R2-S2

R2-S2: ROBOTIC REMOTE-SENSING SCOUT

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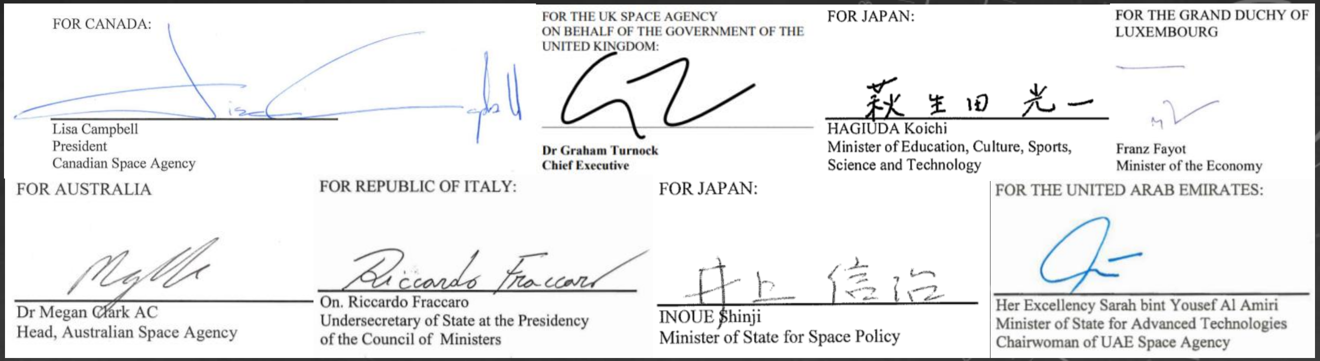
ASTE 527: Space Concept Architectures

CONTEXT: THE U.S. LEADS COMMERCIAL HUMAN SPACEFLIGHT TO THE MOON

- NASA Artemis program establishes international partners for peaceful lunar exploration (2020) [1]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Minister of State for Space Policy
FOR THE UNITED ARAB EMIRATES:
Her Excellency Sarah bint Yousef Al Amiri
Minister of State for Advanced Technologies
Chairwoman of UAE Space Agency

Signatures from Artemis Accords [1]

- Commercial U.S. companies make major strides in crewed missions
  - Virgin Galactic flight with Richard Branson (July 2021) [2]
  - Blue Origin first crewed flight with Jeff Bezos (July 2021) [3]
  - SpaceX Inspiration 4 first civilian orbital flight (Sept. 2021) [4]

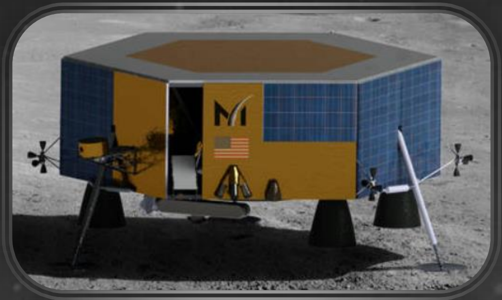




- NASA Artemis selects SpaceX for Human Landing System (2021) [5]

CONTEXT: ROBOTS FOR SUPPORTING CREWED MISSIONS

- Commercial Lunar Payload Services (CLPS) (*Precursor to crewed lunar missions*) [6]
  - Surface measurements
  - Demonstrating navigational technology
- Special Purpose Dexterous Manipulator (DEXTRE) (*On-orbit*) [7]
  - Servicing and Repair
  - Hardware replacement
  - Carries tools during crewed EVA's
- Canadarm (*On-orbit*) [8]
  - Berthing
  - Hardware assembly
  - Astronaut positioning
- Multi-Mission Extra Vehicular Robot (MMEVR) (*On-orbit*) [9]
  - Servicing and Repair
  - Hardware assembly
  - Can mount to Astronaut for augmented dexterity



PROBLEM: THE NEED FOR A ROBOT TO ASSIST CREWED LUNAR OPERATIONS

Space Policy Document 1 (2018):

- "Lead an innovative and sustainable program of exploration with commercial and international partners…
- …the United States will lead the return of humans to the Moon for long-term exploration and utilization" [10]

Moon Village Association (2020):

- "Space actors are encouraged to share information to facilitate international cooperation among governmental agencies, private entities, and the general public in the expansion of lunar activities." [11]

NEEDS:

- Dramatically reduce the risk associated with returning humans to the Moon
- Support the US in leading an innovative & sustainable program of exploration with commercial & international partners

GOALS:

- Provide the capability for remote sensing as well as in-situ mission assistance to commercially & internationally supported crewed Lunar EVA missions

OBJECTIVES:

- Ability to collect environmental data to help determine safety of planned EVA missions
- Ability to explore ahead of crewed missions to determine locations of scientific interest
- Ability to perform exterior inspection of habitats and launch vehicles
- Film EVA operations and livestream to Earth
- Perform specific tasks when commanded by the crew
- Carry emergency oxygen for the crew
- Provide high data-rate communications architecture
- Provide the above capabilities without endangering the crew
- Share all collected sensory data with commercial & international partners

RATIONALE: HOW R2-S2 FULFILLS THE NGO

What is R2-S2?:

- Lunar reconnaissance rover with two primary modes:
  - Teleoperated by Lunar crew prior to EVA ops
  - Autonomously assists alongside the crew during EVA ops

High-Level Problems from NGO:

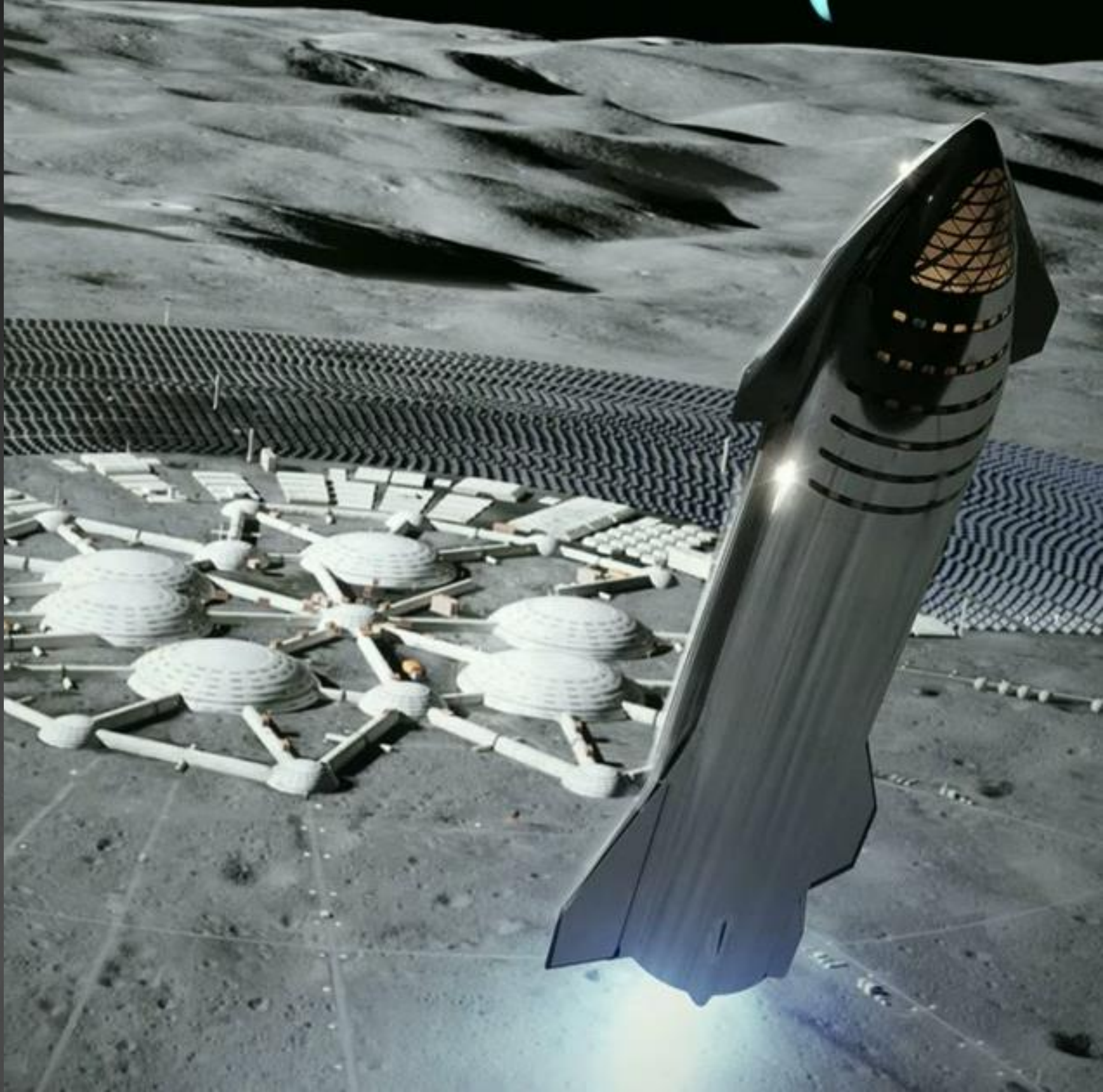
- Dramatically reduce the risk associated with returning humans to the Moon
- Support the US in leading an innovative & sustainable program of exploration with commercial & international partners

How R2-S2 Addresses These Problems:

- ➢ R2-S2 Provides critical information for assessing the safety of Lunar EVA missions
- ➢ Alleviates crew workload during EVA missions and provides emergency capabilities
- ➢ R2-S2 will be a commercial & international effort led by NASA, and all data collected will be shared with commercial & international partners

ASSUMPTIONS

- There is already an established Lunar Habitat
- R2-S2 is brought to the Moon via the Starship HLS
- R2-S2 will not return to Earth



TELEOPERATED MODE: HIGH-LEVEL CONOPS

COMMUNICATION ARCHITECTURE

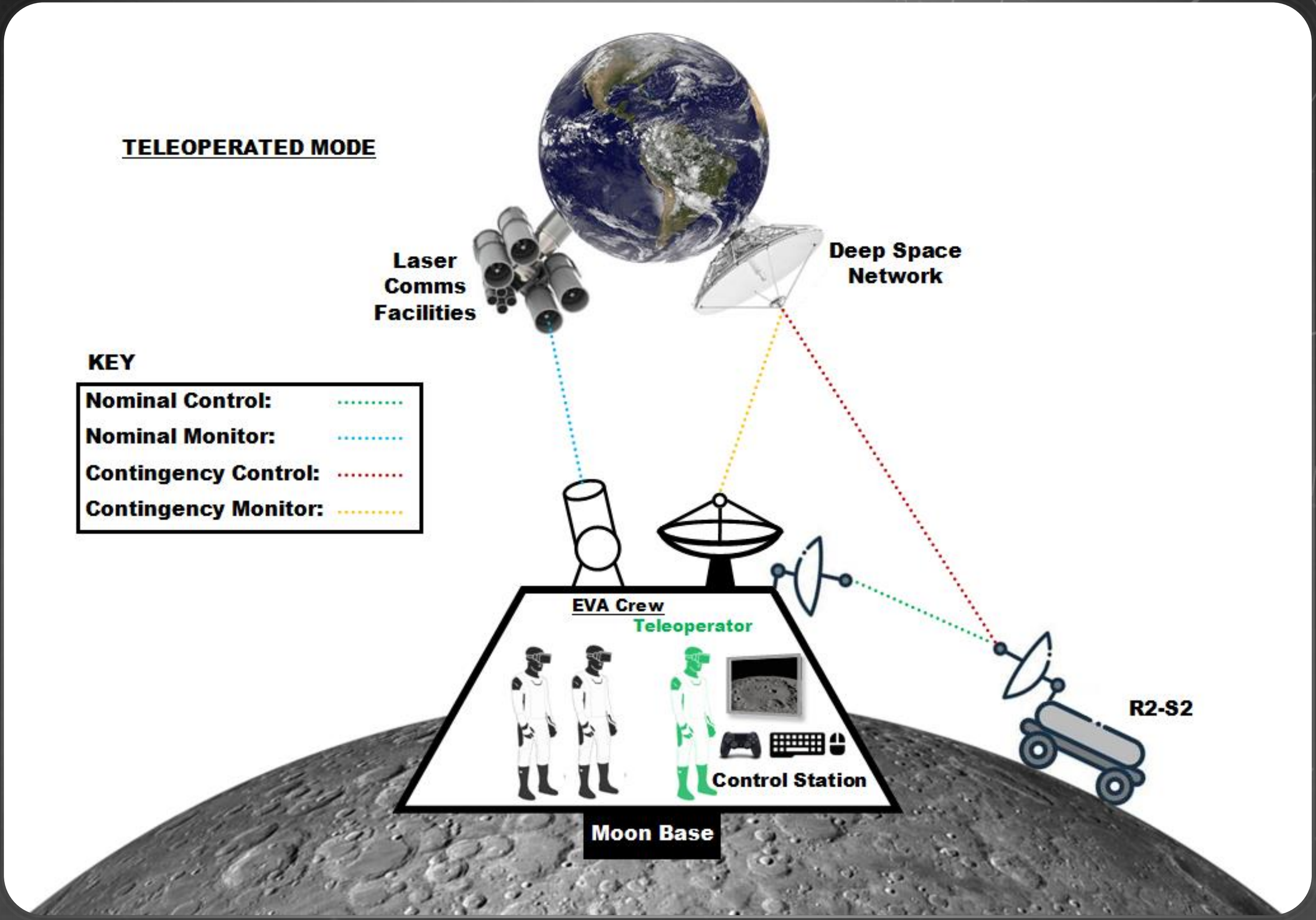
Moon Base <-> R2-S2:
- Radio (Nominal Control)

Moon Base <-> Earth:
- Laser (Nominal Monitor) [12]
- Radio (Contingency Monitor)

Earth <-> R2-S2:
- Radio (Contingency Control)

OPERATIONS

1. EVA crew commander designated as Teleoperator (Teleop)
2. Teleop navigates R2 through terrain to perform desired task
3. R2 autonomously returns to habitat while EVA crew monitors its return and takes manual control if necessary



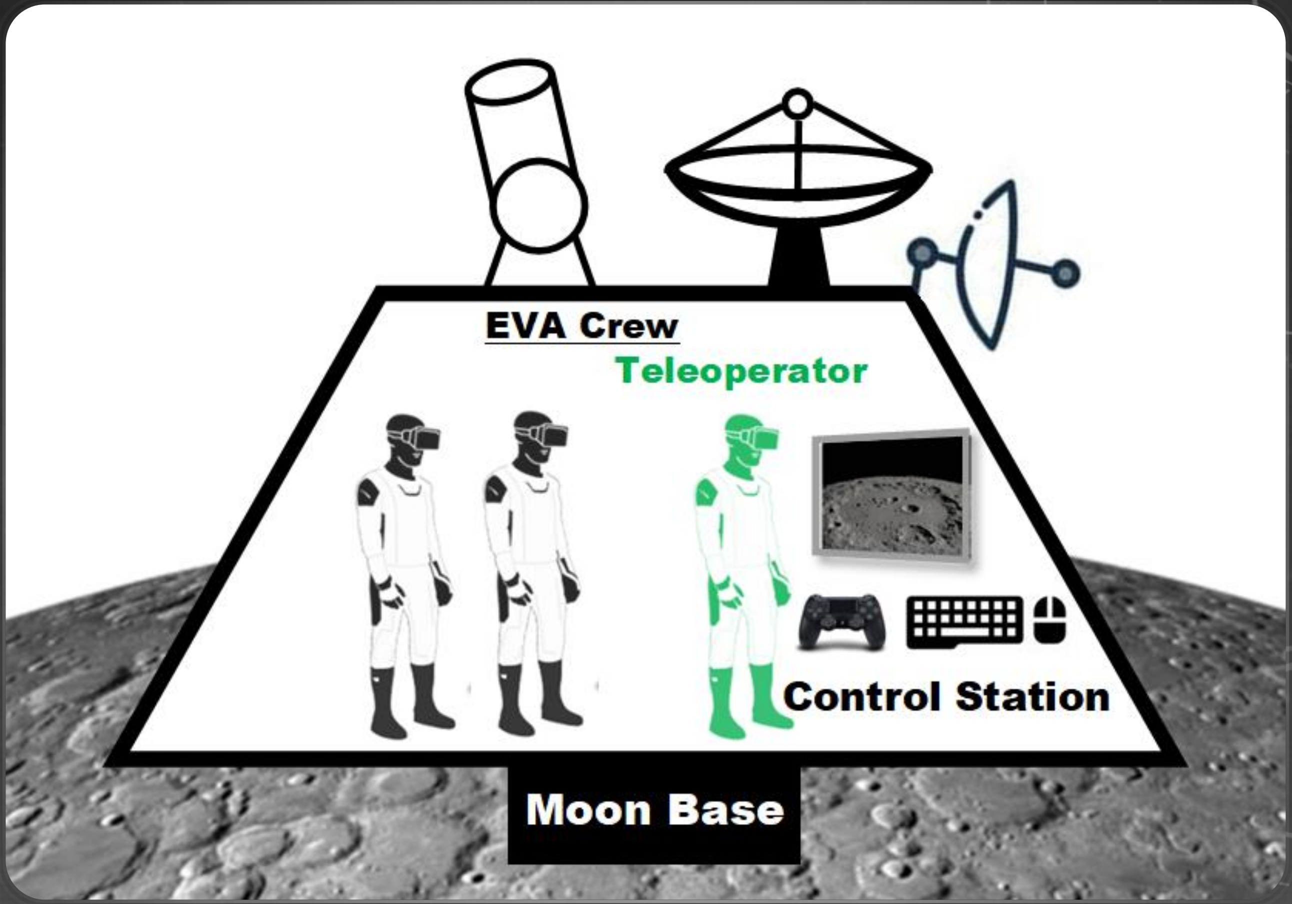
TELEOPERATED MODE: LUNAR CONTROL STATION

Display Interfaces:

- Virtual Reality (VR) headsets for entire EVA crew
  - VR enhances mental preparedness of crew through sensory immersion
- External Monitor (Optional)

Control Interfaces:

- Game Controller
- Mouse and Keyboard (Optional)



TELEOPERATED APPLICATIONS

MISSION RECONNAISSANCE

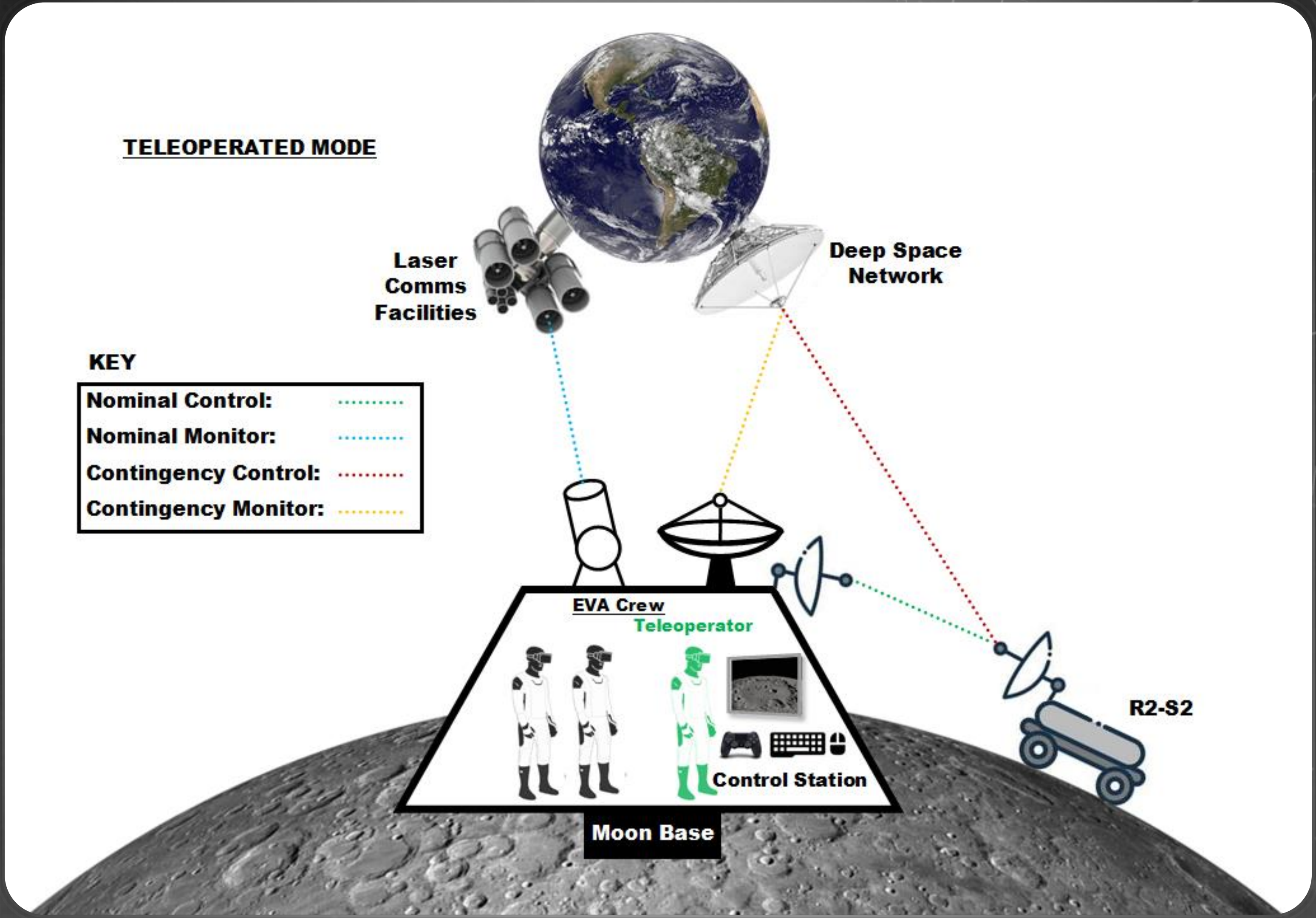
1. A crewed EVA mission is planned
2. R2-S2 is teleoperated to gather data to determine safety of planned EVA mission

REMOTE EXPLORATION

1. Information is needed to plan the next crewed EVA mission
2. R2-S2 is teleoperated to gather information to help inform planning of crewed EVA mission

INSPECTION

1. Habitat exterior, surface vehicle, or launch vehicle needs inspection
2. R2-S2 is teleoperated to desired structure and performs visual inspection
    - 3D imagery, IR, microscopy



AUTONOMOUS CREW-ASSIST MODE: HIGH-LEVEL CONOPS

COMMUNICATION ARCHITECTURE

EVA Crew <-> R2-S2:
- Radio (Control thru voice-command)

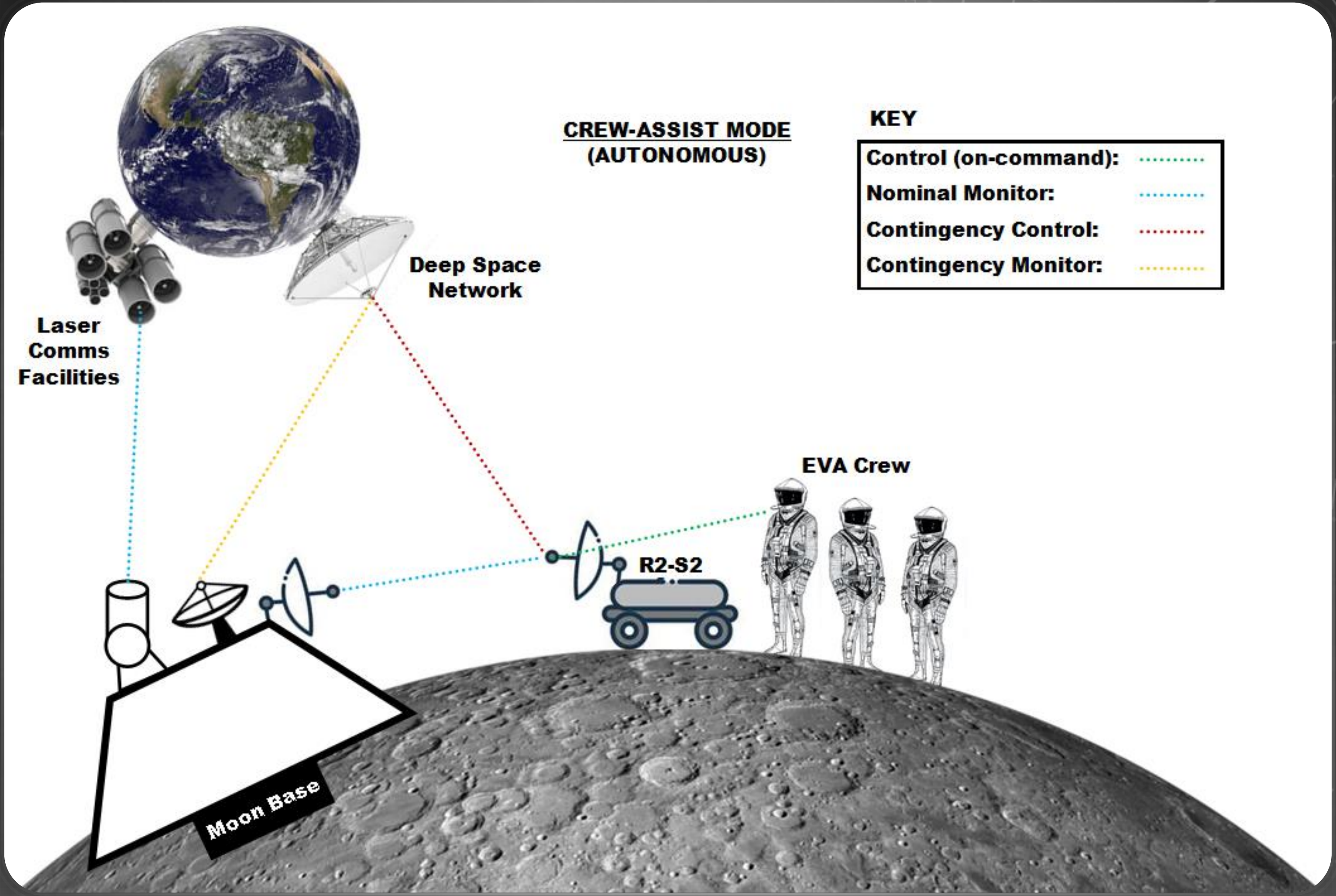
Moon Base <-> R2-S2:
- Radio (Nominal Monitor)

Moon Base <-> Earth:
- Laser (Nominal Monitor) [12]
- Radio (Contingency Monitor)

Earth <-> R2-S2:
- Radio (Contingency Control)

OPERATIONS

1. R2-S2 follows EVA crew while monitoring crew and environment
2. R2-S2 performs specific tasks alongside crew when voice-commanded



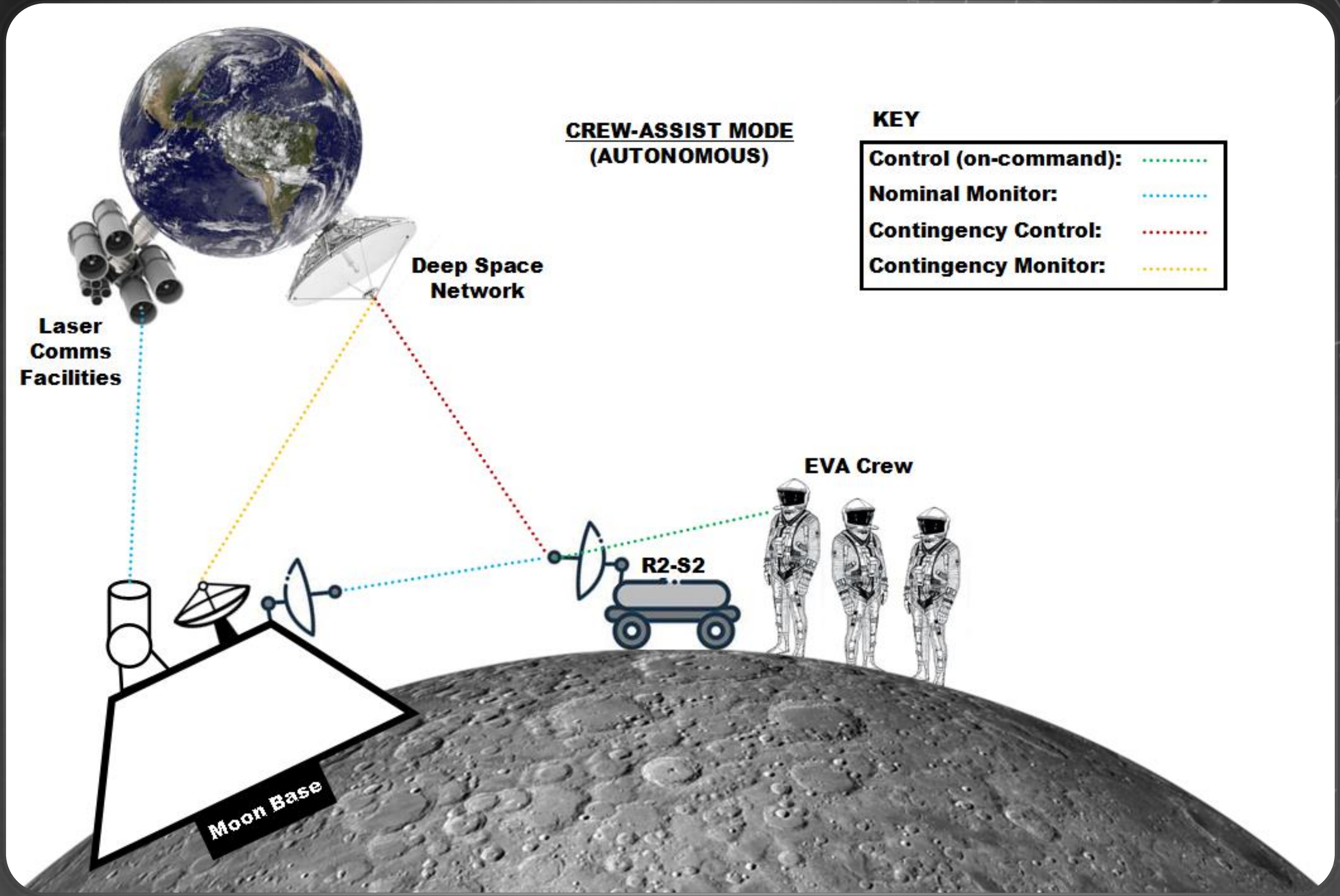
AUTONOMOUS CREW-ASSIST MODE APPLICATIONS

1. Livestreams video of EVA operations to Earth

2. Performs specific tasks when commanded:
    1. Sample collection
    2. Telescoping
    3. Microscopy
    4. In-Situ measurements

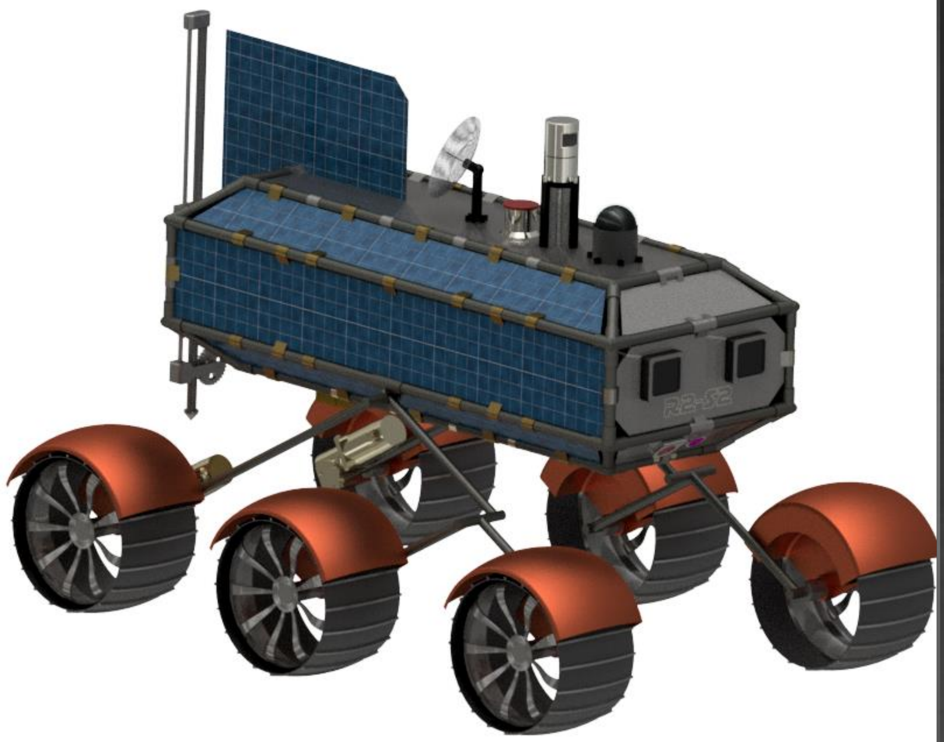
3. Carries tools

4. Provides emergency supplies
    1. Oxygen
    2. Suit repair materials



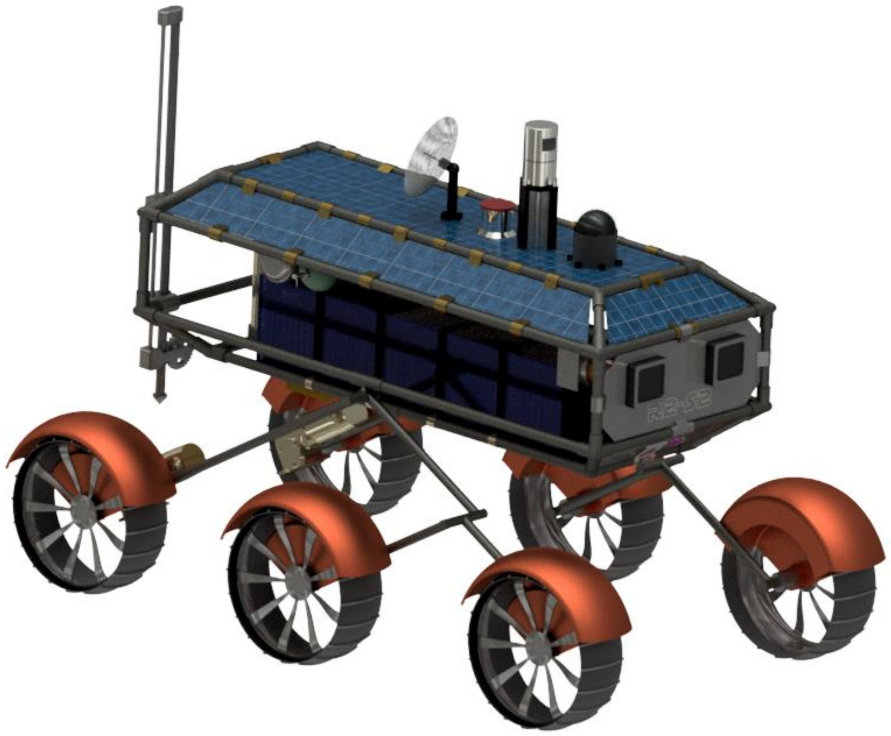
R2-S2 OVERVIEW: POLAR & EQUATORIAL EDITION

Polar



- Wider wheels (Softer terrain) [13]
- Solar panels facing tangent to lunar surface
- Thicker battery back insulation

Equatorial

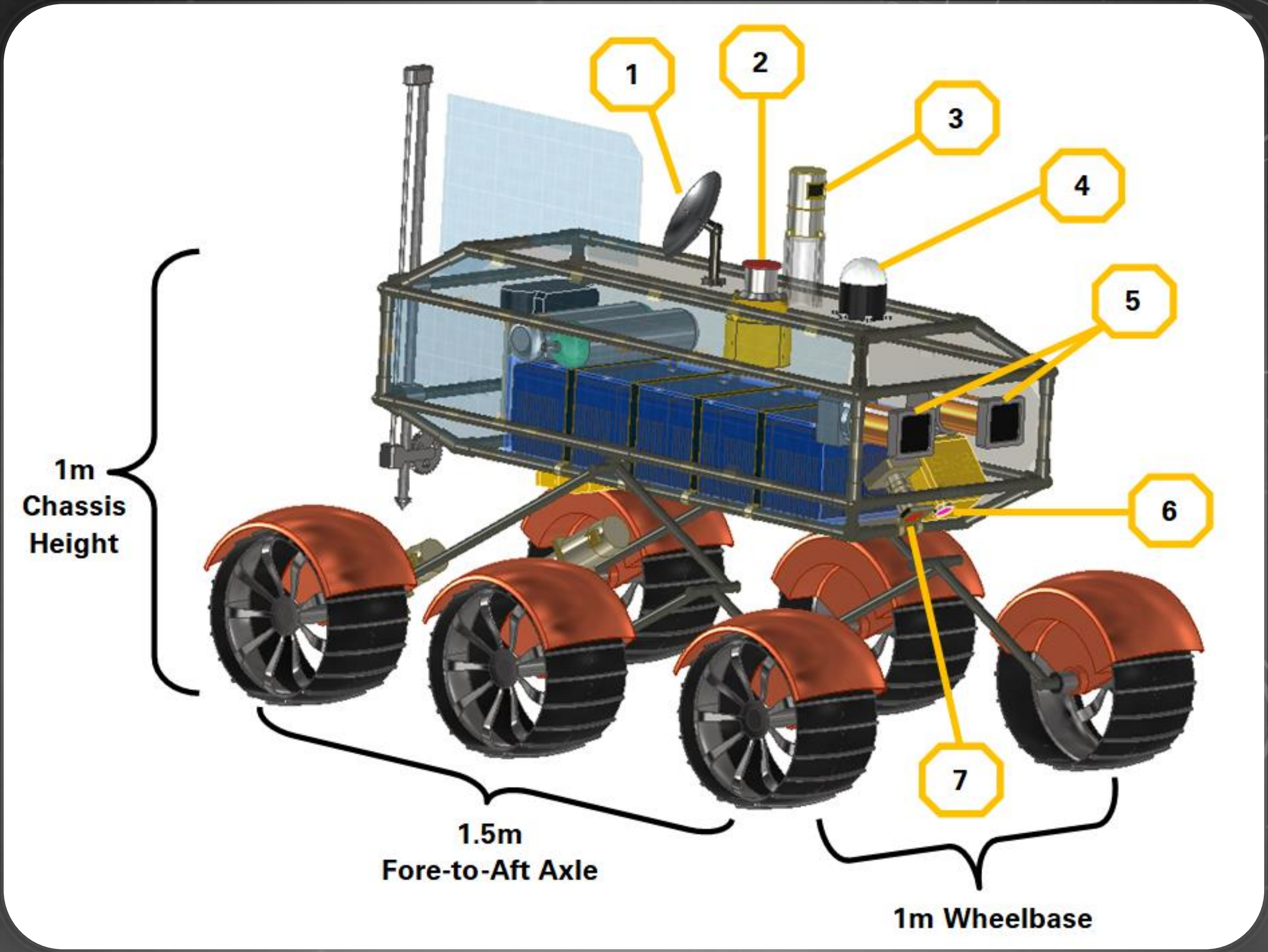


- Narrower wheels
- Solar panels facing normal to lunar surface
- Thinner battery back insulation

Same incident solar area (same charging time)

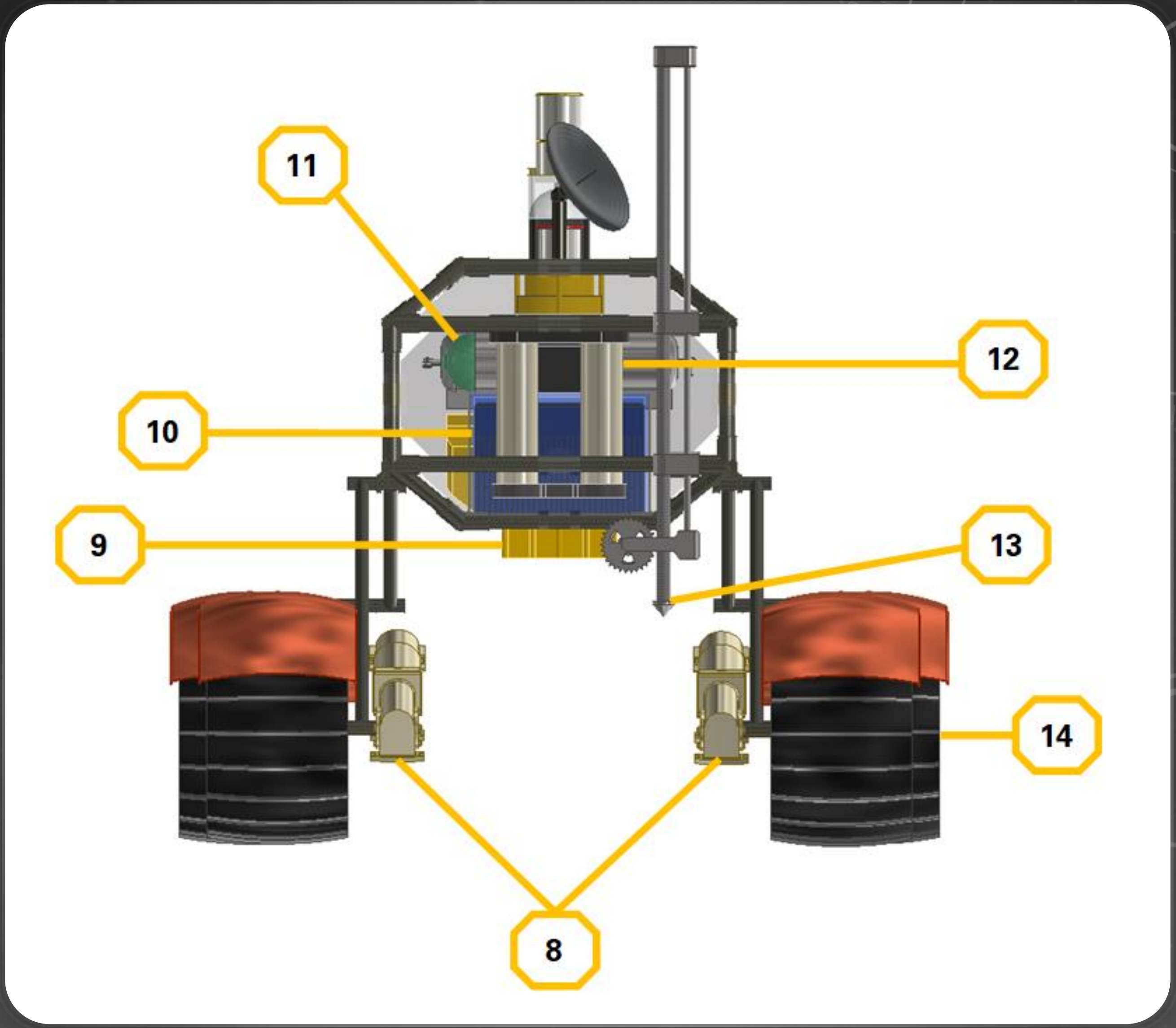
R2-S2 OVERVIEW: CAPABILITIES (PART 1/2)

1. Radio Antenna
   - Nominal use: R2-S2<->Base
   - Capable 10dB SNR to Earth if base comms are lost
2. Radiation Sensor [14]
   - Detects protons, energetic ions, neutrons, & gamma rays
   - Flown on Curiosity
3. 360˚ LiDAR [15]
   - +10˚, -30˚ vertical FOV
   - +/- 2cm accuracy
   - 100m range
4. 360˚ HD Camera [16]
   - 6x digital zoom
5. Stereo Telescoping Cameras [17]
   - HD 3D imaging from afar
   - Flown on Curiosity & Perseverance
6. Infrared Spectrometer [18]
   - Temperature data
   - Detection of volatiles
   - Planned for VIPER
7. Microscope Camera [19]
   - Minerology
   - Flown on Curiosity



R2-S2 OVERVIEW: CAPABILITIES (PART 2/2)

8. Dual DC Motors [20]
    - Total 0.25 hp
9. Subsurface Radar [21]
    - 15-30cm vertical resolution
    - 10m penetration depth
    - Flown on Perseverance
10. Battery Pack
    - 8-hour battery life assuming all systems are being used
    - Aerogel insulation (2x thickness FOS)
        - Polar: 3/8”
        - Equatorial: 1/4”
11. Spare Oxygen Tanks
    - Total 16 hours spare O2
12. Neutron Spectrometer [18]
    - Detects volatiles & surface composition
    - Planned for VIPER
13. Sample Collection Drill [18]
    - 1m long
    - Planned for VIPER
14. Wheels
    - 40cm diameter aluminum rims
    - Titanium spokes
    - Rocker-Bogie configuration



MERITS, LIMITATIONS, & FUTURE STUDIES

MERITS:

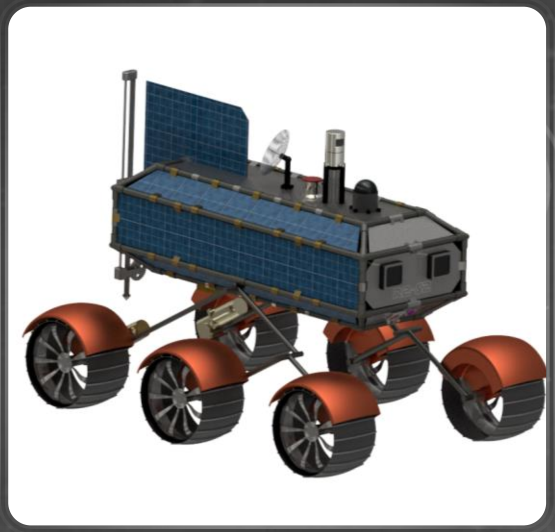
- Provides critical information to inform risk assessment of EVA missions
- Mentally prepares EVA crew through VR immersion
- Assists during crewed EVA excursions
- Shares data with commercial & international partners to further awareness of Lunar environment

LIMITATIONS:

- Terrain traversing abilities of a rover does not match that of a human in an EVA suit
- If R2-S2 becomes stuck, a crewed EVA mission will need to be planned to rescue it

FUTURE STUDIES:

- Robotic arm for more teleoperation capabilities
- Infrastructure for storing R2-S2 between missions
- Optimized drill placement



REFERENCES

[1] “Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes”. *NASA*. June 2021.

[2] Chang, Kenneth. “Highlights from Richard Branson's Virgin Galactic Flight.” *The New York Times*, 15 Sept. 2021, https://www.nytimes.com/live/2021/07/11/science/virgin-galactic-launch-richard-branson.

[3] Wall, Mike. “Jeff Bezos Launches into Space on Blue Origin's 1st Astronaut Flight.” *Space.com*, 20 July 2021, https://www.space.com/jeff-bezos-blue-origin-first-astronaut-launch.

[4] Stein, Vicky. “Inspiration4: The FIRST All-Civilian Spaceflight on SpaceX Dragon.” *Space.com*, 23 Sept. 2021, https://www.space.com/inspiration4-spacex.html.

[5] Lueders, Kathryn. “Appendix H: Human Landing System, Option A Next Space Technologies for Explorations Partnerships-2.” *NASA.* April 16, 2021.

[6] Potter, Sean. “NASA Awards Contract to Deliver Science, Tech to Moon.” *NASA*, 8 Apr. 2020, https://www.nasa.gov/press-release/nasa-awards-contract-to-deliver-science-tech-to-moon-ahead-of-human-missions.

[7] Coleshill, Elliott, et al. "Dextre: Improving maintenance operations on the international space station." Acta Astronautica 64.9-10 (2009): 869-874.

[8] Hiltz, Michael, et al. "Canadarm: 20 years of mission success through adaptation." (2001).

[9] Netti, Vittorio. "Design of an autonomous and teleoperated modular robotic free-flyer for EVA operations." ASCEND 2020. 2020. 4257.

[10] “Presidential Memorandum on Reinvigorating America’s Human Space Exploration Program”. *The White House.* Dec. 11, 2018.

[11] “Best Practices for Sustainable Lunar Activities.” *Moon Village Association.* October 19, 2020.

[12] Boroson, Don M., and Bryan S. Robinson. “The Lunar Laser Communication Demonstration: NASA’s First Step Toward Very High Data Rate Support of Science and Exploration Missions.” Space Science Reviews, vol. 185, no. 1, Springer Netherlands, 2014, pp. 115–28, doi:10.1007/s11214-014-0122-y.

[13] Moskowitz, Clara. “Shadows of the Moon Hide 'Fluffy' Dirt & Water Ice.” *Space.com*, 19 Jan. 2012, https://www.space.com/14284-moon-permanently-shadowed-regions-water-ice.html.

[14] "Radiation Assessment Detector (RAD)." *NASA*. 22 Apr. 2020. Web. 21 Sept. 2021.

[15] "Velodyne's HDL-32E SURROUND Lidar Sensor." *Velodyne Lidar*. 15 Sept. 2021. Web. 21 Sept. 2021.

[16] "Quantum 360 Rover Camera." *Defender*. Web. 21 Sept. 2021.

[17] “Mast-Mounted Camera System (MASTCAM-Z).” *NASA*, https://mars.nasa.gov/mars2020/spacecraft/instruments/mastcam-z/.

[18] Fong, Terry. "Volatiles Investigating Polar Exploration Rover (VIPER)." West Virginia University Robotics Seminar.

[19] “Mahli.” *NASA*, 22 Apr. 2020, https://mars.nasa.gov/msl/spacecraft/instruments/mahli/.

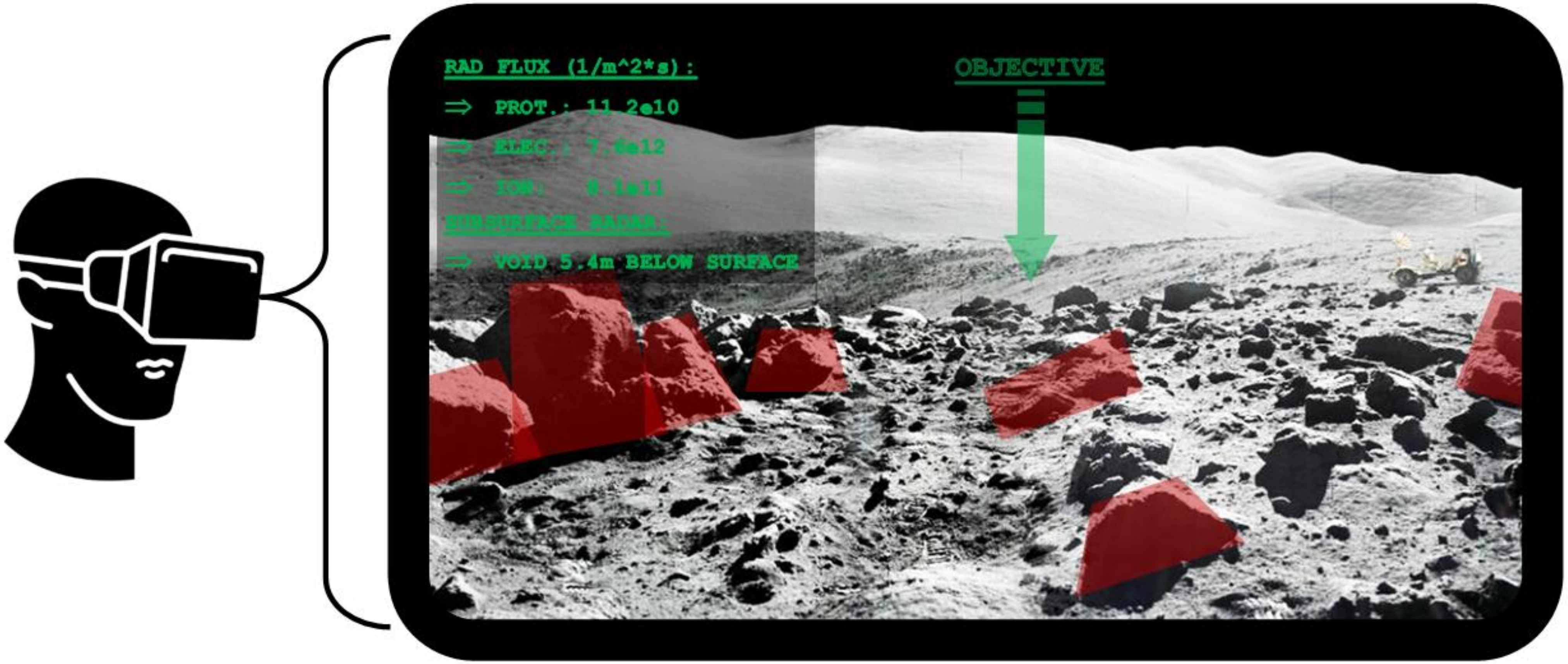
[20] "Right-Angle Shaft DC Gearmotor." *McMaster-Carr*. Web. 21 Sept. 2021.

[21] “Radar Imager for Mars' Subsurface Exploration (RIMFAX).” *NASA*. Retrieved September 21, 2021, from https://mars.nasa.gov/mars2020/spacecraft/instruments/rimfax/.

BACKUP SLIDES

R2-S2 TERRAIN HAZARD DETECTION SYSTEM

1. LiDAR Generates 3D cartography data of Lunar landscape → 2. Topology algorithm determines locations inaccessible to R2-S2 → 3. Terrain hazards are over-layed onto Teleoperator's VR display (shown in red)



ANTENNA SIZING & POWER BUDGET

Link Budget for R2-S2 Direct-to-Earth Communications		
Parameter	Linear Value	dB Value
R2-S2 Antenna (Transmitting)		
Diameter (m)	0.221257	-
Efficiency	0.7	-
Frequency (Hz)	9.00E+09	-
Data Rate (bps)	4.50E+08	86.532
Gain (W)	304.819	24.840
Transmitted Power (W)	90	19.542
Space, Atmospheric, and Line Loss		
Range (m)	3.76E+08	-
Space Loss	-	-223.043
Atmospheric Loss	-	2.000
Line Loss	0.8	-0.969
DSN Antenna (Receiving)		
Diameter (m)	34	-
Efficiency	0.7	-
Frequency (Hz)	9.00E+09	-
Gain (W)	7188	68.572
Attenuation Loss	-	3.000
Temperature Noise (K)	200	23.010
Signal to Noise Ratio		
Desired Eb/No	-	10
*Green Highlighted Cells are backed-out of Eb/No equation		
*Some of these values are estimates to get a rough idea of transmitting antenna diameter		

R2-S2 Power Budget			
Item	**Quantity**	**Power(W)**	**Source**
Motors	2	0.25	Link
Antenna	1	300	Calculations
360 Degree Camera	1	120	Link
LiDAR	1	12	Link
Radiation Sensor	1	4.2	Link
Subsurface Radar	1	9.5	Link
Regolith Drill	1	358	Link
Neutron Spectrometer	1	1.6	Link
Infrared Camera	1	29.56	Link
MastCam-Z	1	17.4	Link
Microscope	1	17.4	Estimate
Total		**869.91**	

$$E_b/N_0 = P_t + L_{l,t} + G_t + L_S + L_a + G_r + L_{l,r} + 228.60 - 10\log T_S - 10\log R$$

RADIO VS. LASER COMMUNICATION

Feature	Radio	Lunar Laser Communication Demonstration (LLCD) [12]
Sensitivity to Atmospheric and Physical Obstruction	Less sensitive (Longer ʎ)	More sensitive (Shorter ʎ)
Sensitivity to long-distance communication	More Sensitive (Greater diffraction)	Less Sensitive (Less diffraction)
Beamwidth	Easier to point (Wider beamwidth)	Stricter pointing requirements; however, it has been demonstrated that vibration control systems increase pointing accuracy (Narrower beam width)
Data Rate/Mass Ratio	Smaller	Larger (Higher frequency means higher data rate, shorter ʎ means smaller apertures and less mass)
Power Requirements	Larger	Smaller
Ground Infrastructure	Complete coverage (Deep Space Network)	Complete coverage

Green = Pros
Red = Cons

RATIONALE FOR COMMS ARCHITECTURE SELECTION

<u>R2-S2 Rover</u>

- Nominal comms: Radio
    - Less strict pointing requirements
        - R2-S2 will be moving around a lot
    - Less sensitive to physical obstruction
        - R2-S2 may need to explore caves and tunnels

<u>Moon Base</u>

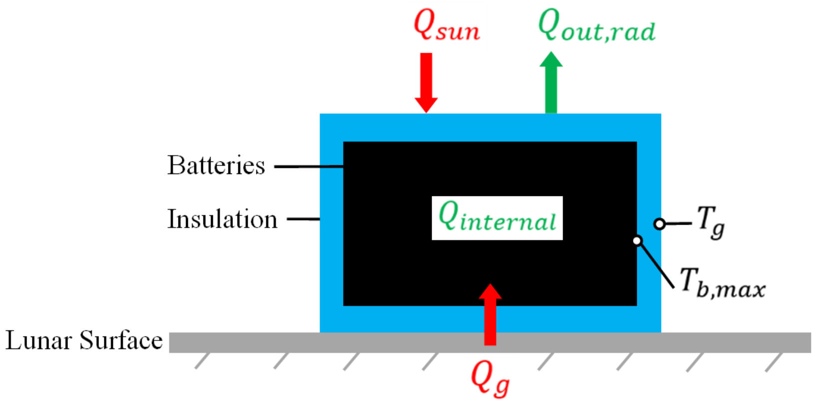
- Nominal comms: Laser
    - Stricter pointing requirements
        - Easy to point at Earth from stationary base
    - Higher data rate
        - Better for HD livestreaming
- Contingency comms: Radio

<u>Earth</u>

- Nominal comms: Laser
    - Stricter pointing requirements
        - Easy to point at the Moon from stationary facility
    - Higher data rate
        - Better for HD livestreaming
- Contingency comms: Radio

BATTERY PACK DESIGN: APPROXIMATE HEAT TRANSFER MODELS

EQUATORIAL DAYTIME OPERATIONS:



$$Q_{sun} + Q_g = Q_{out,rad} + Q_{internal}$$

$$F_s A_{rad} + \frac{(T_g - T_{b,max})}{\left(\frac{L_{ins}}{k_{ins} A_{cond}}\right)} = \varepsilon_{ins} \sigma T_g^4 + \frac{c_b T_{b,max}}{t_{EVA}}$$

In this case, $A_{rad} = A_{cond} = A$

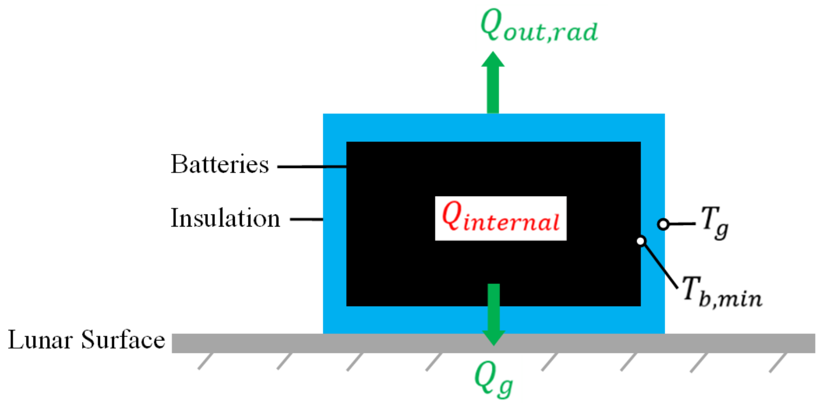
$$L_{ins} = \frac{(T_g - T_{b,max}) k_{ins} A}{\varepsilon_{ins} \sigma T_g^4 + \frac{c_b m_b T_{b,max}}{t_{EVA}} - F_s A}$$

$$c_b = \frac{\sum m_i c_i}{\sum m_i}$$

$$A = \# Batteries * A_{1\ battery}$$

$$\# Batteries = \frac{Power(W) * time(hrs)}{Voltage(V) * Battery\ Capacity(Amp - hrs)}$$

EQUATORIAL NIGHTTIME & POLAR OPERATIONS:



$$Q_{internal} = Q_{out,rad} + Q_g$$

$$\frac{c_b T_{b,min}}{t_{EVA}} = \varepsilon_{ins} \sigma T_g^4 + \frac{(T_{b,min} - T_g)}{\left(\frac{L_{ins}}{k_{ins} A_{cond}}\right)}$$

$$L_{ins} = \frac{(T_{b,min} - T_g) k_{ins} A}{\frac{c_b T_{b,min}}{t_{EVA}} - \varepsilon_{ins} \sigma T_g^4}$$

BATTERY PACK DESIGN: INSULATION SIZING (EQUATORIAL DAYTIME)

# Batteries & Projected Battery Area			
Parameter	Value	Unit	Description
P	870	W	Power required by rover
t_EVA	8	Hrs	EVA time
b_cap	111	Amp-Hrs	Battery capacity
V	12	V	Voltage
A1	0.0516	m^2	Area of one battery
N	5.2252	Batteries	Number of batteries needed
N_ceiling	6	Batteries	N rounded up to integer value
A	0.3093	m^2	Projected area of entire battery pack

$$\#\ Batteries = \frac{Power(W) * time(hrs)}{Voltage(V) * Battery\ Capacity(Amp - hrs)}$$

Heat Capacity			
Molecule	Mi (g/mol)	mi (kg)	ci (J/kgK)
Li	7	1.1624E-26	3582
Fe	55.84	9.27267E-26	450
P	30.974	5.14347E-26	770
O4	64	1.06277E-25	920
LiFePO4	157.814	2.62062E-25	842.333

$$c_b = \frac{\sum m_i c_i}{\sum m_i}$$

Daytime Energy Balance				
Parameter	Value	Unit	Description	Source
Fs	1368	W/m^2	Solar Radiation	-
A	0.3093	m^2	A_rad = A_cond in this case	Calculation
Tg	390	K	Temperature of the ground	Link
Tb,max	333.15	K	Max temperature of the battery	Link
k_ins	0.035	W/mK	Thermal conductivity of insulation	Link
eps_ins	0.9	-	Emissivity of insulation	
Sigma	5.67E-08	W/m^2K^4	Stefan-Boltzmann Constant	-
c_b	842.333	J/K	Specific heat capacity of LiFePO4	Calculation
t_EVA	28800	s	EVA time	-
m_b	79.8	kg	Mass of battery pack	Link
L_ins	0.00040094	m	Thickness of insulation	Calculation
	0.0159	in		

$$L_{ins} = \frac{(T_g - T_{b,max})k_{ins}A}{\varepsilon_{ins}\sigma T_g^4 + \frac{c_b m_b T_{b,max}}{t_{EVA}} - F_s A}$$

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# Batteries & Projected Battery Area			
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Nighttime Energy Balance				
Parameter	Value	Unit	Description	Source
Fs	1368	W/m^2	Solar Radiation	-
A	0.3093	m^2	A_rad = A_cond in this case	Calculation
Tg	95	K	Temperature of the ground	Link
Tb,min	253.15	K	Min temperature of the battery	Link
k_ins	0.035	W/mK	Thermal conductivity of insulation	Link
eps_ins	0.9	-	Emissivity of insulation	
Sigma	5.67E-08	W/m^2K^4	Stefan-Boltzmann Constant	-
c_b	842.333	J/K	Specific heat capacity of LiFePO4	Calculation
t_EVA	28800	s	EVA time	-
m_b	79.8	kg	Mass of battery pack	Link
L_ins	0.00291823	m	Thickness of insulation	Calculation
	0.1159	in		

$$L_{ins} = \frac{(T_{b,min} - T_g) k_{ins} A}{\frac{c_b T_{b,min}}{t_{EVA}} - \varepsilon_{ins} \sigma T_g^4}$$

BATTERY PACK DESIGN: EQUATORIAL CHARGE TIME

Solar Power Charge Time (Equatorial)			
Parameter	**Value**	**Description**	**Source**
A (m^2)	0.724	Solar Panel Area	CAD Model
Fs (W/m^2)	1370	Solar constant on the Moon	-
fp	0.95	Packing factor	Estimate
e	0.2	Efficiency	Estimate
d	0.05	Various other losses	Estimate
g (˚C^-1)	0.001	Thermal losses	Estimate
Tref (˚C)	28	Reference Temperature	-
To (˚C)	116.85	Max Lunar Surface Temperature	Link
P (W)	163.13	Power produced	Calculation
Cap (A-hrs)	666	Battery pack capacity	Calculation
V (V)	12	Battery Voltage	Link
t (hrs)	48.992	Charge time	Calculation
*Charge time represents when the Sun is directly overhead			

$$P_{BOL} = F_S\, A\, f_P\, \varepsilon_{BOL}\, (1.0 - \delta_{loss})\, [1.0 - \gamma_T (t_0 - t_{REF})]$$

BATTERY PACK DESIGN: INSULATION SIZING (POLAR)

# Batteries & Projected Battery Area			
Parameter	Value	Unit	Description
P	870	W	Power required by rover
t_EVA	8	Hrs	EVA time
b_cap	111	Amp-Hrs	Battery capacity
V	12	V	Voltage
A1	0.0516	m^2	Area of one battery
N	5.2252	Batteries	Number of batteries needed
N_ceiling	6	Batteries	N rounded up to integer value
A	0.3093	m^2	Projected area of entire battery pack

$$\# \, Batteries = \frac{Power(W) * time(hrs)}{Voltage(V) * Battery\ Capacity(Amp - hrs)}$$

Heat Capacity			
Molecule	Mi (g/mol)	mi (kg)	ci (J/kgK)
Li	7	1.1624E-26	3582
Fe	55.84	9.27267E-26	450
P	30.974	5.14347E-26	770
O4	64	1.06277E-25	920
LiFePO4	157.814	2.62062E-25	842.333

$$c_b = \frac{\sum m_i c_i}{\sum m_i}$$

South Pole Energy Balance				
Parameter	Value	Unit	Description	Source
Fs	1368	W/m^2	Solar Radiation	-
A	0.3093	m^2	A_rad = A_cond in this case	Calculation
Tg	25.15	K	Temperature of the ground	Link
Tb,min	253.15	K	Min temperature of the battery	Link
k_ins	0.035	W/mK	Thermal conductivity of insulation	Link
eps_ins	0.9	-	Emissivity of insulation	
Sigma	5.67E-08	W/m^2K^4	Stefan-Boltzmann Constant	-
c_b	842.333	J/K	Specific heat capacity of LiFePO4	Calculation
t_EVA	28800	s	EVA time	-
m_b	79.8	kg	Mass of battery pack	Link
L_ins	0.00417767	m	Thickness of insulation	Calculation
	0.1659	in		

$$L_{ins} = \frac{(T_{b,min} - T_g) k_{ins} A}{\frac{c_b T_{b,min}}{t_{EVA}} - \varepsilon_{ins} \sigma T_g^4}$$

BATTERY PACK DESIGN: POLAR CHARGE TIME

Solar Power Charge Time (Polar)			
Parameter	Value	Description	Source
A (m^2)	0.746	Solar Panel Area	CAD Model
Fs (W/m^2)	1370	Solar constant on the Moon	-
fp	0.95	Packing factor	Estimate
e	0.2	Efficiency	Estimate
d	0.05	Various other losses	Estimate
g (˚C^-1)	0.001	Thermal losses	Estimate
Tref (˚C)	28	Reference Temperature	-
To (˚C)	116.85	Max Lunar Surface Temperature	Link
P (W)	168.08	Power produced	Calculation
Cap (A-hrs)	666	Battery pack capacity	Calculation
V (V)	12	Battery Voltage	Link
t (hrs)	47.548	Charge time	Calculation
*Charge time represents when the Sun is directly on the lunar horizon			

$$P_{BOL} = F_S\, A\, f_P\, \varepsilon_{BOL}\, (1.0 - \delta_{loss})\, [1.0 - \gamma_T (t_0 - t_{REF})]$$