hrs
• Surface Traverse Plan baselined: @CDR
R. Vaughan, "VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview," in International Small Satellite Conference, Virtual, 2020.
24



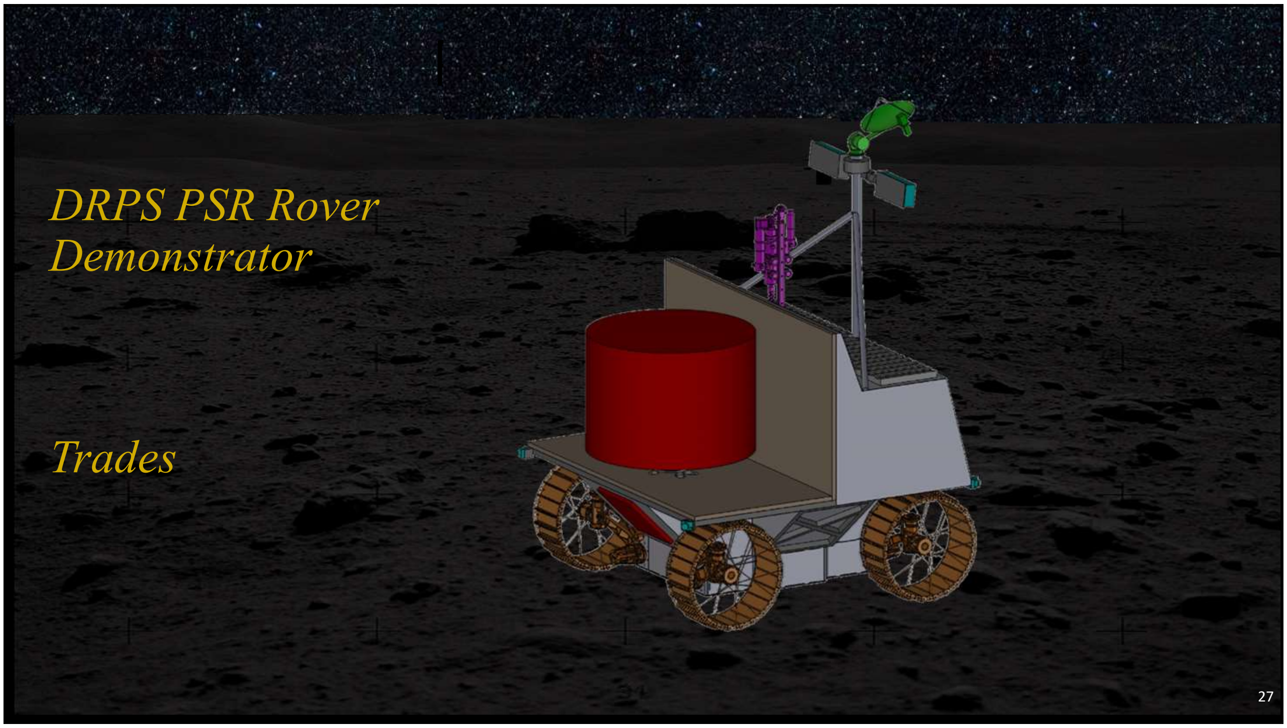
R. Vaughan, "VIPER – Volatiles Investigating Polar Exploration Rover: Mission Overview," in *International Small Satellite Conference*, Virtual, 2020.

25

Potential Route



26



Strawman Rover

- Minimalist Approach:
  - Integrate DRPS into the VIPER rover (already designed to do science and survive short PSR time ~6 hrs)
  - BUT STILL GENERIC: In order to save time no effort will be made to copy the current VIPER design – IF this design looks promising further work could do that
  - Cost: each subsystem try and identify the inheritance of components/design from VIPER
- Lander: Same lander as VIPER (~500 kg rover delivery)
  - Two sets of ramps
  - ~~What needs to change on the lander to land in a 4km deep permanently shadowed crater? Notional changes~~
- Science: three spectrometers and 1 m drill
  - Rough sizes of instruments/placement
  - Will neutrons and gammas from the DRPS interfere with the science?
- Chassis, wheels, motors: assume the same (representative) as VIPER (~15°TBR slope capability)
  - Mobility: same 20 cm/s speed as VIPER
  - Chassis: make room for DRPS installation
- Power: remove solar arrays and minimize battery pack – add the DRPS
  - DRPS: Two main challenges
    - – keeping heat and radiation from DRPS from interfering with science environment, instruments, rover equipment
    - Integrating DRPS into the rover (as well as loading on the pad…)
- Thermal: Continuous operations in PSR, Keep DRPS from impacting science
- Comms: provide nearly continuous link with gateway (astronauts operate rover?) – what data rate for driving? video
- C&DH: with direct comm link autonomous control not primary (or even needed?)
- GN&C: How navigate? Combination of star trackers, Gateway tracking and terrain recognition? Need lights

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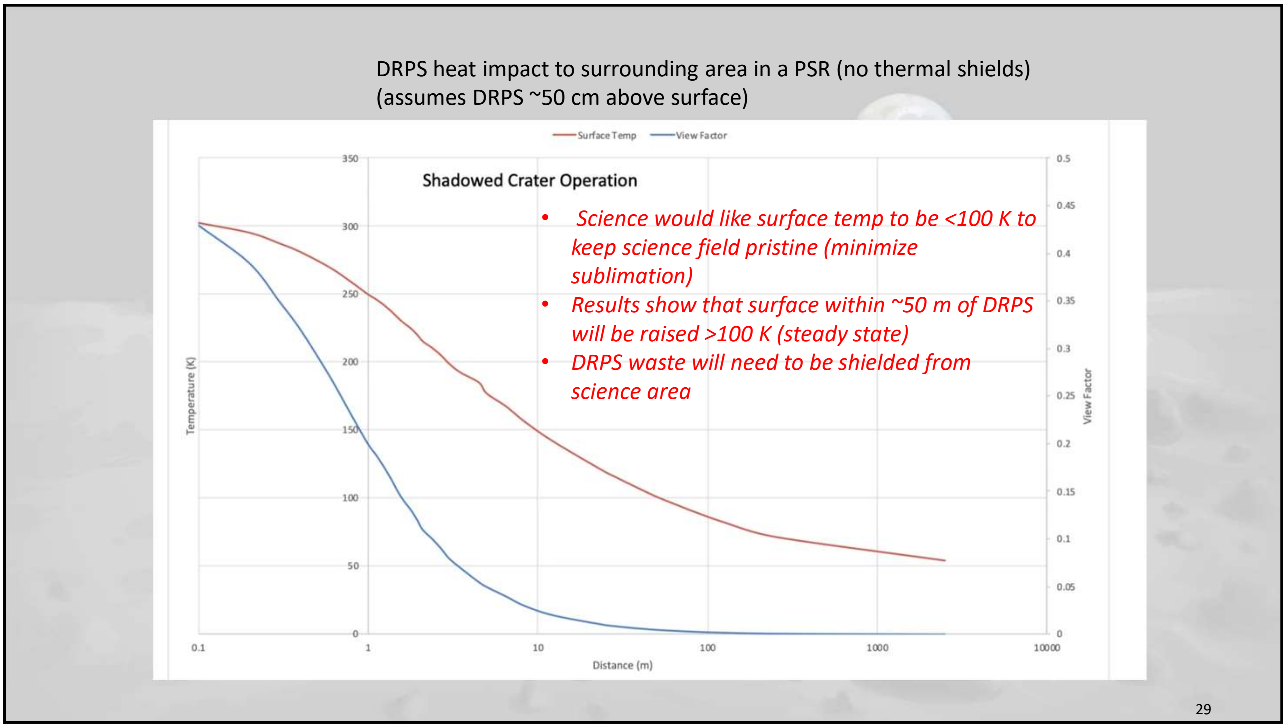
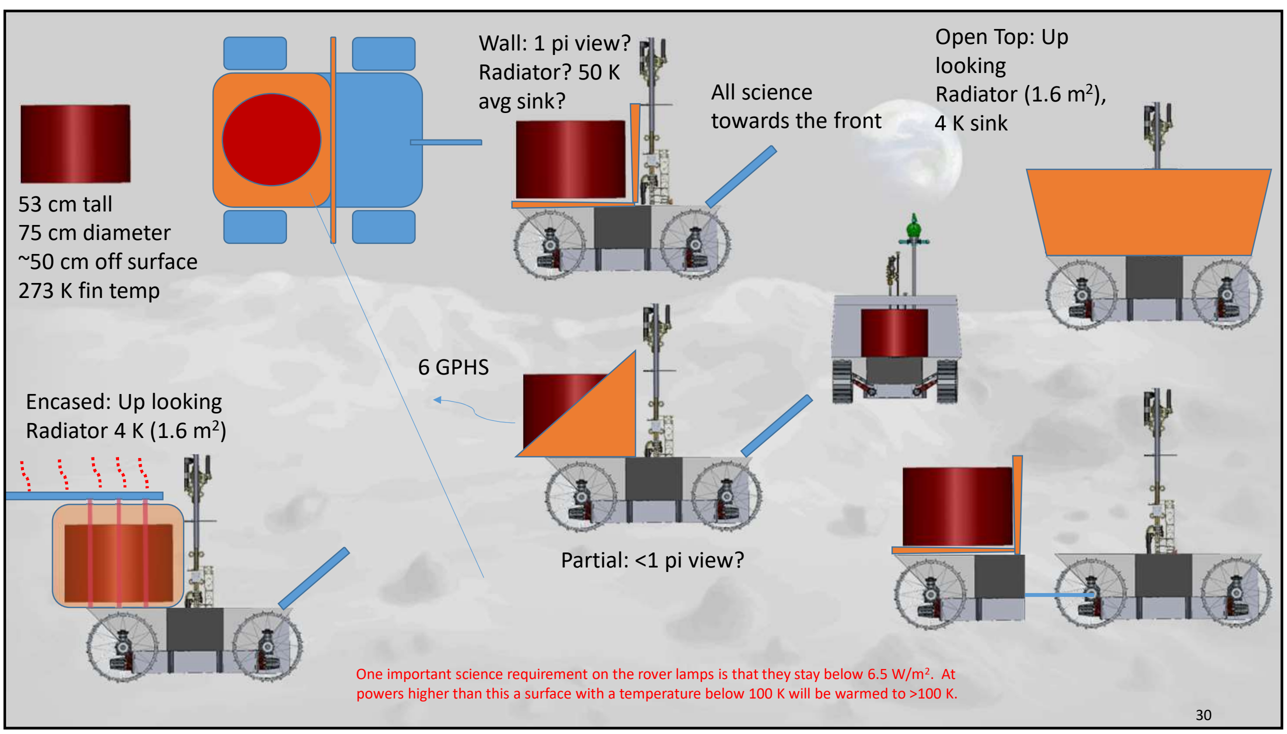
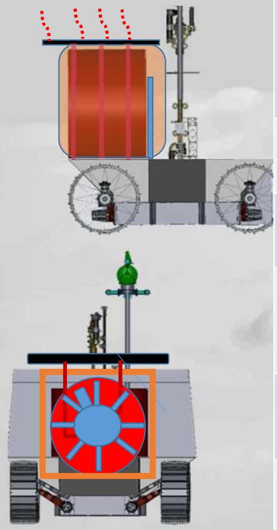

DRPS heat impact to surrounding area in a PSR (no thermal shields)
(assumes DRPS ~50 cm above surface)
Surface Temp
View Factor
Shadowed Crater Operation
• Science would like surface temp to be <100 K to keep science field pristine (minimize sublimation)
• Results show that surface within ~50 m of DRPS will be raised >100 K (steady state)
• DRPS waste will need to be shielded from science area
Temperature (K)
View Factor
Distance (m)
0.1
1
10
100
1000
10000
0
50
100
150
200
250
300
350
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
29


53 cm tall
75 cm diameter
~50 cm off surface
273 K fin temp
Wall: 1 pi view?
Radiator? 50 K avg sink?
All science towards the front
Open Top: Up looking
Radiator (1.6 m²), 4 K sink
6 GPHS
Encased: Up looking
Radiator 4 K (1.6 m²)
Partial: <1 pi view?
One important science requirement on the rover lamps is that they stay below 6.5 W/m². At powers higher than this a surface with a temperature below 100 K will be warmed to >100 K.
30

Two Paths

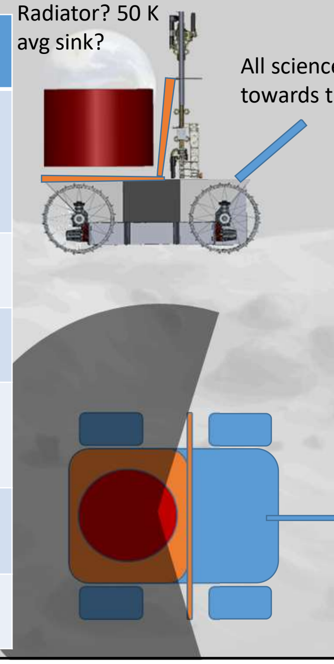
Encased: Up looking Radiator 4 K (~1.2 m^2)



	Encased	✓ Wall
Science	Should give full science access	Will reduce science to <180° in front due to waste heat upping the surrounding temp>100 K out to 40 m – no turn arounds for surface science
Mass	Casing, heat pipes, radiator, batteries, structure will increase mass (20-30 kg)	Adiabatic wall should be lighter
Power	Provide less power (lose ~30 W) – may require more batteries	More power
DRPS Operations	More even temperature distribution, does not demonstrate exposed radiators/operations for other missions (s/c)	May have hot spots next to wall (wall could be cooled –adds heat pipes but is exposed?)
DRPS installation	Much more difficult installations with sealed casing, heat pipes need to be attached to DRPS body	Easier to install
Cost	More systems, more cost	

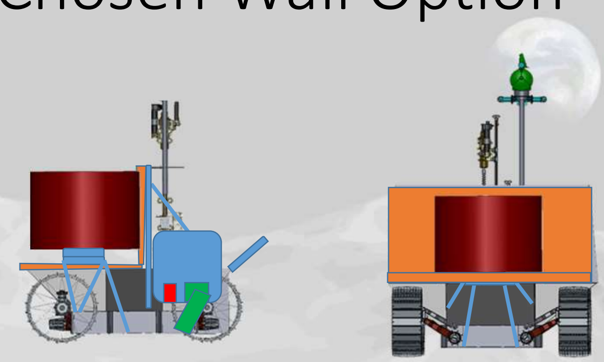
Wall: 1 pi view? Radiator? 50 K avg sink?

All science towards the front



31

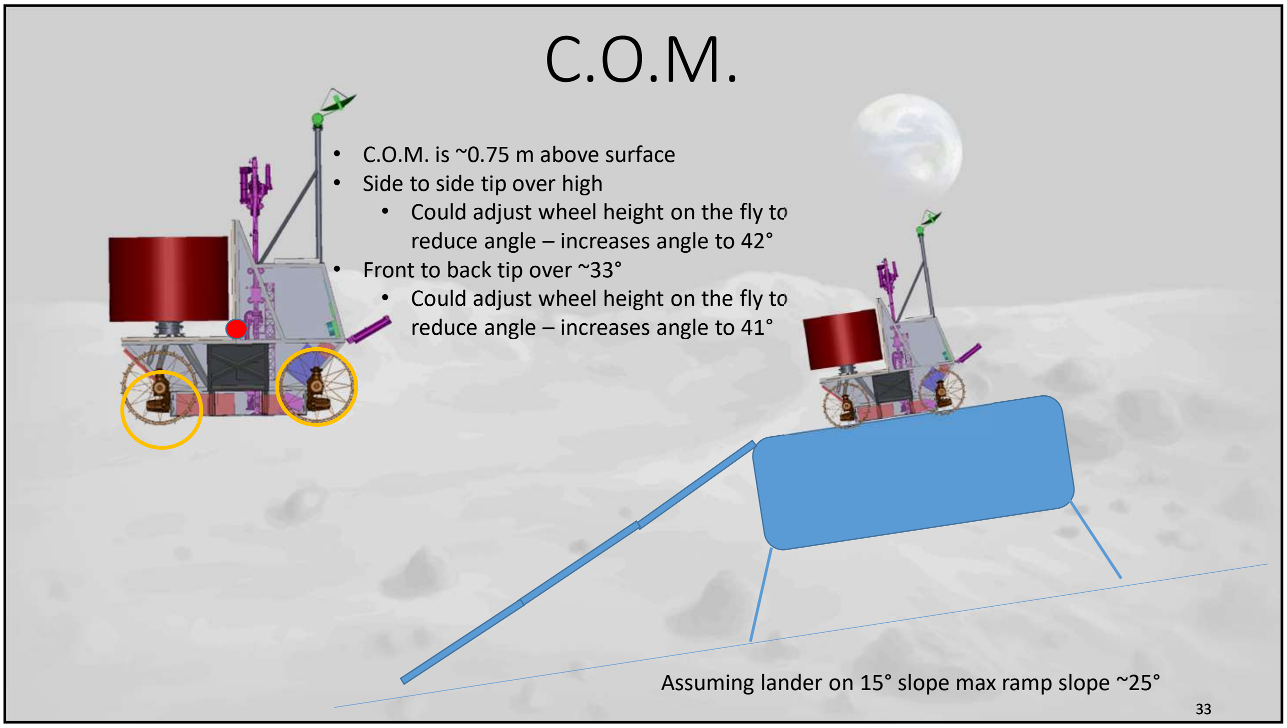
Chosen Wall Option

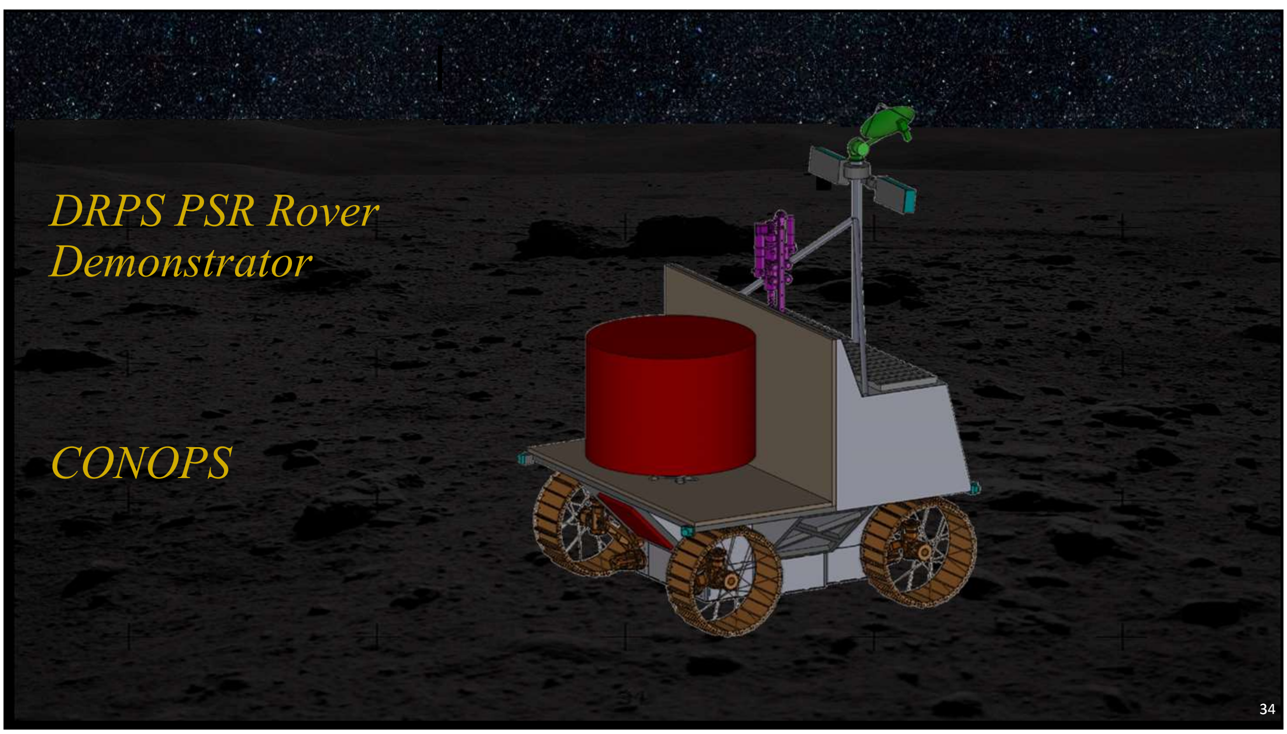


Glass/Epoxy truss

- The forward 180 on a recon mission will inform about surface to satisfy science questions.
  - The rear 180 surface could be modified as you transit but then you have already sampled the surface. Estimate that future mission for resources, like ISRU, would care more about what is under the surface than what is on the surface.
- The WALL saves mass, cost, and is simpler.
  - It does not change the science result writ large. It might limit flexibility in case there is a surprise that science wants to deviate from plan to investigate.

32


C.O.M.
• C.O.M. is ~0.75 m above surface
• Side to side tip over high
• Could adjust wheel height on the fly to reduce angle – increases angle to 42°
• Front to back tip over ~33°
• Could adjust wheel height on the fly to reduce angle – increases angle to 41°
Assuming lander on 15° slope max ramp slope ~25°
33


DRPS PSR Rover Demonstrator
CONOPS
34

ConOps 1

- DRPS loaded into lander on pad
- Launch Vulcan/Falcon 9 class, Assume nuclear material cleared
- Four-day trip to moon, assume rover self powered by DRPS
  - Use built in shunt radiator? And cooling fans (on pad at least)
- Land near Spudis Ridge (near PSRs) in sunlight
  - Astrobotics Griffin lander with tiedowns and ramps: 475 kg rover capability
- Lander deploys ramps, releases rover, safes lander and shuts down (10 hrs)
- Rover checks out (1 day?) – ~250 kbps comms through Gateway for duration of mission with option for DTE when earth in view (also ~250 kbps)
- Rover Descends ramp (1 day?)
- Option to drive with astronauts (<1 sec delay) on Gateway but relay back to Earth (6 sec roundtrip delay) may be better given the waypoint driving and science support

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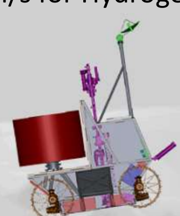
ConOps 2

- Rover performs minimum science (drill) and sample evaluation (1 week)
- Rover begins exploration of various craters on Spudis Ridge at 20 cm/s (10 cm/s for Hydrogen imaging)–remote control from or thru Gateway
  - > 100 km transit over 18 months
  - Slope capability ~15˚
  - Drill and three spectrometers
  - Cameras
  - 10.5 kg TBD for additional payload, 10 W



- Driving/science Conops: 8 hrs on / 16 hrs charging
  - Assume 4 hrs driving / 4 hrs drilling/stationary science, 16 hrs charging
    - at 10 cm/s average speed: 6 m in 1 min, ~1.5 km / day (4 hrs), > 500 km range possible!! In 18 months
    - With turns and obstacles assume 500 m/day
- Roving: NSS plus other two spectrometers, Cameras/lights
- When returned data from spectrometers shows ice – stop and drill
- Drilling: drill 10 cm sections, have Msolo inspect tailings
- Dust mitigation: Cameras at sufficient place to avoid
- Science limited to forward, underneath the rover and below surface due to waste heat from DRPS

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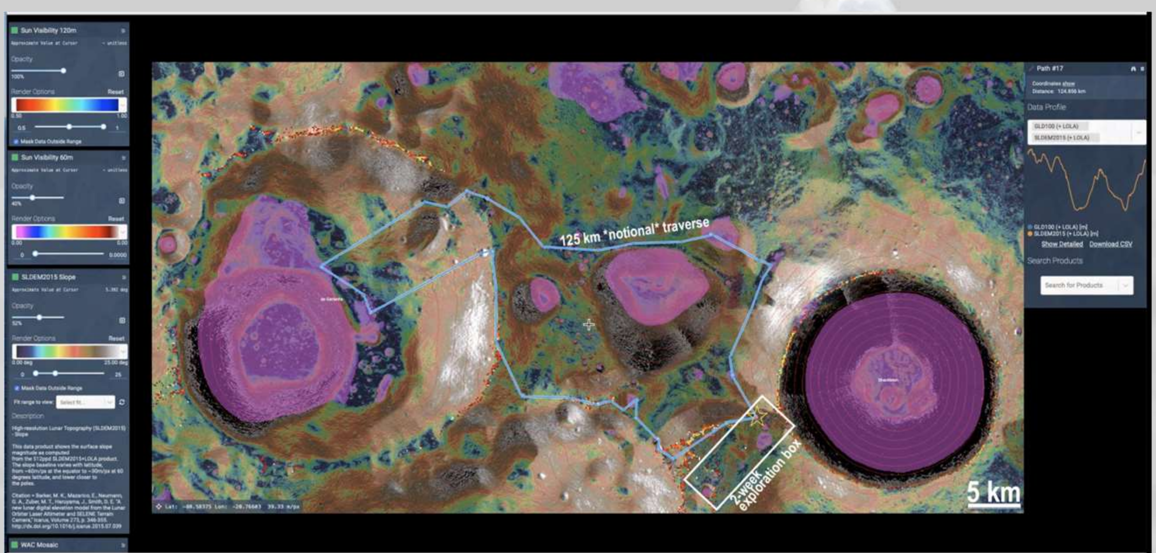
Extended mission: >10 years options

- Find easy paths for ISRU rovers in the future
- Deposition rate of volatiles inside PSRs over time (from lunar atmosphere or lunar impacts): weather?
- Relay/navigation asset for future missions
- Circumference of PSR craters and dip in
- Go to floor of large crater (Shackleton, De Gerlache….)
- Test DRPS for convertor failure and DRPS recovery
- Potential to remove and reuse DRPS for another lunar mission
- Potential to use inductive charging capability for other surface assets
- Potential to provide heat to survive the night

37

Potential Route



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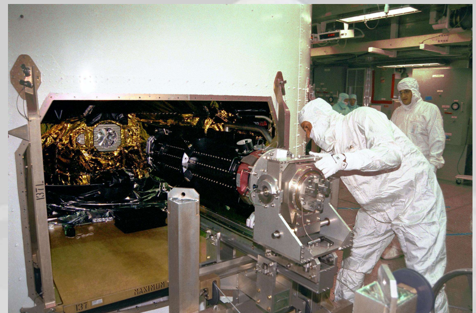
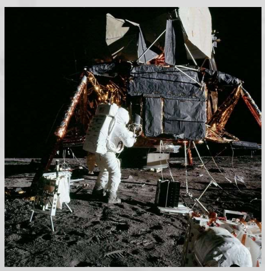
How to load an RTG

Curiosity (1 MMRTG)



Cassini (3 RTG)

Apollo - unloading
(1 RTG core)

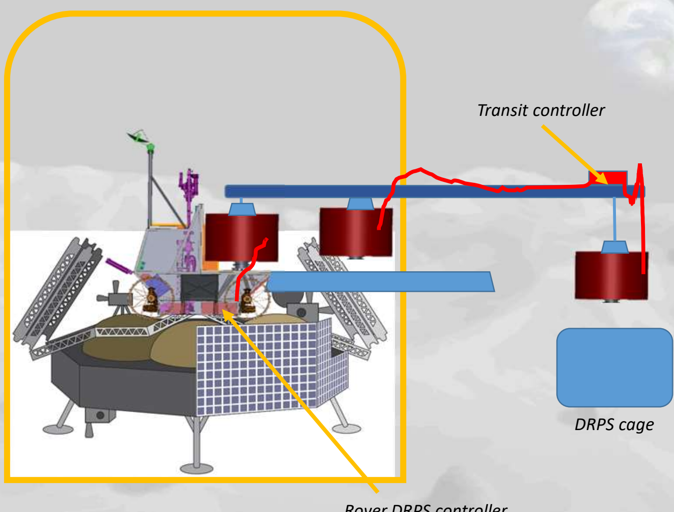


New Horizons (1 RTG)

https://ntrs.nasa.gov/api/citations/19710014816/downloads/19710014816.pdf

39

Notional DRPS loading



- Pick up DRPS from handling cage
- Loads vertically instead of horizontally (past RTGs)
- Load using a beam and crane
- Clamp to top of DRPS
- Push in
- Bottom to allow bolt/cable installation by hand
- DRPS has two controllers
  - One for Transit
  - One on rover
  - Once mechanically attached the controller cable connections are swapped

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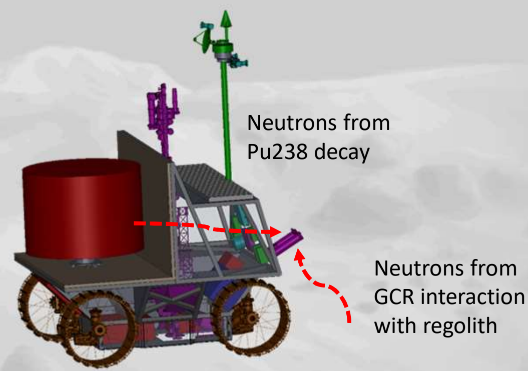
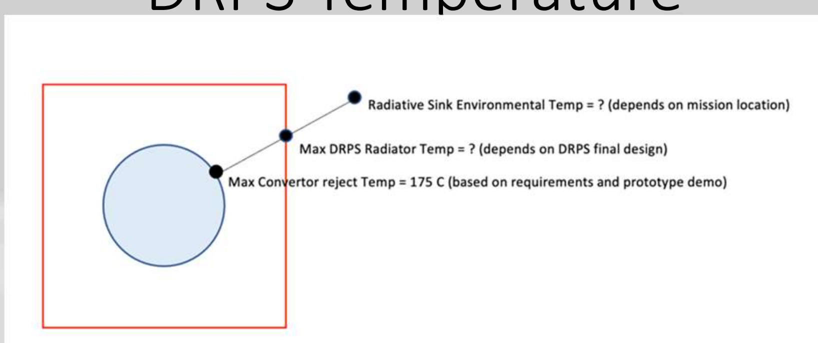
Potential Issue with Pu238 on Science

- At 1 m away the Pu238 will give off ~1e10 #1 MeV neutrons/cm^2 over 1 yr
  - ~300 #1 MeV neutrons /cm^2 per second
- Will this swamp the NSS neutron detector?
- Or can it be filtered out
- Or is it a feature? (can we use the neutron flux for a different instrument?
- Will it impact any other spectrometer?
- *Initial results show neutron energy levels in different spectrums and should not be a problem*
- *See paper "Neutron background environment measured by the Mars Science Laboratory's Dynamic Albedo of Neutrons instrument during the first 100 sols" by I. Jun et. al.*



41

DRPS Temperature



- RPS temperature considerations are driven by radiative sink environmental temperature which will vary per mission
  - Values cited in package are derived from worst-case lunar equator environment
- The DRPS internal temperature is limited by organics, which have a max temperature of 175 C over 17 years.
  - This will correspond to a maximum allowed external DRPS radiator temperature, which is to be determined based on the final DRPS design and configuration

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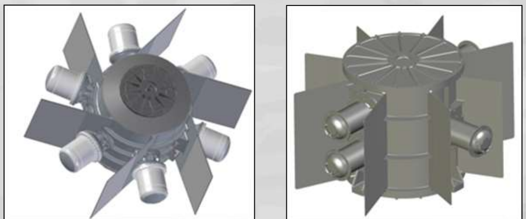
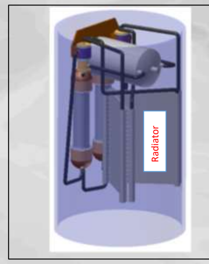
DRPS Size

- Envelope dimensions are expected to be similar to RTG
  - Stirling envelope dimensions (m): 0.8 diameter x 0.5 height
  - Turbo-Brayton envelope dimensions (m): 0.8 diameter x 0.9 height
- Considered configuration options
  - Stirling system; convertors arranged around central heat source with fins extending radially outwards
  - Turbo-Brayton system; radiator not intimately coupled to other components

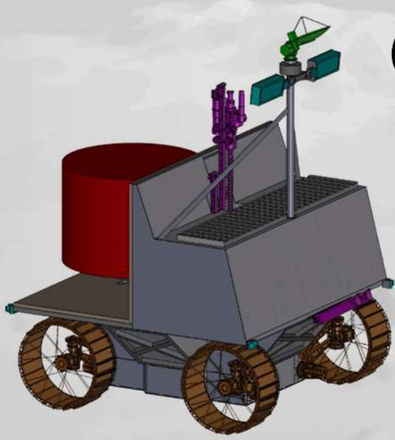


Example DRPS concept images based on Stirling conversion (6 convertors per generator shown)



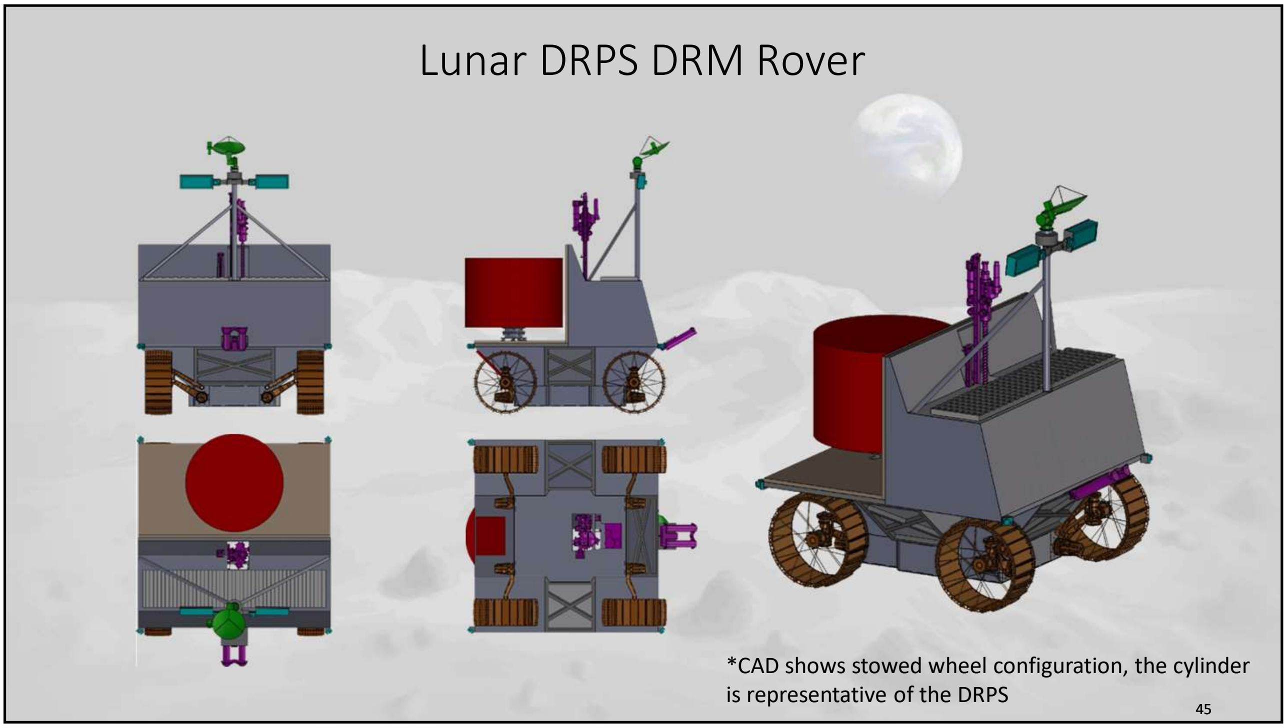
Example DRPS concept image based on Turbo-Brayton conversion (2 convertors shown)

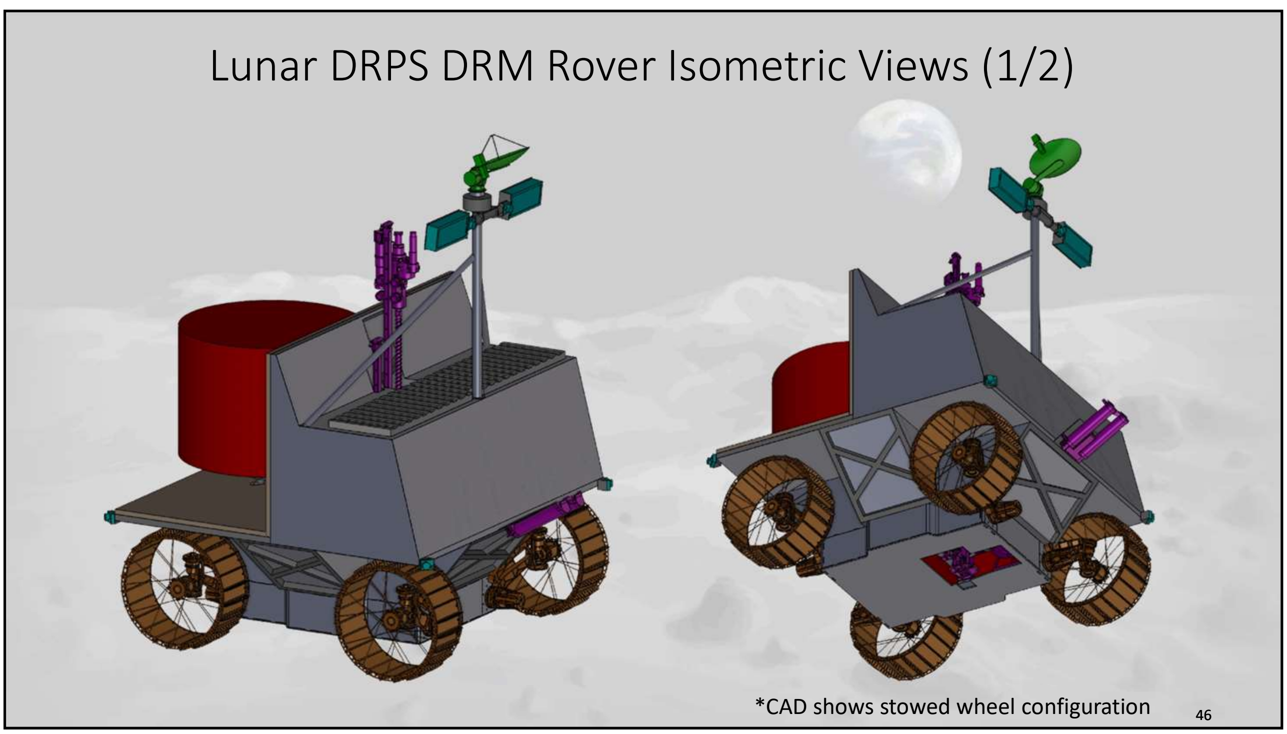
S. O. Scott Wilson, "CONVERTOR DEVELOPMENT FOR DYNAMIC RADIOISOTOPE POWER SYSTEMS," in *Nuclear and Emerging Technologies for Space*, Knoxville, TN, 2020.



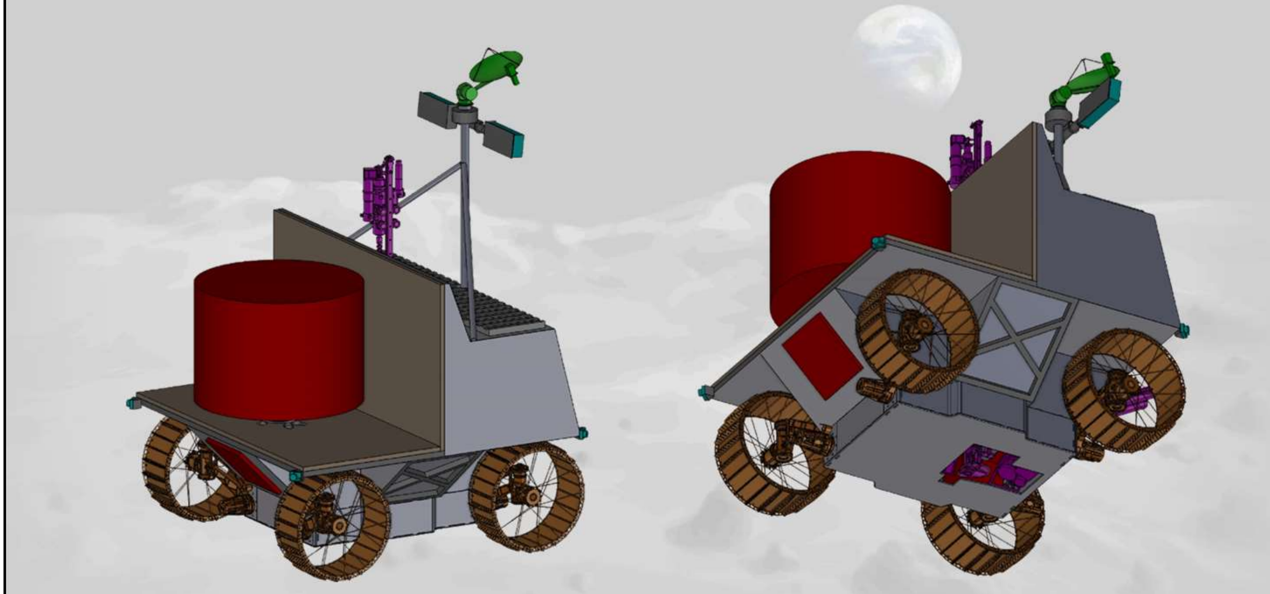
Configuration

Tom Packard


Lunar DRPS DRM Rover
*CAD shows stowed wheel configuration, the cylinder is representative of the DRPS
45


Lunar DRPS DRM Rover Isometric Views (1/2)
*CAD shows stowed wheel configuration
46

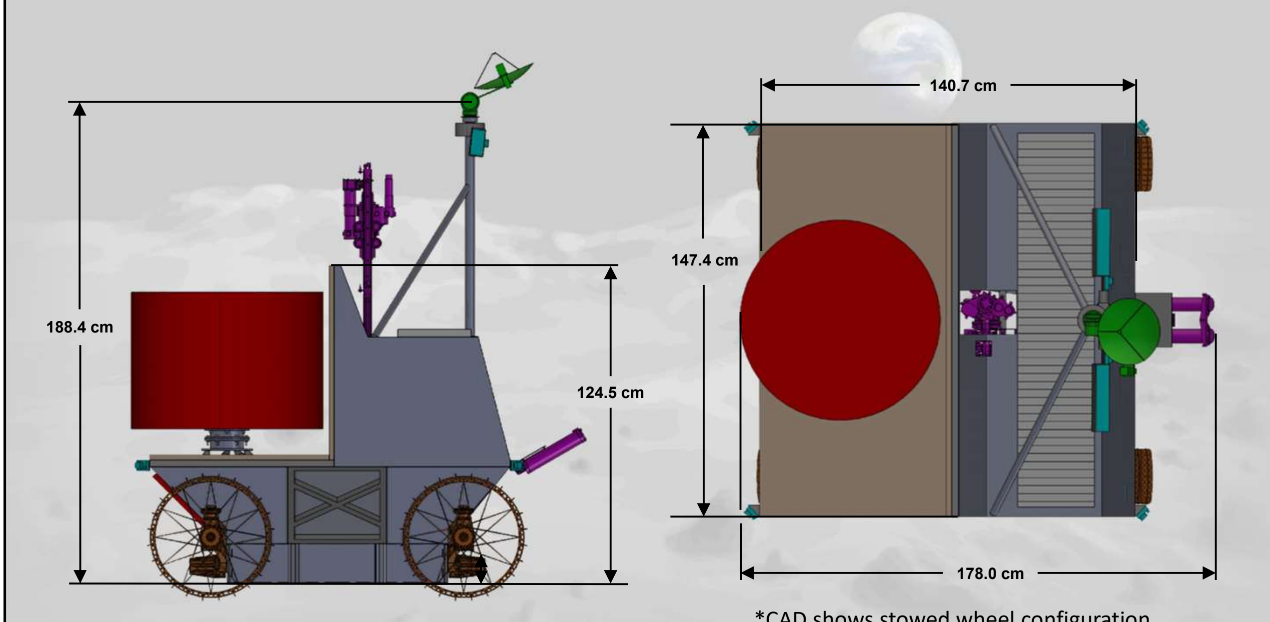
Lunar DRPS DRM Rover Isometric Views (2/2)



*CAD shows stowed wheel configuration

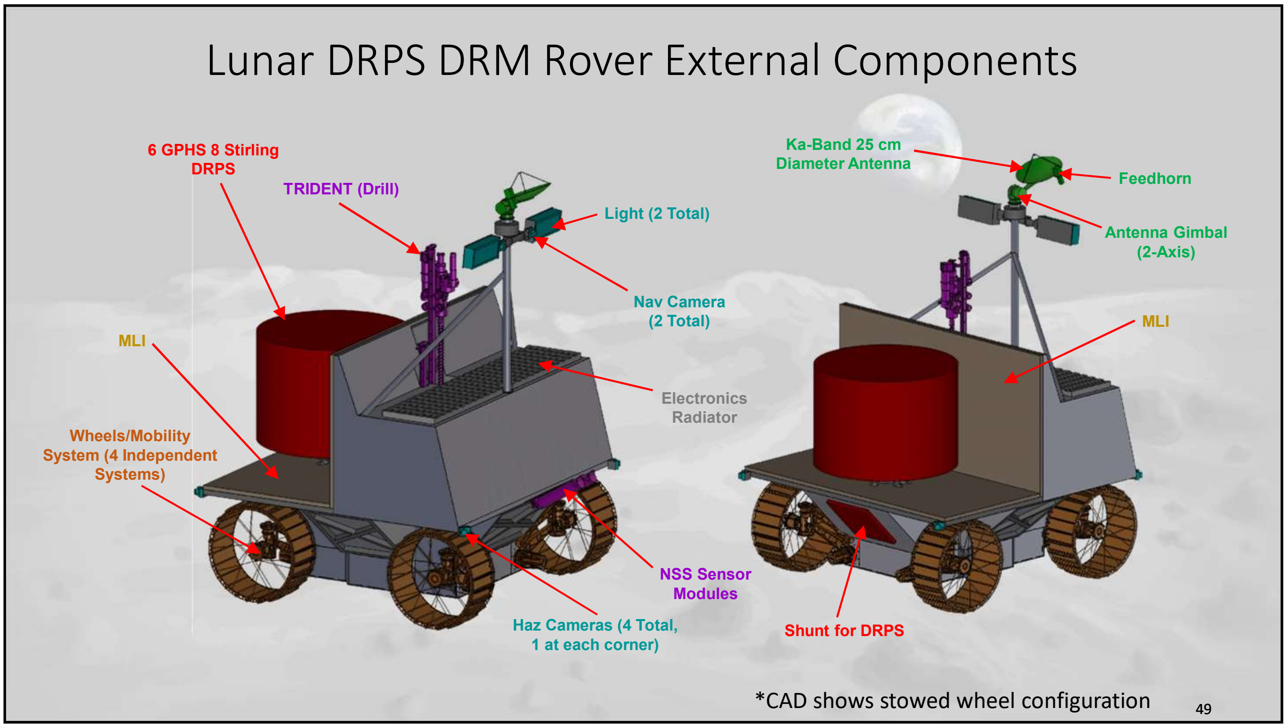
47

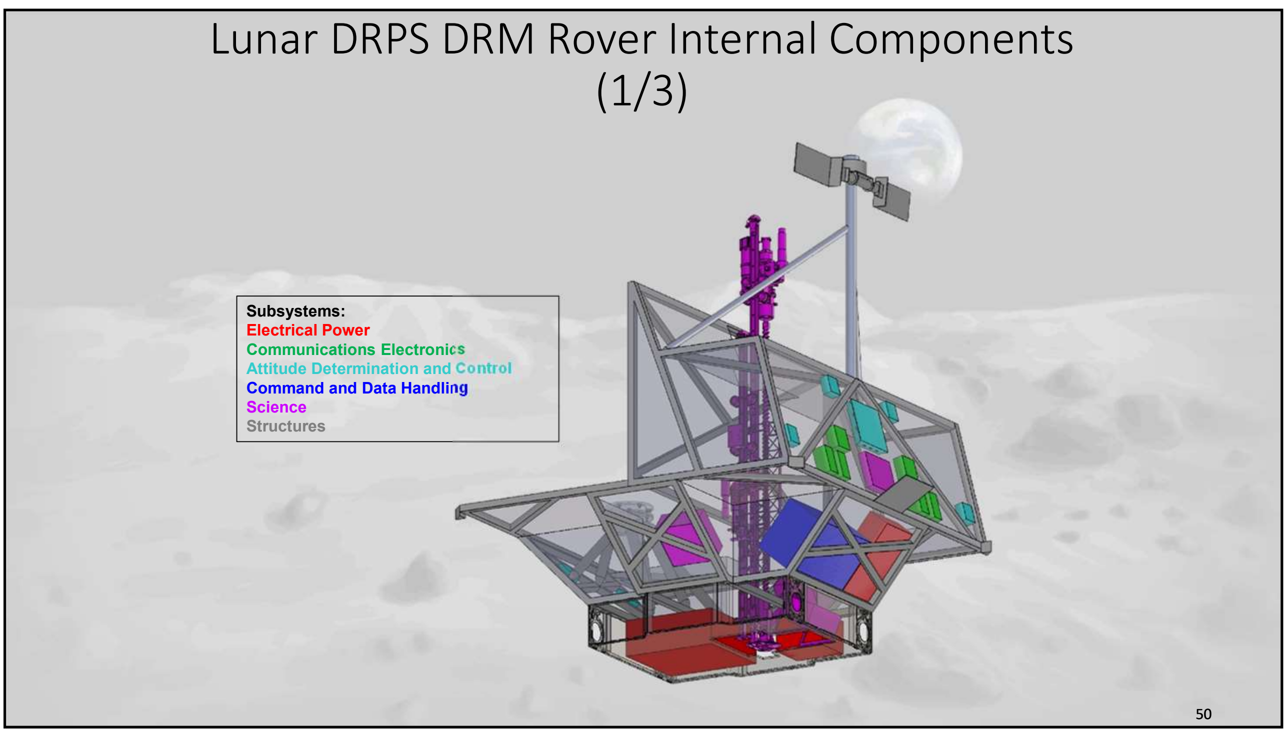
Lunar DRPS DRM Rover Overall Dimensions

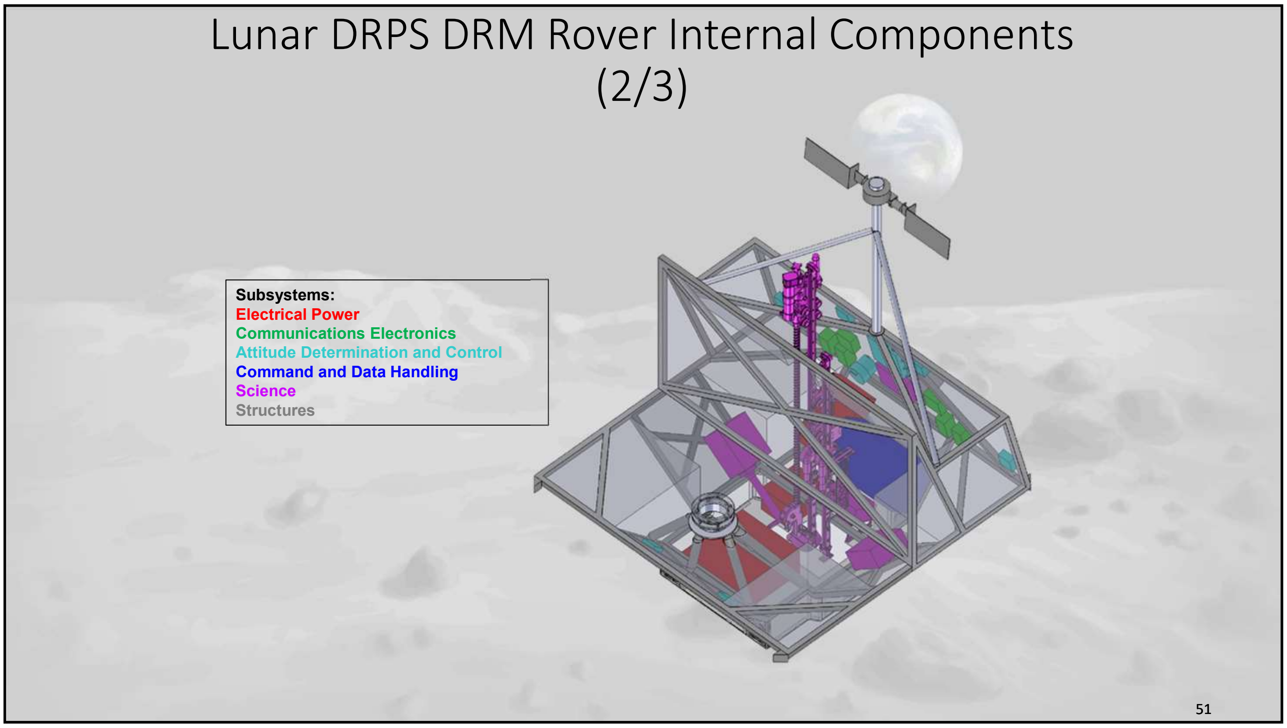


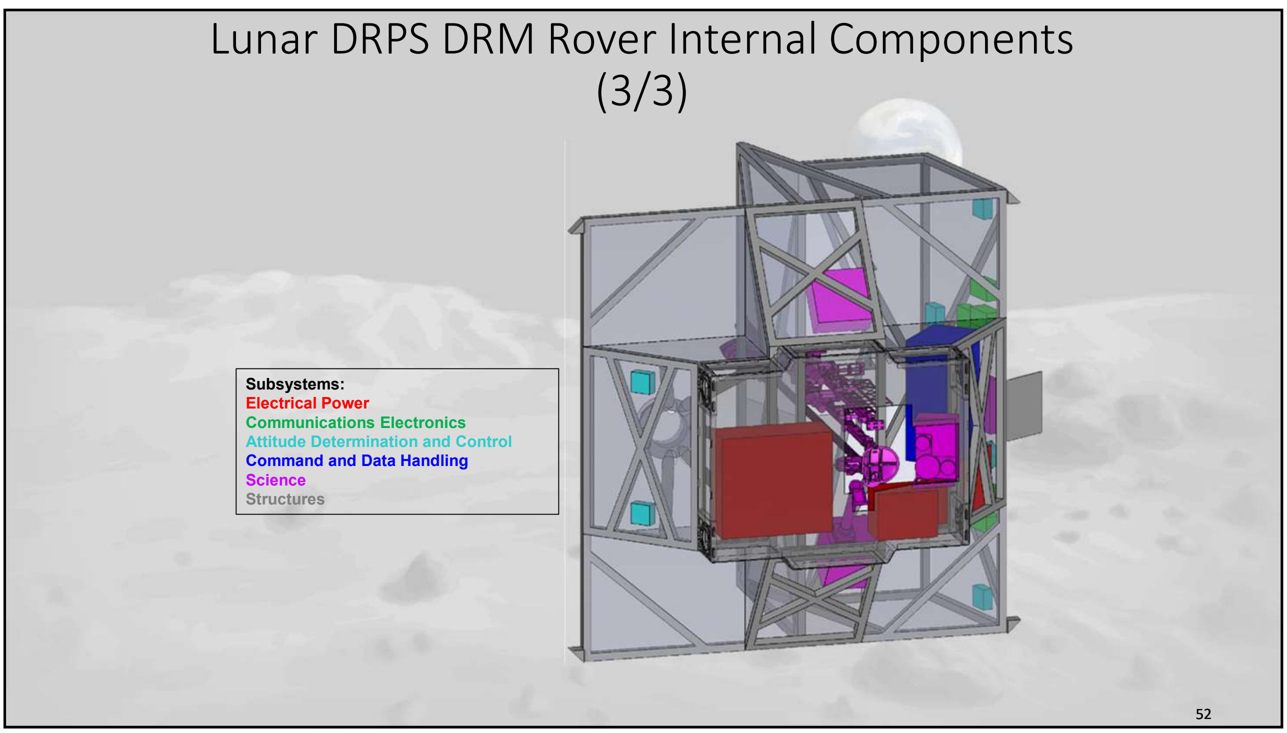
*CAD shows stowed wheel configuration

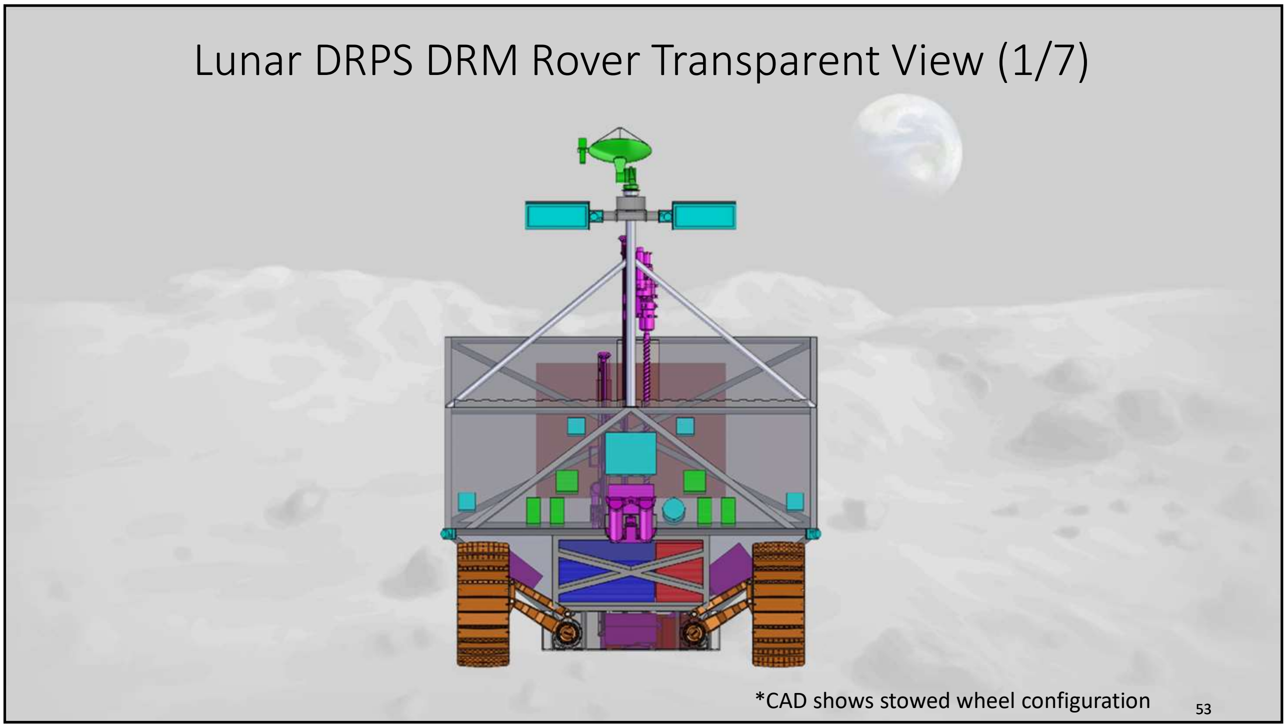
48

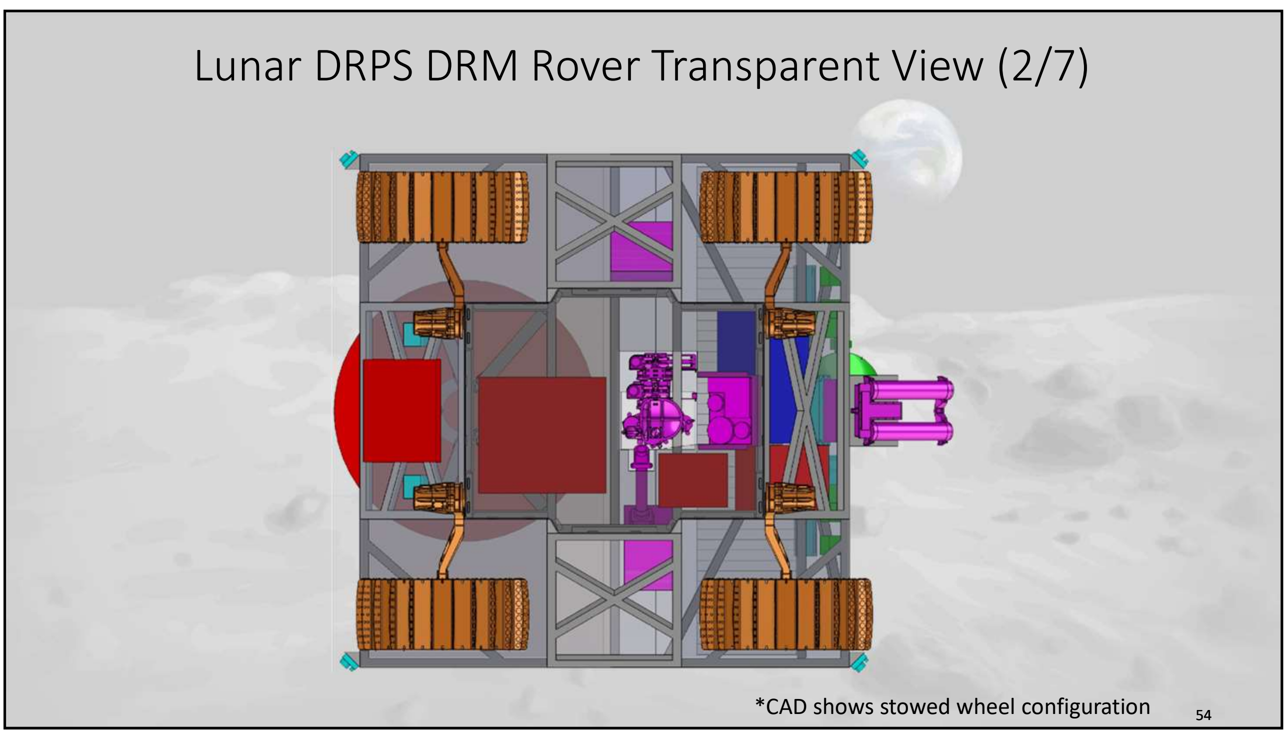

Lunar DRPS DRM Rover External Components
6 GPHS 8 Stirling DRPS
TRIDENT (Drill)
Light (2 Total)
Nav Camera (2 Total)
Electronics Radiator
MLI
Wheels/Mobility System (4 Independent Systems)
NSS Sensor Modules
Haz Cameras (4 Total, 1 at each corner)
Ka-Band 25 cm Diameter Antenna
Feedhorn
Antenna Gimbal (2-Axis)
MLI
Shunt for DRPS
*CAD shows stowed wheel configuration
49

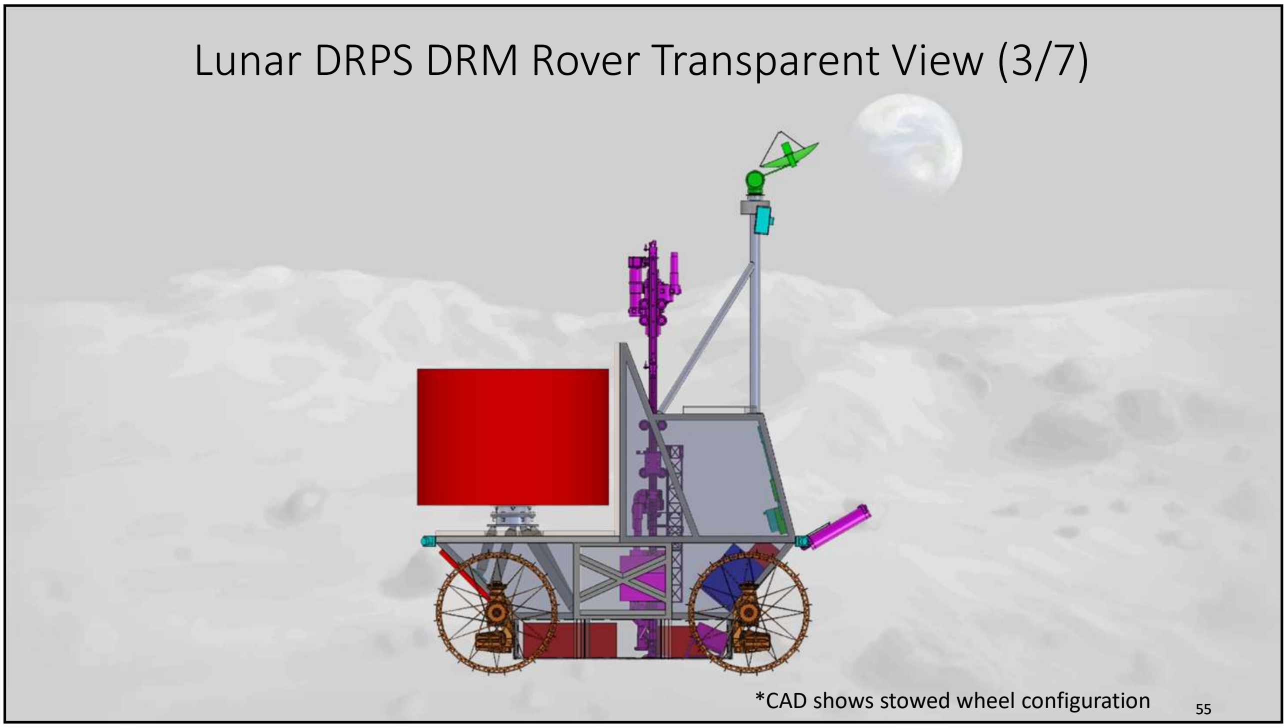

Lunar DRPS DRM Rover Internal Components (1/3)
Subsystems:
Electrical Power
Communications Electronics
Attitude Determination and Control
Command and Data Handling
Science
Structures
50

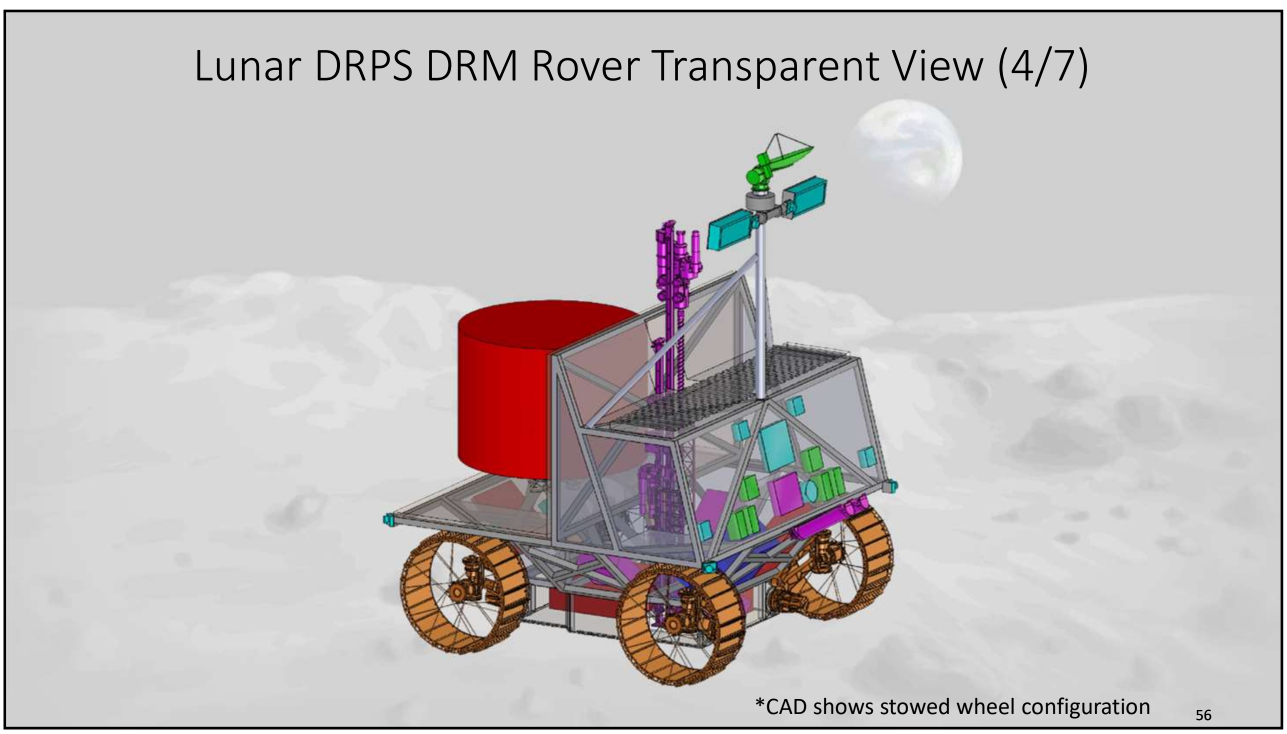

Lunar DRPS DRM Rover Internal Components
(2/3)
Subsystems:
Electrical Power
Communications Electronics
Attitude Determination and Control
Command and Data Handling
Science
Structures
51

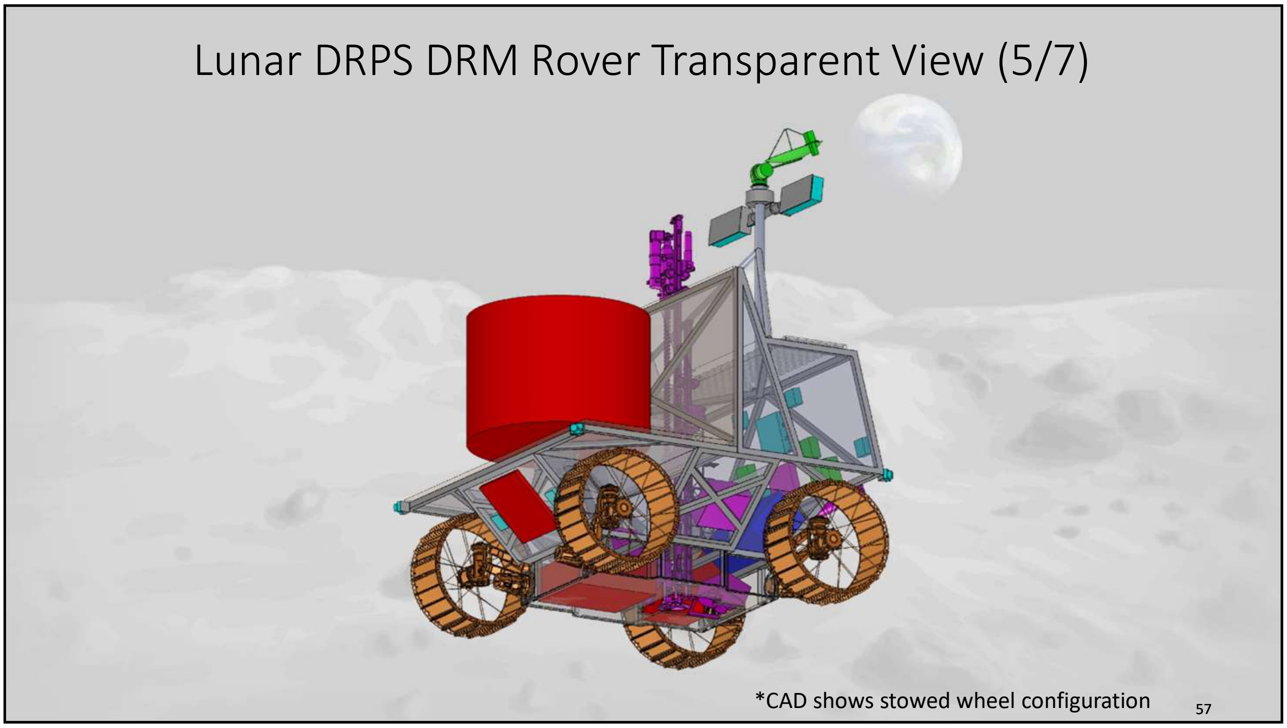

Lunar DRPS DRM Rover Internal Components
(3/3)
Subsystems:
Electrical Power
Communications Electronics
Attitude Determination and Control
Command and Data Handling
Science
Structures
52

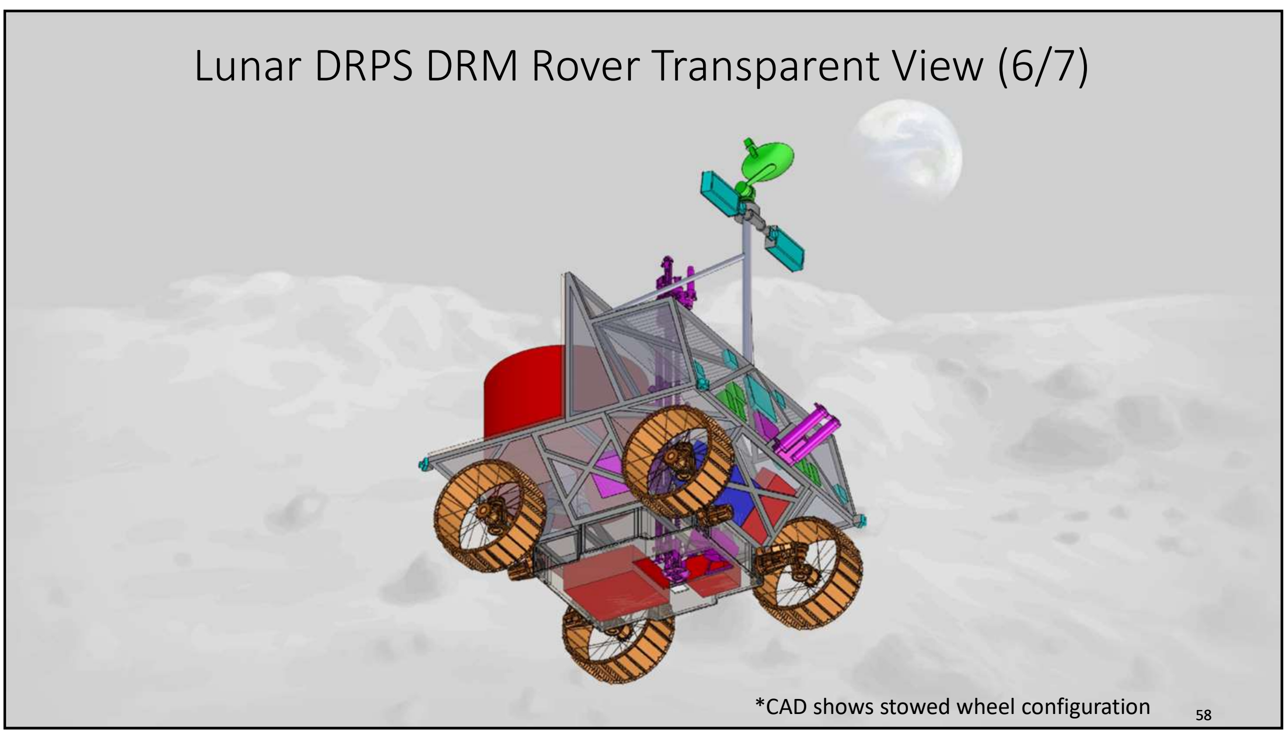

Lunar DRPS DRM Rover Transparent View (1/7)
*CAD shows stowed wheel configuration
53

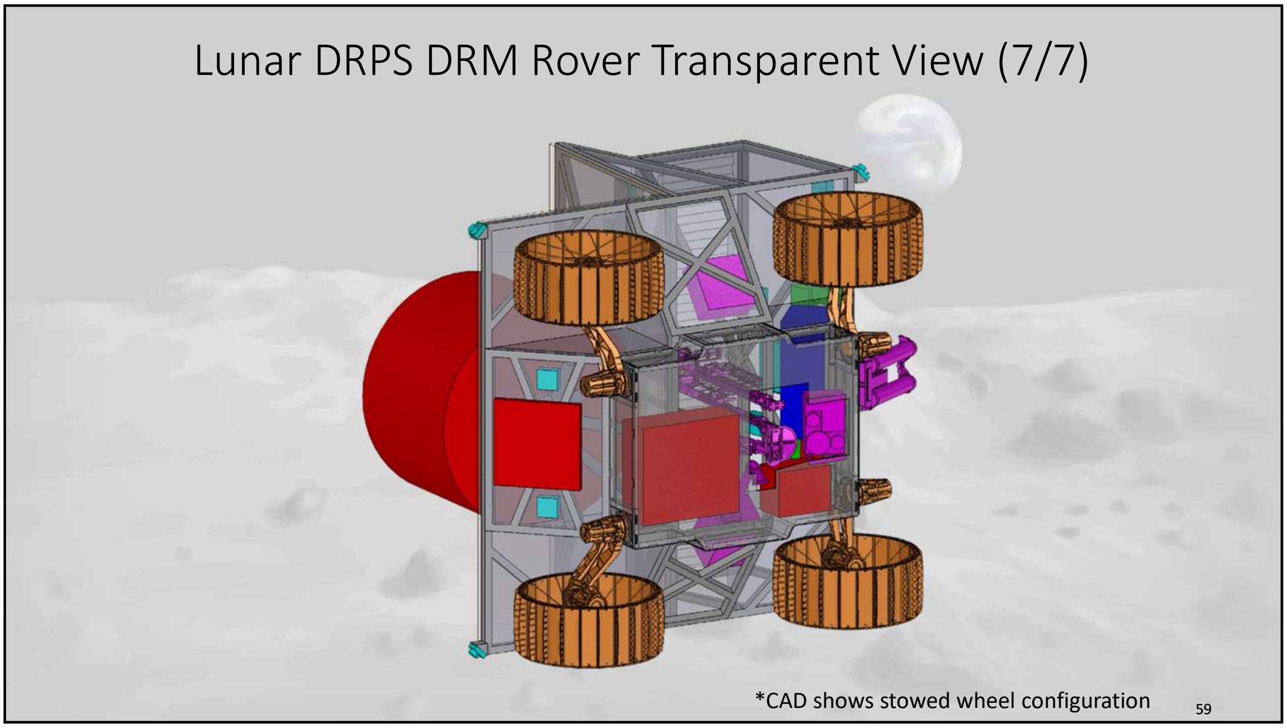

Lunar DRPS DRM Rover Transparent View (2/7)
*CAD shows stowed wheel configuration
54

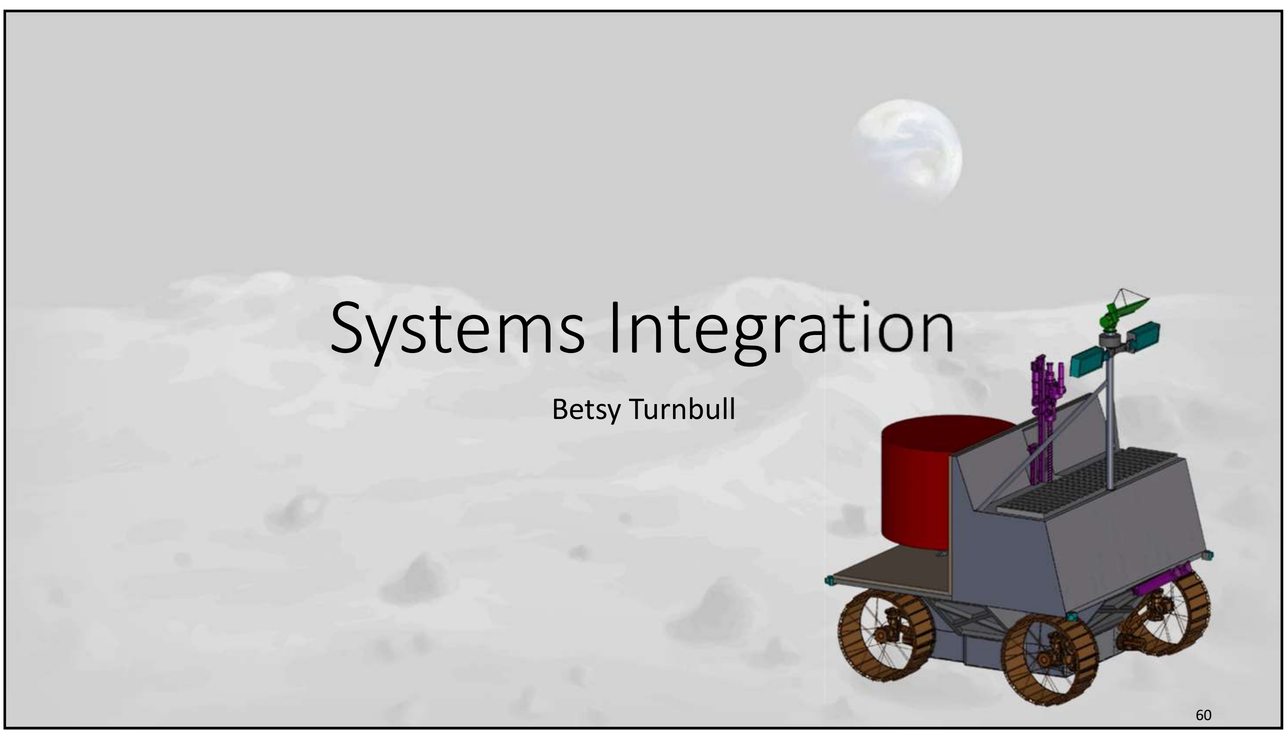

Lunar DRPS DRM Rover Transparent View (3/7)
*CAD shows stowed wheel configuration
55


Lunar DRPS DRM Rover Transparent View (4/7)
*CAD shows stowed wheel configuration
56


Lunar DRPS DRM Rover Transparent View (5/7)
*CAD shows stowed wheel configuration
57


Lunar DRPS DRM Rover Transparent View (6/7)
*CAD shows stowed wheel configuration
58

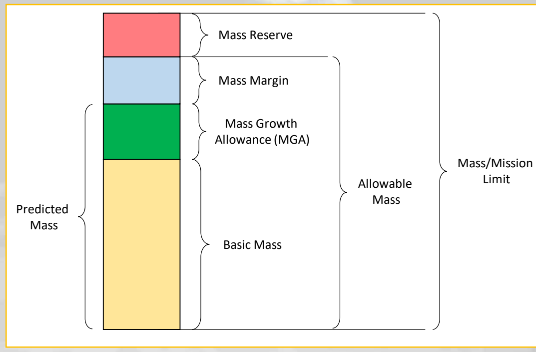

Lunar DRPS DRM Rover Transparent View (7/7)
*CAD shows stowed wheel configuration
59


Systems Integration
Betsy Turnbull
60

Growth, Contingency, and Margin

Compass Policy and Definitions

- ***Basic Mass***
  - *Mass data based on the most recent baseline design. This is the bottoms-up estimate of component mass, as determined by the subsystem leads.*
  - ***Note 1**: This design assessment includes the estimated, calculated, or measured (actual) mass, and includes an estimate for undefined design details like cables, multi-layer insulation, and adhesives.*
  - ***Note 2**: The mass growth allowances (MGA) and uncertainties are not included in the basic mass.*
  - ***Note 3**: Compass has referred to this as current best estimate (CBE) in past mission designs.*
  - ***Note 4**: During the course of the design study, the Compass Team carries the propellant as line items in the propulsion system in the Master Equipment List (MEL). Therefore, propellant is carried in the basic mass listing, but MGA is not applied to the propellant. Margins on propellant are handled differently than they are on dry masses.*
- ***Mass Growth Allowance (MGA)***
  - *MGA is defined as the predicted change to the basic mass of an item based on an assessment of its design maturity, fabrication status, and any in-scope design changes that may still occur.*
- ***Predicted Mass***
  - *This is the basic mass plus the mass growth allowance for to each line item, as defined by the subsystem engineers.*
  - ***Note** : When creating the MEL, the Compass Team uses Predicted Mass as a column header and includes the propellant mass as a line item of this section. Again, propellant is carried in the basic mass listing, but MGA is not applied to the propellant. Margins on propellant are handled differently than they are handled on dry masses. Therefore, the predicted mass as listed in the MEL is a wet mass, with no growth applied on the propellant line items.*



Program Milestone	Recommended MGA (%)[1]	Recommended Mass Margin (%)[1]	MGA + Mass Margin (%)[2]	Grade
ATP	>15	>15	>30	Green
	9<MGA≤15	10<Mass Margin≤15	19<MGA + Mass Margin≤30	Yellow
	≤9	≤10	≤19	Red

Notes:
1. The percentages of MGA and Mass Margin in the above chart are defined as follows:
   MGA = Predicted Mass – Basic Mass
   % MGA = (MGA/Basic Mass) × 100
   % Mass Margin = [(Allowable Mass - Predicted Mass)/Basic Mass] × 100
2. The % (MGA + Mass Margin) is defined as:
   % MGA + Mass Margin = [(Allowable Mass – Basic Mass)/Basic Mass] × 100

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DRPS Lunar Rover: Case 1-Stirling

MEL Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	Basic Mass (kg)
Radioisotope Power	96.4
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	13.4
Thermal Control (Non-Propellant)	34.8
Science	40.0
Mobility	67.0
Structures and Mechanisms	42.1
Element Total	*327.3*
Element Dry Mass (no prop,consum)	327.3
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	53.5
MGA as a %'age	16%
Predicted Mass (Basic + MGA)	380.9
Recommended Mass Margin (Additional System Level Growth) 15%	49.1
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	430.0
Element Inert Mass (Basic+MGA+Margin)	430.0
Total Wet Mass (Allowable Mass)	*430.0*

LV Summary: Case 1_DRPS_DRM_Rover CD-2021-182	Single Launch
Architecture Details	**Rover**
Representative Lander	Griffin Lander
Performance (pre-margin)	475
Margin (%)	0%
Total Wet Mass w/15% Growth	**430**
Available LV Margin	**45**
Available LV Margin (%)	**9%**

- The rover fits within a 475 kg lander limit with green mass risk assessment ratings across the board.
- No margin was carried on the lander capability.

AIAA Mass Risk Assessment Ratings

Program Milestone	Recommended MGA (%)	Recommended Mass Margin (%)	MGA+ Mass Margin (%)	Grade
ATP	>15	>15	>30	Green
	9<MGA≤15	10<Mass Margin≤15	19<MGA+Mass Margin≤30	Yellow
	≤9	≤10	≤19	Red

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Case 1: Master Equipment List

Description Case 1_DRPS_DRM_Rover CD-2021-182	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
DRPS DRM Rover	327	16%	54	381
Rover	327	16%	54	381
Radioisotope Power System	96.4	15%	14.5	110.8
Attitude Determination and Control	4.7	12%	0.6	5.3
Command & Data Handling	18.4	42%	7.7	26.1
Communications and Tracking	10.7	10%	1.1	11.8
Electrical Power Subsystem	13.4	35%	4.6	18.0
Thermal Control (Non-Propellant)	34.8	18%	6.3	41.0
Science	40.0	3%	1.2	41.2
Mobility	67.0	15%	10.1	77.1
Structures and Mechanisms	42.1	18%	7.6	49.6

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Case 1: Power Equipment List

Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7	Power Mode 8	Power Mode 9	Power Mode 10
Case 1_DRPS_DRM_Rover CD-2021-182	DRPS Loading on Pad/ Launch	Lunar Transit and Descent	Rover Checkout	Peak Roving	Roving Science-Sunlit	Drilling Science-Sunlit	Standby Phase (if necessary)	Roving Science-Shadowed	Drilling Science-Shadowed	Standby Phase- In Shadow
	30 days	4 days	1 day	30 mins	8 hours	1 hour	16 hrs	8 hours	1 hour	extended
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
DRPS DRM Rover	86	128	254	564	364	430	174	334	430	132
Rover	86	128	254	564	364	430	174	334	430	132
Radioisotope Power System	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Attitude Determination and Control	0.0	0.0	54.7	54.7	54.7	11.0	7.0	54.7	11.0	7.0
Command & Data Handling	28.0	28.0	28.0	47.6	49.3	49.3	20.4	49.3	49.3	20.3
Communications and Tracking	0.0	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	0.0
Electrical Power Subsystem	10.1	10.1	10.1	30.3	30.3	30.3	15.6	30.3	30.3	15.6
Thermal Control (Non-Propellant)	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Science	1.6	1.6	73.2	43.2	81.2	251.2	43.2	51.2	251.2	43.2
Mobility	0.0	0.0	0.0	300.0	60.0	0.0	0.0	60.0	0.0	0.0
Structures and Mechanisms	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note that the PEL is the same for Case 1 and Case 2

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DRPS Lunar Rover: Case 2-Brayton

MEL Summary: Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	Rover
Main Subsystems	**Basic Mass (kg)**
Radioisotope Power	151.0
Attitude Determination and Control	4.7
Command & Data Handling	18.4
Communications and Tracking	10.7
Electrical Power Subsystem	17.0
Thermal Control (Non-Propellant)	36.2
Science	40.0
Mobility	67.0
Structures and Mechanisms	45.6
Element Total	*390.5*

Element Dry Mass (no prop,consum)	390.5
Element Propellant	0.0
Element Mass Growth Allowance (Aggregate)	63.9
MGA as a %'age	16%
Predicted Mass (Basic + MGA)	454.3
Recommended Mass Margin (Additional System Level Growth) 15%	58.6
Margin as a %'age	15%
Element Dry Mass (Basic+MGA+Margin)	512.9
Element Inert Mass (Basic+MGA+Margin)	512.9
Total Wet Mass (Allowable Mass)	*512.9*

AIAA Mass Risk Assessment Rating, assuming a lander with payload capacity ~515 kgs

Program Milestone	Recommended MGA (%)	Recommended Mass Margin (%)	MGA+ Mass Margin (%)	Grade
ATP	>15	>15	>30	Green
	9<MGA≤15	10<Mass Margin≤15	19<MGA+Mass Margin≤30	Yellow
	≤9	≤10	≤19	Red

LV Summary: Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	Single Launch
Architecture Details	**Rover**
Representative Lander	Griffin Lander
Performance (pre-margin)	475
Margin (%)	0%
Performance (post-margin)	475
Total Wet Mass w/15% Growth	513
Available LV Margin	-38
Available LV Margin (%)	-8%

The Brayton Case has a green rating **ONLY** if a greater payload limit can be procured. Otherwise, the rating is green/red/yellow.

- To fit the 475 kg limit, only 5% margin can be carried (~20 kgs)

AIAA Mass Risk Assessment: MGA and Margin modified to meet lander limit

Program Milestone	Recommended MGA (%)	Recommended Mass Margin (%)	MGA+ Mass Margin (%)	Grade
ATP	>15	>15	>30	Green
	9<MGA≤15	10<Mass Margin≤15	19<MGA+Mass Margin≤30	Yellow
	≤9	≤10	≤19	Red

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Case 2: Master Equipment List

Description Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	Basic Mass (kg)	Growth (%)	Growth (kg)	Total Mass (kg)
DRPS DRM Rover	**390**	**16%**	**64**	**454**
Rover	**390**	**16%**	**64**	**454**
Radioisotope Power System	**151.0**	**15%**	**22.6**	**173.6**
Attitude Determination and Control	**4.7**	**12%**	**0.6**	**5.3**
Command & Data Handling	**18.4**	**42%**	**7.7**	**26.1**
Communications and Tracking	**10.7**	**10%**	**1.1**	**11.8**
Electrical Power Subsystem	**17.0**	**35%**	**5.9**	**22.9**
Thermal Control (Non-Propellant)	**36.2**	**18%**	**6.5**	**42.7**
Science	**40.0**	**3%**	**1.2**	**41.2**
Mobility	**67.0**	**15%**	**10.1**	**77.1**
Structures and Mechanisms	**45.6**	**18%**	**8.2**	**53.8**

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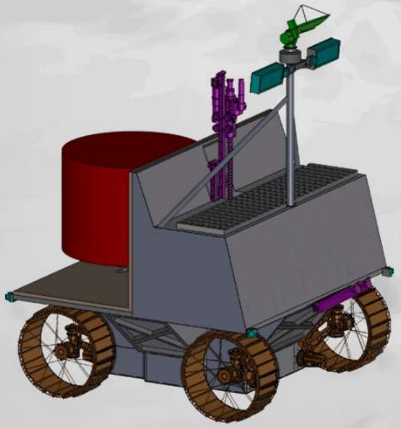

Science

VIPER Science for DRPS Rover

- Representative science instruments were taken from VIPER
- In addition to the instruments detailed by VIPER, a 10.5 kg “TBD Instrument” with 10 W of operating power was carried to either allow for another small additional instrument or serve as a placeholder if the VIPER science package grows in mass. (This instrument is not shown in the CAD model as placement will be highly dependent on the type of instrument selected.)
- Detailed information on the VIPER Science Manifest can be found here:
  - D. Andrews, "VIPER: PATHFINDING IN-SITU RESOURCE UTILIZATION," in *European Lunar Symposium (ELS)*, Virtual, 2020.

Case 1_DRPS_DRM_Rover - Rover: Science

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Science			**40.0**	**3%**	**1.2**	**41.2**
Science Package			**40.0**	**3%**	**1.2**	**41.2**
Main Rover Science			40.0	3%	1.2	41.2
NSS Sensor Modules	1	1.0	1.0	3%	0.0	1.0
NSS Data Processing Modules	1	1.0	1.0	3%	0.0	1.0
NIRVSS Spectrometer Modules	1	1.8	1.8	3%	0.1	1.8
NIRVSS Observation Brackets	1	1.8	1.8	3%	0.1	1.8
Msolo	1	6.0	6.0	3%	0.2	6.2
TRIDENT	1	18.0	18.0	3%	0.5	18.5
TBD Instrument	1	10.5	10.5	3%	0.3	10.8

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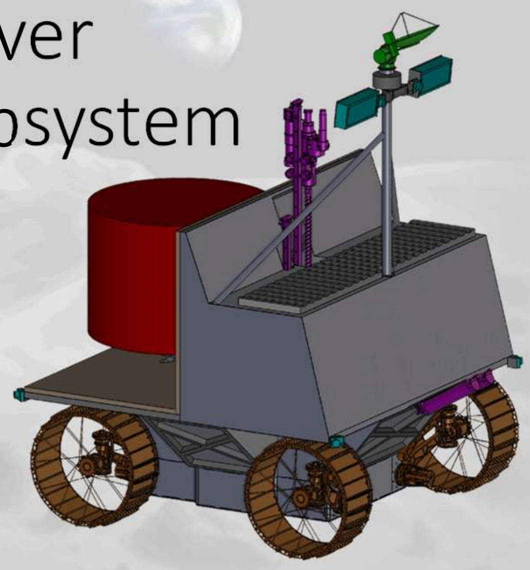
Lunar DRPS Rover Electrical Power Subsystem

Paul Schmitz

Brandon Klefman



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DRPS Requirements

- Provide a DRPS for use on a South Pole Lunar Rover
- Mission Life: 18 months (1.5 yrs.) post-launch, 3 years storage-
  - do not preclude potential 17-year extended mission lifetime.
- DRPS design life: 17 years (14+3 yrs.), includes three year of pre-launch storage after DRPS fueling.
  - Single Fault Tolerance for DRPS generator per RFP
- No set power requirements but should be based upon a 6 GPHS configuration
- Must fit with the DOE shipping container as specified in the DRPS RFP

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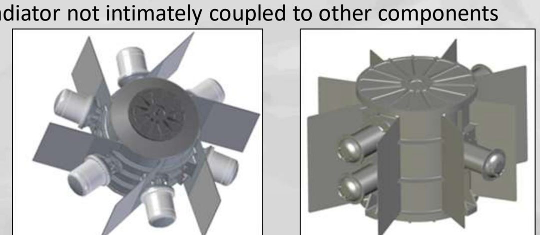
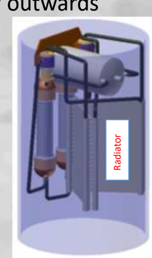
DRPS Overview

- Selected an 8 Stirling Convertor, 6 GPHS Generator as the baseline whose performance was averaged from the AMSC and SunPower designs
  - Performed a design trade at the end to consider the Creare based Brayton DRPS
- Envelope dimensions are expected to be similar to RTG
  - Stirling envelope dimensions (m): 0.8 diameter x 0.5 height
  - Turbo-Brayton envelope dimensions (m): 0.8 diameter x 0.9 height
- Considered configuration options
  - Stirling system; convertors arranged around central heat source with fins extending radially outwards
  - Turbo-Brayton system; radiator not intimately coupled to other components



Example DRPS concept images based on Stirling conversion (6 convertors per generator shown)



Example DRPS concept image based on Turbo-Brayton conversion (2 convertors shown)

S. O. Scott Wilson, "CONVERTOR DEVELOPMENT FOR DYNAMIC RADIOISOTOPE POWER SYSTEMS," in *Nuclear and Emerging Technologies for Space*, Knoxville, TN, 2020.

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Projected DRPS Performance Characteristics

No. of GPHS Modules	Power Output (Electrical) @ BOL W_e	Power Output Degradation Rate- EOL Power % per year-EOM Power- 4.5 years	Thermal Power @ BOL W_{th}	Heat Rejected @ BOL W_{th}	Radiative Sink Env. Temperature °C	Generator Mass kg (Spec Power 3.8 w/kg) (includes controller)
6	353 watts- Deep Space	1.3%/yr – 337 watts	1500	1107	-269	95.3
6	335 watts Next to Thermal Barrier on Rover	1.3%/yr -315 watts	1500	1127	-60	95.3

- Power Adjusted because of thermal barrier which limits sublimation in front of rover
- Overall generator power output degradation rate is expected to be less than 1.3% per year
  - Reduction in thermal output of 0.8% per year due to fuel decay
  - Remaining decline due to lower hot-side temperature and other thermal effects
  - Convertor technology is planned to have no degradation
- $P=P_{BOL}e^{-rt}$ *where r = 0.013 and t = years*

Dynamic RPS Technical Data Sheet

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Available Free-piston Stirling Technologies

Past NASA RPS Program Development Efforts

- Highest TRL RPS convertors include TDC from SRG110 project and ASC from ASRG project
  - SRG110 – started engineering units but project stopped in 2006 before they could finish units
  - ASRG – delivered engineering units for system testing before project ended in 2013
- Longest running TDC: 119,000 hrs (no vibe test) larger more massive convertor uses flexure bearings
- Longest running ASC: 84,000 hrs (vibration tested, hermetically sealed) smaller less massive convertor uses gas bearings

Project & Provider	Test Article	Hrs of Operation
SRG 110 Infinia, Corp.	TDC #13	119,732 (13.7 yrs)
	TDC #15 & #16	112,890 each
	SES #2* (SRG-110 eng unit)	12,523
ASRG Sunpower, Inc.	ASC-E3 #4*, #9	38,148 / 24,191
	ASC-E3 #6*, #8	31,416 / 27,268
	ASC-0 #3*	84,025 (9.6 yrs)
	ASC-L*	46,694 (5.3 yrs)

TDC Extended Operation Testing

ASC-E3 Extended Operation Testing

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Available Free-piston Stirling Technologies

Past DOE ARPA-E Program Development Efforts

- Only functional units in program were Stirling convertors: AMSC and Sunpower
- AMSC 1.4 kW unit was performance tested but 1 yr from the end of the program they decided to use a Qnergy engine, uncertain why change was needed (performance? other?) – Qnergy design not extensible to space applications
- Sunpower 1.1 kW unit was performance tested at full power and met performance requirements, follow on DoD contract for dual-opposed assembly (in progress now) – Sunpower design extensible to space applications

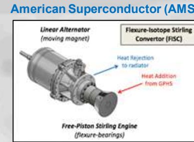
Current NASA RPS Program Development Effort

- Technology development effort aimed to advance the TRL from 4-6
- Phase I: 6 mon design, Phase II: 18 month fab+test, Phase III: 12 mon gov IV&V
- Delays experienced during Phase II, Sunpower was first to demonstrated prototype functionality, AMSC and Creare plan to do so around Dec19/Jan20

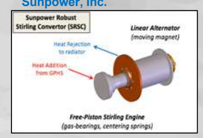
Estimated TRL for available Dynamic Technologies

- Based on past/present NASA and DOE development efforts – Higher TRL and more confidence in being able to demonstrate performance and robustness of Stirling convertors compared to Brayton
- Less similarities between TDC, GENSETS, and FISC (very long life demonstrated but without key environmental tests, GENSETS not space design, FISC now demonstrated), for new power levels that have not been demonstrated the estimated TRL is 3, lower confidence in ability to perform out of the box, would need to identify clean production house
- More similarities between ASC, GENSETS, and SRSC – Environmental testing performed on 84,000 hr unit, GENSETS and SRSC contain all lessons learned from past development efforts, estimated TRL is strong 4, higher confidence in ability to perform out of the box, has clean room capability and iso certification for building space cryocoolers

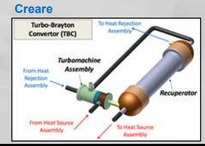
American Superconductor (AMSC)



Sunpower, Inc.



Creare



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DRPS System Summary

DRPS Power System : 95.3 kg (before growth)

Category	Mass (kgs)
Convertors	33.7
GPHS	9.6
Housing	19.7
Fins	4.6
Insulation	10.0
Misc.	3.7
Controller	13.9
Totals	95.3

*does not include shunt radiator-carried in MEL

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EPS Requirements

Description	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7	Power Mode 8	Power Mode 9	Power Mode 10
Case 1_DRPS_DRM_Rover CD-2021-182	DRPS Loading on Pad/ Launch	Lunar Transit and Descent	Rover Checkout	Peak Roving	Roving Science-Sunlit	Drilling Science-Sunlit	Standby Phase (if necessary)	Roving Science-Shadowed	Drilling Science-Shadowed	Standby Phase- In Shadow
	30 days	4 days	1 day	30 mins	8 hours	1 hour	15 hours	8 hours	1 hour	15 hours
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
DRPS DRM Rover	**85.5**	**128.0**	**254.3**	**564.0**	**363.8**	**430.1**	**174.5**	**333.8**	**430.1**	**131.9**
Rover	85.5	128.0	254.3	564.0	363.8	430.1	174.5	333.8	430.1	131.9
Radioisotope Power System	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Attitude Determination and Control	0.0	0.0	54.7	54.7	54.7	11.0	7.0	54.7	11.0	7.0
Command & Data Handling	28.0	28.0	28.0	47.6	49.3	49.3	20.4	49.3	49.3	20.3
Communications and Tracking	0.0	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	0.0
Electrical Power Subsystem	10.1	10.1	10.1	30.3	30.3	30.3	15.6	30.3	30.3	15.6
Thermal Control (Non-Propellant)	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Science	1.6	1.6	73.2	43.2	81.2	251.2	43.2	51.2	251.2	43.2
Mobility	0.0	0.0	0.0	300.0	60.0	0.0	0.0	60.0	0.0	0.0

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Energy Requirements

Power Modes	DRPS Loading on Pad/ Launch	Lunar Transit and Descent	Rover Checkout	Peak Roving	Roving Science- Sunlit	Drilling Science-Sunlit	Standby Phase	Roving Science-Shadowed	Drilling Science-Shadowed	Standby Phase- In Shadow
Duration (hours)	720	96	24	0.5	8	1	15	8	1	15
Bus Power w/ Growth (W)	47.3	102.6	266.7	568.1	367.8	469.0	155.8	328.9	469.0	100.4
EPS Parasitic Power (W)	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
EPS Dissipation (W)	0.0	0.0	0.0	16.8	16.8	16.8	7.9	16.8	16.8	7.9
Total Power (W)	57.4	112.7	276.8	595.0	394.7	495.9	173.8	355.8	495.9	118.4
RPS Power (W)	315.0	315.0	315.0	315.0	315.0	315.0	315.0	315.0	315.0	315.0
Total Battery Power (W)	-257.6	-202.3	-38.2	280.0	79.7	180.9	-141.2	40.8	180.9	-196.6
Battery Energy Consumed (Whr)	**0.0**	**0.0**	**0.0**	**140.0**	**637.6**	**180.9**	**0.0**	**326.0**	**180.9**	**0.0**

- RPS power generation is for DC power output, assuming EOL (4.5 years) capability and includes internal controller losses (39 W).
- Peak system load power is 595 W
- Energy storage requirements driven by roving/science operations of up to 8 continuous hours, plus 1 hr of drilling operations per day
  - Total battery energy consumed estimated at 819 Whr
  - Remaining 15 hrs spent in standby mode to recharge the energy storage

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Energy Balance

Operational Phases	Duration (hrs)	Total Power (W)	RPS Power (W)	Total Battery Power Demand (W)	Battery SOC (%)	Total Battery Energy Consumed (Whr)	Ending Battery SOC (%)
Roving Science Phase	8	394.7	315.0	79.7	100.0%	637.6	46.9%
Drilling Science Phase	1	495.9	315.0	180.9	46.9%	180.9	31.8%
Standby Phase	6	173.8	315.0	-141.2	31.8%	-818.5	100.0%

- Analysis shows battery sizing could support up to 9 hrs of continuous operations (8 hrs roving + 1 hr drilling).
- Ensures maximum depth-of-discharge below 80% to extend battery life
- Full battery recharge will require 6 hrs of continuous standby operations
- This assumes EOL RPS power generation estimates, so early mission operations will have additional flexibility.

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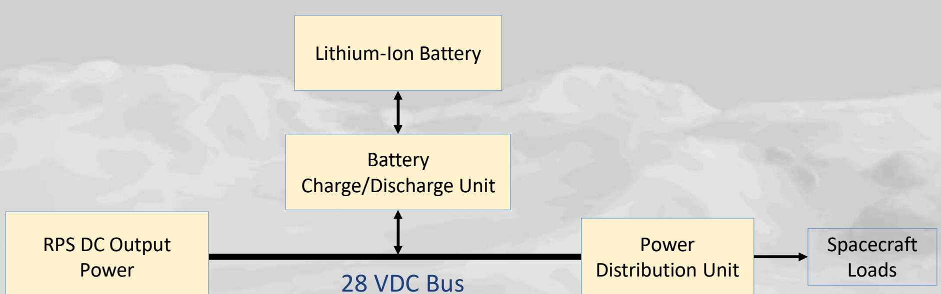
EPS Block Diagram



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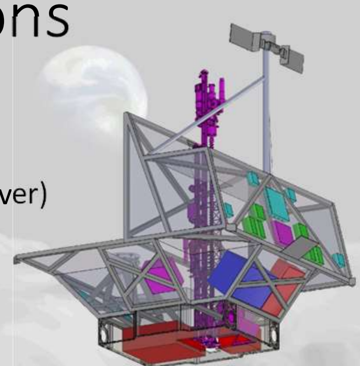
EPS Assumptions

- Energy Storage
  - Lithium-Ion battery technology
  - LG M36T 18650 battery cells (same as VIPER Lunar Rover)
  - Maximum depth of discharge of 80%
  - Nominal 28 VDC battery voltage
  - Includes 1 spare parallel battery string
- Power Management and Distribution (PMAD)
  - COTS 28 VDC Terma Power Distribution Equipment
  - Battery CD Regulation Module and Equipment Power Distribution Module
  - Each PMAD function includes 1 spare card
  - EPS Harnessing assumed to be 25% of base EPS mass



EPS Components shown in red

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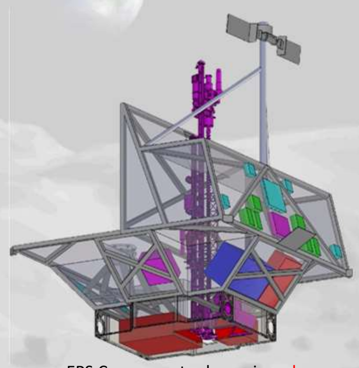
EPS Design

- Lithium-Ion Battery
  - 8S-12P cell design
  - 1200 Whr total battery energy
  - Battery specific energy of ~173 Whr/kg
- 28 VDC Power Electronics Box
  - (3) Battery CD Regulation modules
    - 96.0% battery charge efficiency
    - 94.0% battery discharge efficiency
  - (2) Equipment Power Distribution modules
    - 16 latching current limiter (LCL) outputs per module
    - Maximum of 5 A per LCL
    - 900 W capability per module
  - Estimated enclosure mass and volume included



EPS Components shown in red

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TRL's/Trades

- DRPS
  - Stirling Generator 3
  - Stirling Engines: 3-4
  - Stirling controllers: 4
- Lithium-Ion Battery
  - Uses COTS battery cells with custom battery design – TRL 6
- PMAD
  - Terma PMAD modules have flight heritage – TRL 9
  - EPS harnessing has flight heritage, but custom wiring design and layout for specific spacecraft configuration – TRL 8
- Trades
  - Stirling vs. Brayton
  - Convertor Performance Predicted vs. Tested
  - DRPS performance with and without thermal barrier

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Case 1_DRPS_DRM_Rover - Rover: Radioisotope Power System

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Radioisotope Power System			**96.4**	**15%**	**14.5**	**110.8**
RPS System			**96.4**	**15%**	**14.5**	**110.8**
6 GPHS, 8 Stirling DRPS	1	81.0	81.0	15%	12.2	93.2
Controller	1	14.0	14.0	15%	2.1	16.1
shunt	1	1.4	1.4	15%	0.2	1.6

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Case 1_DRPS_DRM_Rover - Rover: Electrical Power System

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Electrical Power Subsystem			**13.4**	**35%**	**4.6**	**18.0**
Power Management & Distribution			**6.5**	**50%**	**3.2**	**9.7**
28 VDC Power Electronics Box	1	3.8	3.8	15%	0.6	4.4
Harness	1	2.7	2.7	100%	2.7	5.4
Energy Storage			**6.9**	**20%**	**1.4**	**8.3**
Lithium Ion Battery	1	6.9	6.9	20%	1.4	8.3

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Case 2 – Brayton RPS Design

- Reduces RPS power generation capability from 315 W down to 260 W
- Load demand in PEL unchanged
- Reduced RPS capability requires additional battery energy during roving operations
  - Increases battery consumption from ~820 to ~1100 Whr
  - Additional 2.9 kg of battery mass
- Or use same battery design, but limit duration of roving operations
  - Reduce roving from 8 hrs down to 6 hrs
- PMAD design unchanged

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Case 2_Brayton_DRPS_DRM_Rover - Rover: Radioisotope Power System

Description Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Radioisotope Power System			**151.0**	**15%**	**22.6**	**173.6**
RPS System			**151.0**	**15%**	**22.6**	**173.6**
6 GPHS, Brayton Rotating Unit Assembly	1	135.6	135.6	15%	20.3	155.9
controller	1	14.0	14.0	15%	2.1	16.1
shunt	1	1.4	1.4	15%	0.2	1.6

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Case 2_Brayton_DRPS_DRM_Rover - Rover: Electrical Power System

Description Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Electrical Power Subsystem			**17.0**	**35%**	**5.9**	**22.9**
Power Management & Distribution			**7.2**	**55%**	**4.0**	**11.2**
28 VDC Power Electronics Box	1	3.8	3.8	15%	0.6	4.4
Harness	1	3.4	3.4	100%	3.4	6.8
Energy Storage			**9.8**	**20%**	**2.0**	**11.8**
Lithium Ion Battery	1	9.8	9.8	20%	2.0	11.8

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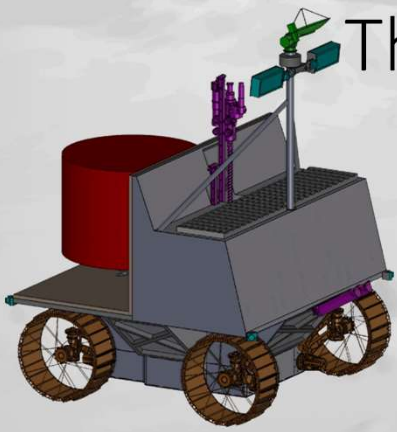

Thermal Control

Tony Colozza

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DRPS Rover Polar Crater Exploration
Thermal Control System

The DRPS rover will collect science data around and within a permanently shadowed crater on the lunar south pole. The rovers' systems requires components to operate in both a permanently shadowed creator as well as in the sunlit ridge outside of the creator. Additional constrains on the system is the need to maintain pristine surface conditions prior to sampling by the science instruments. This requires the area in the front of the rover to be shielded from the heat generated by the radioisotope power system.

The thermal system addresses the thermal control for the components on the rover during operation within the various environments, sunlit and shadowed. As well as addressing the need to maintain the surrounding ground in front of the rover at its ambient temperature condition for scientific investigation. The worst-case thermal operating condition are used to size the thermal components.

Design Approach: For the thermal system there is a worst-case hot and worst-case cold environment. Both of these are used to size different aspects of the system. Solar Intensity and view angle as well as the view to warm bodies such as the sunlit lunar surface along with the internal heat generation are used to determine the worst case hot and cold conditions. Operating on the lunar surface means that the thermal environment will change considerably from daytime to nighttime or from sunlit to shadow operation. Therefore, the worst-case warm conditions occur while sunlit when all internal components are operating maximizing the waste heat generated. Whereas the worst case cold operating conditions occur while in shadow and worst case nonoperational cold conditions occur during night or while in the permanently shadowed creator. The thermal system components are listed below.

Identified Systems :

- Radiator Panel with louvers for removing the waste heat from the electronics.
- Heat pipes and cold plates for moving the heat from the electronics packages to the radiator.
- Multi-Layer Insulation (MLI) to insulate the electronics as well as provide a barrier from the waste heat of the isotope power system to the surface in front of the rover.
- Heaters
- Temperature Sensors, Controllers, Switches, Data Acquisition

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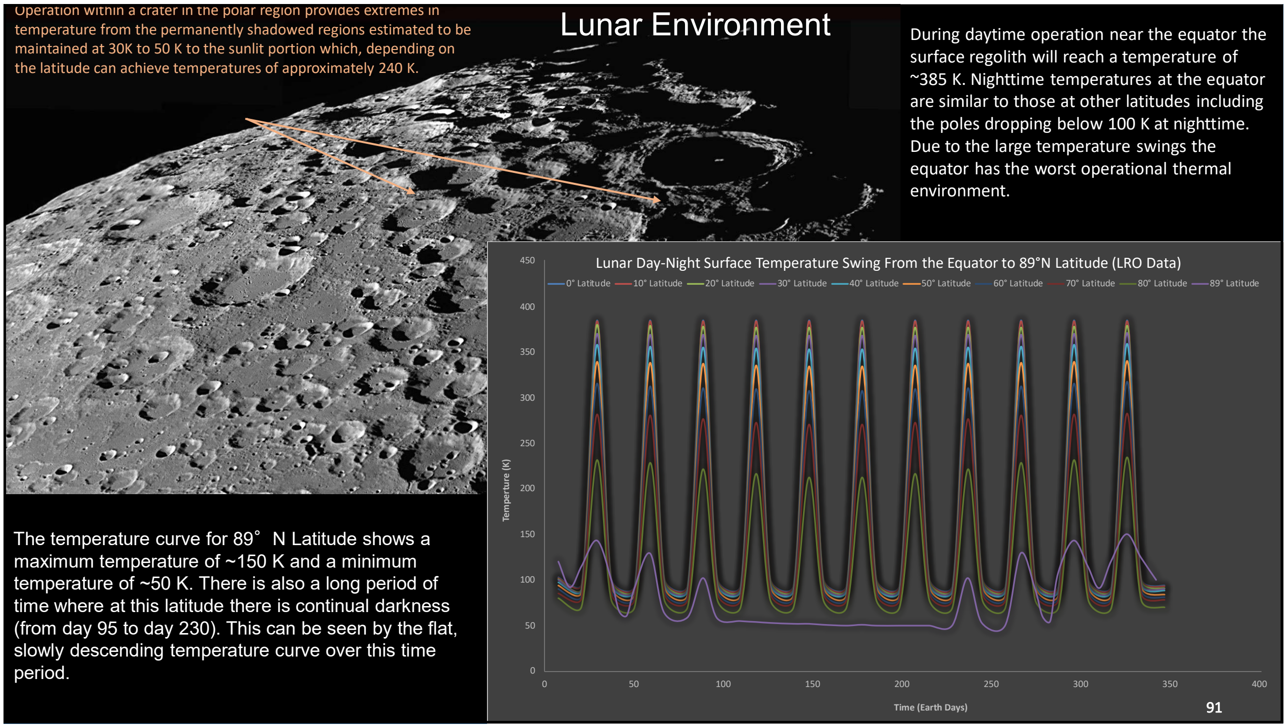
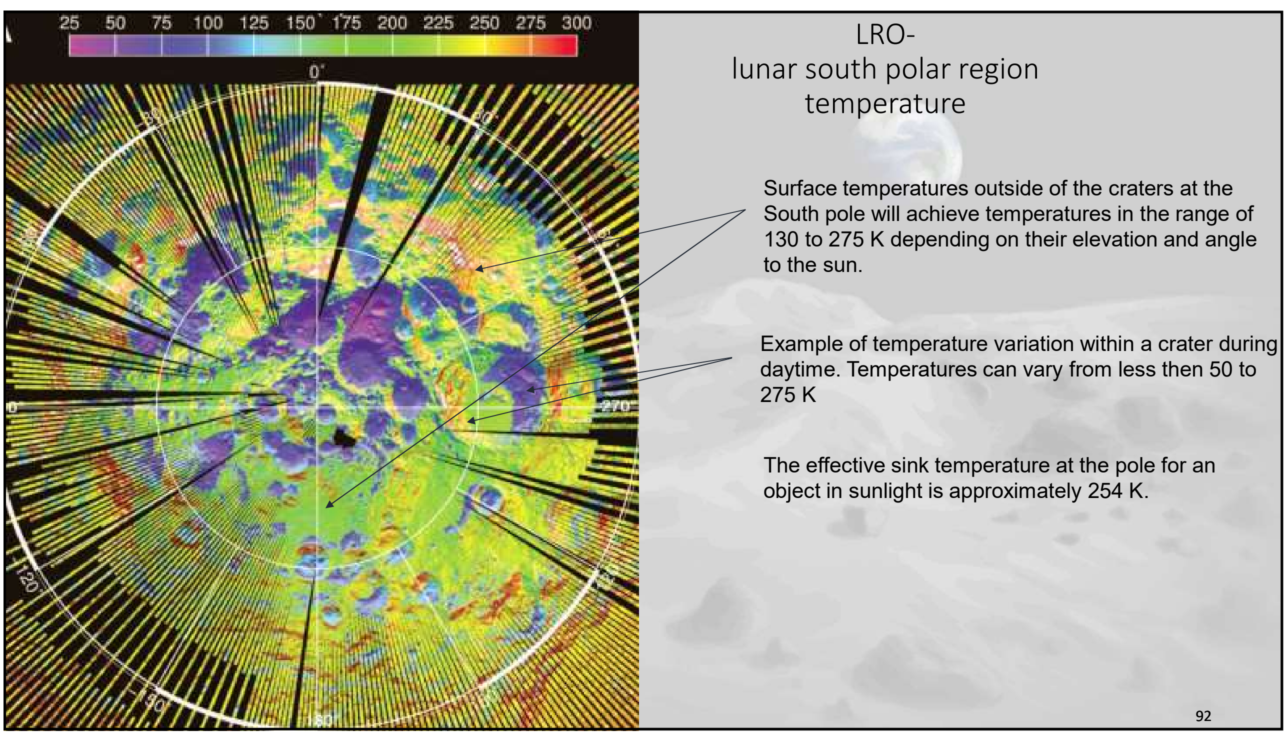

Operation within a crater in the polar region provides extremes in temperature from the permanently shadowed regions estimated to be maintained at 30K to 50 K to the sunlit portion which, depending on the latitude can achieve temperatures of approximately 240 K.
Lunar Environment
During daytime operation near the equator the surface regolith will reach a temperature of ~385 K. Nighttime temperatures at the equator are similar to those at other latitudes including the poles dropping below 100 K at nighttime. Due to the large temperature swings the equator has the worst operational thermal environment.
Lunar Day-Night Surface Temperature Swing From the Equator to 89°N Latitude (LRO Data)
0° Latitude
10° Latitude
20° Latitude
30° Latitude
40° Latitude
50° Latitude
60° Latitude
70° Latitude
80° Latitude
89° Latitude
Temperture (K)
Time (Earth Days)
The temperature curve for 89° N Latitude shows a maximum temperature of ~150 K and a minimum temperature of ~50 K. There is also a long period of time where at this latitude there is continual darkness (from day 95 to day 230). This can be seen by the flat, slowly descending temperature curve over this time period.
91


LRO-
lunar south polar region
temperature
Surface temperatures outside of the craters at the South pole will achieve temperatures in the range of 130 to 275 K depending on their elevation and angle to the sun.
Example of temperature variation within a crater during daytime. Temperatures can vary from less then 50 to 275 K
The effective sink temperature at the pole for an object in sunlight is approximately 254 K.
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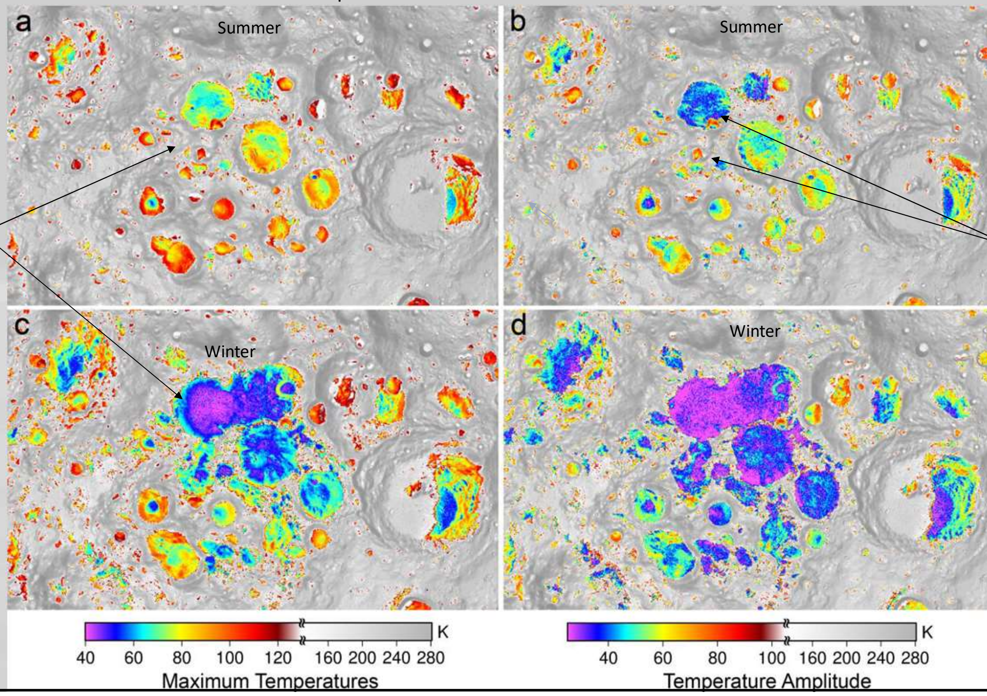
Maximum Temperatures PSRs near the South Pole



Example of temperature variation within a crater between summer and winter 40 to 70 K

Winter temperature within the PSRs are stable with little variation.

Smaller Craters tend to have larger temperature variation then the larger PSR craters

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Thermal Component Specifications and Input Values

The following table identifies the rover specification, assumptions and requirements for the thermal system design and operation.

Specifications	Value/Description
Dimensions: Rover Insulation	Estimated Electronics Enclosure Plus Heat Shielding: Length: 1.0 m, Width: 1.5 m, Height: 1.5 m Insulation surface area: 10.5 m^2
Waste heat:	Electronics Systems: 221.5 W
Operating Temperature	Electronics: 300 K
Insulation (MLI)	25 layers of MLI are used to cover all external surfaces for the electronics boxes and tank.
Environment	Lunar Polar (154 to 50 K) surface temperature range
Radiators	Surface mount radiator for rejecting heat from the electronics. Louvers are utilized on the radiator to adjust the heat flow to the surroundings between operation outside the crater under sunlit conditions and operation within the permanently shadowed crater.
Cooling	Water heat pipes with cold plates are used to move the heat from the electronics to the radiator.
Heating	Electric heaters are used to provide heating to the internal components as needed.

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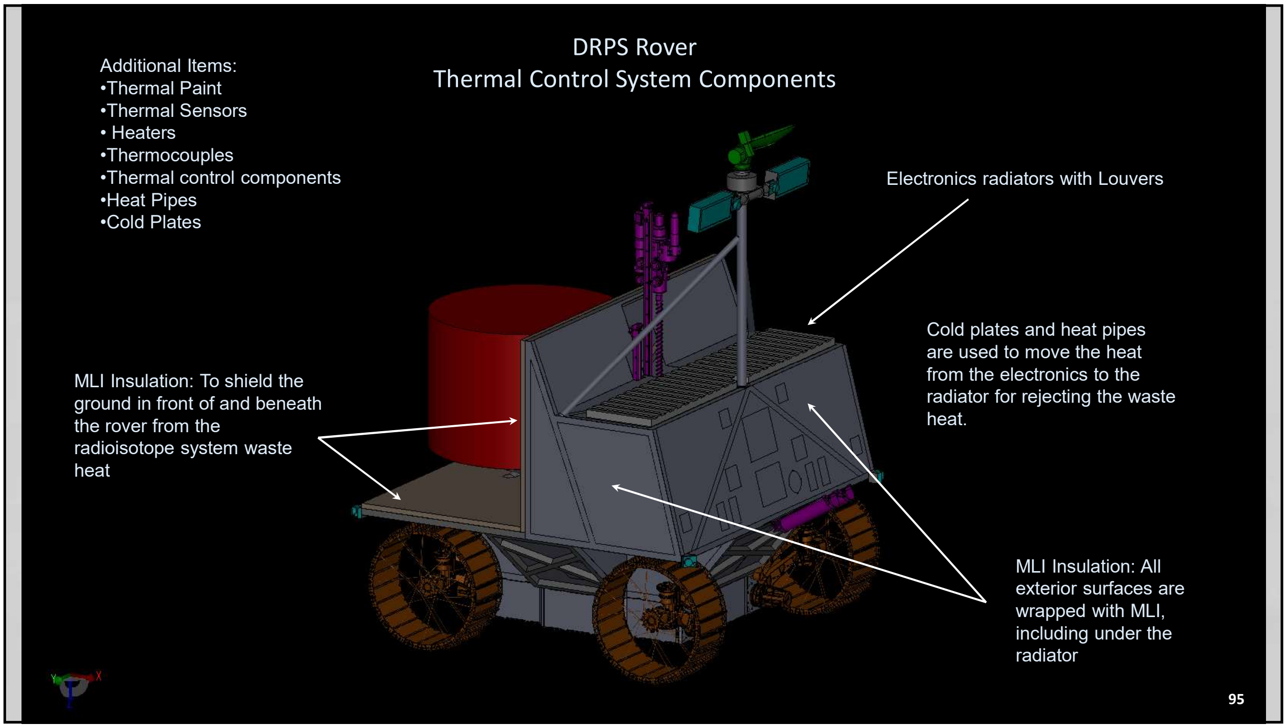
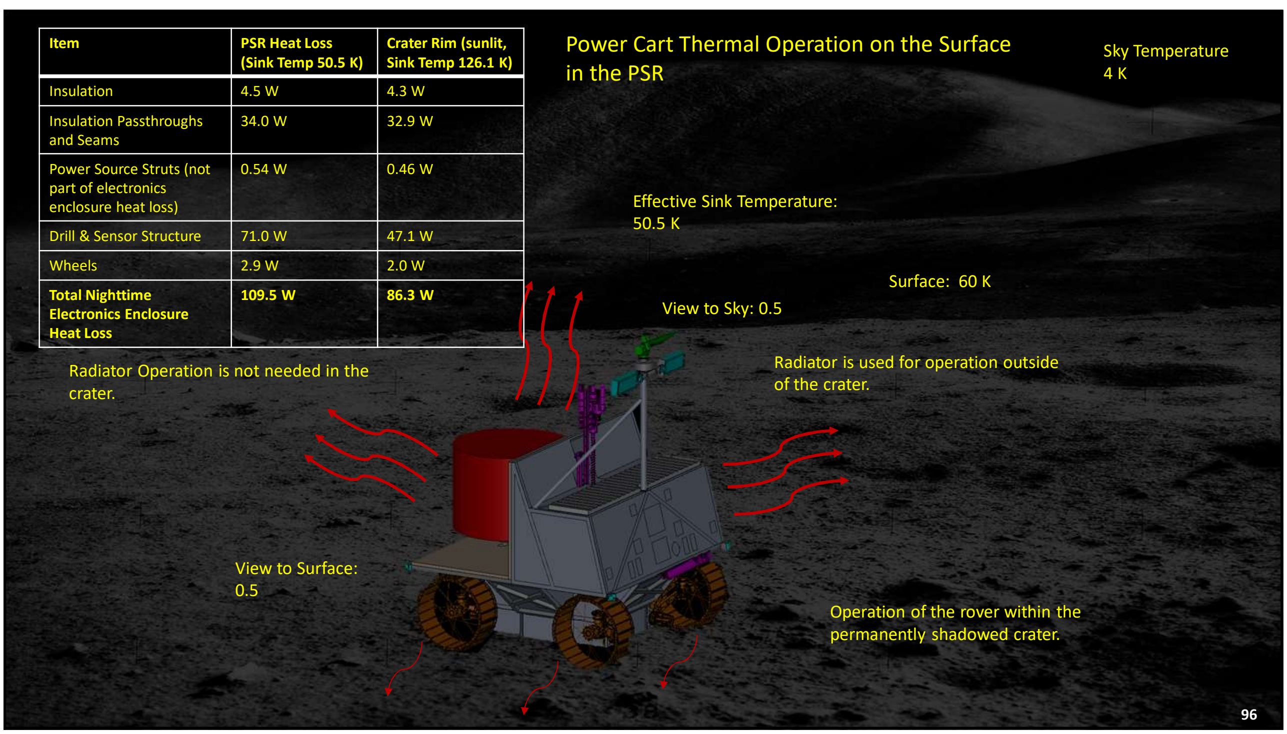
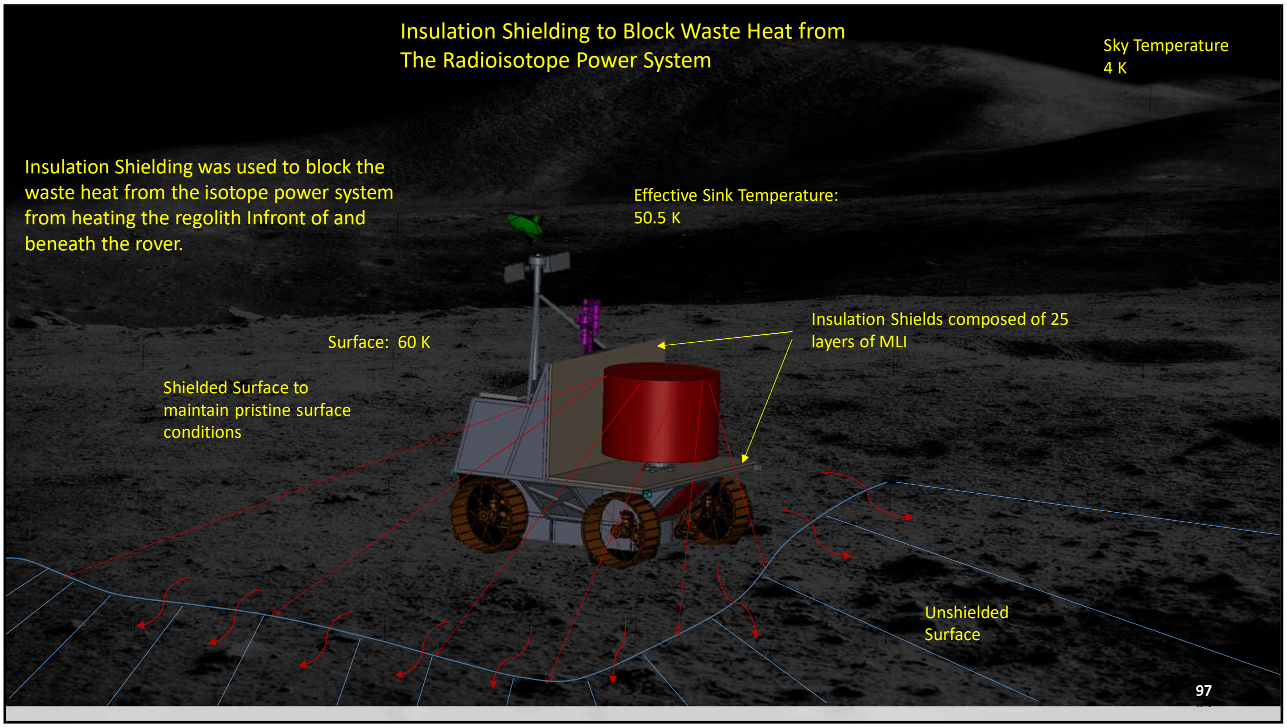
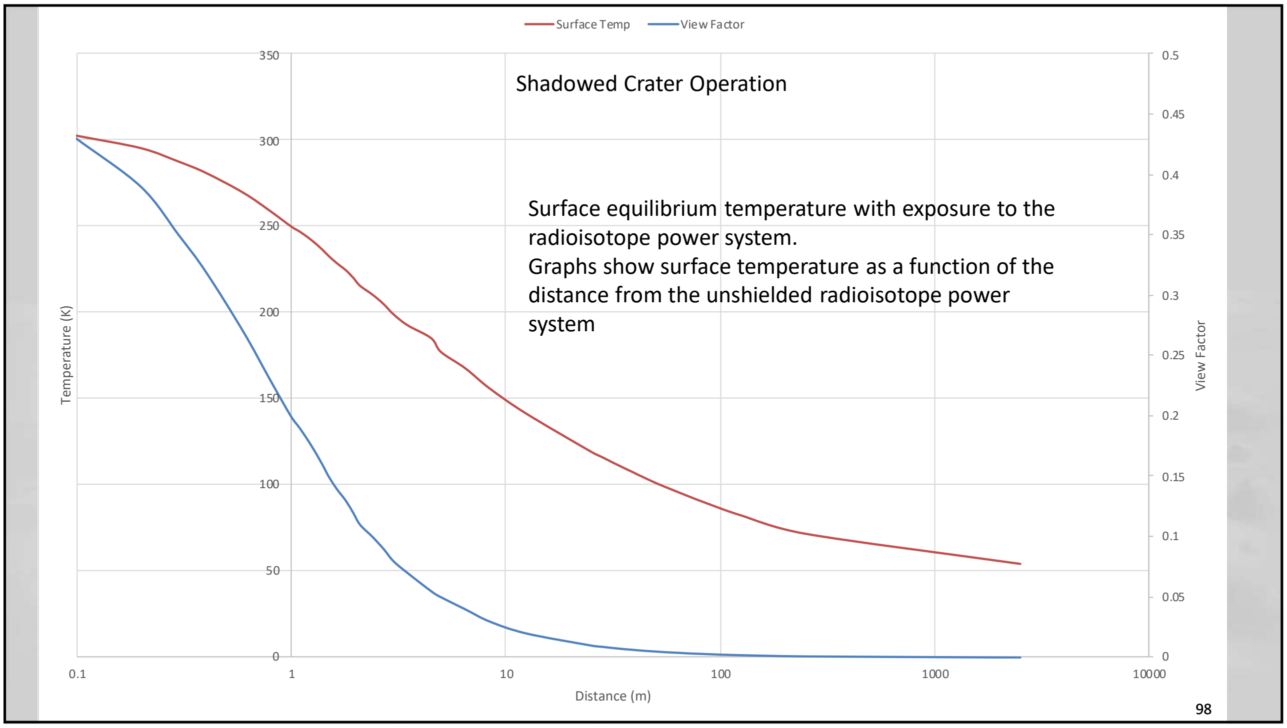




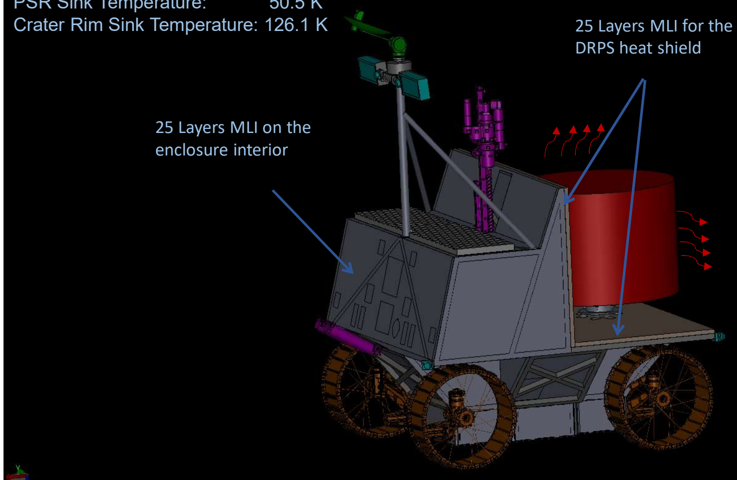
Item	PSR Heat Loss (Sink Temp 50.5 K)	Crater Rim (sunlit, Sink Temp 126.1 K)
Insulation	4.5 W	4.3 W
Insulation Passthroughs and Seams	34.0 W	32.9 W
Power Source Struts (not part of electronics enclosure heat loss)	0.54 W	0.46 W
Drill & Sensor Structure	71.0 W	47.1 W
Wheels	2.9 W	2.0 W
Total Nighttime Electronics Enclosure Heat Loss	**109.5 W**	**86.3 W**

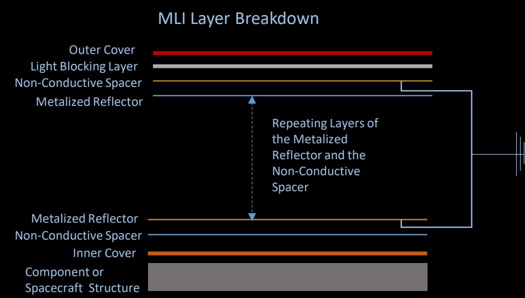

Insulation Shielding to Block Waste Heat from
The Radioisotope Power System
Sky Temperature
4 K
Insulation Shielding was used to block the waste heat from the isotope power system from heating the regolith Infront of and beneath the rover.
Effective Sink Temperature:
50.5 K
Insulation Shields composed of 25 layers of MLI
Surface: 60 K
Shielded Surface to maintain pristine surface conditions
Unshielded
Surface
97


Surface Temp
View Factor
Shadowed Crater Operation
Surface equilibrium temperature with exposure to the radioisotope power system.
Graphs show surface temperature as a function of the distance from the unshielded radioisotope power system
Temperature (K)
View Factor
Distance (m)
0
50
100
150
200
250
300
350
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.1
1
10
100
1000
10000
98

Insulation

PSR Sink Temperature: 50.5 K
Crater Rim Sink Temperature: 126.1 K





Total heater or waste heat power: 109.5 W in the PSR, 86.3 W on the crater rim.
MLI is used to insulate exterior of the electronics and sensor housing.
The insulation has a very low effective thermal conductivity and density.
Effective Thermal conductivity = 0.00016 W/mK
Density = 20 kg/m^3

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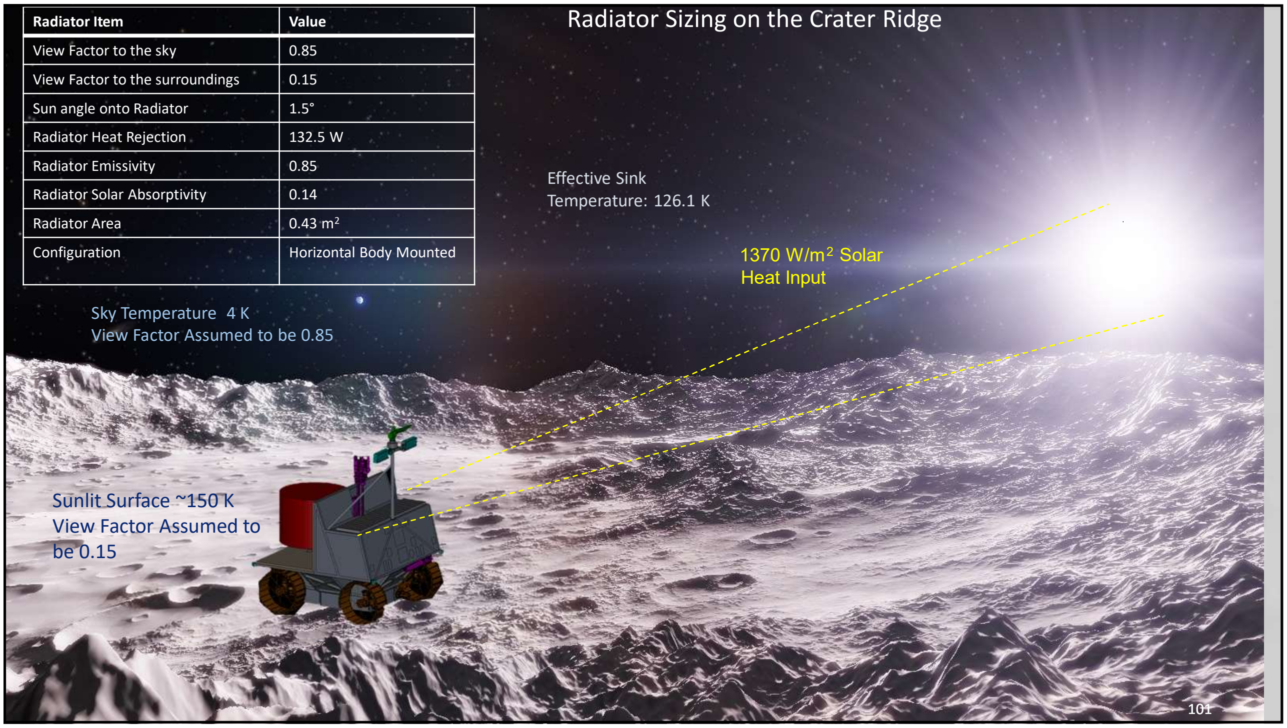
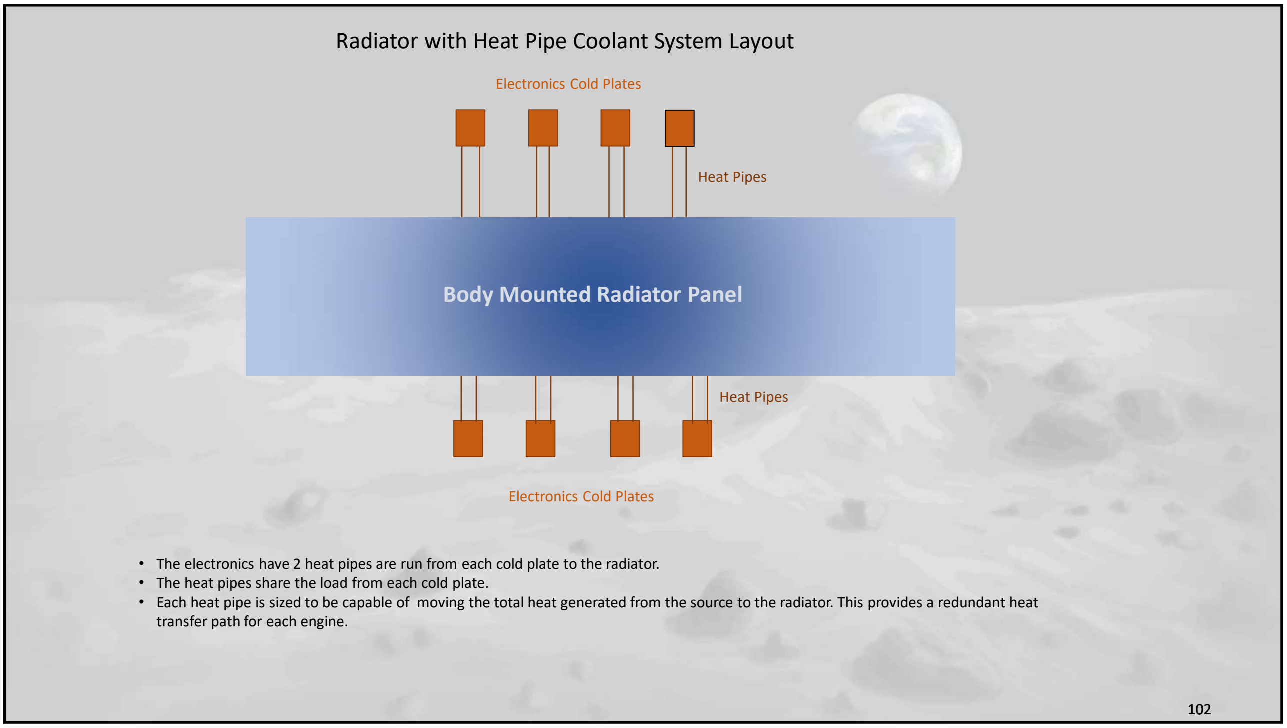
Thermal Analysis: Radiator Sizing

- The radiator is located on the top deck of the DRPS rover. This provides a good view to deep space and minimizes the sun angle to the radiator. There is insulation between the radiator and rover body providing a single surface for radiating. The radiator is connected to the cold plates with heat pipes to move heat from the interior to the radiator.
- The radiator sizing was based on an energy balance analysis of the area needed to reject the identified heat load to space. From the area a series of scaling equations were used to determine the mass of the radiator.
- The radiator was sized to remove the waste heat from the service rover during worst case hot operational conditions which occur while sunlit on the lunar surface with all equipment operating.
- Louvers were used on the radiator to help minimize heat loss during times when the rover will be operating in the PSR.
- The radiator is a body mounted single panel horizontally mounted on the upper deck of the DRPS powered rover.

Variable	Value
Radiator Solar Absorptivity	0.14
Radiator Emissivity	0.84
Max Radiator Sun Angle View Factor lunar surface	1.5˚ 0.15
Radiator Operating Temperature	300 K Crater Rim (sunlight operation) 300 K In PSR
Power Dissipation & Radiator Area:	Total Power Dissipation is 221.5 W of this 89 W are lost as waste heat to the surroundings. Total Rejected Heat: 132.5 W

100


Radiator Sizing on the Crater Ridge
Radiator Item | Value
View Factor to the sky | 0.85
View Factor to the surroundings | 0.15
Sun angle onto Radiator | 1.5°
Radiator Heat Rejection | 132.5 W
Radiator Emissivity | 0.85
Radiator Solar Absorptivity | 0.14
Radiator Area | 0.43 m2
Configuration | Horizontal Body Mounted
Effective Sink Temperature: 126.1 K
1370 W/m2 Solar Heat Input
Sky Temperature 4 K
View Factor Assumed to be 0.85
Sunlit Surface ~150 K
View Factor Assumed to be 0.15
101


Radiator with Heat Pipe Coolant System Layout
Electronics Cold Plates
Heat Pipes
Body Mounted Radiator Panel
Heat Pipes
Electronics Cold Plates
• The electronics have 2 heat pipes are run from each cold plate to the radiator.
• The heat pipes share the load from each cold plate.
• Each heat pipe is sized to be capable of moving the total heat generated from the source to the radiator. This provides a redundant heat transfer path for each engine.
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Case 1_DRPS_DRM_Rover - Rover: Thermal Control

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Thermal Control (Non-Propellant)			**34.8**	**18%**	**6.3**	**41.0**
Active Thermal Control			**2.5**	**18%**	**0.5**	**3.0**
Heaters	8	0.1	0.4	18%	0.1	0.5
Thermocouples	8	0.0	0.1	18%	0.0	0.1
Data Acquisition	5	0.3	1.3	18%	0.2	1.5
Switches	8	0.1	0.8	18%	0.1	0.9
Passive Thermal Control			**27.2**	**18%**	**4.9**	**32.1**
MLI Insulation	1	18.6	18.6	18%	3.4	22.0
Electronics Cold Plates	8	0.1	1.1	18%	0.2	1.3
Electronics Heat pipes	16	0.4	6.6	18%	1.2	7.7
thermal paint	1	0.9	0.9	18%	0.2	1.1
Semi-Passive Thermal Control			**5.0**	**18%**	**0.9**	**5.9**
Electronics Radiator	1	3.2	3.2	18%	0.6	3.8
Radiator Louvers	1	1.8	1.8	18%	0.3	2.2

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Case 2_Brayton_DRPS_DRM_Rover - Rover: Thermal Control

Description Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Thermal Control (Non-Propellant)			**36.2**	**18%**	**6.5**	**42.7**
Active Thermal Control			**2.5**	**18%**	**0.5**	**3.0**
Heaters	8	0.1	0.4	18%	0.1	0.5
Thermocouples	8	0.0	0.1	18%	0.0	0.1
Data Acquisition	5	0.3	1.3	18%	0.2	1.5
Switches	8	0.1	0.8	18%	0.1	0.9
Passive Thermal Control			**28.6**	**18%**	**5.2**	**33.8**
MLI Insulation	1	20.0	20.0	18%	3.6	23.6
Electronics Cold Plates	8	0.1	1.1	18%	0.2	1.3
Electronics Heat pipes	16	0.4	6.6	18%	1.2	7.7
thermal paint	1	0.9	0.9	18%	0.2	1.1
Semi-Passive Thermal Control			**5.0**	**18%**	**0.9**	**5.9**
Electronics Radiator	1	3.2	3.2	18%	0.6	3.8
Radiator Louvers	1	1.8	1.8	18%	0.3	2.2

Case 2 required more MLI to cover the added wall height

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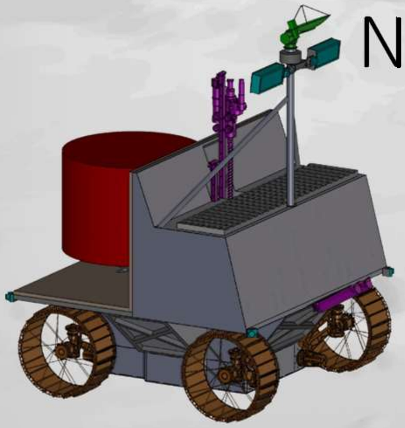
Navigation System



Brent Faller

105

Navigation System: Requirements and Assumptions

- Requirements
  - Zero fault tolerant
  - Provide hardware capability to navigate autonomously between waypoints
  - Provide hardware capability to detect hazards in possible directions of travel
- Assumptions
  - Remote Operator can issue waypoint commands to rover in rover local frame of reference

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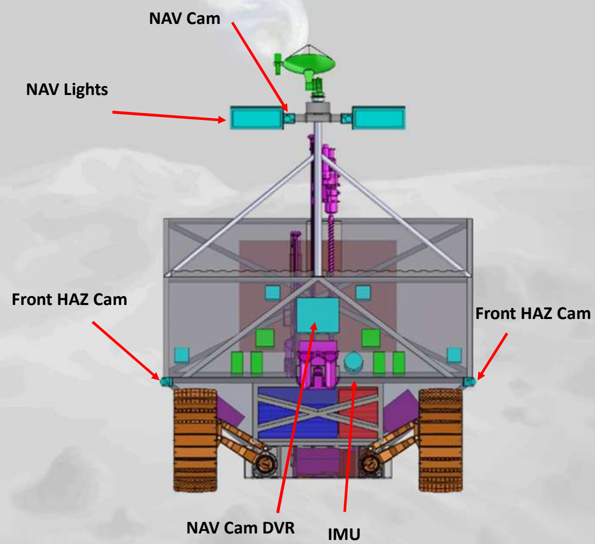
Design Summary

- Inertial Measurement Unit (IMU)
  - Three single-axis rate gyros to measure vehicle body rates
  - Three single-axis accelerometers to measure vehicle body accelerations
  - Both provide information about rover attitude
- Navigation Camera (x2)
  - Based on MSL Curiosity Rover NAVCAMS
  - Stereo Ranging out to ~100 m
  - 45° FOV | 0.5 m DoF
  - Mounted on Articulating Mast
- Hazard Cameras (x4)
  - Based on MSL Curiosity Rover HAZCAMS
  - Stereo Ranging in front of and behind rover to assist in immediate hazard detection
  - One mounted on each corner
  - 120° FOV | 0.10 m DoF
- Navigation Lights
  - Based on VIPER lights
  - LED Array of lights fitted alongside NAVCAMS on mast
  - Can be “charged up” to illuminate ~8 m so the NAVCAMS can image the area



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Navigation Strategy

- Points of Interest are selected by remote operators who command the rover to waypoints. Commands are presented in local frame of rover.
- Primary form of navigation and guidance is autonomous once a waypoint is commanded.
- Rover utilizes a Simultaneous Localization and Mapping (SLAM) algorithm which processes stereo images taken by the NAV Cams in the direction of travel and to establish landmarks that can be used to estimate rover position with respect to the landmarks
- While moving, the rover discharges an energy storage device to illuminate ~8 m out in front of the forward direction once every 30 s (6 m of travel at 20 cm/s)
- Rover can remain stationary and image surrounding terrain to obtain map information and reduce local position uncertainty
- Hazard Cams provide high resolution stereo images of area just in front of and behind rover. Hazard detection and avoidance algorithms employed to make minute adjustments when necessary
- IMU provides additional information regarding effectiveness of commanded motion, tilt, etc.

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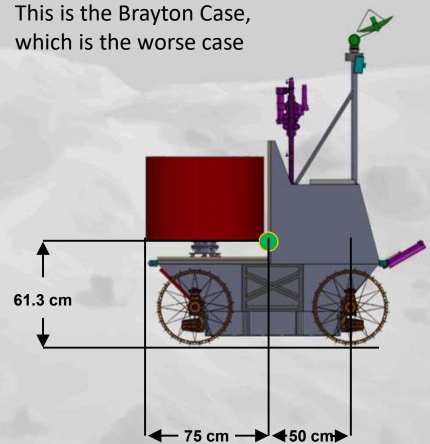
Tip-Over Study

- A static tip-over study was conducted for the configuration of the rover most prone to tip-over (all wheels fully raised)
  - Rover CG
    - The rover CG was estimated using a representative CAD model along with the component masses from the system MEL
    - Forward distribution of components nearly counters significant mass of DRPS
- The shorter wheelbase compared to the wheel track leads to a higher chance of tipping forward or backward

- NOTE: Independent suspension can keep the body of rover level on slopes up to ~14°. This increases the maximum slope the rover can be on to ~47° for static case

CG (Fully Raised)	Tip-Over Angle
(0.0 0.0 111.2)cm	~33°

This is the Brayton Case, which is the worse case



109

Forward Work

- Refine SLAM parameters
  - How often to take images
  - How often is it necessary to take "panoramic" nav images to generate localization and mapping statistics/probabilities?
  - What is the best way to enter a crater using SLAM?
- Perform dynamic tip-over analysis
  - Can mobility system "turn into direction of tip-over" to avoid it?
  - How does slipping down a slope affect the maximum sustainable slope?

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Case 1_DRPS_DRM_Rover - Rover: Attitude Determination and Control

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Attitude Determination and Control			**4.7**	**12%**	**0.6**	**5.3**
Guidance, Navigation, & Control			**4.7**	**12%**	**0.6**	**5.3**
IMU	1	0.8	0.8	5%	0.0	0.8
NAV Camera	2	0.2	0.4	10%	0.0	0.5
HAZ Cameras	4	0.2	0.9	10%	0.1	1.0
OpNav DVR	1	1.1	1.1	10%	0.1	1.2
NAV Lights	2	0.8	1.5	18%	0.3	1.8

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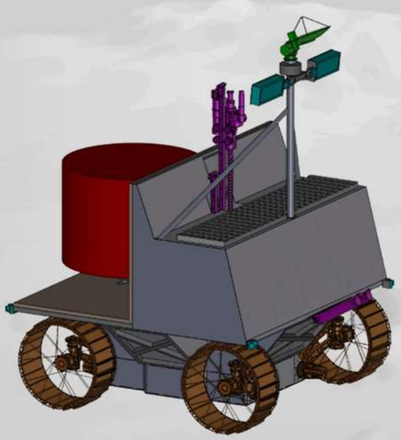
Command and Data Handling



Chris Heldman

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DRPS DRM Rover Avionics Overview

- **Design Requirements**
  - Radiation Hardened Avionics
    - 100 krad TID avionics assumed.
    - SEU/SEFI Detection and Reset for Avionics
  - Single Fault Tolerant Avionics for Science, G&NC, Comm, etc.
  - Mobility System is not Fault Tolerant
  - Avionics provide commanding, control and health management to the following subsystems:
    - Mobility System
    - Science, G&NC, Comm, etc.
- **Design Description**
  - Avionics components based on military/space grade commercially available components from proven aerospace system vendors.
  - All components have a high TRL of 7-8.
  - 3U form factor cards in cPCI card cage with backplane
  - PowerPC-class processor, several types of I/O cards, and actuator driver cards
  - Enclosure package included any necessary DC-DC converters, filter, and EMI shielding.
- **Risks and Comments**
  - Possible Risks:
    - Radiation damage to the electronic hardware
  - Certain command interface information were not known. Assumptions were made in this design and additional hardware may be needed to satisfy requirements

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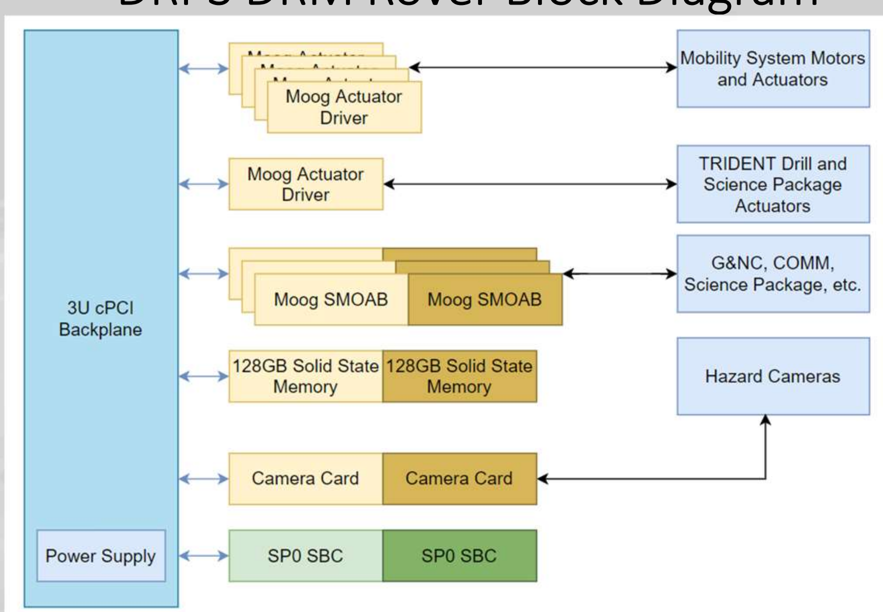
DRPS DRM Rover Block Diagram



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DRPS DRM Rover Actuator Driver Overview

– **Custom Motor/Actuator Driver Electronics**
- Sizing based on Moog Motor control suite performance

Actuator Name	Peak Power/Actuator	Number Actuators
Locomotion	75	12
Science & Navigation	66	1
Drill	175	1
Comm & Track Gimbal	5	4

5 3U cPCI Cards

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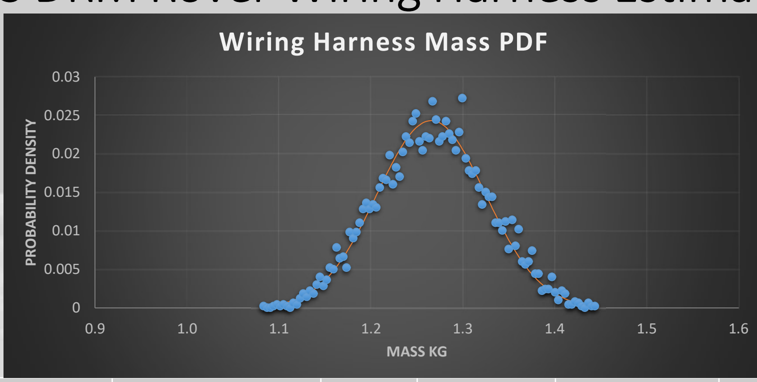
DRPS DRM Rover Wiring Harness Estimation



Cable	Wire Protocol	kg/m	Num. cables	Min Length (m)	Max Length (m)
Suspension Actuators	22 AWG	0.0035	8	0.85	1.2
Steering Actuators	22 AWG	0.0035	8	0.85	1.2
Drive Actuators	22 AWG	0.0035	8	0.85	1.2
Thermal Sensors	24 AWG	0.0022	10	0.5	3.5
NAC Cameras OpNav DVR	Twinax 28 AWG	0.058	5	1.4	1.7
HAZ Cameras	22 AWG	0.0035	4	1.2	1.6
RPS Controller	Twinax 28 AWG	0.058	5	0.65	1.1
SDR - TX/RX	Twinax 28 AWG	0.058	5	1.1	1.45
Antenna Gimbal	24 AWG	0.0022	6	2.4	3.9

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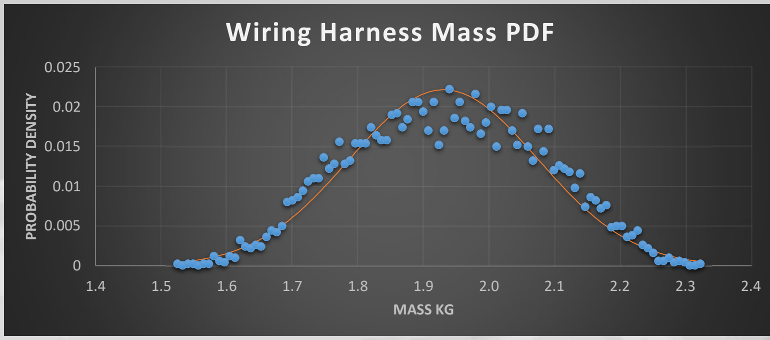
Science Components Wiring Harness Estimation



Cable	Wire Protocol	kg/m	Num. cables	Min Length (m)	Max Length (m)
NSS Sensor Modules	Twinax 28 AWG	0.058	5	0.5	0.8
NSS Data Processing Modules	Twinax 28 AWG	0.058	5	0.25	0.4
NIRVSS Spectrometer Modules	Twinax 28 AWG	0.058	5	0.6	0.8
Msolo	Twinax 28 AWG	0.058	5	0.8	1.2
TRIDENT	Twinax 28 AWG	0.058	5	1.5	2.1
TBD Instruments	Twinax 28 AWG	0.058	5	1	2.5
TRIDENT Drill Drive	20 AWG	0.035	2	1.5	2.1

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Case 1_DRPS_DRM_Rover - Rover: Command and Data Handling

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Command & Data Handling			**18.4**	**42%**	**7.7**	**26.1**
C&DH Hardware			**15.2**	**30%**	**4.5**	**19.7**
AiTech SP0 SBC	2	0.4	0.8	30%	0.2	1.0
Moog Actuator Driver	5	0.5	2.5	30%	0.8	3.3
Moog SMOAB	6	0.4	2.4	30%	0.7	3.1
Moog CASI	2	0.3	0.6	30%	0.2	0.7
M4 Memory	2	1.0	2.0	30%	0.6	2.6
Avionics Enclosure	1	6.9	6.9	30%	2.1	9.0
Instrumentation & Wiring			**3.2**	**100%**	**3.2**	**6.4**
Harness	1	3.2	3.2	100%	3.2	6.4

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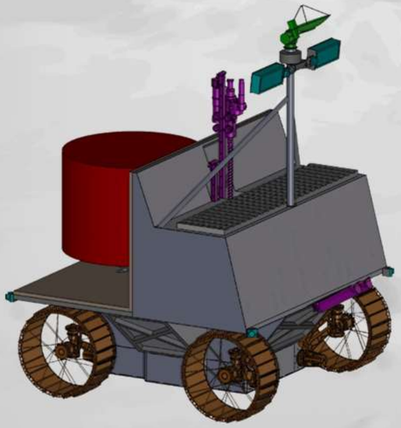
Communications and Tracking

Noulie Theofylaktos



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Mission Communications Summary

- Primary Channel: **230** kbps Transmitted to Gateway (Lunar Orbiter Satellite)
- Emergency Channel: **2** kbps Transmitted via Circular Waveguide Feed-horn
- Distance to Lunar Orbiter Satellite (Apolune) **70,000** km
- Gateway 1.5-m ***Tracking*** Antenna
  - G/T: **16.7** dBi/K (**23.17** GHz, Rx Antenna BW = 0.6^{o})
    - Receive System Temp: 1550 K
  - EIRP: **54.6** dBW (**27.11** GHz, Tx Antenna BW = 0.5^{o})
- Primary DRPS Antenna: **25.4-cm** Ka-band Gimballed Parabolic Reflector
- Emergency DRPS Ant.: Circular Waveguide Feed-horn with Protective Cover
- Ka-Band Transceivers Must be Close to Ka-band Antennas (–0.6 dB/ft cable loss)
- Lunar Temperatures: 30 to 280 K
- DRPS Receive System Operating Temperature: 270 to 320 K (Average 290 K)
- Single-Fault Tolerant Subsystem
- TRL 6 (or higher)

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Information Direction	DRPS HGA to Gateway	DRPS LGA* to Gateway	DRPS HGA to DTE	DRPS LGA to DTE
Carrier Frequency (f, GHz)	23.17		23.17	
Carrier Wavelength (λ, mm)	12.9		12.9	
Transmitter Power (W)	1		1	
Tx Losses (dB)	-1		-1	
Tx Antenna Point Loss (dB)	-0.3		-0.3	
Tx Antenna Diameter (cm)	25.4	–	25.4	–
Tx Antenna Beamwidth (°)	3.6	30	3.6	30
Tx Antenna Gain (dBi)	33.2	12.6	33.2	12.6
EIRP (dBW)	31.9	11.2	31.9	16
Separation Distance (km)	70,000		385,000	
Rx Antenna Point Loss	0		0	
Rx Antenna Diameter (m)	1.5		20	
Rx Antenna Beamwidth(°)	0.60		0.05	
Rx Antenna Gain (dBi)	48.6		71.1	
Waveguide Loss (dB)	0		0	
Receiver Noise Temp (K)	1550		512	
G/T (dBi/K)	16.7		44	
Information Rate (kbps)	245	2	230	2
Bit Error Rate	10^{-7}			
Modulation Scheme	DVB-S2 QPSK			
Implementation Loss (dB)	-3			
Coding Scheme	DVB-S2 (1/4)			
Coding Loss (dB)	-0.5			
Link Power Margin (dB)	3			
Weather Margin (dB)	N/A	N/A	12.7	12.7
	*Circular Waveguide Feedhorn (15dBi) WC-10.06mm (or WC-0.396") Diameter (Mid-K: 20.0 - 24.5 GHz)			

UPLINK BUDGET

TX LUNAR LOCATION: ***SPUDIS RIDGE Crater at the South Pole.***
Connecting Crater with the Gateway Lunar Relay or Direct To Earth

121

	Information Direction	Gateway to HGA DRPS	Gateway to LGA DRPS	DFE to HGA DRPS	DFE to LGA DRPS
2	Information Direction	Gateway to HGA DRPS	Gateway to LGA DRPS	DFE to HGA DRPS	DFE to LGA DRPS
3	Carrier Frequency (f, GHz)	27.11		27.11	
4	Carrier Wavelength (λ, mm)	11.1		11.1	
5	Transmitter Power (W)	—		1	
6	Tx Losses (dB)	—		-1	
7	Tx Antenna Point Loss (dB)	—		-0.3	
8	Tx Antenna Diameter (cm)	150		2000	
9	Tx Antenna Beamwidth (°)	0.5		0.04	
10	Tx Antenna Gain (dBi)	—		72.5	
11	EIRP (dBW)	54.6		71.2	
12	Separation Distance (km)	70,000		385,000	
13	Rx Antenna Point Loss	0		0	
14	Rx Antenna Diameter (m)	0.254	—	0.254	—
15	Rx Antenna Beamwidth(°)	3	30	3	30
16	Rx Antenna Gain (dBi)	34.5	13.5	34.5	13.5
17	Waveguide Loss (dB)	-1.3		-1.3	
18	Receiver Noise Temp (K)	1247		1247	
19	G/T (dBi/K)	4.9	-16.1	4.9	-16.1
20	Information Rate (kbps)	2,200	15	123	1
21	Bit Error Rate	10^{-7}			
22	Modulation Scheme	DVB-S2 QPSK			
23	Implementation Loss (dB)	-3			
24	Coding Scheme	DVB-S2 (1/4)			
25	Coding Loss (dB)	-0.5			
26	Link Power Margin (dB)	3			
27	Weather Margin (dB)	N/A	N/A	14.2	14.2

DOWNLINK BUDGET

RX LUNAR LOCATION: ***SPUDIS RIDGE Crater at the South Pole.***
Connecting Crater with the Gateway Lunar Relay or Direct From Earth

122

LINK.BUDGET

LUNAR LOCATION: SPUDIS RIDGE Crater at the South Pole

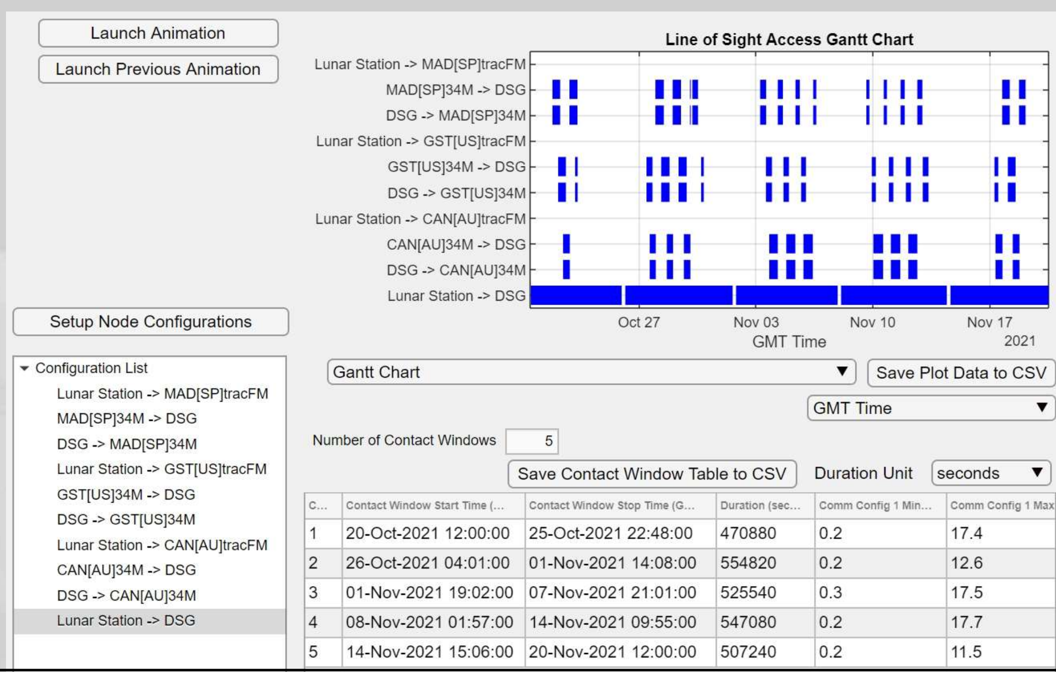
Connecting Crater with the Gateway Lunar Relay (or DTE/DFE)

Information Direction	DRPS HGA to GtWay	DRPS LGA* to GtWay	DRPS HGA to DTE	DRPS LGA to DTE	GtWay to HGA DRPS	GtWay to LGA DRPS	DFE to HGA DRPS	DFE to LGA DRPS
Carrier Frequency (f,GHz)	23.17		23.17		27.11		27.11	
Carrier Wavelength (λ,mm)	12.9		12.9		11.1		11.1	
Transmitter Power (W)	1		1		—		1	
Tx Losses (dB)	-1		-1		—		-1	
Tx Antenna Point Loss (dB)	-0.3		-0.3		—		-0.3	
Tx Antenna Diameter (cm)	25.4	—	25.4	—	150		2000	
Tx Antenna Beamwidth (°)	3.6	30	3.6	30	0.5		0.04	
Tx Antenna Gain (dBi)	33.2	12.6	33.2	12.6	—		72.5	
EIRP (dBW)	31.9	11.2	31.9	16	54.6		71.2	
Separation Distance (km)	70,000		385,000		70,000		385,000	
Rx Antenna Point Loss	0		0		0		0	
Rx Antenna Diameter (m)	1.5		20		0.254	—	0.254	—
Rx Antenna Beamwidth(°)	0.60		0.05		3	30	3	30
Rx Antenna Gain (dBi)	48.6		71.1		34.5	13.5	34.5	13.5
Waveguide Loss (dB)	0		0		-1.3		-1.3	
Receiver Noise Temp (K)	1550		512		1247		1247	
G/T (dBi/K)	16.7		44		4.9	-16.1	4.9	-16.1
Information Rate (kbps)	245	2	230	2	2,200	15	123	1
Bit Error Rate	10^{-7}							
Modulation Scheme	DVB-S2 QPSK							
Implementation Loss (dB)	-3							
Coding Scheme	DVB-S2 (1/4)							
Coding Loss (dB)	-0.5							
Link Power Margin (dB)	3							
Weather Margin (dB)	N/A	N/A	12.7	12.7	N/A	N/A	14.2	14.2

*Circular W/G Feedhorn (15dBi): WC-10.06mm (or WC-0.396") Diameter (Mid-K: 20.0 - 24.5 GHz)

123

Average Access Window **145 hours** at a **max of 72°** away from DSG **Field-Of-View** Vector Axis in any Direction



C...	Contact Window Start Time (...	Contact Window Stop Time (G...	Duration (sec...	Comm Config 1 Min...	Comm Config 1 Max
1	20-Oct-2021 12:00:00	25-Oct-2021 22:48:00	470880	0.2	17.4
2	26-Oct-2021 04:01:00	01-Nov-2021 14:08:00	554820	0.2	12.6
3	01-Nov-2021 19:02:00	07-Nov-2021 21:01:00	525540	0.3	17.5
4	08-Nov-2021 01:57:00	14-Nov-2021 09:55:00	547080	0.2	17.7
5	14-Nov-2021 15:06:00	20-Nov-2021 12:00:00	507240	0.2	11.5

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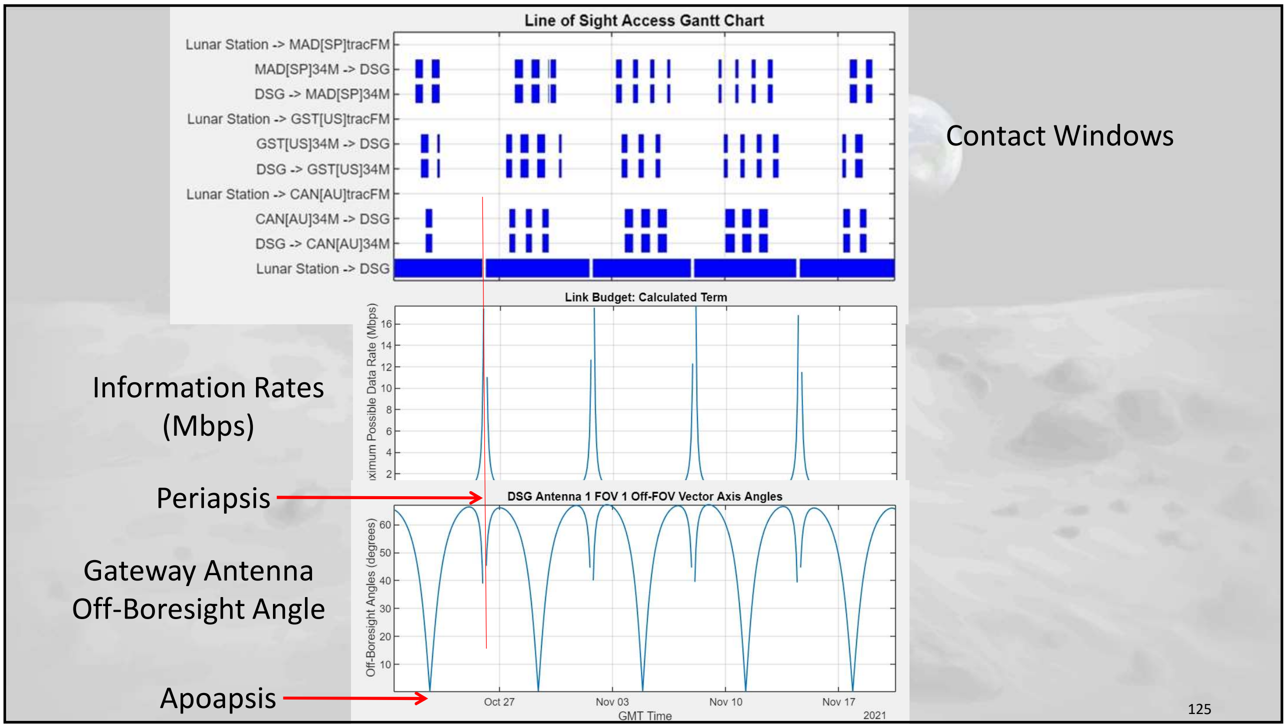
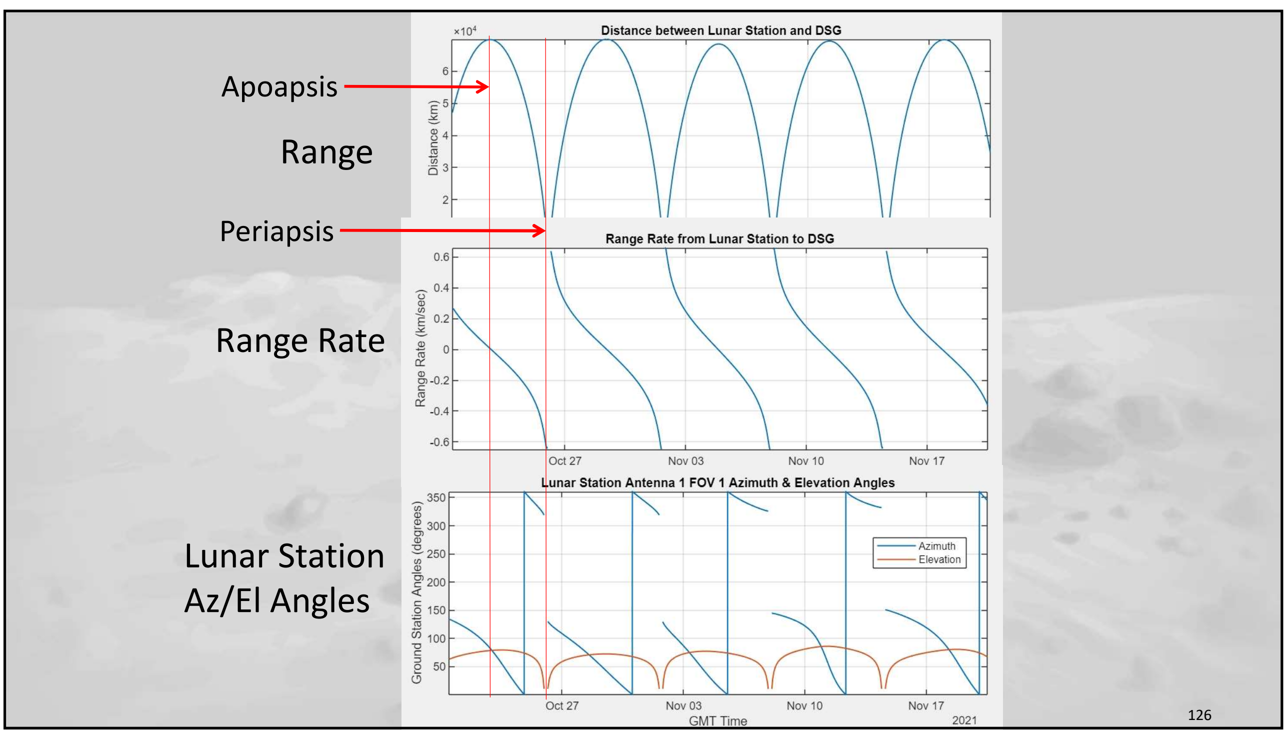
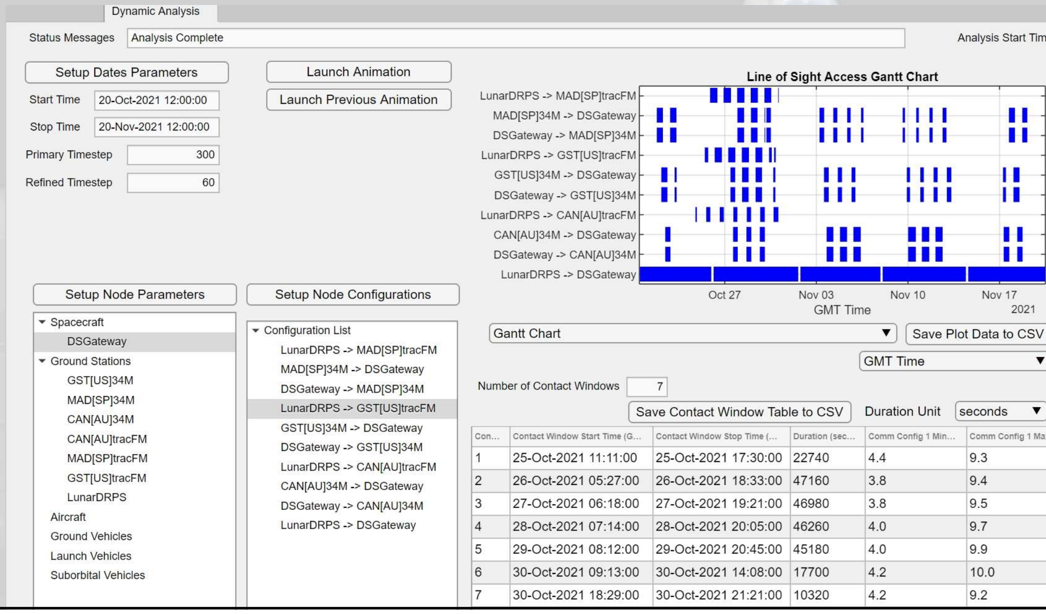

Line of Sight Access Gantt Chart
Lunar Station -> MAD[SP]tracFM
MAD[SP]34M -> DSG
DSG -> MAD[SP]34M
Lunar Station -> GST[US]tracFM
GST[US]34M -> DSG
DSG -> GST[US]34M
Lunar Station -> CAN[AU]tracFM
CAN[AU]34M -> DSG
DSG -> CAN[AU]34M
Lunar Station -> DSG
Contact Windows
Link Budget: Calculated Term
Information Rates (Mbps)
Periapsis
DSG Antenna 1 FOV 1 Off-FOV Vector Axis Angles
Gateway Antenna Off-Boresight Angle
Off-Boresight Angles (degrees)
Apoapsis
Oct 27
Nov 03
Nov 10
Nov 17
GMT Time
2021
125


Distance between Lunar Station and DSG
Apoapsis
Range
Distance (km)
Periapsis
Range Rate from Lunar Station to DSG
Range Rate
Range Rate (km/sec)
Lunar Station Antenna 1 FOV 1 Azimuth & Elevation Angles
Lunar Station Az/El Angles
Ground Station Angles (degrees)
Azimuth
Elevation
Oct 27
Nov 03
Nov 10
Nov 17
GMT Time
2021
126

Maximum of 72° away from the DSG **Field-Of-View** Vector Axis in any Direction.
Based on Primary Antenna Beamwidth of 3.6° (±1.8°),
Minimum DRPS Elevation Angle 2° Chosen



Con...	Contact Window Start Time (G...	Contact Window Stop Time (...	Duration (sec...	Comm Config 1 Min...	Comm Config 1 Max
1	25-Oct-2021 11:11:00	25-Oct-2021 17:30:00	22740	4.4	9.3
2	26-Oct-2021 05:27:00	26-Oct-2021 18:33:00	47160	3.8	9.4
3	27-Oct-2021 06:18:00	27-Oct-2021 19:21:00	46980	3.8	9.5
4	28-Oct-2021 07:14:00	28-Oct-2021 20:05:00	46260	4.0	9.7
5	29-Oct-2021 08:12:00	29-Oct-2021 20:45:00	45180	4.0	9.9
6	30-Oct-2021 09:13:00	30-Oct-2021 14:08:00	17700	4.2	10.0
7	30-Oct-2021 18:29:00	30-Oct-2021 21:21:00	10320	4.2	9.2

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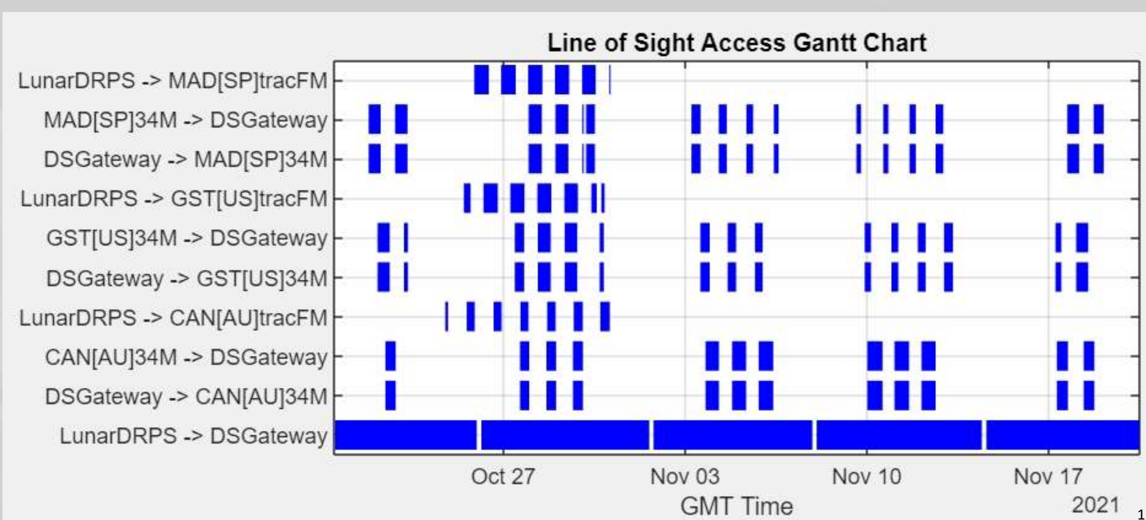
Minimum Lunar DRPS Elevation Angle 2° for Direct-To-Earth
Emergency Feed-horn Beamwidth ±15°
Part of the Emergency Beam radiated below local lunar horizon.



128

Average Access/Contact Window to Canberra (Australia) 7 hours

Number of Contact Windows 7

Save Contact Window Table to CSV   Duration Unit seconds ▼

Con…	Contact Window Start Time (G…	Contact Window Stop Time (…	Duration (sec…	Comm Config 1 Min…	Comm Config 1 Max
1	24-Oct-2021 18:08:00	24-Oct-2021 20:38:00	9000	0.6	2.8
2	25-Oct-2021 13:57:00	25-Oct-2021 21:20:00	26580	0.5	2.9
3	26-Oct-2021 14:51:00	26-Oct-2021 22:09:00	26280	0.5	2.8
4	27-Oct-2021 15:39:00	27-Oct-2021 23:04:00	26700	0.6	3.0
5	28-Oct-2021 16:20:00	29-Oct-2021 00:06:00	27960	0.6	3.2
6	29-Oct-2021 16:56:00	30-Oct-2021 01:11:00	29700	0.6	3.6
7	30-Oct-2021 17:28:00	31-Oct-2021 02:17:00	31740	0.6	4.1

99% Annual Link Availability

129

Average Access/Contact Window to Goldstone (US) >9 hours

Number of Contact Windows 7

Save Contact Window Table to CSV   Duration Unit seconds ▼

Con…	Contact Window Start Time (G…	Contact Window Stop Time (…	Duration (sec…	Comm Config 1 Min…	Comm Config 1 Max
1	25-Oct-2021 11:11:00	25-Oct-2021 17:30:00	22740	4.4	9.3
2	26-Oct-2021 05:27:00	26-Oct-2021 18:33:00	47160	3.8	9.4
3	27-Oct-2021 06:18:00	27-Oct-2021 19:21:00	46980	3.8	9.5
4	28-Oct-2021 07:14:00	28-Oct-2021 20:05:00	46260	4.0	9.7
5	29-Oct-2021 08:12:00	29-Oct-2021 20:45:00	45180	4.0	9.9
6	30-Oct-2021 09:13:00	30-Oct-2021 14:08:00	17700	4.2	10.0
7	30-Oct-2021 18:29:00	30-Oct-2021 21:21:00	10320	4.2	9.2

99% Annual Link Availability

130

Average Access/Contact Window to Madrid (Spain) >11 hours

Number of Contact Windows: 6

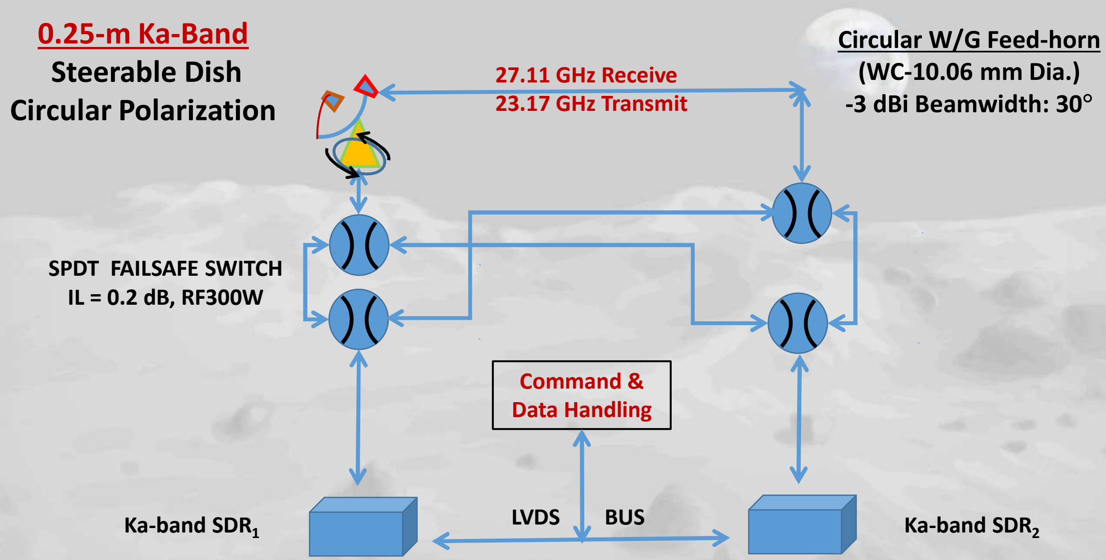
Save Contact Window Table to CSV | Duration Unit: seconds

Con...	Contact Window Start Time (G...	Contact Window Stop Time (...	Duration (sec...	Comm Config 1 Min...	Comm Config 1 Max
1	25-Oct-2021 20:55:00	26-Oct-2021 10:23:00	48480	0.8	4.7
2	26-Oct-2021 21:44:00	27-Oct-2021 11:13:00	48540	0.8	4.8
3	27-Oct-2021 22:39:00	28-Oct-2021 11:57:00	47880	0.8	4.9
4	28-Oct-2021 23:37:00	29-Oct-2021 12:36:00	46740	0.8	5.0
5	30-Oct-2021 00:40:00	30-Oct-2021 13:11:00	45060	0.8	5.1
6	31-Oct-2021 01:45:00	31-Oct-2021 02:56:00	4260	0.9	2.9

99% Annual Link Availability

131

DRPS Ka-BAND COMMUNICATIONS with Lunar Gateway



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Case 1_DRPS_DRM_Rover - Rover: Communications and Tracking

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Communications and Tracking			**10.7**	**10%**	**1.1**	**11.8**
Ka Band System			**10.7**	**10%**	**1.1**	**11.8**
Parabolic Dish	1	2.0	2.0	10%	0.2	2.2
Feedhorn	1	0.04	0.0	10%	0.0	0.04
SPDT	4	0.5	2.0	10%	0.2	2.2
WR-42 to WC-10.06mm	1	0.03	0.0	10%	0.0	0.03
GIMBAL	1	5.0	5.0	10%	0.5	5.5
SDR-TX/RX	2	0.5	1.0	10%	0.1	1.1
CABLES	2	0.3	0.6	10%	0.1	0.7

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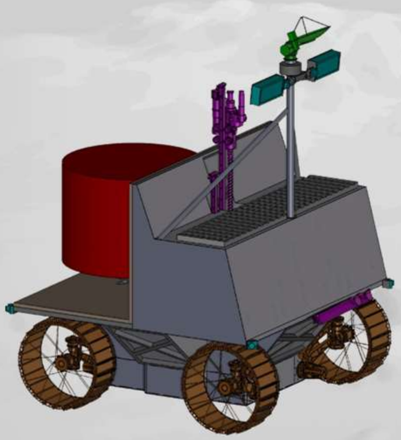


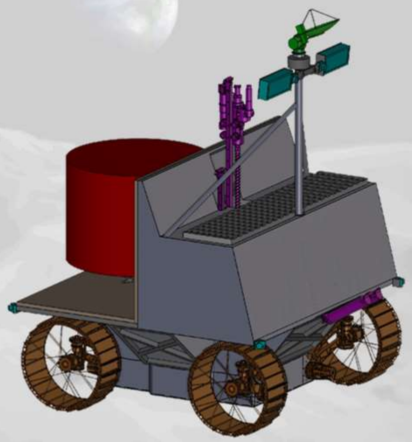
Mobility

Jim Fittje

134

Capabilities Overview

- Capabilities
  - Top Speed of ~20 cm/s
  - Prospecting Speed of ~10 cm/s
  - Obstacle Clearance of ~20 cm
  - Slope Capability up to +/-15 Deg
  - Nominal Wheelbase of ~1.5 m x ~1.5 m
  - Peak Mobility Power of 300 W
  - Nominal Mobility Power of 60 W
  - Steering Range of ≥ +/-45 Deg
  - Suspension Travel Range of ~+/-40 Deg
  - Designed to Survive Cryo Hibernation w/o Heat



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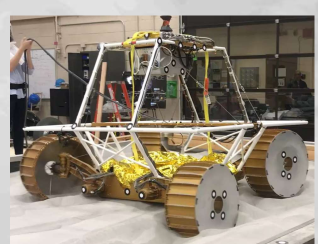
Mobility System Overview

- Mobility via Four Wheel Modules
  - All Wheel Independent Steering
  - All Wheel Independent Suspension
  - All Wheel Independent Drive Motors
  - Dual Suspension Arms per Wheel Assembly
- All Mobility Motors Utilize 24 VDC Bus Voltage
- High Gear Ratio Gear Trains
- Triple Seal System at Rotational Joints for Dust Mitigation
  - Labyrinth Seal, Felt Ring, Spring Energized Seal
- Braycote 600/601EF/602EF Lubricants

Outdoor Mobility System Testing



Mobility System Testing w/ Lunar Simulant

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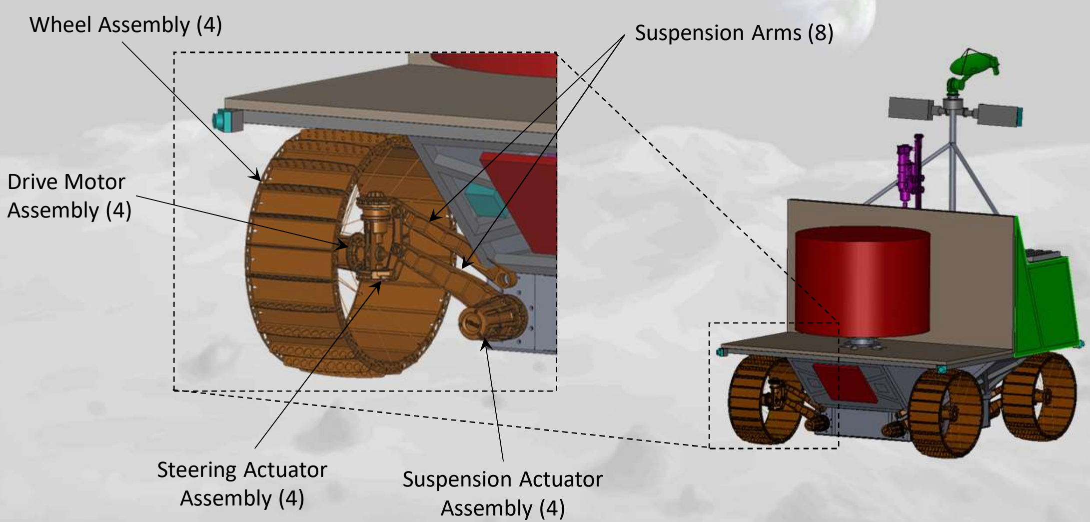
Mobility System Layout



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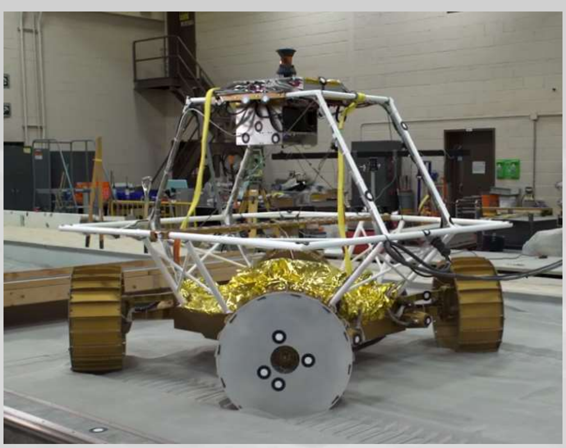
VIPER Steering Travel



All Wheels Rotated to 45 Degrees

All Wheel Independent Steering

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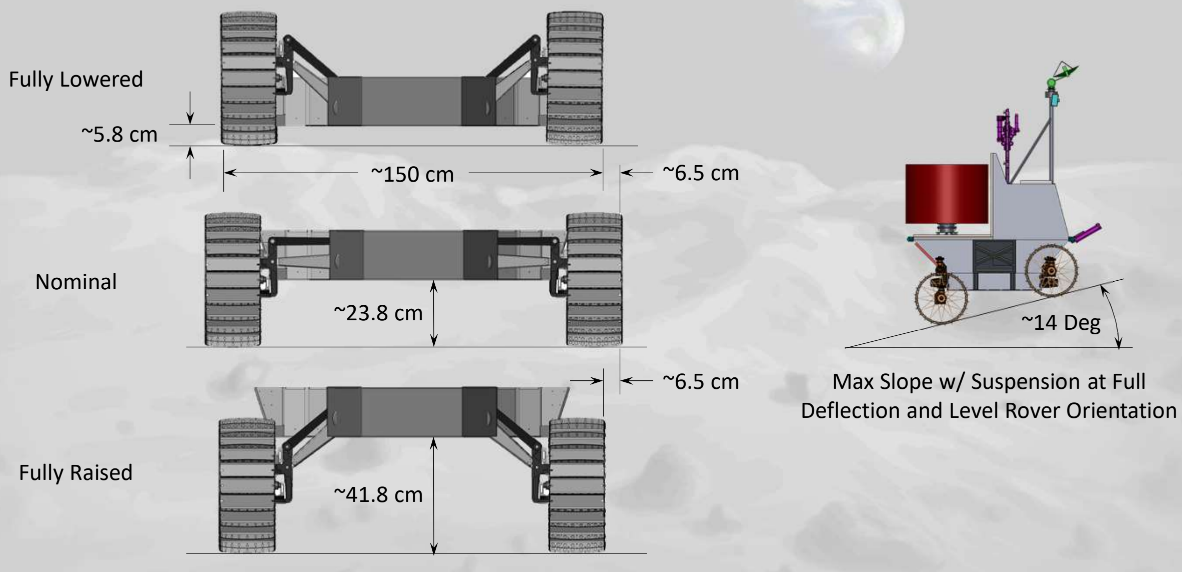
VIPER Suspension Travel



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Risks

- **Lunar Dust Mitigation**
  - **Likelihood = 5, Safety = 3, Cost = 3, Schedule = 3, Performance = 4**
  - Lunar dust can be very invasive and cause excessive wear on mechanical joints. The current rover design utilizes a new triple seal design to protect the mobility system. This new design has shown promise in testing, but currently has no flight heritage. Therefore, there is a risk it not performing as anticipated.
  - Prototype testing, and proper design can minimize this risk.
- **Operation in Extreme Thermal Environment**
  - **Likelihood = 5, Safety = 3, Cost = 3, Schedule = 3, Performance = 4**
  - Although the mobility system has been designed to withstand cold Lunar temperatures, and the appropriate lubricants used, there is a risk of unknown issues due to the lack of operational experience in the cold Lunar environment.
  - Analytical modeling, prototype testing, and proper design can minimize this risk.

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Mobility Component TRLs

Component	TRL
Steering Actuation Assembly	5
Drive Motor Assembly	5
Suspension Actuation Assembly	5
Wheels	5-6
Cryo-Vac Compatible Gear Lubricants	5-6
Triple Seal System	5-6
Mobility Electronics	6

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Future Work

- Mobility System Blanket 'Socks' May be Required
  - Encapsulates Drive Motors and Suspension System
  - Composed of Abrasion Resistant Outer Shell and Inner MLI Layers
  - Protects Against Dust, Abrasion, and Thermal Deviation
  - Required to not Appreciably Increase Motor Power or Limit Range of Motion
  - Attaches to Drive Actuator and Rover Chassis

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Case 1_DRPS_DRM_Rover - Rover: Mobility

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Mobility			**67.0**	**15%**	**10.1**	**77.1**
Mobility System			**67.0**	**15%**	**10.1**	**77.1**
Mobility System Hardware			67.0	15%	10.1	77.1
Supension Actuators	4	4.5	18.0	15%	2.7	20.7
Steering Actuators	4	4.5	18.0	15%	2.7	20.7
Drive Actuators	4	4.5	18.0	15%	2.7	20.7
Supension Arm Assemblies	4	2.0	8.0	15%	1.2	9.2
Wheels	4	1.3	5.0	15%	0.8	5.8

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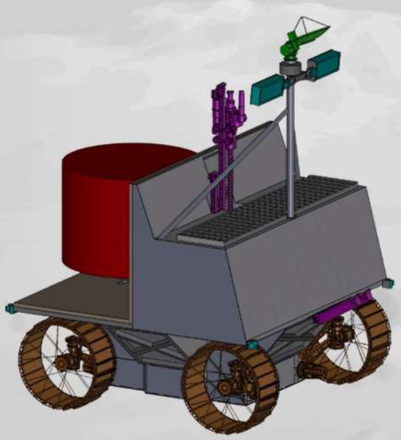
Structures and Mechanisms

John Gyekenyesi



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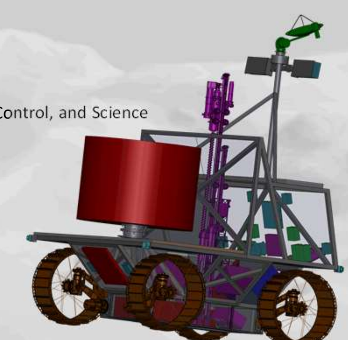
Structure Subsystem – Description
DRPS DRM Lunar Rover

- Structures and Mechanisms Design Requirements
  - Contain necessary hardware for power and thermal systems
  - Withstand applied mechanical and thermal loads
    - Macro level loads from launch
      - Other operational loads not evaluated at this conceptual stage
    - Launching
      - 5.5 g axial and 0.5 g lateral
      - 2.0 g lateral and 4.0 g axial
    - Loads imparted from attached segments
  - Provide minimum deflections, sufficient stiffness, and vibration damping
  - Minimize mass

Structure Subsystem – Description
DRPS DRM Lunar Rover

- Structures assumptions
  - Provides structures backbone for the assembly
  - Materials: aluminum, titanium, and glass/epoxy composite
  - Tubular members and shells
  - Bonded and threaded fastener assembly
- The structures subsystem
  - Tubular members and shells bearing all operational loads
  - Attached systems
  - Structures for supporting C&DH, Communications, Electrical Power, Thermal Control, and Science
- Main structure material and design choice:
  - Aluminum 7075, MMPDS-11 (former MIL-HDBK-5)
    - TRL6
  - Glass/Epoxy S2-449 43.5k/SP 381, MIL-HDBK-17
    - TRL6
  - Titanium Ti-6Al-4V
    - TRL6
- Primary Structure Mass:
  - Aluminum
- Secondary Structure Mass:
  - Installations



Rover w/transparent panels for illustration purposes

Structure Subsystem – Description

DPRS DRM Lunar Rover

- Design Highlights
  - Aluminum
  - Glass/Epoxy strut tubes w/titanium ends for low thermal conductivity
- Analytical Methods
  - Analytical methods with spreadsheet and simplified FEA for stress analysis
  - Material: **Aluminum 7075-T6**
    - **Allowable stress: 337 MPa (49 ksi)** at RT based on
      - Ultimate strength σ_u = 476 MPa (69 ksi)
      - Yield strength σ_y = 421 MPa (61 ksi)
      - Safety factors on ultimate strength of 1.4 and yield strength of 1.25 from NASA-STD-5001
      - Young's modulus E = 71.7 Gpa (10.4x10^6 psi)
      - Density ρ = 2.80 g/cm³ (0.101 lb/in.³)
      - Poisson's ratio ν = 0.33
  - Laminated glass/epoxy **S2-449 43.5k/SP 381** composite w/unidirectional plies $[0/60/30/-30/-60/0]_{2S}$
    - Ply thickness = 89 µm (0.0035 in.)
    - Laminated Composite: E_1 = 31 GPa (4.5x10^6 psi)
    - **Allowable stress σ_{allow} = 119 MPa (14.0 ksi)** Tsai-Hill failure theory and SF = 2.0 per NASA-STD-5001
      - Via HyperSizer

Rover w/transparent panels for illustration purposes

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Structure Subsystem – Description

DRPS DRM Lunar Rover

- Analytical Methods
  - DRPS support struts
    - Assume equal load distribution
      - 1.29 kN (291 lb) per strut
    - Peak stress, σ_{max} = 5.36 MPa (780 psi)
    - σ_{Allow} = 97 MPa (14 ksi)
    - Margin = 16.9

Rover w/transparent panels for illustration purposes

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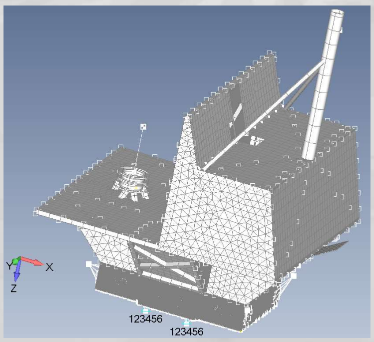
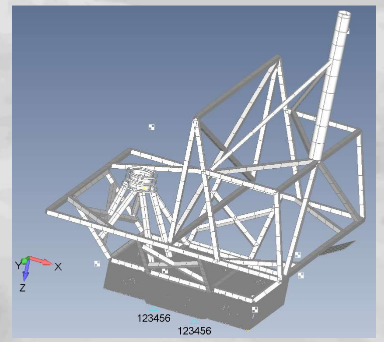
Structure Subsystem – Description
DRPS DRM Lunar Rover

- Finite Element Analysis (FEA) w/NASTRAN
  - Beam elements, linear
  - Plate elements, linear
  - Concentrated masses
  - Rigid elements, RBE2
  - Constrained at three points on base plate
    - Stowed configuration



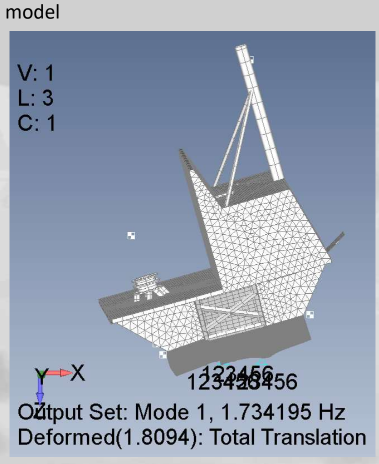


Rover w/hidden panels for illustration purposes

149

Structure Subsystem – Description
DRPS DRM Lunar Rover

- 1st modal frequency at 1.7 Hz
  - All the flexing in the base floor plate
  - Assumed to be a flat plate in model



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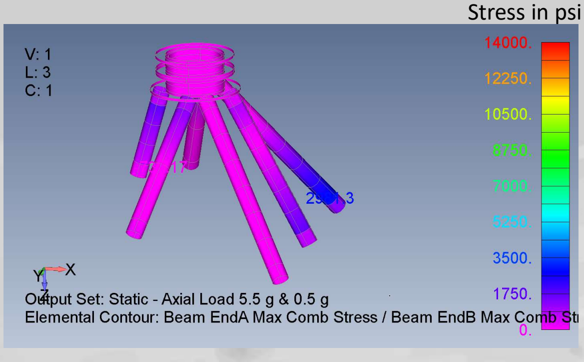
Structure Subsystem – Description

DRPS DRM Lunar Rover

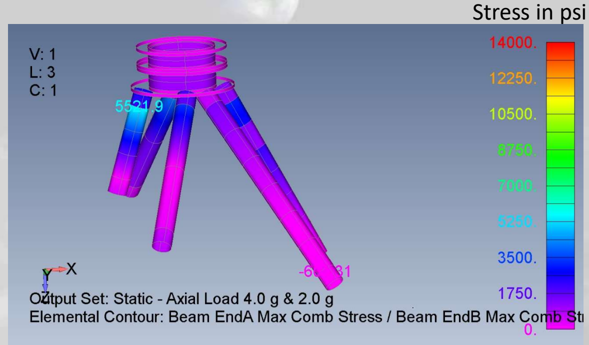
- Stress in RTG support strut tubes under launch loads

Stress in psi



Body load: 5.5 g axial & 0.5 g
Strut tube stress, glass/epoxy S2-449 43.5k/SP 381
σ_{allow} = 119 MPa (14.0 ksi)
σ_{max} = 21 MPa (3.0 ksi)
Margin: 3.7

Stress in psi



Body load: 4.0 g axial & 2.0 g
Strut tube stress, glass/epoxy S2-449 43.5k/SP 381
σ_{allow} = 119 MPa (14.0 ksi)
σ_{max} = 38 MPa (5.5 ksi)
Margin: 1.5

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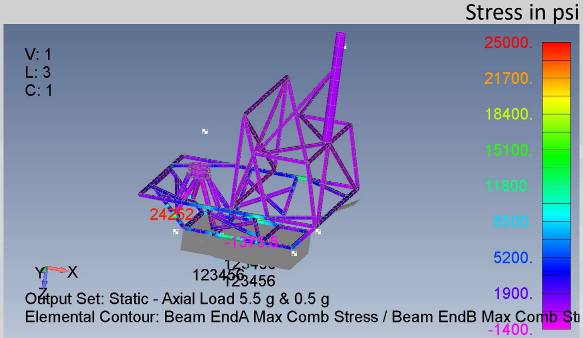
Structure Subsystem – Description

DRPS DRM Lunar Rover

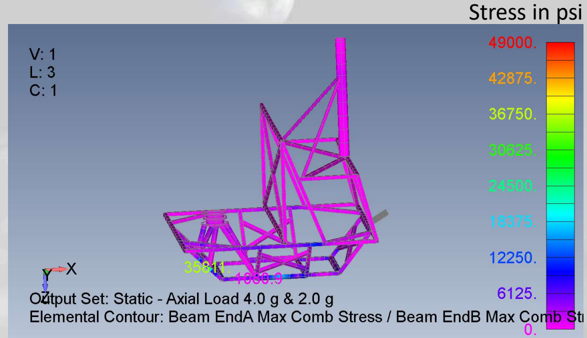
- Stress in space frame tubes under launch loads

Stress in psi



Body load: 5.5 g axial & 0.5 g
Space frame tube stress, aluminum 7075
σ_{allow} = 337 MPa (49.0 ksi)
σ_{max} = 167 MPa (24.3 ksi)
Margin: 1.0

Stress in psi



Body load: 5.5 g axial & 0.5 g
Space frame tube stress, aluminum 7075
σ_{allow} = 337 MPa (49.0 ksi)
σ_{max} = 247 MPa (35.8 ksi)
Margin: 0.37

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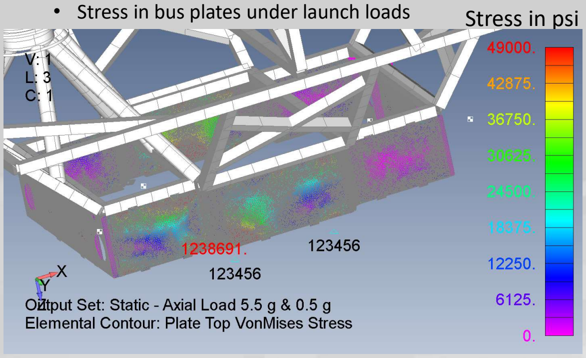
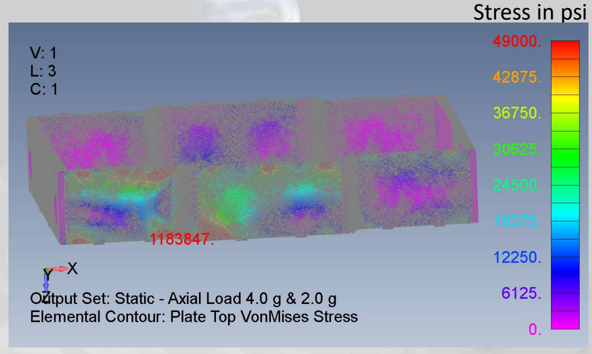
Structure Subsystem – Description

DRPS DRM Lunar Rover

- Stress in bus plates under launch loads



Body load: 5.5 g axial & 0.5 g
Base support plate stress, aluminum 7075
Thickness, t = 0.8 mm (0.032 in)
σ_{allow} = 337 MPa (49.0 ksi)
σ_{max} = 8540 MPa (1238 ksi)
Margin: -0.96



Body load: 4.0 g axial & 2.0 g
Base support plate stress, aluminum 7075
Thickness, t = 0.8 mm (0.032 in)
σ_{allow} = 337 MPa (49.0 ksi)
σ_{max} = 8162 MPa (1184 ksi)
Margin: -0.96

Note: Thicker base plates would be needed and greater fidelity with the FEA model base would provide improved results.

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Structure Subsystem – Description

DRPS DRM Lunar Rover

- Analytical Methods (continued)
  - Mass for installation
    - 4% of mass of installed hardware*
      - Thermal Control
      - Command and Data Handling
      - Communication and Tracking
      - Electrical Power
      - Science
      - Propulsion

Rover w/transparent panels for illustration purposes

*Heineman Jr., W. "Design Mass Properties II: Mass Estimating and Forecasting For Aerospace Vehicles Based On Historical Data." NASA JSC 26098, Nov. 1994.

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Structure Subsystem – Description

DRPS DRM Lunar Rover

- Mechanisms assumptions
  - Frangibolt camera release, qty. 2
- Trades considered in analysis
  - N/A
- Recommendations
  - N/A

Rover w/transparent panels for illustration purposes

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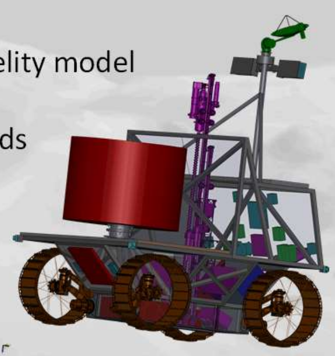
Structure Subsystem – Description

DRPS DRM Lunar Rover

- Options to reduce mass, increase stiffness, and recommendations:
  - Model an orthogrid base plate
  - Increase wall thickness of base support plates
  - Detailed stress analysis using FEA with higher fidelity model
    - Determine modal frequencies
    - Evaluated with other possible operational loads
  - Greater use of advanced materials
    - Composites with carbon/epoxy
    - And/or orthogrid or isogrid panels



Rover w/transparent panels for illustration purposes

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Case 1_DRPS_DRM_Rover - Rover: Structures and Mechanisms

Description Case 1_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Structures and Mechanisms			**42.1**	**18%**	**7.6**	**49.6**
Structures			**30.1**	**18%**	**5.4**	**35.5**
Primary Structures			14.9	18%	2.7	17.6
Base Plate Assy.	1	6.4	6.4	18%	1.2	7.6
Space Frame	1	8.0	8.0	18%	1.4	9.4
Mast	1	0.2	0.2	18%	0.0	0.2
Mast Braces	2	0.2	0.3	18%	0.1	0.4
Secondary Structures			15.2	18%	2.7	17.9
RTG Support Strut Assy.	1	3.9	3.9	18%	0.7	4.6
RTG Adapter Set	1	1.2	1.2	18%	0.2	1.5
Cover Set	1	9.7	9.7	18%	1.8	11.5
Cover Bracket Set	1	0.3	0.3	18%	0.0	0.3
Mechanisms			**12.0**	**18%**	**2.1**	**14.1**
Power System Mechanisms			0.5	18%	0.1	0.5
Camera/Light Elevation Gimbal	1	0.2	0.2	18%	0.0	0.3
Camera/Light Turning Gimbal	1	0.2	0.2	18%	0.0	0.3
Adaptors and Separation			0.1	2%	0.0	0.1
Frangibolt Camera Release	2	0.0	0.1	2%	0.0	0.1
Installations			11.5	18%	2.1	13.5
C&DH Installation	1	0.6	0.6	18%	0.1	0.7
Comm. & Tracking Installation	1	0.4	0.4	18%	0.1	0.5
Electrical Power Installation	1	0.5	0.5	18%	0.1	0.6
Thermal Control Installation	1	1.4	1.4	18%	0.3	1.6
Science Installation	1	3.9	3.9	18%	0.7	4.5
Mobility Installation	1	3.0	3.0	18%	0.5	3.6
Chemical Propulsion Installation	1	1.6	1.6	18%	0.3	1.9

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Case 2_Brayton_DRPS_DRM_Rover - Rover: Structures and Mechanisms

Description Case 2_Brayton_DRPS_DRM_Rover CD-2021-182	QTY	Unit Mass	Basic Mass	Growth	Growth	Total Mass
Structures and Mechanisms			**45.6**	**18%**	**8.2**	**53.8**
Structures			**31.5**	**18%**	**5.7**	**37.1**
Primary Structures			15.5	18%	2.8	18.3
Base Plate Assy.	1	6.4	6.4	18%	1.2	7.6
Space Frame	1	8.6	8.6	18%	1.5	10.1
Mast	1	0.2	0.2	18%	0.0	0.2
Mast Braces	2	0.2	0.3	18%	0.1	0.4
Secondary Structures			16.0	18%	2.9	18.8
RTG Support Strut Assy.	1	3.9	3.9	18%	0.7	4.6
RTG Adapter Set	1	1.2	1.2	18%	0.2	1.5
Cover Set	1	10.5	10.5	18%	1.9	12.4
Cover Bracket Set	1	0.3	0.3	18%	0.0	0.3
Mechanisms			**14.1**	**18%**	**2.5**	**16.6**
Power System Mechanisms			0.5	18%	0.1	0.5
Camera/Light Elevation Gimbal	1	0.2	0.2	18%	0.0	0.3
Camera/Light Turning Gimbal	1	0.2	0.2	18%	0.0	0.3
Adaptors and Separation			0.1	2%	0.0	0.1
Frangibolt Camera Release	2	0.0	0.1	2%	0.0	0.1
Installations			13.6	18%	2.4	16.1
C&DH Installation	1	0.7	0.7	18%	0.1	0.9
Comm. & Tracking Installation	1	0.4	0.4	18%	0.1	0.5
Electrical Power Installation	1	0.7	0.7	18%	0.1	0.8
Thermal Control Installation	1	1.4	1.4	18%	0.3	1.7
Science Installation	1	6.0	6.0	18%	1.1	7.1
Mobility Installation	1	2.7	2.7	18%	0.5	3.2
Chemical Propulsion Installation	1	1.6	1.6	18%	0.3	1.9

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