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Visualizing Mission Initiative for Space Exploration

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Visualizing Mission Initiative for Space Exploration

Abstract

This thesis investigates how multi-dimensional, interactive visualizations can impact the development, operations, and exploration initiatives of unprecedented planetary rover missions, inquiring how such visualizations bring people on Earth closer to the experience of space. The context for exploring visualization methods and mission design is MoonRanger, a lunar micro-rover landing at the south pole of the Moon in 2022. This is unprecedented by way of its mechatronics, autonomy, destination and scientific purpose. There are three key values at the core -- visual decision making, mission planning, and scientific initiative. Research presents planning methodologies, technical development, and prototypes specific to this first-ever Commercial Autonomous Science (CAS) class of micro-rovers. The work discusses the prototyping experience, ideal planning interface capabilities, and mission operations design considerations for CAS missions. A resulting series of produced systems and prototypes are directly used within the context of MoonRanger's mission. The thesis concludes with comments on a visual approach to space exploration and larger implications of the work.

KEYWORDS: Visualization, Mapping, Space Exploration, Rover, Surface Operations, Mission Operations, Mission Planning, Design, Interaction Design, Exploratory Data Analysis, Autoethnography, MoonRanger

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1. Introduction

1.1. Preface

Space exploration has adopted two approaches -- humans and robots. From the 1950's through the 70's, the US and Russia competed in the space race, resulting in the first lunar rover, the Lunokhod, and the first humans on the Moon with the Apollo 11 mission (Siddiqi, 2000). Humans are intelligent, curious, have goals and initiatives, and can experience events in a meaningful way. Ideally, humans would be at the center of space exploration, able to explore for themselves the various realms of space. Unfortunately, for humans the new frontiers of space present significant risks given the hazards at hand and the current state of technology, hence robotic exploration has become optimal. With humans now analyzing data and experiencing far off environments virtually, would there be a way for humans, specifically rover-mission development teams, to continue and explore, be curious, and experience immersion in a way that transports individuals to an interactive, exploration-analogue environment? How can the development, operations, and exploration initiatives of a lunar rover mission benefit from multi-dimensional, interactive visualizations that bring people on Earth closer to the experience of space?

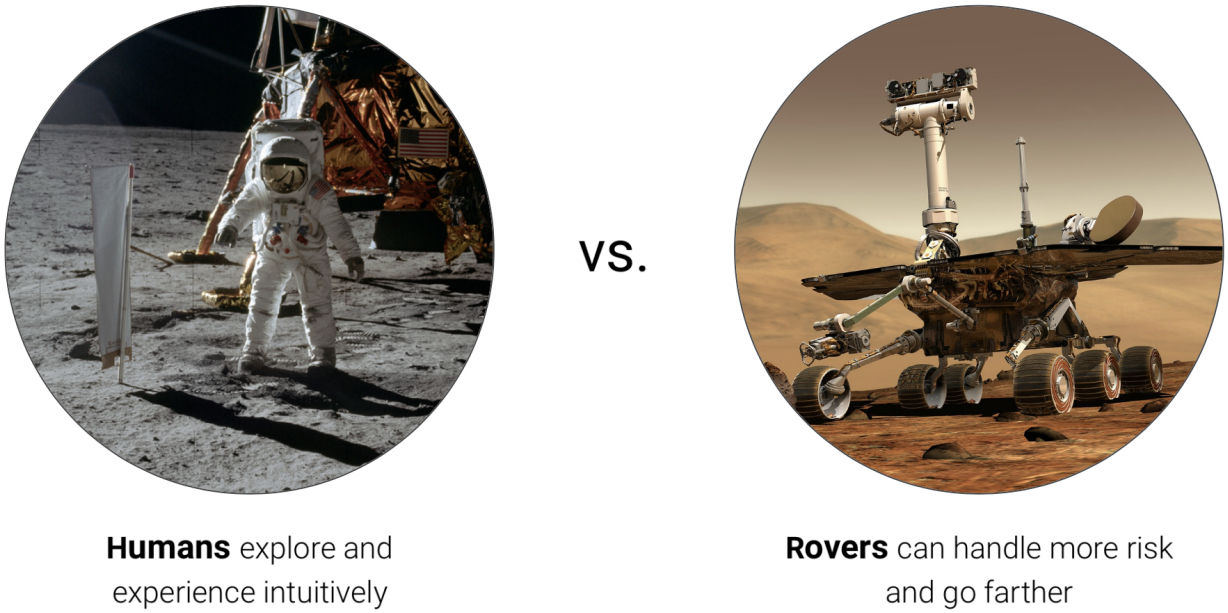


Figure 1. Dichotomy of Human vs. Rover space exploration. Image of astronaut on the Moon (left) and rendering of Mars rover (right), (NASA, 1969) (NASA, 2003).

1.2. Scope

Rover mission operations, one of the many efforts involved in a mission, is specifically dedicated to defining scientific and technological mission initiative, planning how the rover will go about achieving those goals through rover operations, and designing a mission control system to facilitate operator and rover interaction during the mission both for quasi-real-time

and high-latency missions. Mission operations teams, both for pre-launch planning and during rover operations, need to be able to process lots of information and make mission critical decisions as best they can. These kinds of decisions can range from deciding what environments are not suitable for rover traverses to what re-scoped mission goals might look like given a fault during rover operations.

Within the umbrella of planetary rover space exploration, there exist different classes of rovers. Mars Exploration Rovers (MER), for instance, are a typical example of traditional, big-budget exploration (NASA Mars, n.d.). These rovers weigh in the order of 1,000 kg, have speeds in the order of 1 centimeter per second on average, cost upwards of 2.5 billion dollars, and carry radios for direct Down-to-Earth (DTE) communication (McCarthy, 2021). On the other end of the spectrum, micro-rovers are small, lower budget missions with certain constraints and capabilities unique to their kind (Marirrodriga, 1997). Constraints will be described further in the thesis document (see Chpt 3, MoonRanger), but capabilities are likewise worth noting. This class of rover takes much less time, money, and resources to build compared to their larger counterparts. While they don't have the mass to carry direct DTE communication radios, they can exhibit autonomy, which allows them to explore at a faster speed-made-good (see appx. B) and produce more data over a short period of time. Because of these capabilities, these missions are often preferable for the recent surge of commercialized missions which collaborate with multiple organizations, payloads, and can often produce significant science return regardless of the micro-scale. These missions can ultimately save time and money and result in quick technology demonstrations, fast science return, and mean more information and insight to prepare for large scale missions.

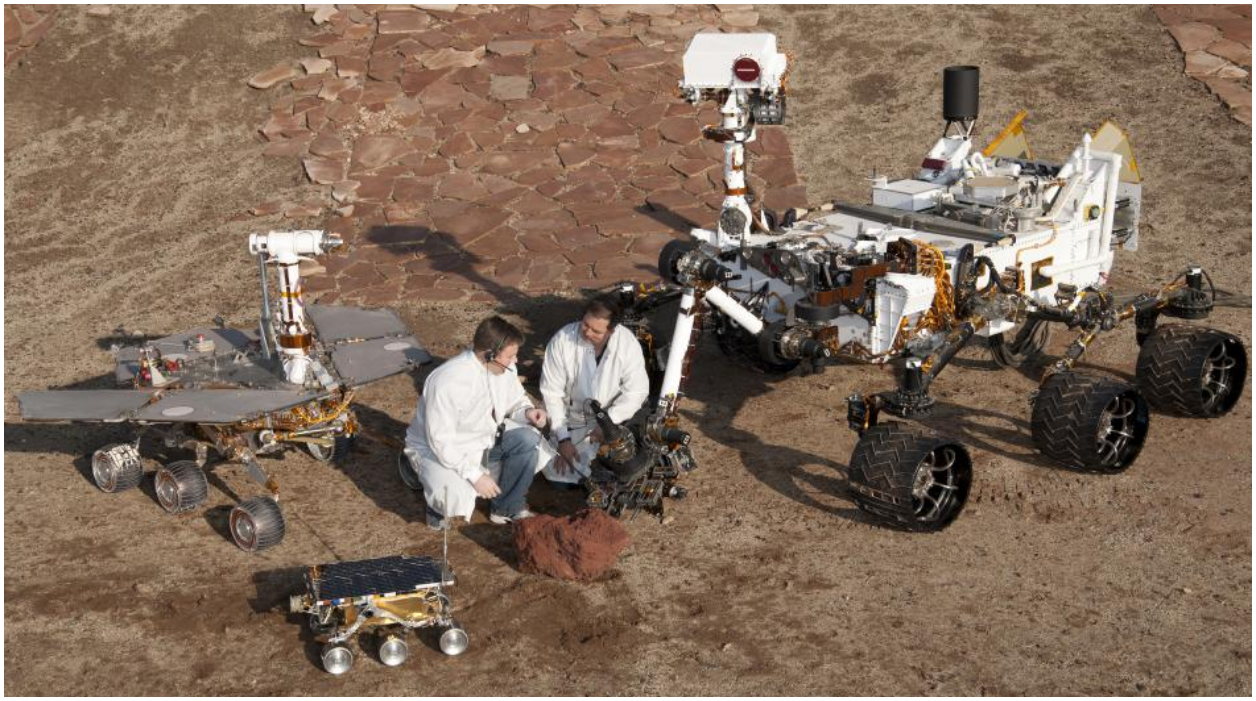


Figure 2. Three sizes of rovers, the smallest (a micro-rover), an analogue to the Mars Sojourner rover is front and center. The rover on the left is a MER test unit, the rover on the right, the largest, is a Curiosity test unit (Greicius, 2019).

For mission operations alone, mission planning is a niche sub-focus involving topics of environmental analysis, surface operations planning, and global planning among others. Planning and operations are challenged in a couple ways -- (a) so much information analysis is required to make decisions, pre-launch and on-surface and (b) operators must make decisions quickly[1], all the while taking into consideration the best interests of the entire system. Mission planning is crucial but can also be overwhelming. While multiple tools already exist for mission planning, none combine all the relevant considerations for an up and coming class of rovers, which I define as Commercial Autonomous Science (CAS) micro-rovers, and none provide a productive and intuitive mechanism for adaptive and exploratory surface operations design.

1.3. Goals

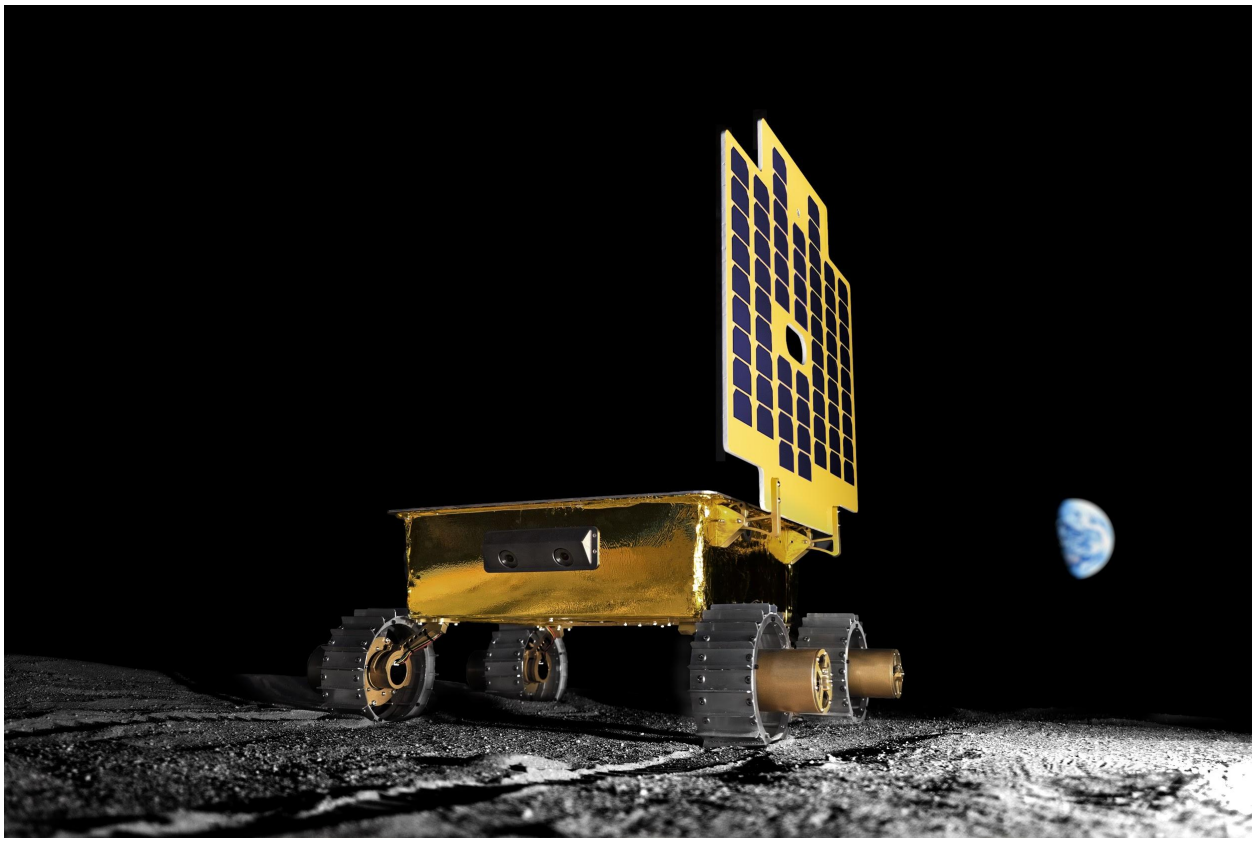


Figure 3. MoonRanger rover prototype modeled in a lunar-like environment (Khera, 2020).

This research will focus on mission planning for Commercial, Autonomous, Science (CAS) micro-rovers, zeroing in on one specific case study mission — MoonRanger. MoonRanger is an autonomous micro-rover bound for the lunar South Pole with both science and technology purpose (Schweitzer, 2020). By the end of this masters thesis, MoonRanger's mission will still be in development, with the rover flight model due in December of 2021 and operations in transit and on the Moon to occur a year later in December of 2022. Within the mission, I take an embedded role, leading the MoonRanger team at large and two sub-teams focussed each on

[1] For quasi-real time missions, the approach taken for CAS micro-rovers

mission operations and science integration. My research topic deals specifically with mission planning for CAS micro-rovers and visualization mechanisms integral to the process. Within the context of my research, visualization refers to the broader concept of interface design, incorporating ideas of map design (Andrienko, 2010), game design (Schell, 2008), and exploratory data analysis (Tukey, 1977). Through my research, I intended to explore visual decision making mechanisms and evaluate these mechanisms throughout the development of the mission by means of autoethnography[2] (Desjardins, 2019), practice missions, surveys, and structured review, through investigation of the following core question:

How can the development, operations, and exploration initiatives of a lunar rover mission benefit from multi-dimensional, interactive visualizations that bring people on Earth closer to the experience of space?

My intention is to work within the space field, so this embedding was not purely for the purpose of investigating this research question, but more so to fully integrate and explore the opportunities, advantages, and challenges of using visualization techniques within the space field. This approach allowed me to develop experience which will be beneficial for my future, allowing me to deeply understand mission planning and operations design.

A core goal of this research is to develop a visualization-based design methodology for CAS micro-rover mission planning which can be applied or adapted for use during future similar missions. During the progression of my work, three additional research questions surfaced:

RQ1: What mission design methodology could apply to this newer class of autonomous micro-rovers?

RQ2: How can and do visual decision making techniques play a role?

RQ3: Could an interface structure influence the decision making process of a team?

Going into this research, my hypothesis was that while visualization tools do exist within the space mission planning environment, they play an auxiliary role — not directly contributing to key functionality but allowing teams to appreciate, inquire, or analyze after the fact. Through my work, I can easily say my assumption was wrong. This thesis leaned into the processes and journey, integrating visualization inquiry with a fully fledged mission, ultimately offering informed results arguing the truly significant power of visualization mechanisms.

1.4. Audience

The intended audience for this research is threefold, addressing the space exploration mission development community, the design-thinking community, and those within the general public with an interest in space and/or design at large.

[2] See Section 2.8. Precedent Methodologies for further description of autoethnography.

At the micro scale, no pun intended, the mission design system and methodologies are meant to be directly beneficial for mission operations teams of future micro-rover missions. Even more applicable if these future mission developers are focussed on a polar-bound, autonomous micro-rover. Because micro-rovers possess a specific set of constraints and capabilities, the work of this thesis does present some bias in relation to mission design overall. The more related mission planning is to the context of this mission, the more useful the work and content will be from this document.

A second intended audience is those within the design field. This work is meant to show applications of computational design practices and methodologies to a relatively new field for the community. In the discussion section, Chpt 7, I will address how visual strategies and design thinking existed throughout my experience with the case study in which I was involved and which new techniques or strategies I employed throughout.

Finally, space exploration is not only just a community for engineers, but equally an open-minded environment for design-thinkers. Furthermore, to the general public and to those interested in or in pursuit of space, I hope to show opportunities that prevail. The experiences shared in Chpt 7, will directly address my perspective as someone with no formal degree in either engineering or science stepping into an embedded technical role on a mission.

1.5. Significance

Mission development has expanded with the New Space Movement (Orlova, 2020), a step towards commercializing and making accessible technical and scientific missions. Recent implementations such as NASA's Commercial Lander Payload Services (CLPS) and Lunar Science Instrument and Technology Payload (LSITP) programs are in place to develop smaller-scale, quick-return, commercialized missions which cost them less and open the field for creative ideation (Northon, 2019). Micro-rovers such as MoonRanger, which is directly involved with both CLPS and LSITP, are prime examples of this new era of space missions. New approaches to planning will be necessary as these missions look quite different from traditional MER-scale missions.

The space exploration field has for generations praised and embraced the science and engineering fields. Design and visualization have always played an important role under-raps, but have never become a key focus within mission design and development. Rover mission exploration means that humans are likely not on a planet with the rover. Humans are now distanced from experiencing exploration first hand. Mission operations as a field is evolving to now include technologies such as VR (Samuelson, 2018), but it is time for the early planning components of mission operations to fully embrace visualization mechanisms.

Visualization has long been proven as an effective mechanism for the communication of data and information (Tufte, 1983). Within the context of space exploration mission planning, visual decision making, quick visual problem solving, and information visualization are heavily relevant. This research will build on the embedded space-mission research of Vertesi (as

discussed in Chpt 2) and Jeff Norris's (also see Chpt 2) space operation interface development, with an emphasis on interface design. Computational Design (CD) practices have only recently integrated deeply within space exploration missions and this research intends to continue the exposure of the CD field to the field of space.

1.6. Chapters

This research will begin by exploring existing projects and literature related to operations and design considerations (Background & Related Work, Chapter 2). I will then provide an overview of the entire MoonRanger mission/system and the role I took during my involvement (Chapter 3), which is both interesting and useful for understanding design and methodology choices made during the research process. With a context outlined, I describe the research methods and evaluation mechanisms employed (Chapter 4, Methodology). The next section details my design approach to mission operations as a high level effort within a CAS micro-rover mission environment and the specific methodologies and technical work I developed for various operations efforts within MoonRanger. These cover topics of planning considerations, surface operations, mission success definition, environmental analysis, and global planning (Chapter 5, System Design). I then describe a series of prototypes I developed or configured iteratively as the mission progressed, each with a distinct mission-planning purpose, leveraging visualization and design techniques. Each prototype is characterized with intended and actual purpose, capabilities and limitations, and interactions, with an evaluation and discussion of future work (Chapter 6, Prototypes). The thesis will converge to discuss findings and realizations achieved through the work, characteristics of an ideal planning tool, and mission operations design considerations for CAS micro-rover missions (Chapter 7, Findings & Discussion). I will conclude by presenting next steps (Chapter 8, Future Work), and significant takeaways (Summary, Contributions, and Conclusion, Chapter 9).

2. Background & Related Work

2.1. Visualization

This research investigates visualization as an integral component to decision making and operations planning for a mission. Within the context of this research, visualization is a broader term that refers to four subcategories. These are map design, exploratory data analysis, game design, and visual analytics. Concepts of interface design emerge within each of these categories. This chapter will address all of these ideas in the subsequent sections.

2.1.1. Exploratory Data Analysis

Exploratory Data Analysis (EDA) is a term first introduced in 1977 by J. W. Tukey. Tukey defines EDA as "detective work -- numerical detective work -- or counting detective work -- or graphical detective work," (p. 1). In Tukey's book, *Exploratory Data Analysis*, EDA is used to describe existing terms and concepts that represent relationships between numbers or are a way of presenting otherwise hidden information in an enlightening manner. Tukey (1977) advocates for the power of visualizing information stating, "The greatest value of a picture is when it *forces* us to notice what we never expected to see," (p. vi).

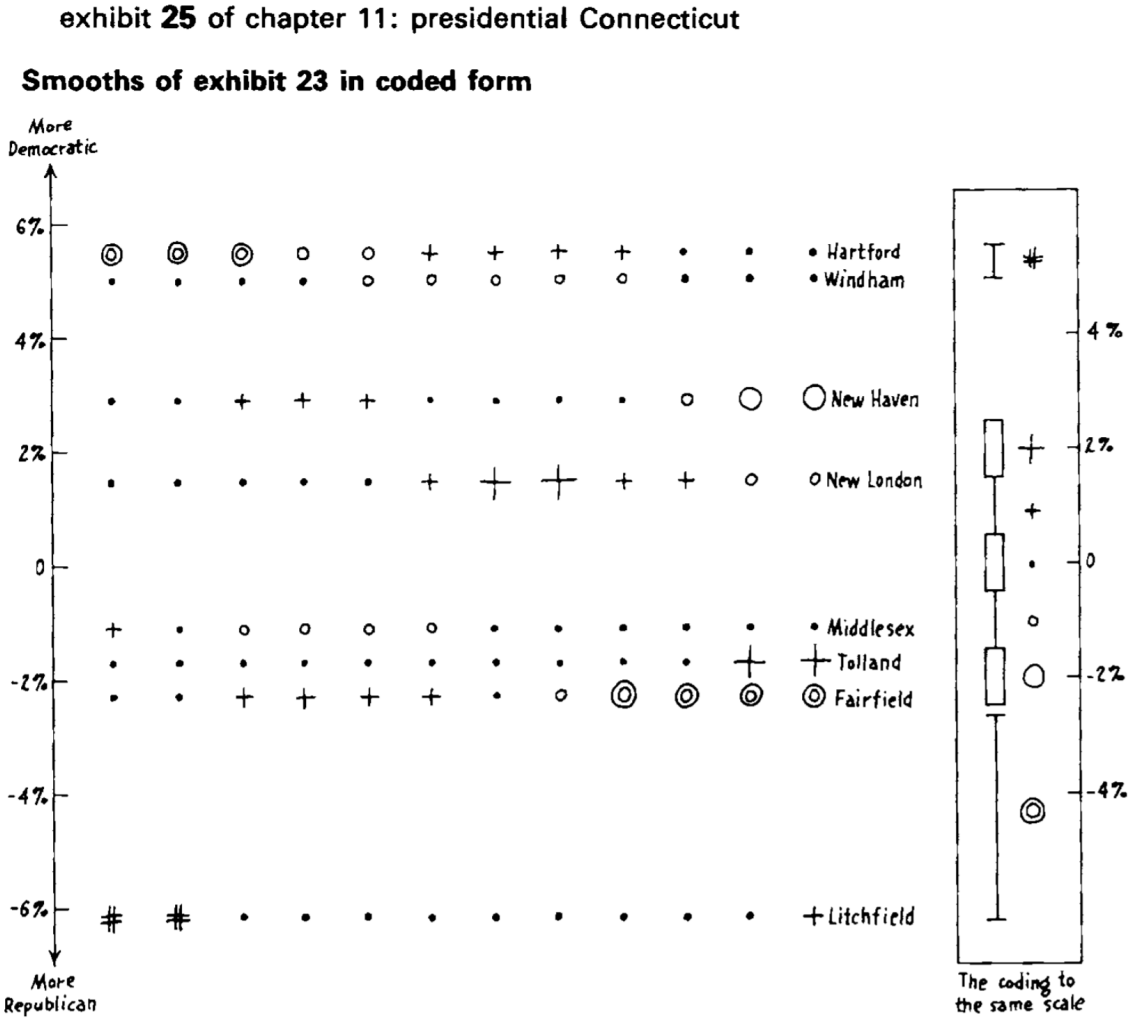


Figure 4. Plot from Exploratory Data Analysis*, indicating the extent republican or democratic different counties of Connecticut voted during a 1964 election (Tukey, 1977, p. 394). Circles and pluses are encodings to represent smooths and roughs, where the addition of a smooth and rough results in the residual (Tukey, 1977, p. 392).*

2.1.2. Map Design

Mission planning depends on maps for the complex information they provide about the mission destination. Maps have evolved from static representations to interfaces which include advanced user-interaction.

Gennady and Natalia Andrienko discuss the potential of interaction design in an article describing Decartes, a "cartographic visualization" tool leverages interaction with maps to allow "data exploration" and the ability "to facilitate revealing unknowns," (Andrienko, 2010, p. 372). This tool supports many types of interaction such as "brushing," a method where users can select or highlight an area of one data set or map and see the same selection in another view or application.

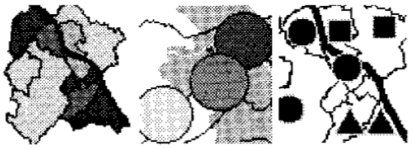
N	Type(s) of variable(s)	Relationship (where appropriate)	Visual variables	Presentation methods	Examples
=1	nominal (including logical)		colour or shape	area colouring, coloured signs, shape signs	
=1	ordinal		value	area shading, shaded signs	
=1	numeric		value or size	area shading, standalone bars	
>1	logical		colour	structured signs varying by presence or absence of coloured sectors	
>1	numeric	comparable	size	parallel bars	
>1	numeric	included in a common total	size	pies, standalone segmented bars, parallel bars	
>1	numeric	ordered inclusion (a>b>…)	size	nested squares, parallel bars	

Figure 4. Table 1 from "Interactive maps for visual data exploration" (Andrienko, 2010, p. 360).

Andrienko (2010) discusses the importance of allowing multiple different views or means of presenting information, leaving flexibility for users, who are not necessarily cartographers, to have autonomy over a display most beneficial for their use. Figure 4 shows a series of such example presentation types from which users of Descartes can choose. The table indicates the type of data, relationship between visual elements, what visual parameters are displayed (such as color indicating different values), presentation method, and a small diagram for each type of data presentation. This flexibility in presentation method also "greatly support(s) the variety of activities comprising data analysis, especially exploratory analysis," (Andrienko, 2010, p. 359). In a similar vein, mission planning relies on understanding the same information but on different

levels. For example, in order to assess the viability of a landing site, rover teams might be curious about implications of slope data on each the mobility system and the thermal system of the rover.

One area of interaction the Andrienko's fail to mention is the capability to combine maps, allowing users to see the relationship between data sets in one single map. This thesis further investigates this functionality, produces examples directly beneficial for the MoonRanger mission, and argues the power this map has on the initial rover design.

In the paper "Animation and the role of Map Design in Scientific Visualization," David DiBaise et. al. (1992) advocate for an exploratory data analysis approach to visualizing map information (p. 201). DiBaise emphasizes that "animation expands the graphic symbolization options available for visual thinking and communication, and how dynamic displays can be used to generate multiple alternative views in the spirit of exploratory data analysis," (p. 203). For CAS micro-rover mission planning, the ability to view dynamic datasets is essential in order to plan waypoints and paths along a nearly continuously illuminated region, considering the changing sun angle at lunar polar regions over time. The dynamic nature of surface operations execution during different mission phases, also time-based, is another example of the dynamic opportunity for visualization.

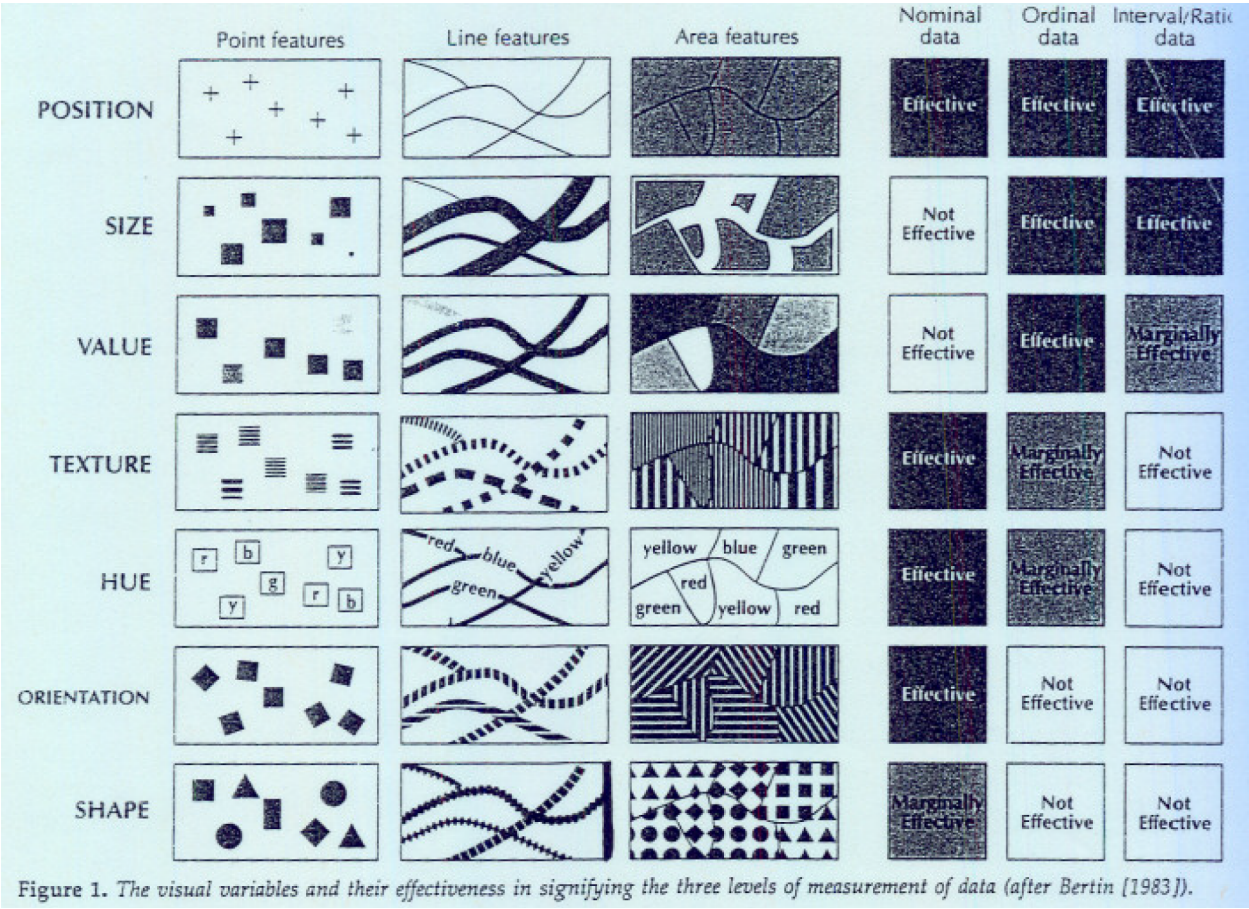


Figure 5. Image illustrating various features and how effective they are at conveying meaning for nominal data, ordinal data, and interval data. (DiBaise, 1992, p. 204)

DiBaise (1992) argues not just for the dynamic nature of map displays but the interactive ways in which a user can involve (p. 205). The paper explores different mechanisms for interaction and dynamism when displaying maps, all of which focus specifically on the changing variables or data directly associated with the map data or information. DiBaise doesn't account for human agenda related to maps. A surface operations diagram, for instance, is a tool used within the context of Mission Operations to visualize specific goals or maneuvers on the surface at the site of exploration. This diagram is dynamic in nature because operations occur at a certain time. The diagram is also interactive in the sense that operators or planners define maneuvers, goals, and traverses. The definition of map visualization techniques should expand to include interactive methods of time-dependent operation sketches, which could show sequences of events and regions of interest along with the changing environmental data in order to provide planning teams with the best sense of conditions at the given time of an operation.

2.1.3. Game Design

A key aspect of computer games involves users making decisions along a journey. In a similar sense, mission planning is like a game. When deciding between possible paths a rover might take, a team needs to evaluate the value of each path -- what is the balance of mission return and risks? Decisions both during early planning and surface operations once the rover has landed on the Moon both involve decisions on what path to take or otherwise. Chris Crawford (1982) discusses the information pipeline between an interface and a human, emphasizing "The game must be designed in such a way that the information given to the player flows naturally and directly," (p. 46). Crawford (1982) laments the situation where too many design issues inhibit a player from truly enjoying the experience. In a similar way, mission planning tools can involve too much of a learning curve, too little information, or too little interaction for a planner to fully embed in the experience of exploratory data analysis. Crawford (1982) also discusses how the user's experience is heavily influenced by the design approach. In the same way that games can be designed around either their internal game structure versus the input and output of a user, so can planning tools around the technical objectives versus the user experience. While both game structure and technical objective are important, the key distinction is where the design begins and the result of designing around a user's interaction with an interface can result in a much smoother experience and a more successfully interpreted structure (Crawford, 1982, p. 46). Many planning tools designed for and within private missions are driven by a technical agenda as opposed to a user experience. This thesis explores the effects of more user-centered planning interfaces and their implications on operation decisions.

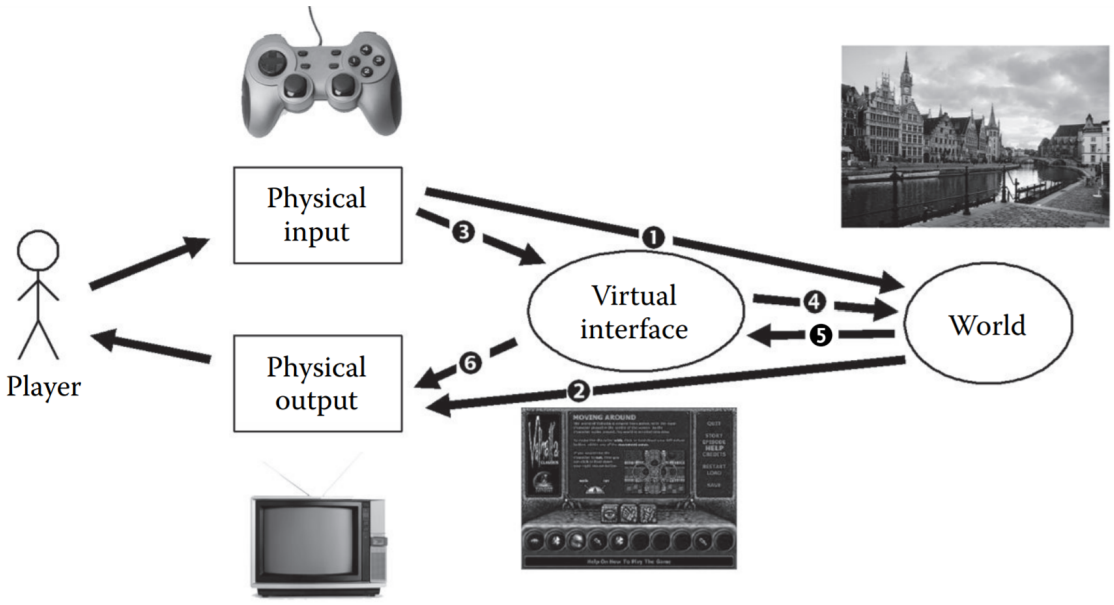


Figure 6. Diagram of interaction between a user and a world (Schell, 2008).

Jesse Schell takes a similar stance in the importance of user-centered design, arguing that "the goal of a good interface . . . isn't 'to look nice' or 'to be fluid,' although those are nice qualities. The goal of an interface is to make players feel in control of their experience," (Schell, 2008, p. 254). Schell categorizes game design into a series of lenses. Within *Lens 59: The Lens of Control*, Schell (2008) stresses a designer ask themself a series of questions, two of which stand out -- "When players use the interface, does it do what is expected? If not, why not?" and, "Intuitive interfaces give a feeling of control. Is your interface easy to master or hard to master?" (p. 254). Schell (2008) describes interaction between a user and a world through a series of interfaces, as shown in figure 5. The "Virtual Interface" is the element which connects the world to the user through physical input and output. In *Lens #61: The Lens of Virtual Interface*, Schell emphasizes smooth information delivery between the user and the game world, specifically what information is most critical and how it is best communicated, asking, "What information does a player need to receive that isn't obvious just by looking at the game world?" and "How can this information be delivered to the player in a way that won't interfere with the player's interactions with the game world?" (p. 258). Like Crawford, Schell advocates for an interface which is intuitive, enabling users to fully immerse themselves in the experience. This thesis explores and challenges the design choices of existing planning tools, developing a series of prototypes, some which prioritize user experience and some which prioritize technical capabilities.

2.2. Mission Planning Interfaces

Mission operations identifies scientific and technological mission objectives, develops the Concept of Operations (CONOPs) (see appx. B), and is responsible for carrying out operations and planning in real time during the mission. Planning and operations are challenged in a couple ways -- (a) so much information analysis is required to make decisions, pre-launch and on-surface, (b) operators must make decisions quickly for CAS missions, all the while taking into

consideration the best interests of the entire system. Mission planning is crucial, complex, and involves analyzing and processing lots of information. While multiple tools exist and provide platforms for mission planning, none combine all the relevant considerations for planning nor do they provide a productive and intuitive mechanism for surface operations development and design.

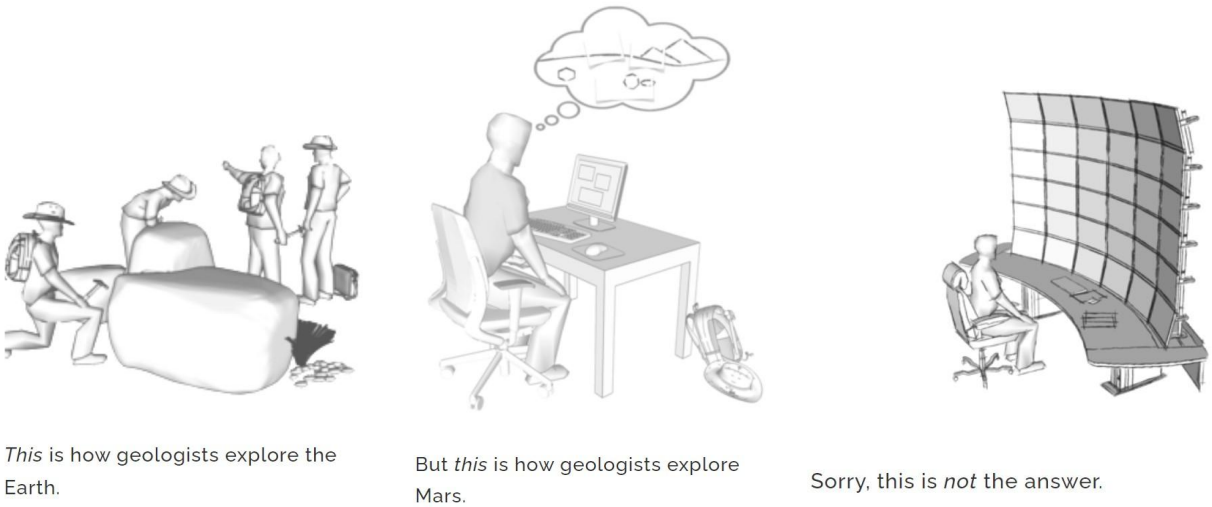


Figure 7. Jeff Norris, Project Manager of NASA's Mars OnSight articulates the dichotomy of physical vs. virtual exploration in the article "Immersed on Mars," (2016).

The complexity of space missions involves a conglomeration of knowledge and perspective from all mission aspects, ranging from mobility, visibility, and mechanical structures and electronics survival, to the scientific purpose and landing location. Using software tools for data analysis often means breaking down these various information aspects piece-wise to try and understand the whole in a manual fashion. Furthermore, there exists the question of how specifically scientific initiative can be simulated. Usually, the mission's Science Principal Investigator offers domain experience and direction to the team, leading them towards the scientific goals within the bounds of their capabilities.

Quite a few software tools exist supporting lunar site analysis. The table below details a list of these. The most relevant works are detailed further in the following paragraphs.

Software	SIM	DEM	Data Analysis	Personalized	Available
MATLAB	✖	✖	✔	✔	✔
MoonTrek	✖	✖	✔	✖	✔
Gazebo	✔	✖	✖	✔	✔
LunaRay	✔	✖	✖	✔	?
DEMkit	✖	✔	✖	✔	?
Lunar Polar Sim	✔	✖	✔	✔	?
Mars OnSight	✖	✔	✖	✖	~ ✔

Table 1. Table of existing software used in space mission contexts and their capabilities. Own work.

Table 1 lists multiple existing software tools and their capabilities to simulation the lunar environment (SIM), interact with a key data product - a DEM[3], perform data analysis, allow for personalization (i.e. open source), and whether or not they are available for public or MoonRanger use. In the paragraphs to come the first three software tools are described in more detail.

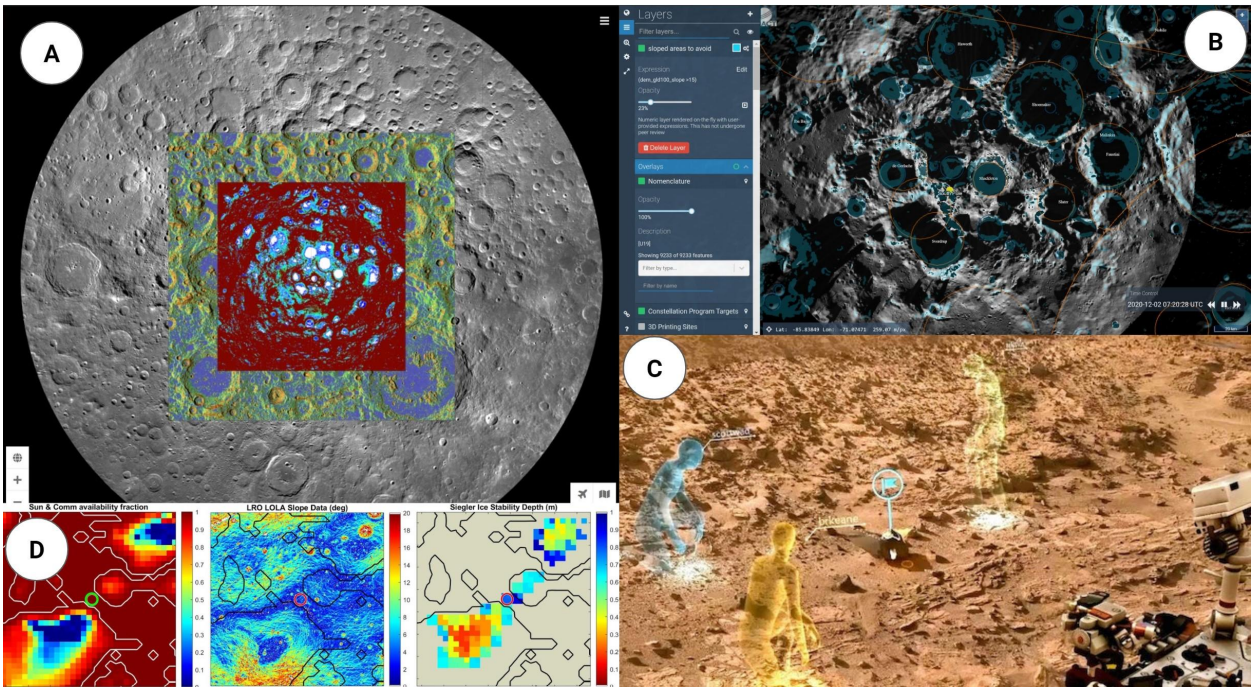


Figure 8. Related work. A) Moontrek interface with ice stability data layered on top of slope data (Lunar and Planetary Mapping and Modeling Project, 2017). B) Quickmap viewing crater names and Permanently Shadowed Regions (Arizona State University, 2020). C) Mars OnSight (Abercrombie, 2017). D) Lunar maps processed and visualized using Matlab (own work).

MoonTrek

This web-based environment is the photoshop of the space world, allowing users to select a broad region of the Moon (north pole, south pole, equatorial region) and view datasets in 2D layers. MoonTrek (fig. 8a) platform provides access to many datasets and the option to make a free account, allowing users to request more detailed data from NASA related to a certain location. Of the preloaded datasets, resolution is low. If a user requests additional data, it can take weeks to months to get a reply and the data provided is not loadable into the software, but sent as a CSV or .txt file. Within MoonTrek users can select multiple datasets and view these as layers and adjust opacity. While viewing overlaid datasets can be beneficial, these are limited and don't show the relationships between datasets. This software doesn't allow users to upload their own datasets or perform additions/multiplications between datasets (Lunar and Planetary Mapping and Modeling Project, 2017).

Quickmap

Quickmap (fig. 8b) is very similar to MoonTrek in the sense that it allows a layered view of datasets, but the application provides a set of uniquely processed data features and user data

[3] Digital Elevation Model of terrain.

manipulation capabilities. Users can view sun incidence over time starting at a time/date of their choice, even into the future. Quickmap provides layers for Permanently Shadowed Regions (PSRs) (appx. B), identifies craters, and allows users to add points, polygons, and lines to the maps they view. Users can export a link which saves all the app information settings. Some limitations still remain however. The illumination viewed overtime doesn't integrate ray tracing, a technique which accounts for any terrain hills or dips which could produce shadowed regions on other terrain, it only accounts for the lunar phase. Both the identified PSRs and craters are only large scale, too low resolution and not beneficial for rover-scale planning. While points, lines, and polygons are helpful, they cannot be named, labeled, or set to a specific size in Quickmap, something essential for surface operations diagrams. The dataset manipulations, such as `sine(datasetA) * datasetB`, are only available for select datasets. These datasets are low resolution and not beneficial for rover scale planning (Abercrombie, 2017).



Figure 9. Gazebo, an existing software tool used to simulate mobile robots in an user-designed environment (Pant, 2021).

Gazebo

Gazebo (fig. 9), one of the most commonly used tools for space simulation, is not a 2D environment for data analysis, but a simulation environment specifically for rover mobility, optics, and software analysis. It is open-source, so allows a user to develop to their heart's content the terrain, rover, and lighting specifications. However, it is incredibly non-intuitive, comes with a steep learning curve, and is good only for rover-scale simulation, not global planning. The terrain in this environment can be very visually interesting and beautiful, it is usually not representative of the actual lunar environment and therefore no lunar datasets can be overlaid or analyzed within this context. Surface operations can be tested by simulating the rover to perform certain paths, but not surface operation design is supported (Koenig, 2004).

Matlab

Matlab (fig. 8d), a software commonly used in the math and engineering communities, allows for extensive data analysis (Thompson, 1995). It is built for matrix manipulation, which is very helpful for viewing and configuring lunar datasets, but is also non-intuitive. While indeed optimized, the software can still take a long time to load datasets, sometimes between 15 minutes and 1 hour for lunar maps specifically. In order to combine maps, view overlays, or add features such as circles or lines to the maps, users must manually write a script and update it as needed. This is a useful, but clunky software when it comes to surface operations planning. Advanced diagrams are a possibility but the process of producing those comes with a steep learning curve and requires expert domain knowledge of Matlab programming. CAS micro-rover teams may not be equipped with the resources, time, or budget to recruit or support such an expert individual or team. Even if such an individual was aboard a team, passing this information along to other users, whether they be planners during the mission or other parties exploring or digesting information, the level of available interaction with the software would be quite limited.

Mars OnSight

Mars OnSight (fig. 8c) is a virtual reality environment constructed from the stereo images collected from the Mars Curiosity rover. Scientists can enter the environment, explore rock features, science data collected by the rover, and feel like they're exploring Mars itself. This tool is the most experience-based, immersive environment available. The downsides of Mars OnSight are that the environment only comes to life once the rover is on the surface of Mars and while that does allow operators to plan surface operations in mission real time to some extent, no planning using this tool can occur prior to landing and deployment of the rover. It is true that operations change and require planning as the rover explores during the mission, but most planning takes place well before launch and this platform does not support that capability (Abercrombie, 2017).

Each of these aforementioned software environments provide very helpful functionalities, yet none fully support the scope of mission planning for CAS micro-rover missions. This thesis sets out to address these gaps and find opportunities for planning insight through the combination and extension of visual decision making and information representation technologies.

Customized Mission Specific Tools

Several missions, including many government-run missions, produce their own private tools for planning. These tools do support functionality such as dynamic data interfacing, waypoint planning, and ellipse plotting. For instance, NASA Ames uses a "Planetary Rover Simulation for Lunar Exploration Missions," which is most similar to a configured Gazebo environment (Allan, 2019). The software allows individuals to operate a rover in a lunar-analogue environment which is hyperrealistic with a crater and rock distribution and high-fidelity modeled illumination. Other missions such as NASA's VIPER rover have their own planning tools, some which are 2D map visualization based software interfaces and others which are more immersive and virtual-reality based. These tools, however, are not available publicly to support CAS micro-rover missions and themselves require a steep learning curve.

2.3. Precedent Methodology

In a similar initiative to embed and explore topics of visualization, Janet Vertesi's work is particularly relevant. In addition to visualization, Vertesi has explored topics of culture, remote operation, development strategies, and the influence of team structure on space exploration missions (Vertesi, 2015). The difference between her and my approach is that she took an embedded but more distanced role as an ethnographer whereas my role within MoonRanger is directly embedded and deeply involved as opposed to distanced. Ethnography is defined by John Brewer (2000) as,

> "...the study of people in naturally occuring settings of 'fields' by means of methods which capture their social meanings and ordinary activities, involving the researcher participating directly in the setting, if not also the activities, in order to collect data in a systematic manner but without meaning being imposed on them externally." (p. 10)

For Vertesi, her embedded role meant attending meetings to observe, participating in various mission events, observing individuals as they performed analysis, interviewing individuals, among other forms of interaction. As an ethnographer, returning to Brewer's definition, Vertesi performed her research in a way to not impose personal opinion, or "meaning" on the missions studied. In contrast, my involvement in MoonRanger does not involve an approach to withhold meaning, but instead moreso to produce meaning as systems and tools leveraging visualization mechanisms are produced and used. My work advocates for the use of visualization tools within the context of mission planning, directly in the context of a particular mission (discussed in Chpt 3, MoonRanger), also while observing the effects of these tools and mechanisms on the team and mission itself.

In order to capture similar insights, specifically about the avenues and relationships for visual decision making processes, I utilize autoethnography as a method. Audrey Desjardins (2019) describes autoethnography as focussing "personal experiences to understand broader cultural meanings of technology," (p. 386). Desjardins illuminates a space of research reserved for individual, first-person investigation, describing this method approach as including "research that involves data collection and experiences from the research themselves, as opposed to external users," (p. 385, 386). The method has been used by others such as Marta E. Cecchinato et. al. (2017), Andres Lucéro (2018), and Kristina Höök (2010) within the fields of design and interaction design. This research particularly involves prototype and system development for very niche areas within the MoonRanger mission and some tools are only used fully by myself to perform certain analysis or planning for the mission. Therefore, autoethnography is a key mechanism for both informing and evaluating the produced technologies. Through the methodology and prototype development process, part of my evaluation will be to understand the effect of these tools on the culture of the mission, understand their effectiveness for CAS micro-rover specific planning, and assess their ability to communicate ideas and information between the team and to others. The evaluation will explore these capabilities primarily as they relate to interface design, map design, and exploratory data analysis.

Vertesi's recent work discusses the role team organization plays on how decisions are made in her book *Shaping Science*. She states "the organization of scientific teams affects the construction of knowledge claims -- that is, the different forms of organizing and enacting a scientific collaboration play into how decisions are made, how instruments are built and operated, and how objects in the solar system are crafted and known," (Vertesi, 2020). Through my work, I hope to extrapolate on her observations that organizational structure can influence how instruments are built and operated, hypothesizing that an inverse could occur. **Could interface design and functionality influence mission decision making?**

Finally, while all existing planning tools provide specific functionality, few address the idea of human experience. The Mars Onsight initiative is one of the only efforts inquiring in this domain. With advanced technologies in Augmented Reality (AR), Virtual Reality (VR), and otherwise, the potential for immersive, augmented, remote exploration exists. This research intends to investigate ideas of remote-exploration for two main audiences -- those directly involved in mission planning with relevant domain knowledge as well as for those in the general public.

3. MoonRanger

Before discussing the details of this research, understanding the mission space in which my work manifested is integral.

MoonRanger is an autonomous micro-rover bound for the lunar south pole to explore for hydrogenous volaties (See Appendix B). The mission is part of the 19-C mission funded by NASA CLPS and is a LSITP payload (See Appendix B for all CLPS, LSITP, payload). The rover will fly aboard the Masten XL-1 lander along with seven other payloads (Potter, 2020). MoonRanger's mission will launch in 2022 for surface operations to occur ~December 7th through the 18th (Schweitzer, 2021, p. 1).

At the core, MoonRanger's mission purpose is to characterize hydrogenous volatiles while demonstrating autonomous micro-rover capabilities during lunar polar exploration. This mission purpose is both a science and technology purpose with science involving the characterization of hydrogenous volatiles and the technology demonstration involving autonomous exploration.

The mission operates under several constraints, which fall into two categories, micro rover mission and lunar polar environment constraints. As a micro-rover mission, the rover is limited in mass and size with a cap at 18kg, has a limited schedule for development and mission at about 4 years total, and is equipped with fewer resources than most MER scale missions (Appendix B). The lunar polar environment presents its own set of constraints. Lighting at the pole is low angled and produces sharp, dark shadows which can be a challenge for perception, thermal, and power systems. In dark regions temperatures can get as cold as ~50°K and as hot as ~300°K in well illuminated areas (Schweitzer, 2021, p. 9). Finally, precedence is an important challenge. No rover has yet roved at the poles of the Moon, meaning limited information on methodologies and best practices specific to that environment exist to help development and planning.

3.1. System

To discuss MoonRanger's approach, we will begin with an overview of the system. The rover's mission purpose pulls from the four highest level mission objectives which feed hierarchically into mission, system, and subsystem level requirements. These objectives are as follows:

OBJ-001: Hydrogenous Volatile Measurement

MoonRanger will facilitate the characterization of hydrogenous volatiles at a polar lunar location.

OBJ-002: Autonomous Micro-rover

MoonRanger will demonstrate autonomous microrover capabilities at a polar lunar location.

OBJ-003: Flight Contract

MoonRanger will comply with specified NASA contract and fly on a commercial lunar lander.

OBJ-003: Regulations

MoonRanger will comply with relevant governmental regulations.

The system follows the verification and validation process shown in figure 10. At the time of writing this chapter, the mission is in between detailed design and implementation. Following the mission's CDR (Appendix B), early system level integration, testing, and verification will begin.

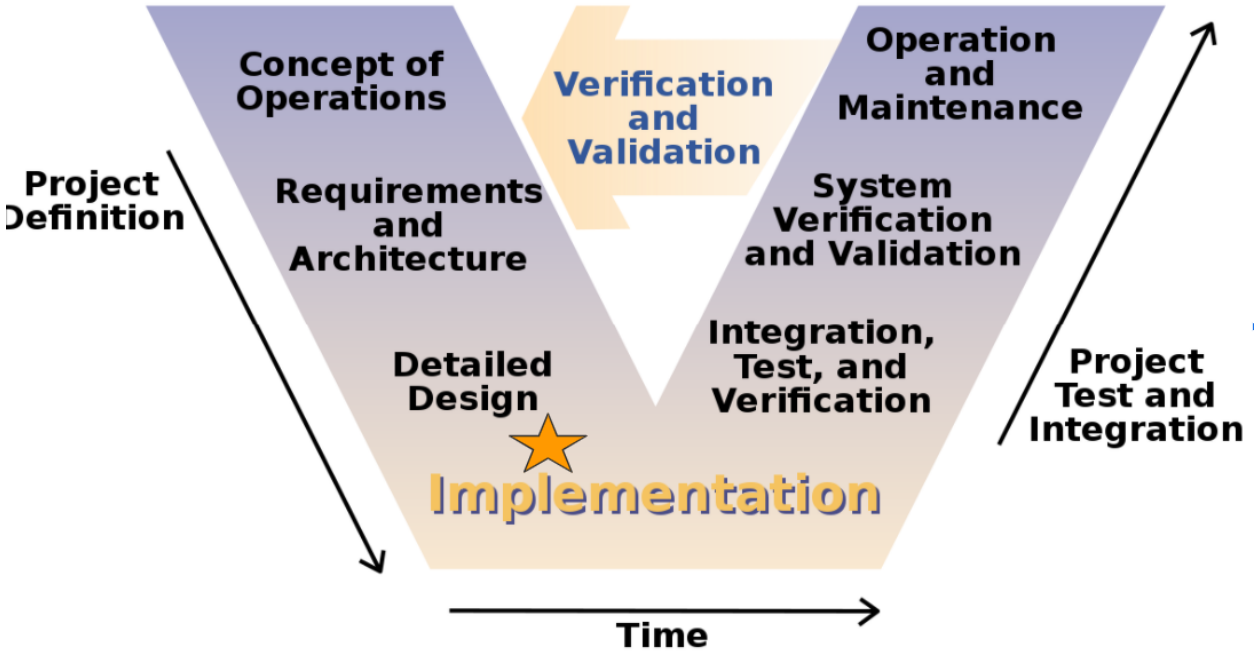


Figure 10. Verification and Validation process (Shea, 2017). Orange star indicates MoonRanger's status at the time of its Critical Design Review.

Many larger missions have the budget and resources to produce a flight spare rover and/or a rover analogue on Earth to help troubleshoot during surface operations. MoonRanger's mission is different. As a protoflight program, the mission will develop a series of prototype rovers with select system capabilities leading up to launch for preliminary testing and system verification, ultimately producing a single flight rover which will be subject to final environmental tests and will then be delivered in December of 2021 and launched to space a year later.

3.2. Science

MoonRanger's science objectives revolve heavily around a science instrument payload. The rover will carry a Neutron Spectrometer System (NSS) (Appendix A and B) developed by the NASA Ames Research Center (ARC) (Schweitzer, 2021, p. 9). This instrument consists of a sensor module on the left of and a data processing module on the right of figure 11 (NASA Ames, n.d.).

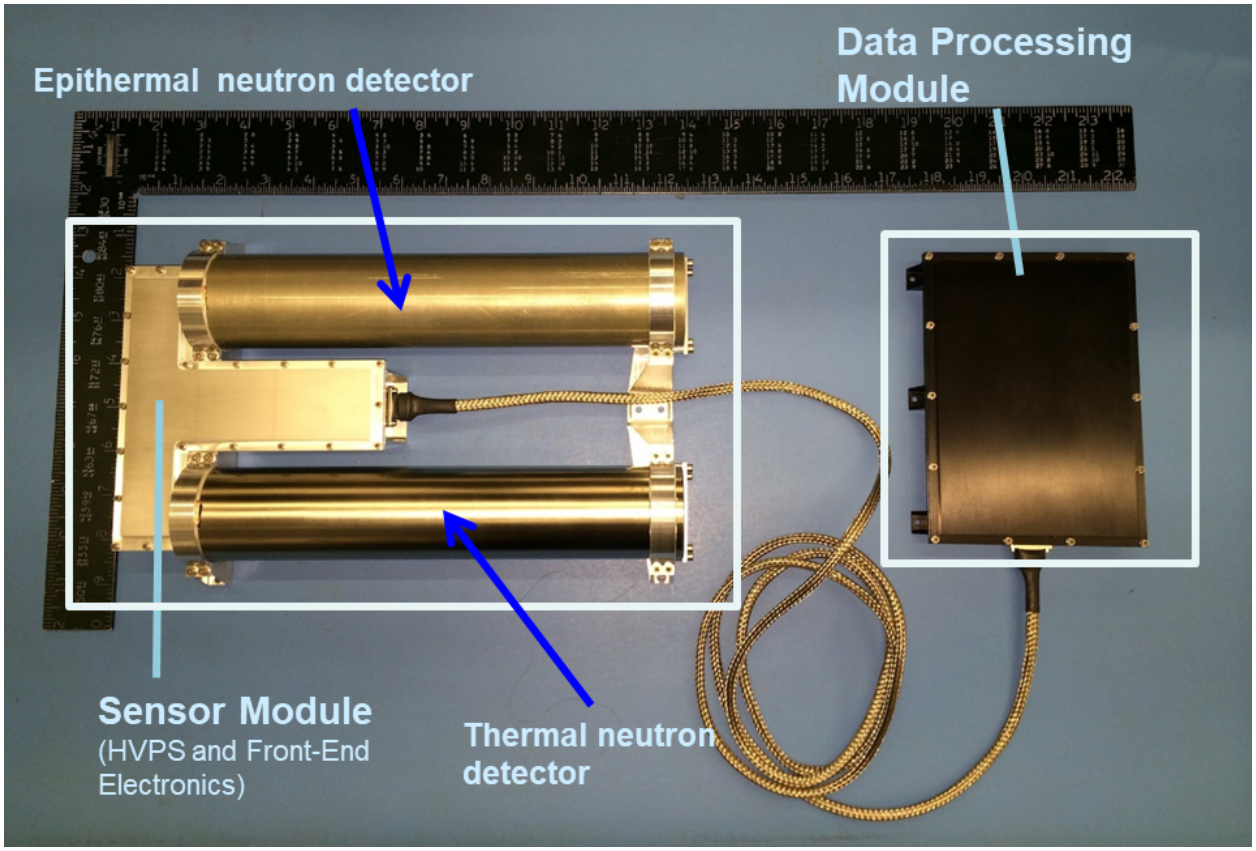


Figure 11. Neutron Spectrometry System (NSS) shown with sensor module on the left and data processing module on the right. Photo credit NASA ARC.

The instrument is capable of measuring changes of leakage flux of low energy neutrons coming out of the lunar regolith and is able to detect these neutrons within the first upper meter of the lunar surface, not sensitive to ice below a 1 meter depth (Elphic, 2017).

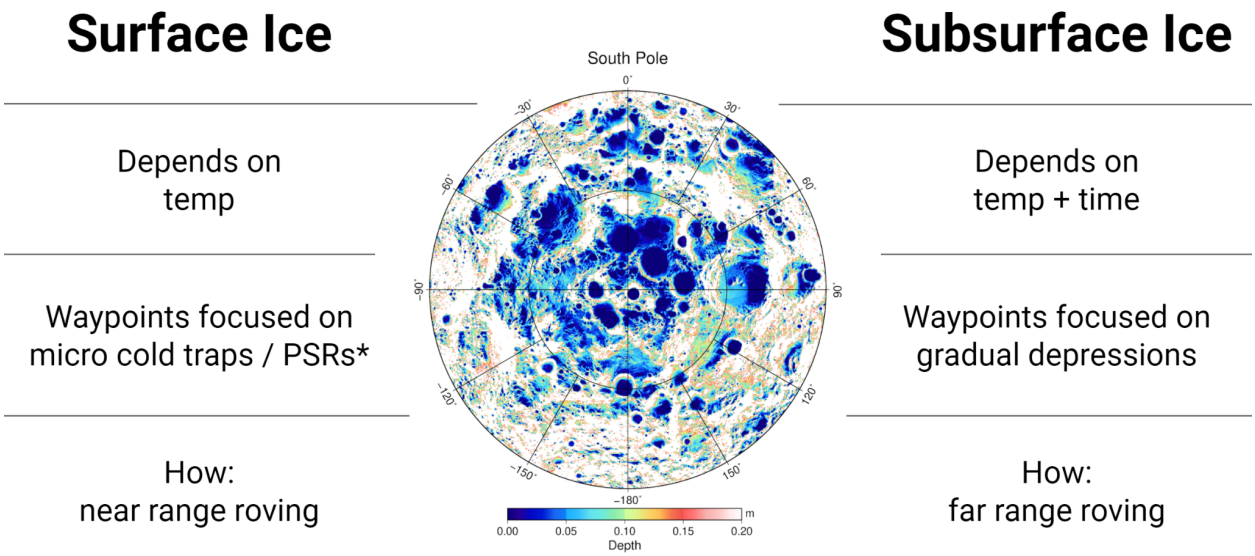


Figure 12. Surface and subsurface ice exploration dependencies with planning and roving specifications. Diagram -- own work, center image (Schorghofer, 2007) .

Waypoints, which are selected coordinates planned out for the rover to follow during surface operations, are categorized into navigational and scientific waypoints. Because there is no ground truth data on the existence of surface ice and stable surface and subsurface ice, science waypoints or waypoints of interest (WOIs) are planned around the conditions conducive to the possible existence of this ice. Surface ice exploration waypoints depend on the maximum surface temperature, the lower this maximum temperature is over time, the more favorable the conditions for surface ice existence. Permanently shadowed regions for instance are very cold regions at the south pole with a higher chance of the existence of surface ice because the terrain within PSRs never sees light. For MoonRanger's exploration, surface ice exploration waypoints focus on micro cold traps, or permanently shadowed regions. Micro cold traps are very small craters cold enough to possibly support ice. These micro cold traps can be as small as 10cm in diameter (Hayne, 2021). At the latitude of MoonRanger's landing site, most small craters seen from NAC (Appendix A and B) imagery, are micro cold traps depending on local slopes, meaning micro cold traps will be very frequent even close to the lander's well-illuminated location. Because of this, the rover can traverse near-range to the lander to explore these regions. Subsurface ice on the other hand depends on the temperature profile of the subsurface. Areas that exhibit these characteristics are regions which don't receive much illumination at all, whose surrounding terrain is also cold which means the area isn't warmed due to regolith heat transfer, and their locations aren't usually close by a well-illuminated landing location. Specifically, large craters, such as Shackleton, Haworth, among others are examples in the extreme of locations which could possibly exhibit stable subsurface (as well as surface) ice. The downside of exploring such large craters, however, is that the rover cannot handle the associated slopes due to its limited mobility system. Instead of defining these waypoints within craters, the mission defines these waypoints within gradual depressions, areas whose slopes prevent constant illumination and mean the rover could survive the traverse. For the rover to reach these regions, it must traverse farther from the lander's wel-illuminated location.

3.3. Operations

MoonRanger's landing site has been selected near Haworth crater at the lunar South Pole.

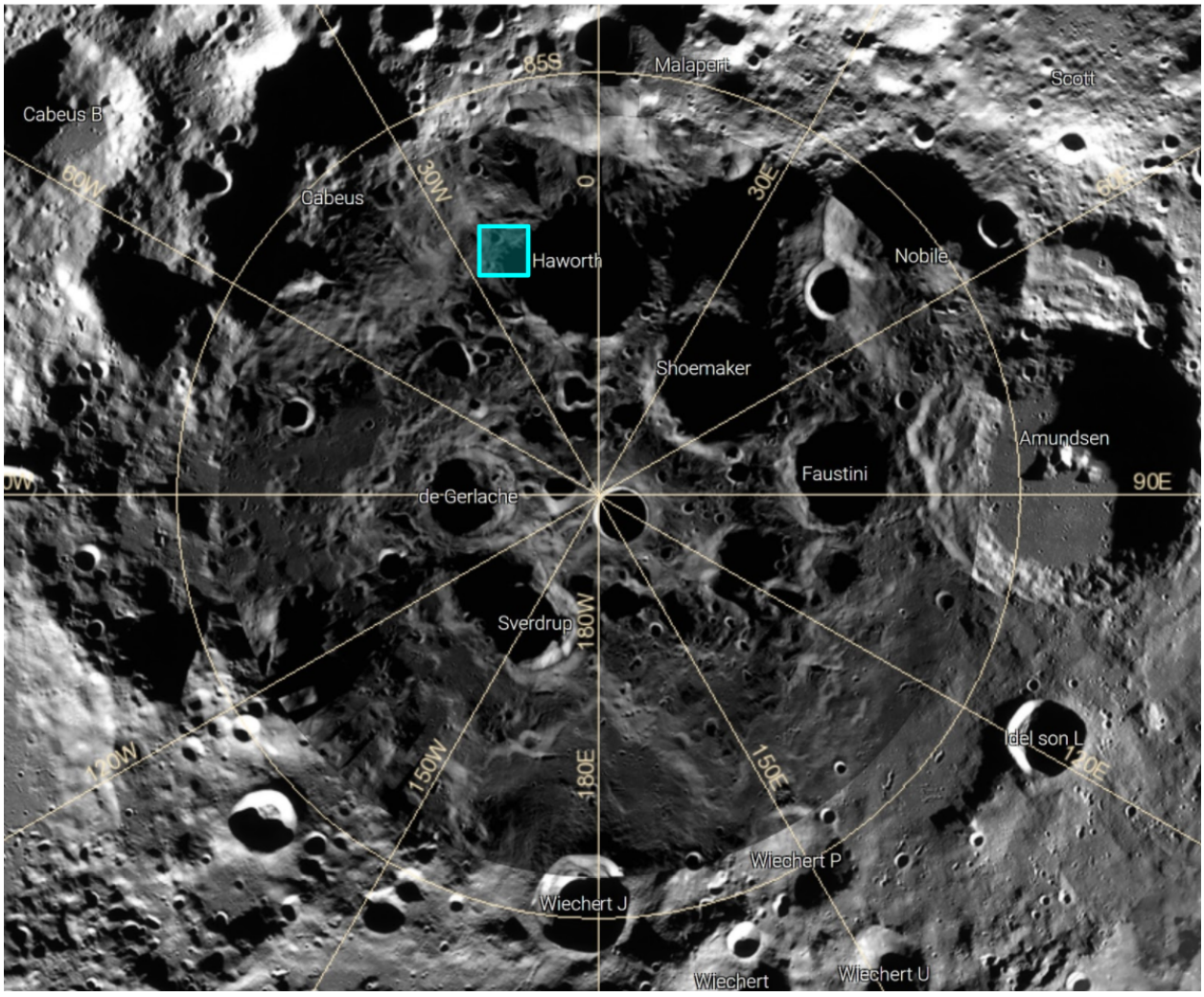


Figure 13. MoonRanger's selected landing site is near Haworth crater rim. Own work.

The site provides adequate illumination and shallow slopes for the lander and the rover along traverses as well as regions of possible stable ice for rover science exploration operations.

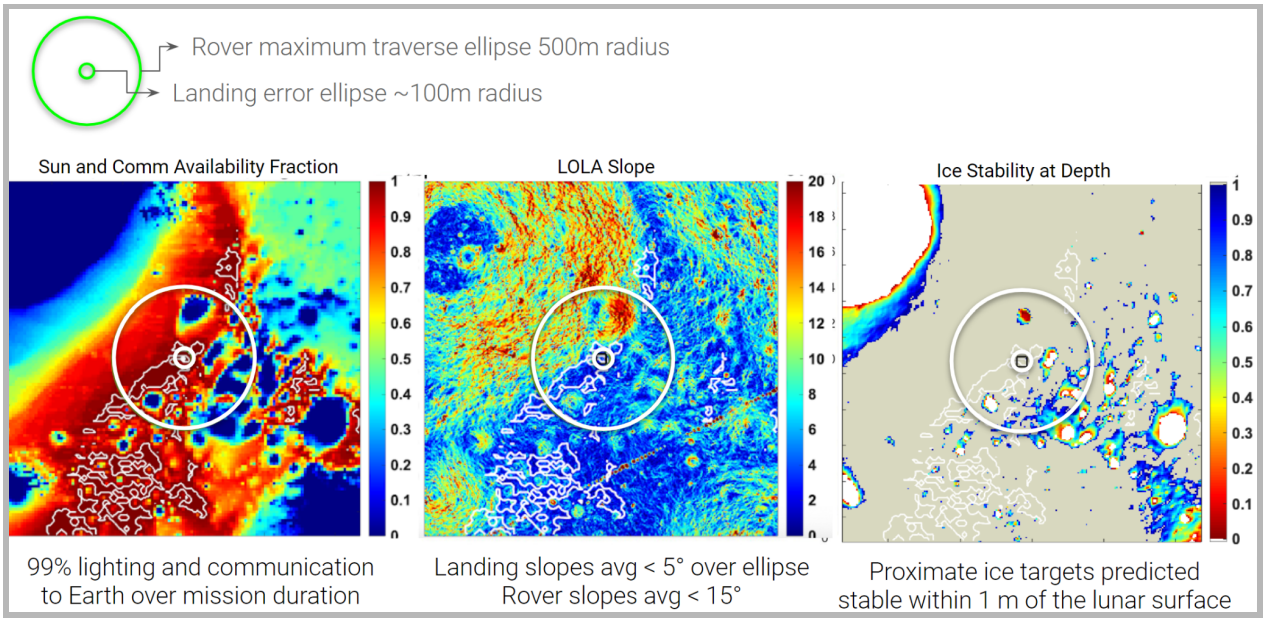


Figure 14. Three maps show viable conditions at MoonRanger's selected landing site. Maps are detailed further in section 5.5. Environmental Analysis. Own work.

The double circles shown in figure 14 are important to know. The inner circle is a landing error ellipse (Appendix B), in this case 100m in radius, and the outer circle is a maximum rover traverse ellipse of 500m in radius. This rover maximum traverse ellipse shows how far from the lander the rover can travel in any direction for the mission's risk comfort. The three maps in figure 13 will be discussed further in section 5.5.

The rover's surface operations will take place in December of 2022 and will begin with initial functional and operational check outs.

To expand upon MoonRanger's primary science objective, "to characterize hydrogenous volatiles at the lunar south pole," the mission has defined three science goals which its surface operations will aim to achieve (own work). These science operations are in order of execution as follows:

1. Investigate regions which potentially support stable subsurface ice as projected from manually produced ice stability models (Siegler, 2015)
2. Investigate regions where the pumping process of ice may have occurred (Schorghofer, 2007)
3. Investigate small Permanently Shadowed Regions (PSRs) or cold traps (Hayne, 2021)

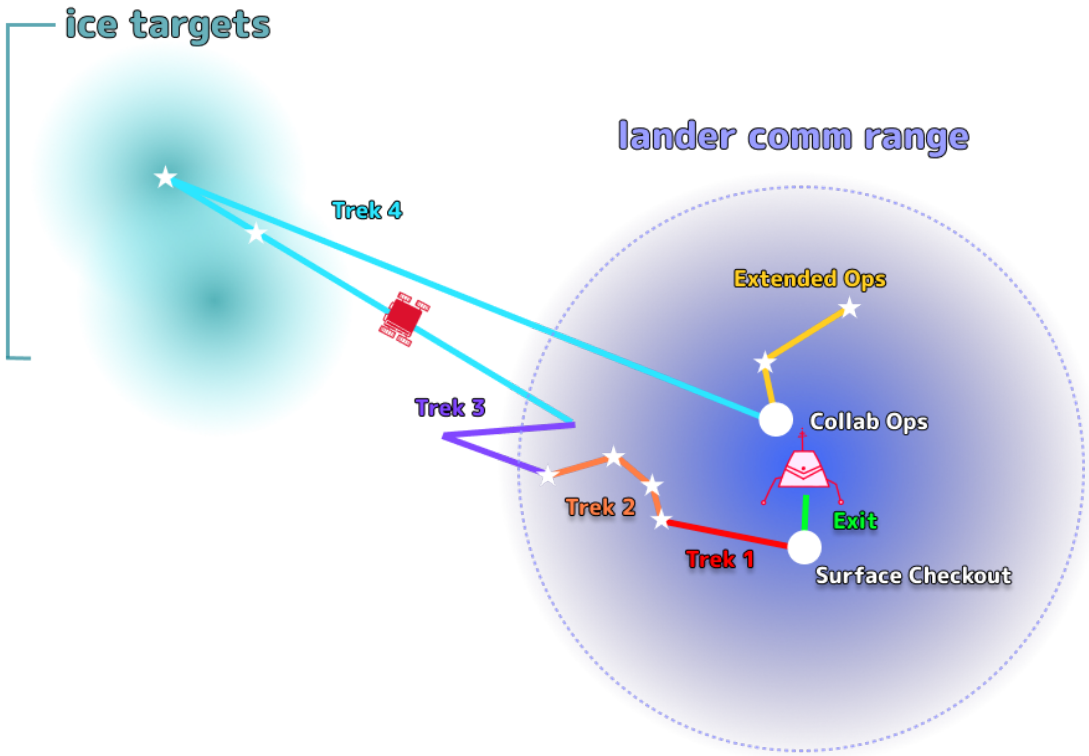


Figure 15. MoonRanger surface operations diagram. The lander is a red triangular icon at the center of the lander comm range circle, which is ~80m in radius. Own work.

Lunar operations (own work) will consist of an initial series of checkouts followed by 4 main treks to ultimately demonstrate the rover's technical capabilities and satisfy the mission's primary science objective. Initial checkout operations ensure all avionics are operational and baseline roving modes for teleoperation, perception in various lighting conditions, science maneuvering, and autonomous navigation are fully functional. Trek 1 tests science operations 1 & 2 autonomously in lander communication range, performing continuous and waypoint-targeted NSS data collection. During Trek 2 rover operations will focus on science operation 3, investigating small Permanently Shadowed Regions (PSRs) ranging from ~10cm to 1m in diameter. Trek 3 will demonstrate and verify the rover's ability to autonomously leave the lander's wifi communication range and return to re-establish communication. During Trek 4, the rover will perform long-range autonomous exploration, targeting science operations 1 & 2, which will occur beyond wifi communication range up to 500m of the lander. Following these four treks, the rover will return to the lander and commence any collaborative science-return operations with the other payloads aboard the Masten lander. Site, functionality, and resources permitting, MoonRanger's extended operations will continue to explore within lander communication range to maximize science return and investigate regions of slightly higher risk.

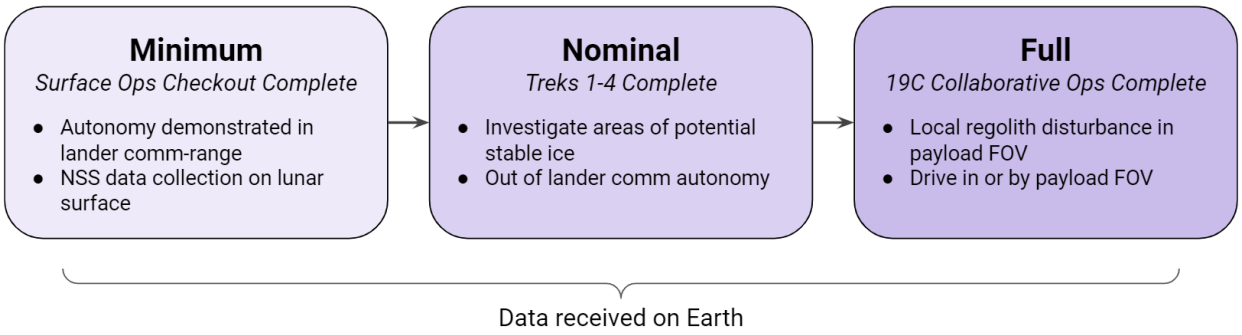


Figure 16. MoonRanger mission success defined on three levels. Own work.

MoonRanger's mission success (fig. 16) is defined on three levels (own work). Minimum, nominal, and full. Minimum mission success means that the surface operations checkout has been completed, nominal mission success means that treks 1 through 4 have been completed, and full mission success means that the collaborative and extended operations have been completed. More detail on this success criteria will be provided in Chpt 5.4.

As a micro-rover, MoonRanger doesn't have the mass for a full down to Earth radio communication system, as do other MER and Curiosity-scale rovers (Lakdawalla, 2018, p. 70). Instead, the rover is autonomous and communicates messages and data to the lander via WiFi, similar to Mars Pathfinder and Sojourner. The mission is designed to an ~80m-radius wifi communication range between rover and lander in any direction. MoonRanger's mission control station communicates up to the rover via the lander mission control station and lander as seen in figure 28. Where larger missions are equipped with continuous down to Earth communication, MoonRanger is also limited. Instead the mission is supplied with 2, 2 hour communication windows every 24 hours. This means operations must leverage the communication windows provided wisely. In-Earth communication windows include initial functional checkouts, any data transfer down to Earth, and near-teleoperation roving. In-Earth communication periods are less risky, allow operators to closely monitor the rover, and are conditions which allow quick information transfer back to Earth. The rover's longer range autonomous driving outside of lander Wifi communication range as well as operations planning both occur when the lander is not in communication with Earth. This scenario means no communication between rover and lander from Mission Control stations on Earth and is more risky.

3.4. Autonomy

The autonomy and low level functions of the rover operate on two separate computers — the central computer or GPGPU and the peripheral computer, which is a microcontroller. The central computer uses Linux as an operating system and handles all the higher level autonomy while the peripheral computer uses free RTOS and handles all lower level sensing and control.

The rover's perception system includes both cameras and lasers for vision in all lighting conditions. Two cameras (stereo pairs) in both the front and back of the rover allow it to see and drive in both forward and backward driving directions. This camera system allows the rover to see in well illuminated environments, but not so well in the dark. To help the rover navigate in

darker conditions, laser systems mounted to the rover project dots onto the lunar surface, which the rover's cameras see and use to navigate. Both the camera and laser systems allow the rover to see and navigate in full light, partial light, and full dark conditions. From the images it takes, the rover produces a point cloud which is used for local navigation. These point clouds are translated into mesh maps which the rover uses to identify local obstacles, such as local craters and rocks, around which it can then plan and navigate. This local obstacle detection and navigation on board the rover is part of local planning, which is different from global planning handled by mission operations on Earth (Kumar, 2020).

3.5. Configuration

The rover's configuration, which at a high level encompass its mechanical properties, must be able to survive the intense vibrations during the launch into space, endure cold temperatures, radiation, vacuum, and other environmental conditions such as electrostatic regolith, and exhibit the mobility necessary to complete the rover's longest traverses.

To survive the extreme hot and cold temperature it will experience, the rover's thermal system leverages both passive and active thermal solutions. Passive thermal solutions include thermal coatings which optimize heat rejection, insulating and non-conductive materials, Multi-Layer Insulation (MLI) (Appendix A and B), and heat spreaders and thermal straps. Active thermal solutions include heaters, which regulate sensitive components, and the solar panel configuration which can take a stowed or deployed position either sealing in heat or allowing it to dissipate more quickly. Figure 17 shows a thermal model of the rover with its solar panel in a deployed configuration.

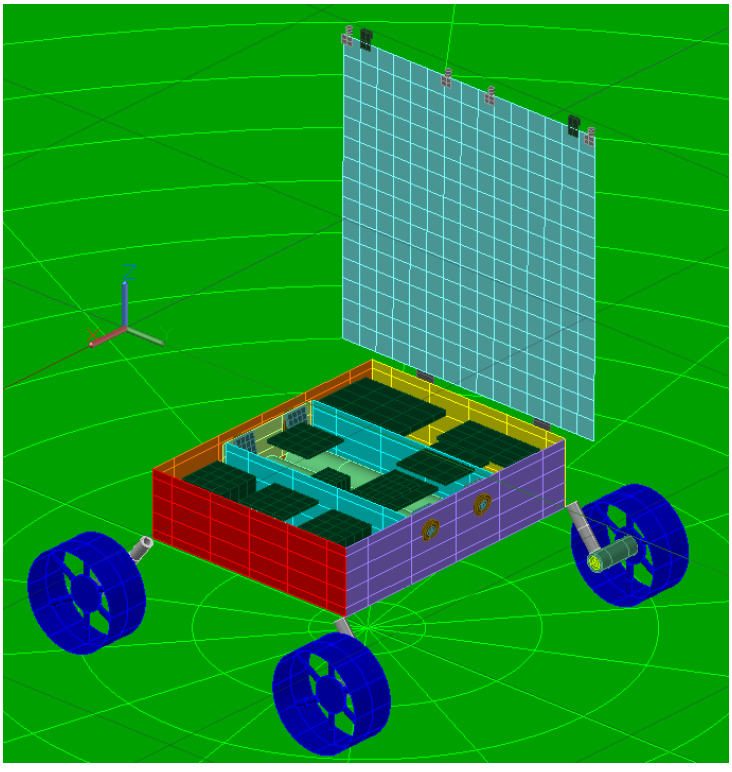


Figure 17. MoonRanger's thermal model in simulation (Fisch, 2020).

The rover structure consists of three main sub assemblies. These are the rover's chassis, solar panel, and wheel modules (fig. 18). To launch into space and get to the Moon, the rover is bolted up underneath the lander with the solar panel stowed flat to the chassis (Appendix B).

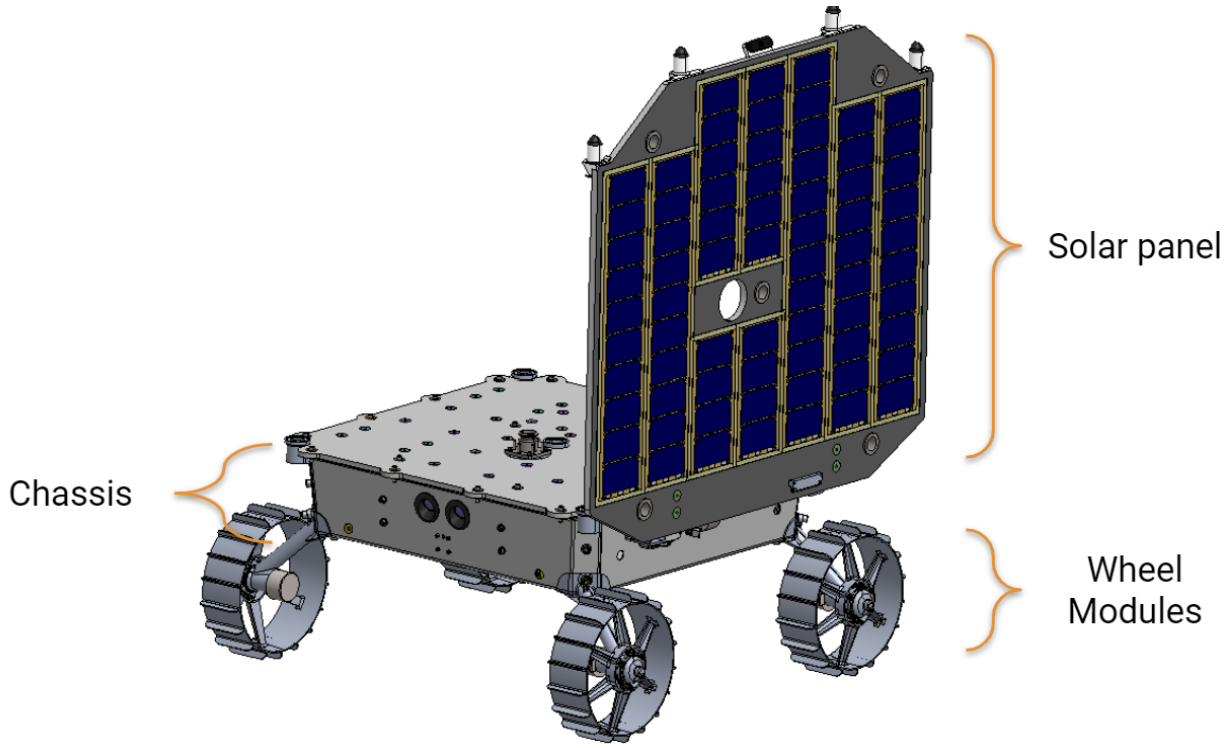


Figure 18. MoonRanger rover sub-assemblies: chassis, solar panel, and wheel modules. MoonRanger mechanical team.

When the lander lands at the lunar south pole the rover drop deploys from the lander with the solar panel still stowed close to the chassis. Once it drives clear of the lander, it can deploy the solar panel to a vertical position and begin charging.

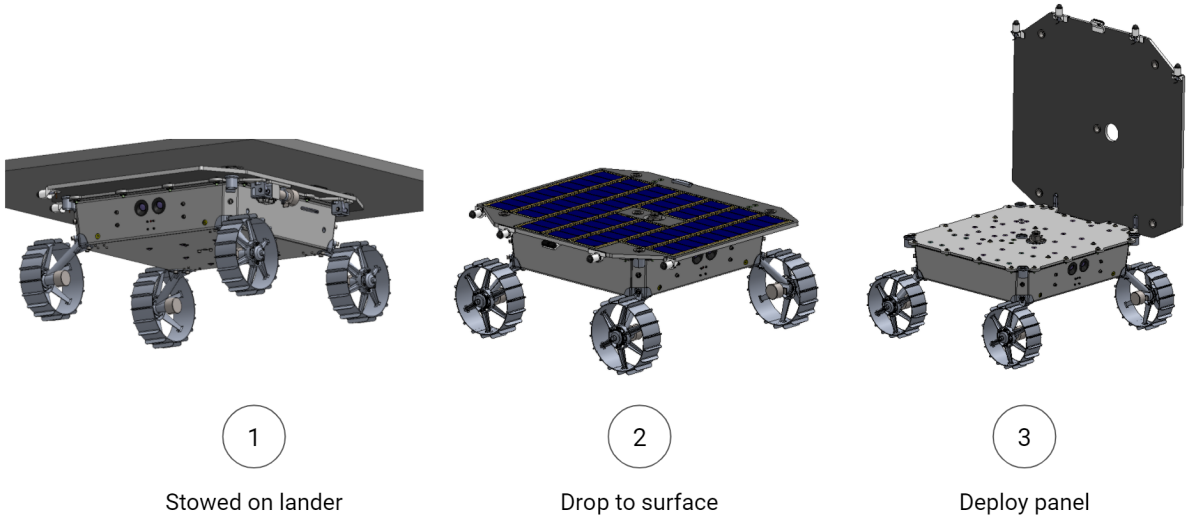


Figure 19. MoonRanger rover in pre-deploy (1), drop (2) and fully deployed (3) configurations. MoonRanger mechanical team.

The solar panel is capable of producing 68 Watts of nominal power. It is coated in a high-emissivity, low-absorbance coating which protects it from cold and hot temperatures it will experience during transit and on the lunar surface. Seventy-two total cells cover a single side of the panel. A single sided solar panel allows all cells to efficiently provide the rover with power while the other side radiates excess heat produced to space. This single-sided array also means that operations must orient the cell-side in as much of a sun-facing direction as possible in order to achieve optimal power generation during operations. A single sided solar panel is also an ideal choice for a micro-rover mission with both limited budget and limited mass. MoonRanger's 18 kilogram mass limit can be a significant factor for design decisions.

The radiator plate is one of the passive temperature regulation systems. It too is thermally coated. Lightweight aluminum honeycomb is an ideal solution for both the mass constraint. All avionics, except the NSS sensor module, mount to this radiator and are thermally strapped with shims and are protected from the radiation environment of space with aluminium enclosures.

The neutron spectrometer instrument measures constantly once the rover drops to the lunar surface and there could additionally be two pending operations during transit. The data processing module is mounted to the rover's radiator plate and the sensor module is mounted to the floor of the chassis.

MoonRanger's chassis is built from lightweight but strong carbon fiber which is strengthened with aluminium stabilizing stiffeners. It is wrapped on the outside with MLI for thermal protection

The wheel modules allow for the rover to drive in both forward and backward driving directions. These wheels are fixed to the rover's chassis and allow the rover to be skid steered. The wheels have a rim diameter of 17 centimeters, have 18 grousers, and actuators are heated as these are outside of the rover's chassis and are slightly more exposed than some of the other avionics, which are more thermally regulated inside the chassis (Schweitzer, 2020, p. 6).

3.6. Avionics

The rover's avionics also leverage this two-computer-architecture. A central computer handles all autonomy and higher level processing. All of this is handled by an Nvidia Jetson TX2i and Connect Tech Spacely carrier board. A peripheral computer handles all lower level computing and safeguarding, specifically an ISIS On Board Computer (iOBC). Both of these computers are connected and can communicate with each other. The central computer is notably connected to a high speed WiFi module for high-bandwidth lander communication, four total cameras, and an Inertial Measurement Unit (IMU). The peripheral computer is also connected to a WiFi module used for communicating telemetry, an omnidirectional WiFi antenna which helps the rover/lander signal strength as the rover traverses in both driving directions, a sun sensor to help the rover with bearing to the sun and position estimation (Appendix B), and the NSS instrument. The peripheral computer is also responsible for motor control and power and thermal management (Schweitzer, 2020, p. 7).

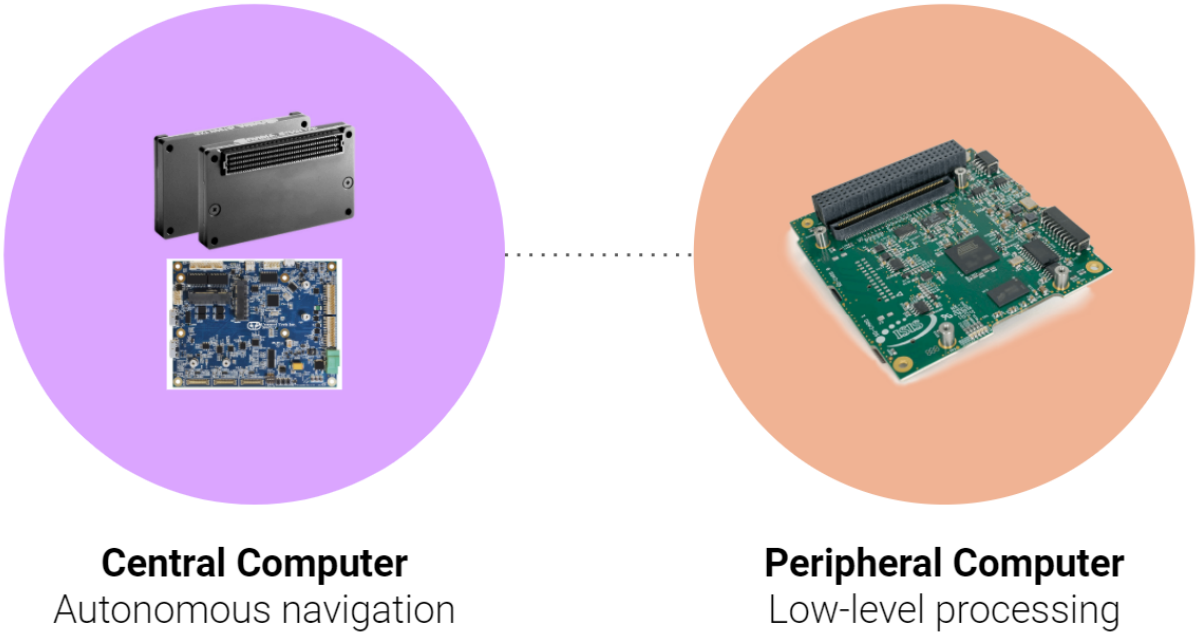


Figure 20. MoonRangers central and peripheral computers work together to cover low and high level functionality on board the rover. Own work.

If a component is needed , the first question that is asked is, is there an existing suitable component with spaceflight heritage short lead time that is affordable. If that's the case this is the selected component. If not, the next question is, is there a commercial off the shelf shelf component (COTS) component. If so, this component goes through a series of rigorous environmental tests (Appendix B) and if it passes all the environmental tests this is the selected component. If not, the team designs and fabricates hardware in-house, which also goes through a series of rigorous environmental tests and if that survives that is the component that is selected.

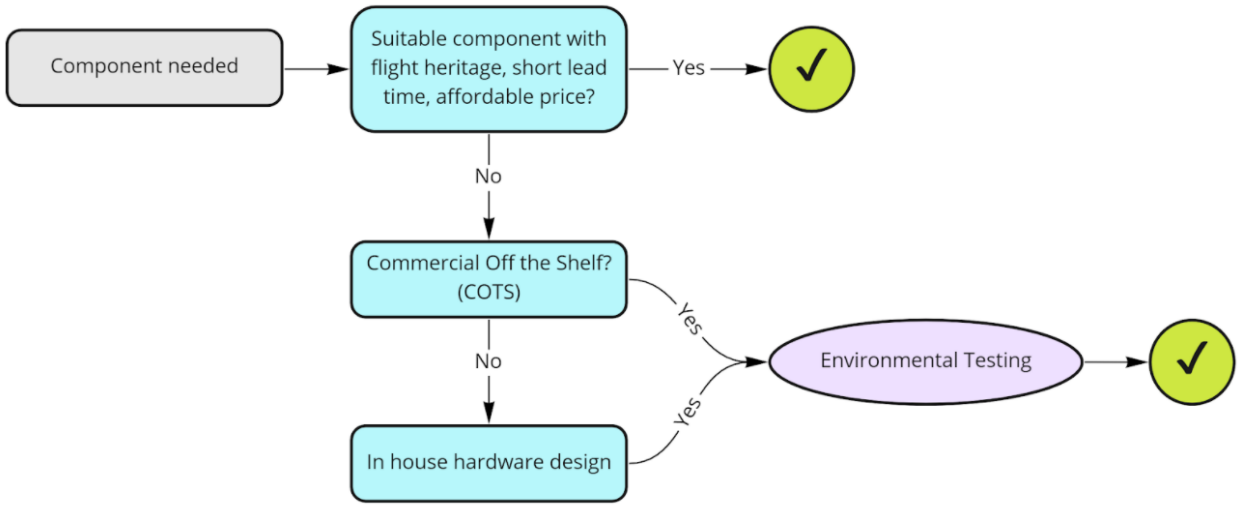


Figure 21. MoonRanger's avionics selection process stems from Careful COTS (Sinclair, 2013). Image - own work.

3.7. Culture

I will now describe the culture of MoonRanger's mission and development environment through a depiction of the involved stakeholders and the influencing constraints and capabilities of the mission.

3.7.1 Stakeholders

MoonRanger's mission involves several stakeholders. These will be bolded in the following description and also shown in figure 22. The rover itself carries a science instrument produced by **NASA Ames Research Center (ARC)**. MoonRanger's mission and rover is a joint contract between **Carnegie Mellon University (CMU)** and **Astrobotic**. For a spacecraft to arrive at the Moon, a rocket is necessary to launch into space and release the spacecraft on a lunar-bound trajectory. The rocket for MoonRanger's mission is provided by **SpaceX**. The lander is attached to the rocket, is released into trajectory (Trans Lunar Injection, TLI), and enters lunar orbit before touching down at a specific site. MoonRanger's lander, **Masten**, will carry the rover as well as seven other **Payloads**, which are all a part of the collective 19 C Mission landing at the same location. NASA's Commercial Lander Payload Services (CLPS) and Lunar Surface Instrument and Technology Payload Services (LSITP) are two parties (NASA CLPS/LSITP) which oversee the integration and development of all stakeholders. For greater detail on the roles of each stakeholder see Appendix C.

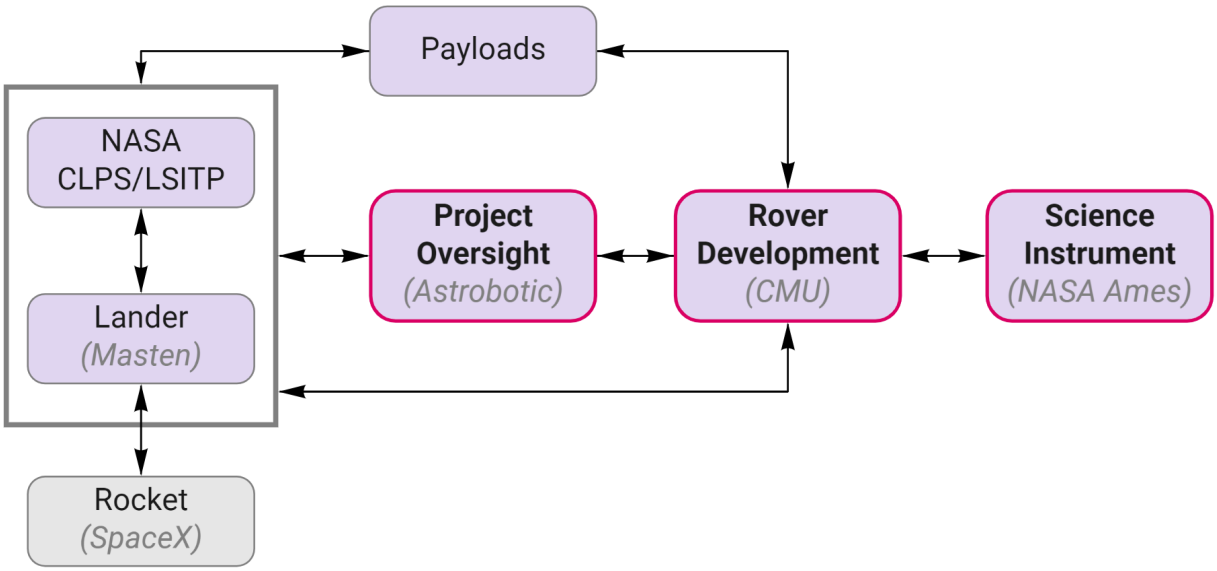


Figure 22. Stakeholders and communication pipeline. Boxes with a red border are directly involved with MoonRanger's contract. Purple boxes are those with whom I directly interacted. Own work.

MoonRanger's project specifically is an endeavor by three core organizations. Astrobotic, a local lander provider in Pittsburgh, handles all of the project management, support, and general oversight. All mission design and rover development is handled by CMU. CMU communicates directly with NASA ARC, which is responsible for the manufacturing and design of the science payload instrument which is the Neutron Spectrometer System (NSS).

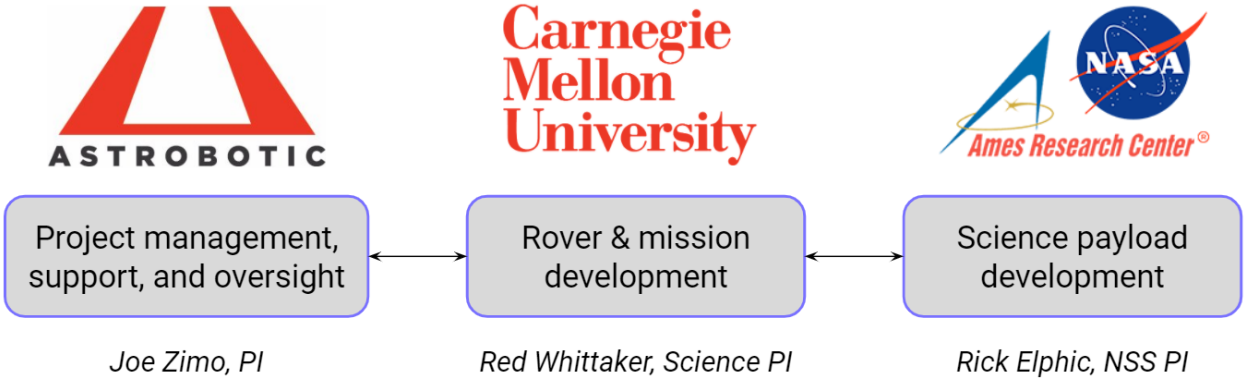


Figure 23. MoonRanger's contractual organization as a payload between Astrobotic and Carnegie Mellon University with the university communicating to the science sub-payload team at NASA Ames Research Center. Own work.

At CMU, mission development is led by Red Whittaker who is the Science Principal Investigator (PI) for the mission. A few key leading personnel include Heather Jones, a Co-Investigator (Co-I), Chuck Whittaker who leads testing, Jim Teza who is in charge of avionics testing, and David Wettergreen who is also a Co-I. Together with MoonRanger, these individuals work closely with core teams which include Systems, Mechanical, Operations, Thermal, Avionics, and Software.

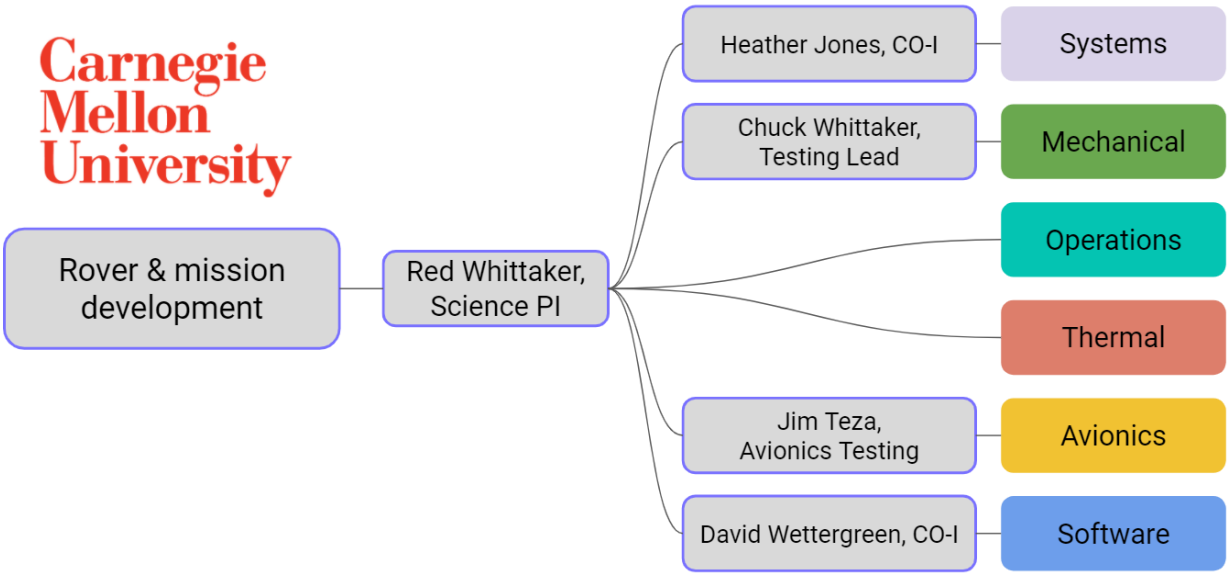


Figure 24. MoonRanger's internal development team structure at Carnegie Mellon University. Own work.

3.7.2. Constraints

MoonRanger's mission specifically is constrained to a mass limit of 18 kilograms and a restricted payload volume or limit on dimensions for its host lander. The rover's mass has resulted in design decisions that limit the power system and mobility. Suspension is fixed and the rover is skid-steered due to the mass limit and the detail and time it would take to design and qualify a highly-mobile configuration safe during launch vibrations and the rover's solar panel has cells on only a single side partially due to budget and mass constraints.

MoonRanger's mission and rover development time, at roughly 4 years total including surface operations, is much shorter than those of MER-scale rovers which can last sometimes greater than 10 or 15 years.

The lunar polar environment similarly presents its own set of constraints. Like the Earth, the Moon rotates around an axis. The Moon's axis is less angled than that of the Earth and is nearly perfectly vertical at a tilt of only ~1.5 degrees (Bussey, 1999, p. 1187). This means that the sun never fully illuminates all terrain at the lunar poles. Some regions of higher elevation receive near constant illumination and others never see the sun at all. Overall, these illumination conditions with low angled, directional lighting and sharp, dark shadows present a challenge for perception, thermal, and power systems. The other challenge of lunar polar exploration is precedents. At the time of this research 2019-2021, no rover has yet explored the lunar south pole, so there is no existing mission information from which the development of this specific mission or others similar to its kind can be drawn. The equatorial regions of the Moon are much more favorable largely due to ~14 days of full illumination before lunar night and even after rovers have begun exploring the poles, much less information will exist compared to equatorial rovers for a while (Bussey, 1999, p. 1189). MoonRanger's mission took these lighting, thermal, and power conditions into account during design.

3.7.3. Capabilities

As an autonomous rover, MoonRanger has the advantage of high mission return over a short period of time. While traditional MER-scale rovers can have similar nominal speeds to MoonRanger's 5 cm/sec, their speed made good is much lower due to lower risk tolerance and need for operator teleoperation. Planning maneuver sequences for MER missions take careful thought and a great deal more time. Once these maneuvers are planned and sent to these rovers, they are executed autonomously. MoonRanger too is autonomous, but doesn't have continuous Earth-communication for close monitoring and doesn't have the mission length for days of planning, so it has a robust autonomous navigation system for operating in the light and dark. This allows it to rove without as much need for operator input, able to detect obstacles, identify paths, and safeguard itself. The rover's resulting speed-made-good (see Appx B) is ~2.5 centimeters per second.

With water as a primary scientific motivator for lunar polar missions, rovers must be able to rove towards any regions in question. Autonomous micro-roving allows a rover the ability to traverse beyond a well-illuminated lander Wifi communication range to investigate colder regions with more possibility of scientific return.

Particularly in these current early stages of water-ice investigation at the poles, nothing is for sure. No ground truth rover-scale data yet exists regarding the existence of water, so early missions act as scouts. Micro-rovers are prime candidates for this intention. Not only do they allow the formerly mentioned higher scientific return over fewer days, they also can be sourced out commercially through programs like LSITP, ultimately costing NASA less time, money, and resources. The playing field is now open to non-Governmental entities such as universities or private companies to explore.

3.8. Impact

MoonRanger's impact falls into three main categories at the core — micro-rover technology and methods, scientific return, and environmental insights.

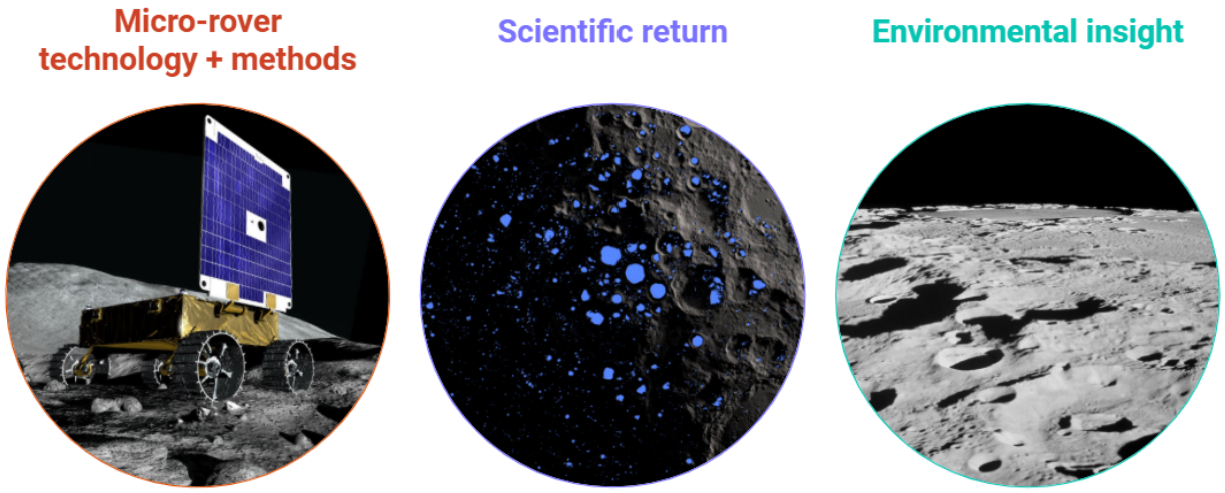


Figure 25. Three categories of impact for the MoonRanger mission. Own work.

As a micro-rover, MoonRanger falls under a specific class of rovers, newer and less developed compared to larger MER-scale rovers. This thesis refers to this class of rovers as Commercial, Autonomous, Science (CAS) micro-rovers. The design of MoonRanger's mission comes with a certain set of capabilities and constraints alike and is very different from larger scale missions and technologies. This rover mission in particular, first to rove at a lunar pole, first micro-rover to a pole, first university-developed science purpose mission, will provide precedents and information for future micro-rover development teams like never before.

MoonRanger's science return has an important impact. The Neutron Spectrometry System (NSS) that the rover is carrying is capable of measuring hydrogeneous volatiles and will ultimately provide amazing scientific insight about regolith, thermal, and terrain properties at the lunar south pole. These insights could give context to existing manually produced scientific datasets describing the assumed temperature, regolith, and depth relationships to stable and surface ice. All data that the rover produces, some of which includes NSS readings, images, telemetry, and 3D terrain reconstruction, will aid in the scientific return.

Environmental insight is another key impact because no rover has yet explored the lunar south pole. Specific environmental conditions unique to the poles, such as low angled lighting, terrain, and temperature profiles, have not yet been traversed and lived through by a rover, let alone a micro rover. Both the data, mission performance, and experiences that will result from the mission will provide information about how rovers can traverse in such environments.

Within the context of lunar missions, MoonRanger is setting out to do what has never been done before. This rover will be the first to rove a lunar pole, the first to explore for lunar ice, and the first to collect the highest resolution data on ground truth lunar ice composition. Among the space exploration community, ice is considered possibly one of the most valuable resources in

the solar system. With the opportunity water presents for drinking, growing food, generating oxygen, and producing fuel, the success of this mission would not only be incredibly exciting for the space community but also provide a stepping stone of valuable ground truth data and tested technology for the space exploration and habitation of the future.

3.9. Role

As a member of the MoonRanger team at CMU, my work primarily involved collaboration among others aboard the CMU team, which consisted of about ~25 total active members at a time. Both faculty and staff at CMU, students (the majority of the team), and external volunteers with backgrounds including engineering, architecture, computer science, design, robotics, and business, among others, composed this development team. Within the MoonRanger mission, I took several different roles. My role as a lead for the CMU MoonRanger team at large began early on in the first few months of the mission informally and has developed into a more formal title of Project Lead. This role has taken several different functions, but is primarily related to tracking progress of the collective team towards our goal of flight-rover completion and mission success, as well as team well-being, coordination, communication, and integrity. In addition to this high level role, I have worked in three distinct efforts throughout the process.

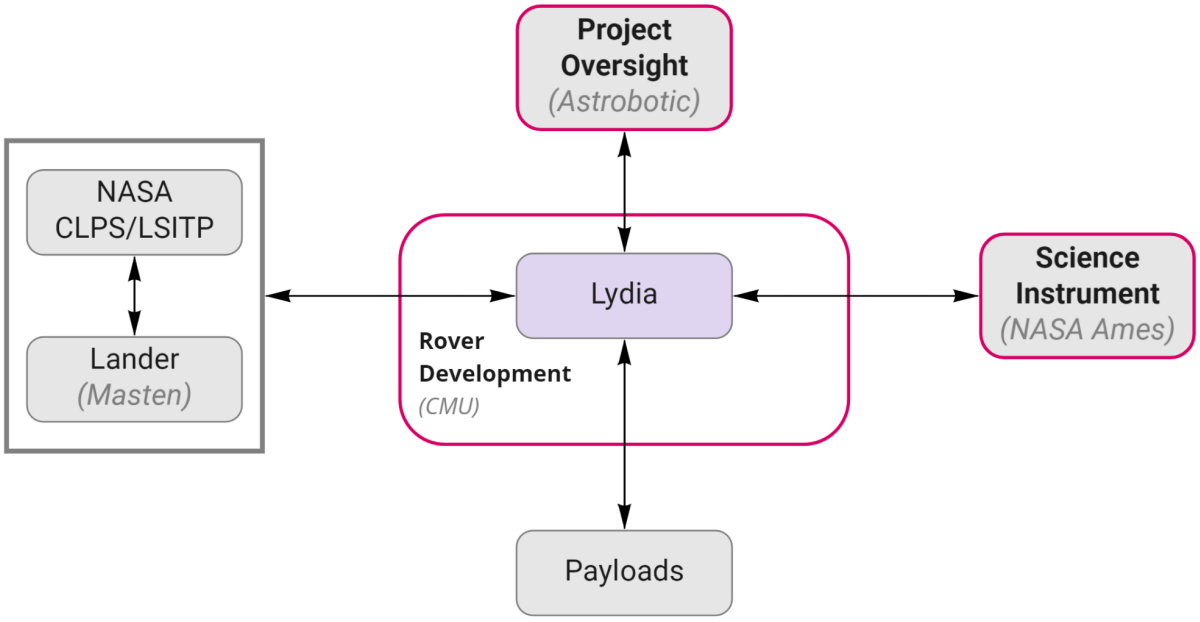


Figure 26. Stakeholders I interacted with during the MoonRanger mission. Own work.

Systems Engineering

As the mission started I led the Systems Engineering effort. This team is responsible for defining requirements or goals for the entire rover and mission system which pull from the core objectives and requirements, defining risks the rover or program might need to deal with, and overseeing and managing development and integration among all relevant subsystems. At this time the team was organized into sub teams of mechanical, software, avionics (aka electronics), thermal, software, and systems. As the mission progressed and a polar landing region was defined, mission operations added to this list of sub teams. Within this role, I worked heavily

with Joe Zimo, who at the time was a systems engineer at **Astrobotic**, the local lander company in Pittsburgh, hired on the project to assist with that effort (Astrobotic, n.d.). During the first semester, I interacted for the first time with one of the mission's external stakeholders, **NASA CLPS/LSITP**, through a presentation of lander requirements which I organized and co-presented with ~5 other team leads.

Science Integration
During the winter of 2019/2020 the mission developed from initially just a technical purpose to both technical and scientific purpose with the addition of a science instrument. Beginning in January 2020, I began leading the mission's science integration, organizing bi-weekly meetings with the science instrument team at **NASA ARC** (Colen, 2015) to facilitate MoonRanger's understanding of the instrument, what development would be required to ensure it's proper integration, and understand their needs from our rover. In the early efforts planning the addition of the science instrument, I worked with Red Whittaker, Joe Zimo, and a couple other key project faculty or staff to propose the addition to NASA CLPS/LSITP. Collaboratively, we developed a document to submit to the NASA team and had several phone conversations with NASA representatives and the Science Principal Investigator of the science instrument team at NASA ARC to organize the change to the mission.

Mission Operations
In August/September of 2020, I transitioned from leading Systems Engineering to leading the Mission Operations team, which had been led by another individual for a semester prior. This team focused on developing a Concept of Operations (CONOPs), operator roles and shifts, global planning procedures, scenarios, and conducting environmental analysis. Within this team, I continued to interact with Joe Zimo of Astrobotic, now appointed a Principal Investigator, along with Red Whittaker, of MoonRanger as well as the NASA program managers. As the mission was assigned a lander, I also began interaction with the **Masten** lander team (Potter, 2020), virtually defining requirements between rover and lander, and sharing information so each team could further understand one another. Also aboard the lander were seven other payloads in addition to MoonRanger. As a landing site selection was underway, I handled environmental analysis for MoonRanger, communicating landing site characteristics to NASA stakeholders and the lander. I began interfacing with the other **payload teams** to discuss landing site analysis, individual payload capabilities/objectives/constraints, and further down the line, possible collaborative operations among instruments.

4. Methodology

This chapter will discuss the data collection and evaluation mechanisms used within this research (4.1. Data Collection & Evaluation), which tools and interfaces already exist within the MoonRanger mission (4.2. The Existing Interaction Playing Field), and the system design, prototype design, implementation, and evaluation approach I take within my work (4.3. Approach).

4.1. Data Collection & Evaluation

This research takes both an exploratory and qualitative approach. One intention behind defining my research question the way I did was to leave room to explore my defined topics of interest in a fast-paced changing and developing mission environment. With an exploratory approach, I had room to explore different facets of my initial research question as I learned more about mission planning foundations. This exploratory tactic meant I could develop a series of ideas and content without a defined outcome trajectory. Exploratory evaluation mechanisms included surveys, interviews, observations, and reviews. With an understanding of the playing field, the qualitative approach allowed me to evaluate this set of ideas and content, asking what areas were successful but also why and how. Qualitative evaluation mechanisms included my embedding in a case study, autoethnography, tests such as Paper Missions, and reviews like CDR (see Appx B). All evaluation mechanisms will be detailed in the remainder of this section.

Four core mechanisms for evaluation and data collection were used during development. For testing mission planning interfaces, Paper Missions were the primary mechanism. Paper Missions are a mission operations approach testing all mission functionality iteratively as the mission progresses and develops. By the end of the development timeline right before full operations, Paper Missions test the highest fidelity of mission operations tools. These tools range from operator roles and communication strategies, messages and data types between the rover and mission control station, mission control software, scenarios, as well as mission planning techniques. Data resulting from Paper Missions includes internal mission operations team member observations, transcript of the event, feedback from all stand-in operators from surveys, and feedback from all additional attendees from surveys.

A second form of evaluation are mission reviews. These reviews are formal NASA reviews where the mission presents its state of development during a two-day review and lasts about 5 hours each day. Each subsection of the mission is presented and evaluated by a formally assigned team of largely NASA personnel called an Independent Assessment Team. In addition to this review committee, informal observers are invited as well. These observers are experts in their fields with specific experience and knowledge relevant to each subject area of the mission. This group of observers ends up amounting to about 60 individuals. Reviews are held in sequence based on the development status of the mission and begin with a System Requirements Review (SRR), a Preliminary Design Review (PDR), a Critical Design Review (CDR), and a System Integration Review (SIR). MoonRanger has recently completed its CDR on March 4th and 5th of 2021. These reviews result in observer feedback emailed and submitted via surveys.

The third method of data collection is centered around autoethnography. Because of my level of involvement within MoonRanger's team, ethnography is not the best approach. Ethnography would not include the level of influence my work had on the development of the mission. Instead, I employed autoethnography as a research method. Autoethnography allowed me to take an active and influencing role in the MoonRanger mission, developing prototypes, conducting analysis, leading teams, and making decisions. This method also meant I critically observed the cultural and technical effect of the work I produced and the domain of my

research. It meant I could reflect on my experience as a developer while acknowledging my bias and embedded perspective.

During my time working on the mission, I recorded observations and evidence through (daily) field notes that captured anecdotes, activities, and impressions. Once completed, a skilled practitioner in ethnographic methods interviewed me about my experiences to help digest, sensemake and draw out reflections on the embedded experience. The interview was conducted over five hours, was audio recorded, transcribed and later analyzed.

4.2. The Existing Interaction Playing Field

Going into the MoonRanger mission, I was unaware to what extent software tools, all ranging differently on the visualization spectrum, were already existent. I realized that both the team at large as well as each individual team leveraged different interaction tools. These are shown in Table 2 with corresponding stakeholders.

	NASA CLPS/LSITP	**Masten**	**Payloads**	**Astrobotic**	**CMU**	**NASA Ames**
1. Thermal SIM (Thermal Desktop)						
2. Software SIM						
3. Mobility SIM						
4. Vibration SIM (ANSYS)						
5. CAD software (Solidworks)						
6. CNC software						
7. Shared Whiteboard (Miro)						
8. Sharded Illustrations (Figma)						
9. Google Suite						
10. Schedule (Smartsheet)						
11. Google Drive						
12. Messaging (Slack)						
13. Virtual Meetings (Zoom)						
14. Visualization Software (D3js)						
15. Map Visualization Tools						

Table 2. Existing interfaces used within the MoonRanger mission team on the far left column, numbered. All relevant stakeholders to the mission in the top row. Cells are colored green signifying a MoonRanger-related interaction between a stakeholder and an existing interface. Green cells do not necessarily indicate what software tools are used by stakeholders within their own programs or work. Own work.

Interfaces directly related to the work in this thesis include numbers 7 through 15. Map Visualization Tools are at the core of all prototyping which occurred during my research. Note that this is one of two areas out of all fifteen that is relevant in some way to all stakeholders.

As a lens to evaluate the prototypes detailed in Chpt 6, I will reference which stakeholders interact with each and describe the kind of interaction which occurred. These types of interactions are categorized in the following three ways:

1. Time (Synchronous/Asynchronous)
2. Location (Remote/In-Person)
3. Type (Review/Work-Session)

Synchronous interaction refers to two or more individuals interacting at the same time on a given artifact. Asynchronous interaction is two or more individuals interacting at different times on an artifact. Remote interaction occurs on any virtual platform such as Zoom, Webex, Teams, Slack, or over the phone, and in-person occurs with two or more people in the same physical location. Review interactions are more static and refer to any transfer or presentation of information transfer with or without expectation of feedback. Examples of review could include sending someone a document over email, showing a spreadsheet at a meeting for awareness or mutual understanding, or showcasing data in a slide deck at a formal presentation event. Work-Session interactions are more dynamic and involve two or more parties evaluating in real-time, making changes, or making decisions. Examples of work-sessions could include two or more parties using a tool to evaluate assumptions, meeting up to accomplish a test and using a spreadsheet in the process, or planning different options for a configuration.

Stakeholders related to these interactions are described in Section 3.7.1. All prototypes in Chpt 6 are positioned using this interaction lens, which helps highlight which artifacts have more visibility or importance with the mission, which have less, and in what ways.

4.3. Approach

My research approach is first to understand the framework (mission constraints and capabilities) to produce a set of systems or methodologies, and second, to develop a set of both iterative and unique visualization-based prototypes. Both the systems and the prototypes could evolve as more information is understood, and both help each other. Prototyping puts to test the systems in place and the system tests the value of the prototype within a larger context. For further discussion on prototyping, see Chpts 6 and 7.

Stepping back from the mission in both micro and macro ways is essential for gaining perspective on the systems, prototypes, and visualization impact. Regular reviews throughout the mission were one way of accomplishing this. An interview of myself conducted by a fellow Computational Design PhD student was a macro-approach here. Overall, any instance of communicating information was, on some level, a mechanism for gaining perspective and reviewing the work.

5. System Design

This chapter describes systems and technical content I developed during my research. The technical content in this section directly relates to the MoonRanger mission. Systems and methodologies included also are similarly directly applicable to MoonRanger, but could also be largely relevant for similar lunar or non lunar CAS micro-rover missions.

5.1. Mission Operations Organization

To understand clearly the relationships between mission operations' three core functions, mission initiative, rover operations, and mission control, a conceptual architecture is needed.

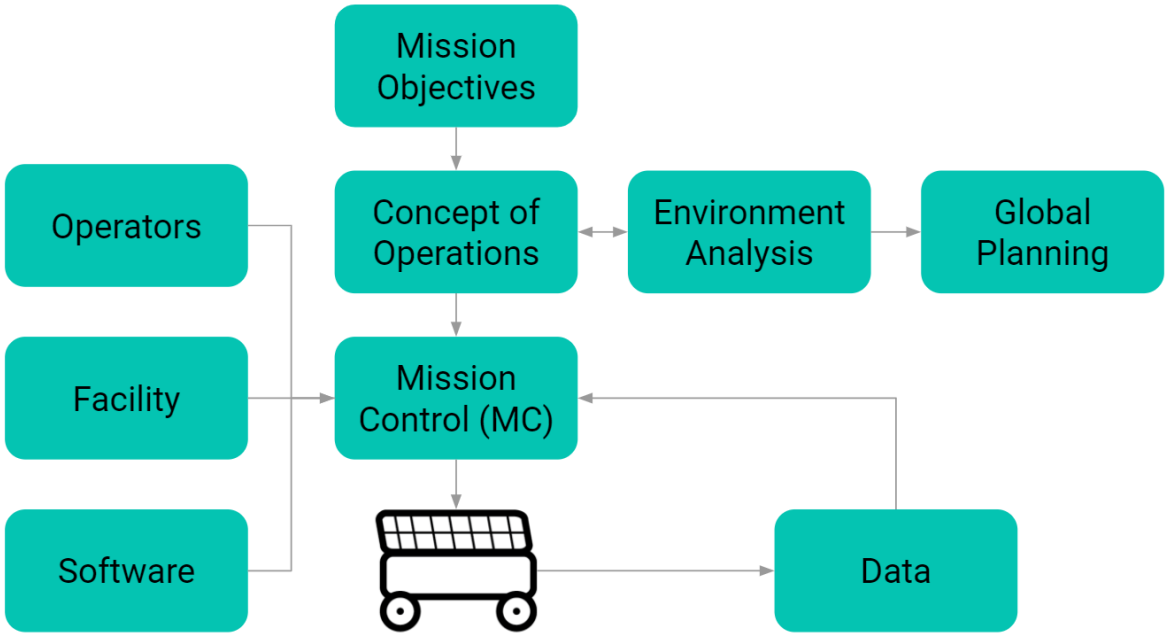


Figure 27. Mission operations conceptual architecture. Own work.

The mission objectives feed from both the science and technology mission purpose, for MoonRanger a demonstration of autonomy and investigation of hydrogenous volatiles. These mission objectives feed into the development of the concept of operations (CONOPs) (Shea, 2017, p. 50), which includes the lander integration phase, any transit operation, and also the surface operations. The concept of operations is informed by environmental analysis because it's important to understand the context in which the rover will be operating given its capabilities and constraints. Environmental analysis also informs global planning, which in the case of an autonomous rover, is different from local planning.[4] Mission Control uses the CONOPs to carry out the maneuvers and the operations with the rover itself and is a combined effort between operators, the mission control facility, and the mission control software. Mission Control will communicate via the designated communication pipeline ultimately to the rover, which will produce data as it roves the surface of the Moon and sends back through the same communication pipeline to be received by mission control.

[4] See Chpt 3.4. Autonomy for more information

5.2. Planning Around Constraints & Capabilities

Mission operations combines three core efforts. These are the mission initiatives, rover operations which encompass lander integration through the surface operations, and mission control. The mission initiative encompasses the goals of exploration, involving either a science purpose, technology purpose, or both, and pulling from the highest level mission objectives. Rover operations are designed around these mission goals and take into account mission constraints and rover capabilities. Mission control is the infrastructure, organization, and roles designed to guide the decision making process during any transit and surface operations in a way that facilitates the accomplishment of mission goals.

For a micro-rover mission with all the aforementioned micro-rover constraints[5], mission operations will likely be equipped with fewer resources, less time for operations, and limited DTE communication. Traditional missions usually have a copy of the rover on Earth for troubleshooting, MoonRanger's mission will not, and will instead use bench-top hardware or preliminary prototype rovers each with a specific purpose and fidelity to help with troubleshooting. Most MER-scale missions are equipped with continuous DTE communication which allows for close monitoring, carefully calculated rover operations with low risk, and high data return volume. MoonRanger's mission operates with about 15% the communication of these larger scale missions and must prioritize data downlink in order to best facilitate decision making during operations (figure 28).

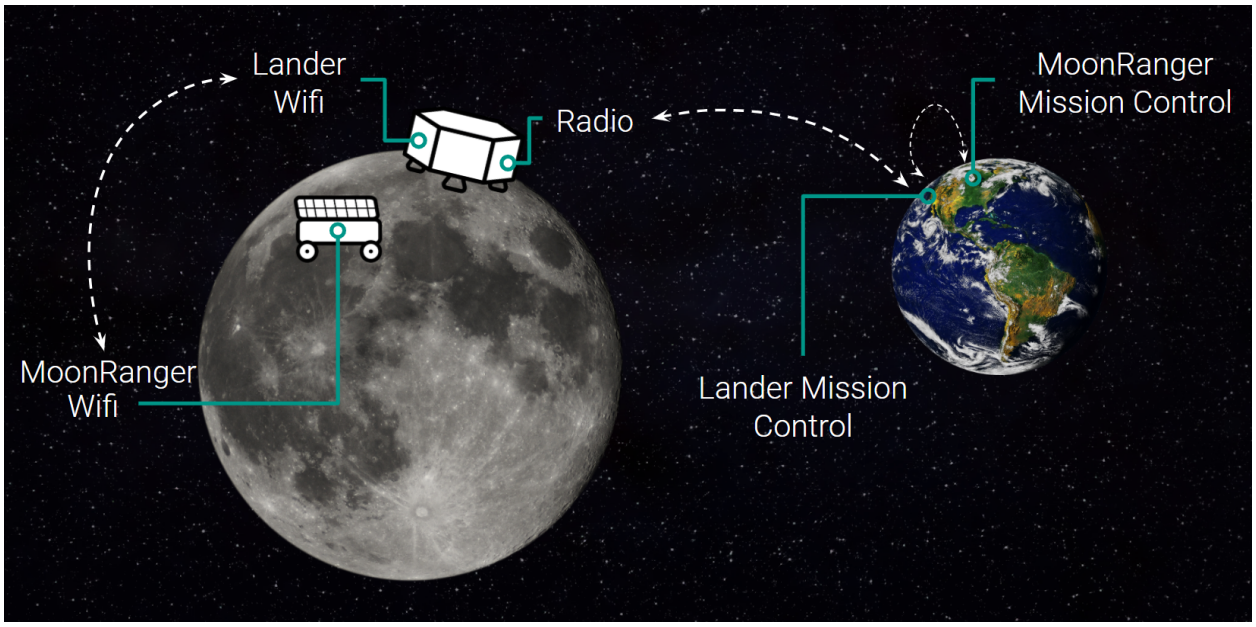


Figure 28. MoonRanger's communication pipeline. Operators at the rover's mission control station communicate through the lander's mission control station and via the lander. The rover and lander communicate over a ~80m radius WiFi range. Own work.

Limited by mass, MoonRanger's rover will also not carry a direct to Earth radio communication system. While the rover is indeed autonomous, this lack of radio means, in combination with

[5] See Chpt 3.7.2. Constraints for more detail

sparse windows of DTE communication, specific maneuvers or operations cannot occur as ture-teleoperation. Instead, operations are closely monitored when possible for initial checkouts to occur, data is downlinking to Earth, and near teleoperation[6] maneuvers. Outside of DTE windows, the rover can perform longer range driving, operating fully autonomously, and operators can perform any additional planning to prepare for future operations.

5.3. Surface Operations

Autonomous micro-rovers without direct communication to Earth continuously must both prioritize operations for reduced risk between DTE communication windows, but also phase operations in order to prepare the rover for increased risk and operational complexity. An initial phase should be reserved for powering on the rover, internal instruments, and performing functional checkouts, additionally verifying functionality of all operation maneuvers, specifically science and autonomy maneuvers. All following phases should be structured least risky to most risky, leaving the most risky operations to the end of the surface mission to maximize the chances of rover survival.

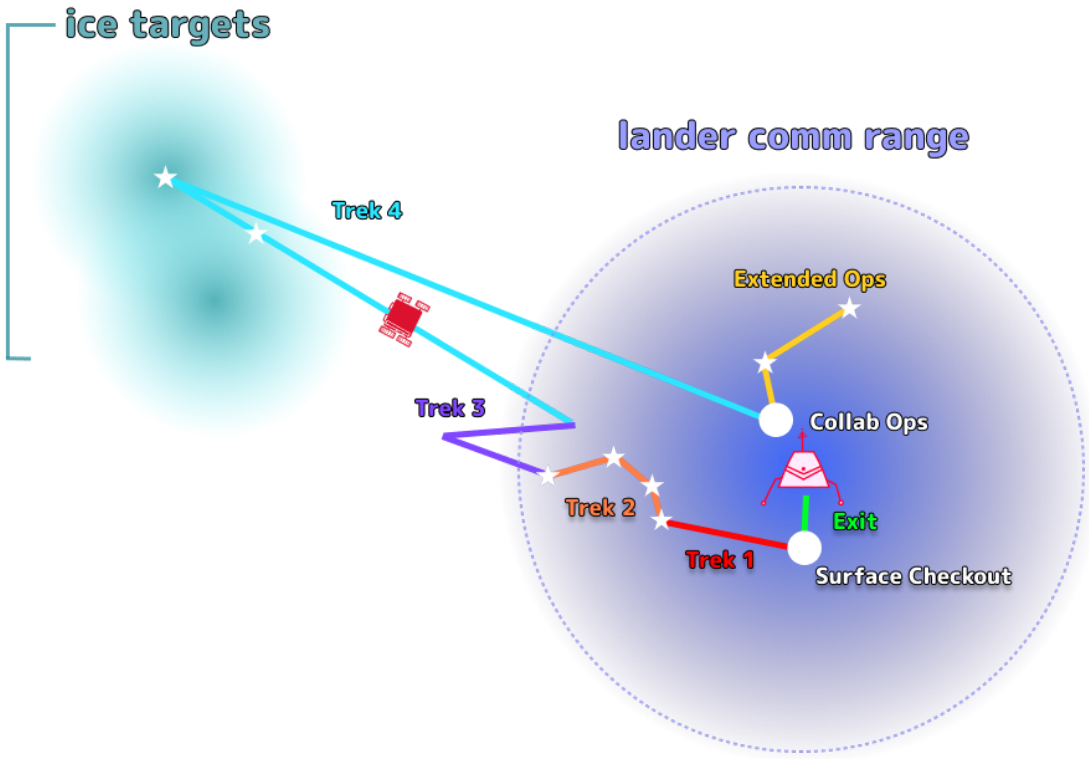


Figure 29. MoonRanger's surface operations diagram. Own work.

As a key contribution to this research, I developed the detailed surface operations of MoonRanger's mission. Specifics of these can be found in Chpt 3.3. Operations. In order to

[6] Due to the communication pipeline between MoonRanger's mission control station and the rover along with the fact that the rover is autonomous means true teleoperation cannot occur. Instead the term near-teleoperation is used to define operations where data and message communication and return is near continuous and in as real time as possible.

develop the level of detail of the surface operations and also in order to define MoonRanger's mission success, I expanded MoonRanger's core science objective "to characterize hydrogenous volaties," into the three science goals seen in Chpt 3.3.

From the surface operations described in Chpt 3.3, Phase 1 encompasses deployment from the lander, exit from beneath the lander, and the surface operations checkout. Phase 2 involves the completion of treks 1 and 2. Phase three involves completion of threks 3 and 4. The riskiest operations are saved until the end of mission after the rover's primary objectives are achieved and are a part of Phase 4, which includes collaborative operations with the other payloads aboard the lander as well as the extended operations[7].

5.4. Mission Success

Defining different levels of mission success helps operations and planning prioritize the development of different rover and mission functionalities (Shea, 2017). Mission success also communicates what kinds of and quantity of data is deemed sufficient at each level to any relevant stakeholders. Mission success is defined on three levels, categorized from least return to most. These are the floor, nominal, and full mission success definitions. For this class of micro-rover missions, "Floor", the lowest level of mission success is defined by the completion of Phase 1. Following the phase-definition strategy detailed in the previous section, at this point in the operations, the rover should have completed basic functionality checks for both technical and scientific capabilities. "Nominal" mission success will likely involve the completion of all Phases except for the last, riskiest phase of the mission, which is accomplished at the end and defined as "Full" mission success.

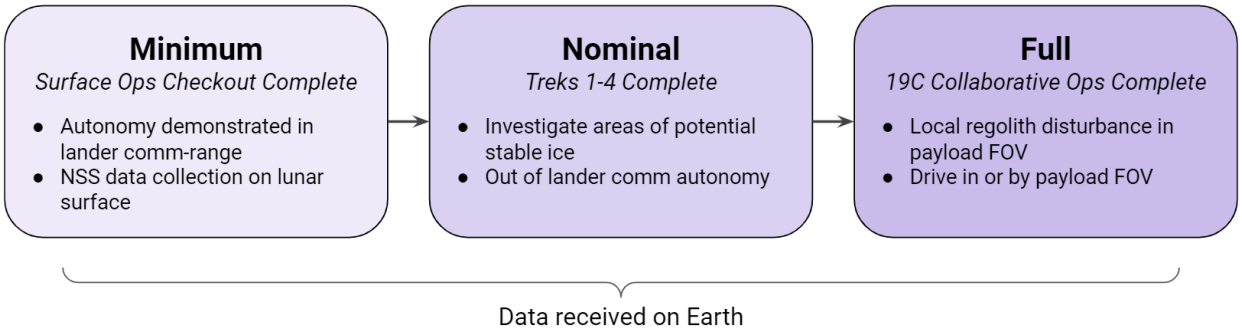


Figure 30. MoonRanger mission success defined on three levels. Own work.

In the case of MoonRanger, minimum mission success involves the completion of the surface operations check out (Phase 1), which demonstrates both autonomous-traverse capability, and science maneuvering. During the surface operations check out, autonomy is demonstrated for the first time during the mission and the science instrument, the Neutron Spectrometry System (NSS), will have been on and operational since the rover dropped to the surface. By the end of the surface operations check out, NSS data will have been collected over about a total of 80 meters. The other data products from the completion of the surface operations checkout will include images, telemetry 3D terrain reconstruction. All data will be both position and

[7] Mission phases defined by Anthony Perry, MoonRanger Mission Operations team, 2021

time-tagged. Nominal mission success is defined as the completion of treks 1 through 4 (Phases 2 and 3). Autonomy for these operations is exhibited outside of rover-lander WiFi communication range and specific science maneuvers will result in targeted NSS, image, telemetry, and 3D terrain data collection. This will result in very specific data return and in total the NSS data at the end of trek 4 will have been collected over about 1700 meters in total. Full mission success involves the completion of the collaborative operations and extended operations (the last phase, Phase 4). By this time autonomy has already been demonstrated outside of the rover-lander communication range. The core focus of full mission success is the collaborative operations and the science data return package that could benefit the collective science return of the mission overall. At this point in the mission, the completion of all of the operations including the collaborative operations in the extended operations would include NSS data collected over about 2000 meters in total.

5.5. Environmental Analysis

All missions have limits which constrain the kind of exploration that can be done, what terrain is traversable, and what environments are best suited to the operations. Mission planning must consider three core aspects to environment analysis. This provides a mission-unique, situational understanding of the environmental relevance and relationship between the rover's own capabilities such as mobility, power, thermal, and perception, any scientific initiative of the mission, and the environment within which the rover will operate (fig. 31). Each of these three ideas translate to a specific process for translating relevant datasets or key pieces of information into a unique set of maps directly related to the traversability and exploration of the rover at hand.

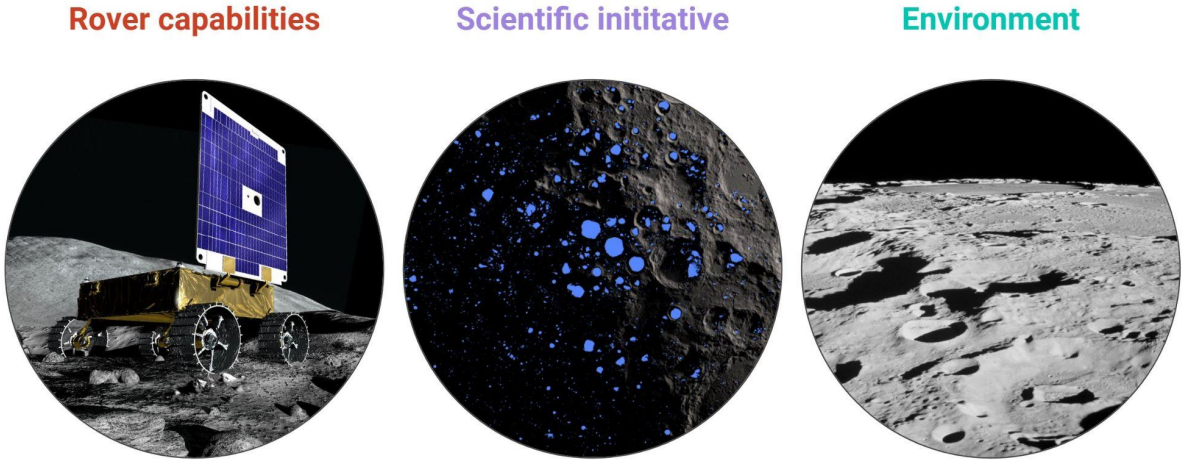


Figure. 31. Three core considerations for mission planning. Own work.

Rover Capabilities

The rover's capabilities help define what terrain can be safely traversed. Terrain traversability is informed by the rover's belly clearance and mobility configuration (i.e. suspension or lack thereof), specifying obstacle height and maximum degrees of slopes the rover can handle. Illumination is informed by the rover's power generation system, thermal capabilities, and perception system, which define what lighting conditions the

rover can explore, if the rover can operate in cold/hot or dark/well-lit regions, and if so, for how long. Missions can fall into two categories, those with a science purpose and those with a technology purpose. Some include both. Those with technology purpose would provide additional specifications or criteria which would fall under the rover's capabilities. MoonRanger's mobility system is a combination of belly clearance, resulting in obstacle traverse limit, and wheel configuration along with center-of-gravity, which results in a limit on traversable slopes. Because the rover has no suspension, is skid steered, and a belly clearance is about ~17 cm results in quite limited traversable slopes.

Scientific Initiative

A mission with a scientific purpose usually is accompanied by a certain set of environmental desires, besides or in addition to slopes and illumination. This set of environmental characteristics are all the pieces of information (i.e. conditions, datasets, information, questions) that lead to a certain environmental condition the rover seeks to explore. MoonRanger's scientific purpose focuses on the characteristics of hydrogenous volatiles. Understanding the environmental conditions, where hydrogenous volatiles might be located on the surface, is an essential part of surface operations planning.

Environment

The lunar polar environment brings challenges of its own with dark, sharp shadows, extreme temperature ranges, and terrain unknown to rover exploration. Many missions don't have full say regarding the selection of a landing site, so being able to adapt operations to the conditions of the environment is key. MoonRanger's system must be able to survive these conditions and operations must take these into account.

Given the former highest level focus of planning, the next steps involve analyzing and understanding the relevant and available data in order to define waypoints, paths, and ultimately full operations. In general, missions consider three overall classes of datasets. One pertaining to slopes, another pertaining to illumination and communication to Earth, and a third related to the science initiative of the mission. Let's address each individually. Illumination from the sun and DTE communication can be paired because they each involve the elevation of a celestial body above the horizon of the Moon at the rover's position. Elevation of the Earth is important because for autonomous micro-rovers, DTE data communication relies on the communication pipeline through a lander. A lander must be able to have line of sight down to Earth as much as possible during the entire surface mission to facilitate this data communication. When analyzing for DTE communication, it is important to consider effects of multi-path interference, which can occur when the elevation can seem workable given datasets, but striations in the coverage can indicate an elevation too-low where radio waves are interfered by the local horizon. While communication DTE is a key factor for site analysis, more related to micro-rover mission planning is solar elevation, or illumination. Micro-rovers, because of their limited mass and size, likely won't have enough mass to include a Radioisotope Thermoelectric Generator (RTG), which is a common component to many MER-scale rover missions such as Perseverance (Lorenz, 2020). Instead micro-rovers can leverage the use of lighter-weight solar panels to generate power. With solar as a part of the power system, adequate illumination is essential for rover survival. The degree of illumination necessary depends on the configuration of the panel.

Some panels have the capability to rotate and adjust for varying sun angles, others do not. For micro-rovers, again due to mass limitations, the latter is likely the case. When analyzing illumination from the sun, it is important to not only consider the illumination directly at the landing site, but also at surrounding regions where the rover could traverse. Slope data is used to rule out regions too steep for the rover's mobility system, and the scientific-related dataset relevant to lunar polar exploration is ice-stability at depth. Ice, one of the most valuable resources in the solar system, has been confirmed at the lunar south poles, but detailed data at a rover-scale resolution has yet to exist. Polar exploration now and into the future will revolve to a large extent around the investigation and in-situ utilization of this water for both scientific, solar system exploration, and lunar habitation purposes. Because no high-resolution ground truth data yet exists, manually constructed datasets modeling polar temperature at depth over deep time can be used to analyze a landing region.

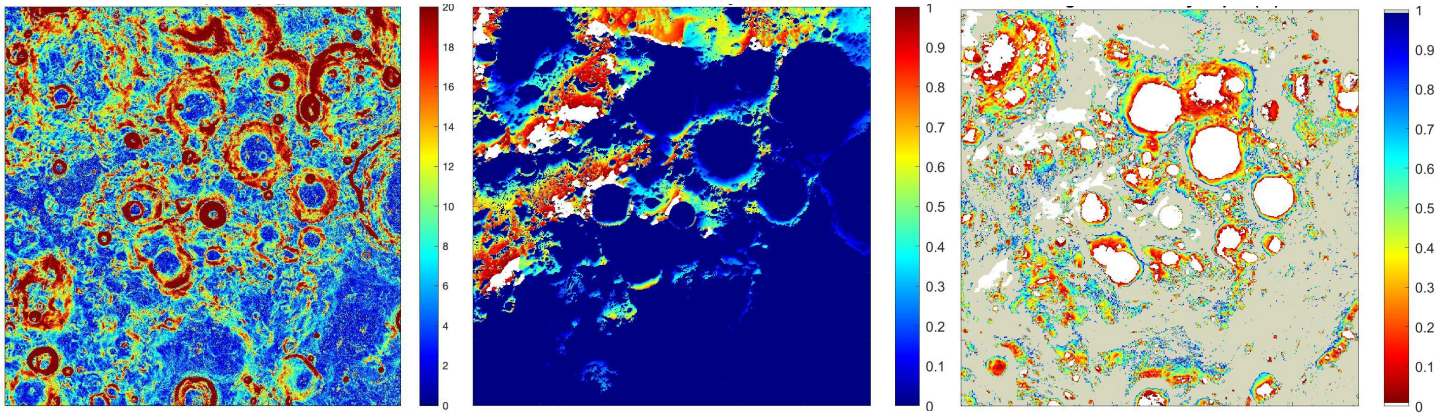


Figure 32. From left to right: slope data filtered to show slopes < 20° (Smith, 2015), fraction of illumination over a 12 day mission (Elphic, 2020), ice stability at depth filtered to show stable ice within 1 m of the lunar surface (Siegler, 2015).

Datasets and specifications for MoonRanger's specific mission are detailed below.

Slope:

Slope data at 40 meter posting out to 80 degrees latitude, interpolated from the Lunar Reconnaissance Orbiter's (LRO's) Lunar Orbiter Laser Altimeter (LOLA) elevation data (Smith, 2015) (fig. 32, left), and at 1 meter posting local to the Haworth Crater region (provided by VIPER, NASA ARC) are used for path planning and waypoint selection.

Illumination Map:

Because MoonRanger is a solar powered micro rover, solar illumination significantly affects its power and thermal systems. Mission planning utilizes several types of illumination data The first is fraction illumination, produced by incrementing of a 12 day surface mission to determine if a pixel receives illumination at a given time, then taking the fraction by dividing by the total number of increments taken (Elphic, 2020). The second is similar, but results in a series of separate illumination maps which represent increments of time over the full 12 days. For instance, the first in a series would represent the fraction illumination seen over a 2 hr increment, the second is the fraction

seen over the next 2 hr increment, and so forth. These incremental maps ultimately represent solar influx, which is defined as the orientation of the sun with respect to the Moon. Solar influx helps dictate the path orientation to maximize the power produced by MoonRanger's solar panel. This development of this map-set is still underway and in the meantime, mission planning will use the aforementioned single fraction illumination map shown in figure 32, middle.

Ice stability:
The science goals are divided into 2 parts: investigating surface ice and subsurface ice. Waypoints towards subsurface ice leverage manually-produced Siegler Ice Stability at Depth maps which model surface temperature over deep time. Subsurface ice locations are likely farther away from the designated landing site, which is well illuminated to support the lander's power system, while surface ice locations are likely much closer.

Descent Imagery:
The second component to MoonRanger's science investigation involves surface ice. These correlate closely with Permanently Shadowed Regions (PSRs). At the latitude of MoonRanger's landing location, most small craters, visible from lunar surface imagery, are small PSRs or micro cold-traps, depending on local slopes. MoonRanger sets out to investigate these micro cold-traps within lander WiFi communication range and given the low resolution of elevation data, imagery must instead be used to plan these waypoints out specifically. To help solve this issue, descent imagery from the Heimdall payload, also aboard the Masten lander, will be leveraged to understand and plan at a more detailed level, the local landing site terrain.

Some of the maps mentioned from this stage of the system design will show a series of overlaid circles. Seen in figure 33, an inner green circle denotes a landing error ellipse. A lander will try its best to land at the specified landing location but may be off to some degree due to local descent maneuvers or error in calculations (Lakdawalla, 2008). The landing error for MoonRanger's mission is ~100m in radius. For reference, the rover and lander wifı range is indicated in purple. The outer green ellipse shown is the rover maximum traverse, which is the maximum range the rover can traverse in any direction from a lander location at the center of the landing error ellipse.

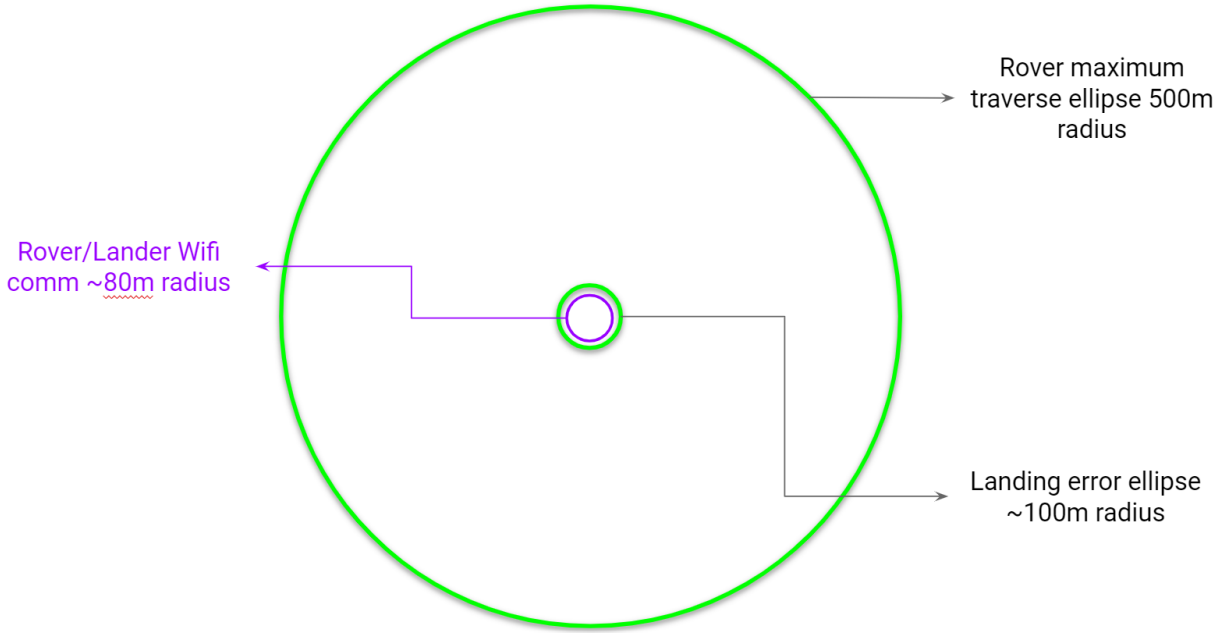


Figure 33. Two ellipses are used for waypoint selection and planning - the landing error ellipse (center green circle), and rover maximum traverse ellipse (outer green circle). An inner purple circle is shown to reference the rover-lander WiFi communication range.

In order to understand and visualize directly what terrain the rover can traverse, both slope and illumination maps are thresholded to the rover's specific capabilities. Figure 34 shows both illumination and slope maps zoomed into MoonRanger's landing location. These maps are thresholded to translate all no-go regions into black pixels and all viable regions into a scale between light and dark where the darker the pixel, the less favorable the terrain is for the rover.

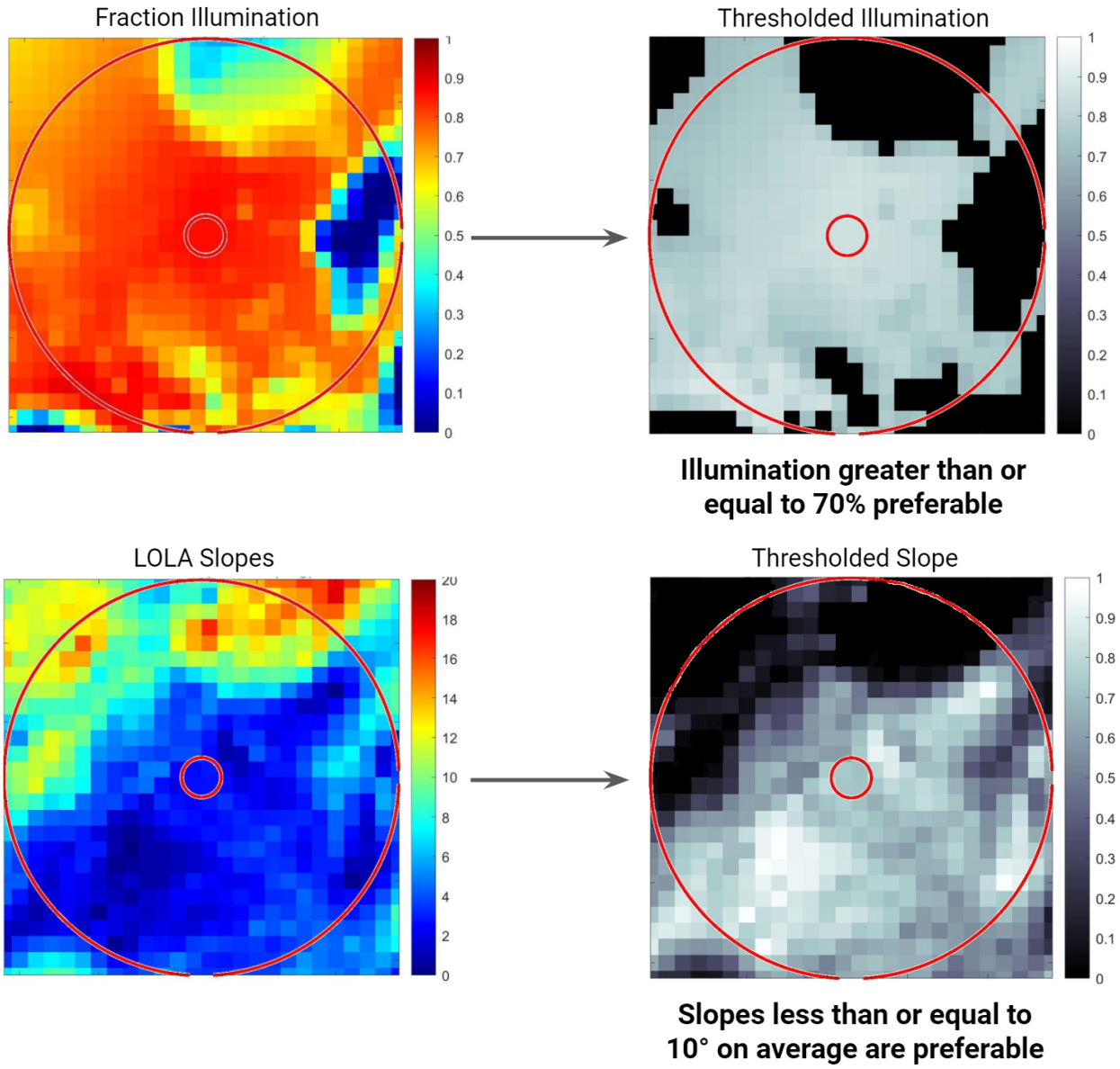


Figure 34. Illumination (Elphic, 2020) and slope maps (Smith, 2015) zoomed to MoonRanger's landing site (left), thresholded to black-out no-go traverse regions and scale traversability where dark pixels are riskier and lighter pixels are more viable (right). Landing error ellipses, Rover Maximum Traverse Ellipses, thresholded maps (Viable Terrain Maps) own work.

Ultimately these individually thresholded and scaled illumination and slope maps can be multiplied together to achieve an overall Viable Traverse Map (VTM), as seen in figure 35. The VTM shows collectively the rover's traversable regions for both key datasets and is used during the waypoint selection process detailed in section 4.3.2.6.

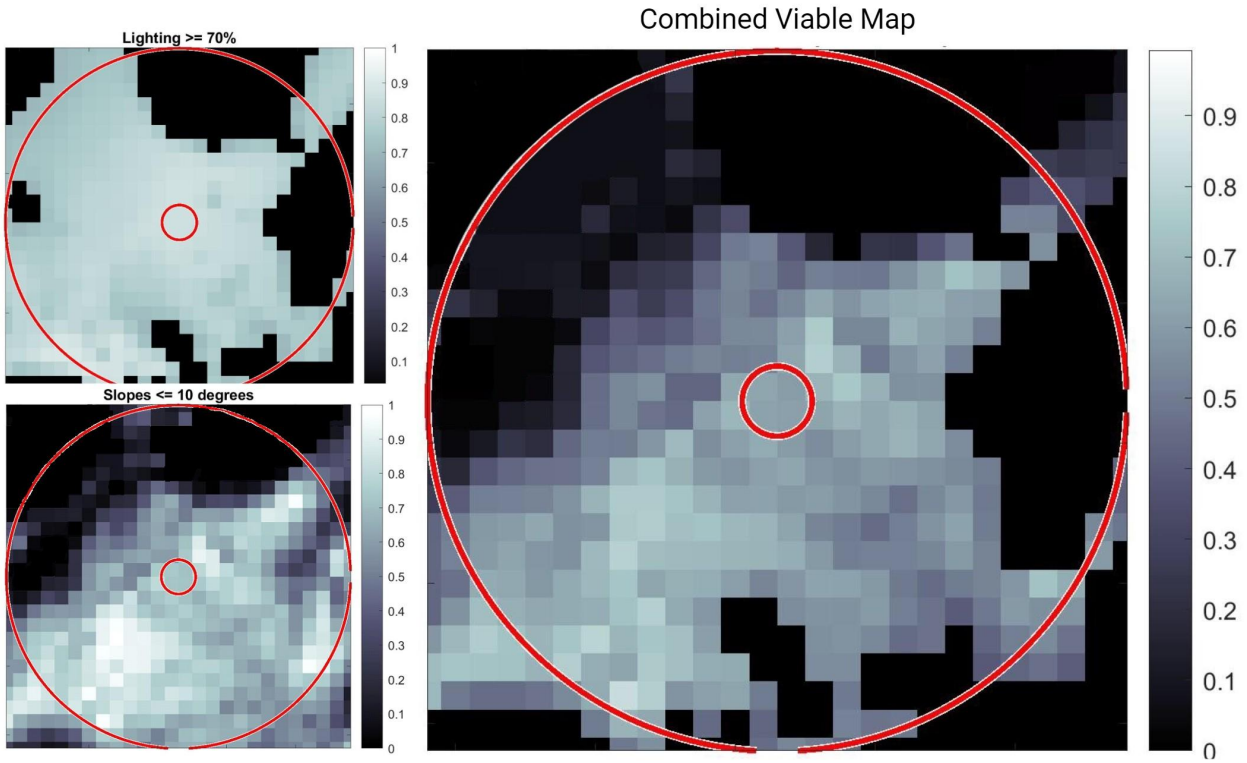


Figure 35. Illumination (top left) thresholded to 70% fraction illumination and above, slope (lower left) thresholded to slopes less than or equal to 10 degrees, and combined viable traverse map (right). Inner and outer circles show a landing error ellipse with 100m diameter and rover maximum traverse ellipse of 500m diameter. Own work.

5.6. Global Planning

Global planning is responsible for defining MoonRanger's lunar destinations, operations, and high-level rover paths. It is the process which identifies long-range and short-range waypoints towards areas of scientific interest and away from hazardous areas. Global paths are calculated to optimize both for lunar environmental conditions, such as slope and sun illumination, and also for rover conditions, such as total energy of the rover.

Before discussing the global planning pipeline in depth, it is worth noting the difference between local and global planning. Local planning occurs on the rover itself as the rover operates autonomously (fig. 36, left). The rover uses its local planning capability to navigate around obstacles it can see within its field of view such as local craters or rocks. These local obstacles are too small to be detected from orbit using existing measurements. Global planning, on the other hand, is computation which occurs completely on Earth and involves planning at a high level the waypoints of interest (WOI) (fig. 36, right). Given these waypoints the global planning process can provide the local planner aboard the rover with rover-safe-zones between high level goal waypoints. Rover safe zones are important for the local planner because they tell the local planner how much room for error it has both for distance and for time allocated to each traverse.

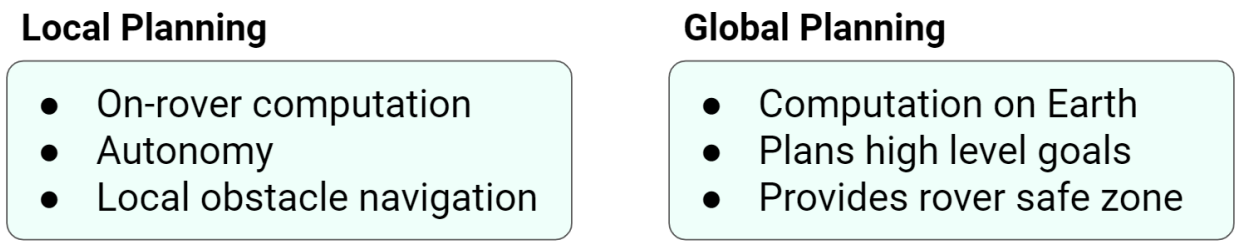


Figure 36. Differences between autonomous micro-rover local and global planning. Own work.

The global planning pipeline shown below illustrates a process for conducting successful waypoint selection and path planning.

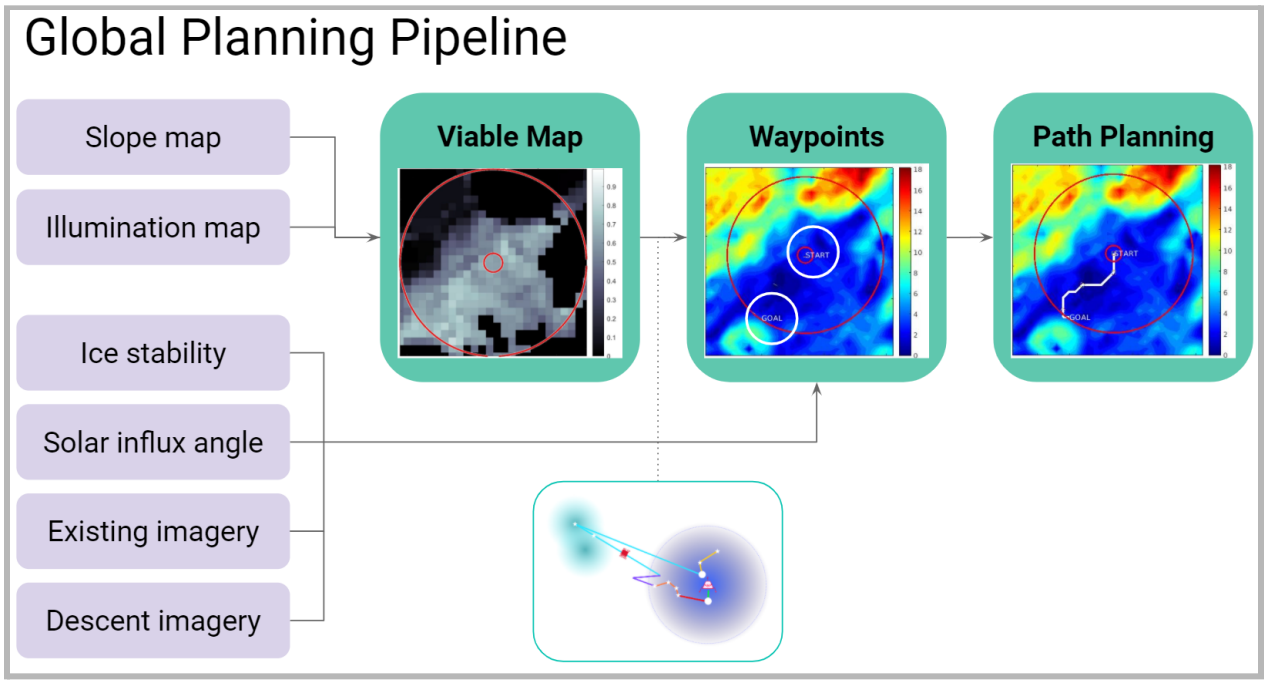


Figure 37. Global planning pipeline for lunar polar micro-rovers. Work in collaboration with Abha Agrawal.

This process follows the following stages:

1. Both the slope map and illumination map, discussed in section 5.5., are used to construct the Viable Traverse Map (or VTM).
2. This VTM along with several other influencing factors aid in the definition of waypoints. These other datasets include the science-oriented dataset, solar influx angle, existing imagery such as Narrow Angle Camera (NAC) imagery (Robinson, 2012), and the surface operations, which preserves the ideas and operations integral for satisfying the mission goals and levels of success (for term definition see Appendix B). Figure 37 shows a Waypoint example where a start and end waypoint have been selected within the inner circle and near the outer circle.
3. These waypoints are fed in a desired sequence to the global planner, which constructs a high level path between waypoints. This path planning process is also used to generate the aforementioned margin of safety and time which will be described in detail in the latter portion of this section.

It is worth mentioning that up until this point in the pipeline, all planning has occurred on the Earth well before surface operations or even launch. All the mentioned pieces of information can be used to define surface operations, construct the VTM, select waypoints, and define multiple series of paths. However, some key additional details will be available upon landing. The final process indicates this step.

4. Upon landing, the exact lander location is known within the landing error ellipse and specific waypoints and paths can be selected. In some cases, descent imagery may also be available for use. This imagery from the lander, or camera systems aboard the lander, is especially useful for identifying any obstacles unseen before due to the lower resolution of datasets used for initial planning. These newly observed obstacles can influence the selection of additional waypoints to guide the rover between science areas of interest.

Waypoint and Path Planning Process

The following process can be used to baseline waypoints, test selection procedures, compute paths, apply margin, and feed to the local planner.

Step 1 -- Pre-plan science waypoints before launch

Waypoints, as defined by MoonRanger's operations team, are locations defined to direct the rover towards areas of scientific interest and around obstacles it must avoid at a global scale. Roughly ~90% of all waypoints will be selected prior to launch and more waypoints than will be used will be defined and labeled. Having defined all of these waypoints prior to launch does not mean the rover needs to traverse to them, it instead means operators will be able to quickly select waypoints, paths, and conduct efficient planning during operations. The remaining ~10% of waypoints will be determined following analysis of high resolution descent imagery, which will be received upon landing (figure 38).

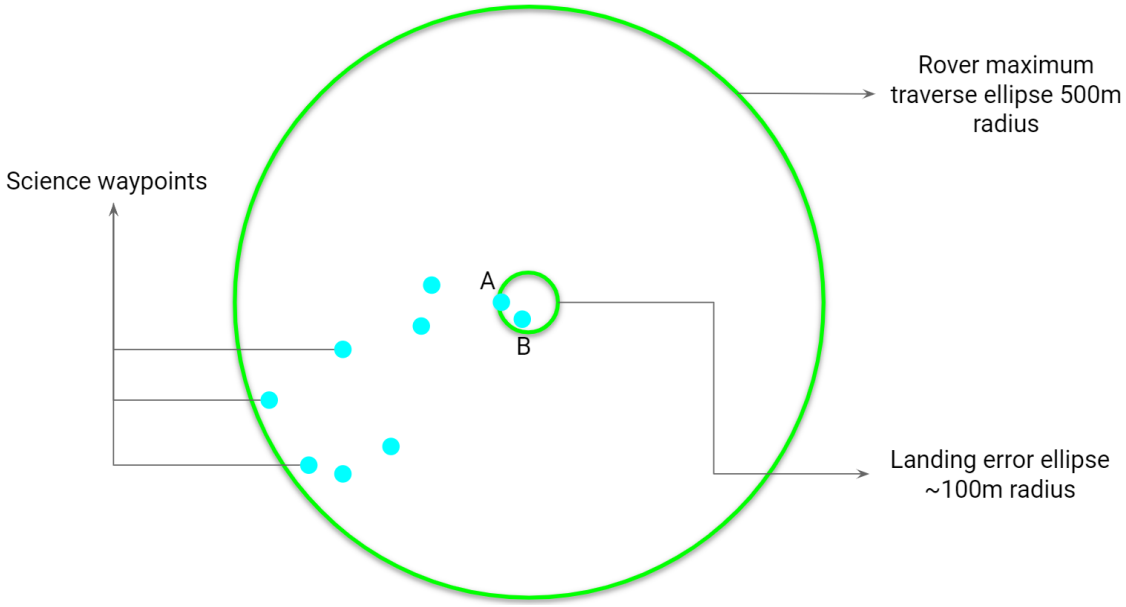


Figure 38. Step 1, identify and define all possible science waypoints, not accounting for order or sequence. Own work.

Step 2 -- Determine lander location

Defining multiple sets of waypoints also allows for flexibility. Once the lander actually lands and the exact landing site coordinates are known, operators can begin to make decisions between waypoints. The process of selecting test lander sites within the landing error ellipse can be used to simulate operations and prepare the planning team and all relevant operators before launch and surface operations begin. In this case we point B might be selected over waypoint A given the lander location (figure 39) .

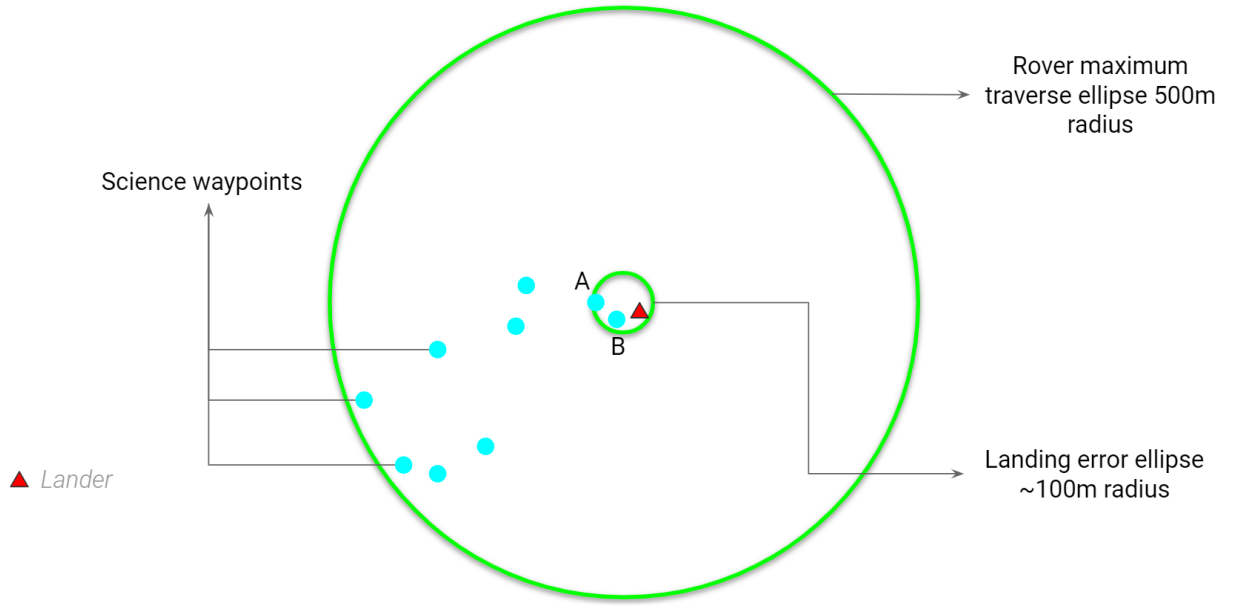


Figure 39. Step 2, identify actual landing location within the landing error ellipse. Own work.

Step 3 -- Evaluation of Viable Traverse Map

Viable Traverse map helps selection of specific science waypoints. Mission planners can use this map, as well as the individual slope, illumination, and science-oriented datasets to evaluate what terrain is best for the rover given the landing site (figure 40).

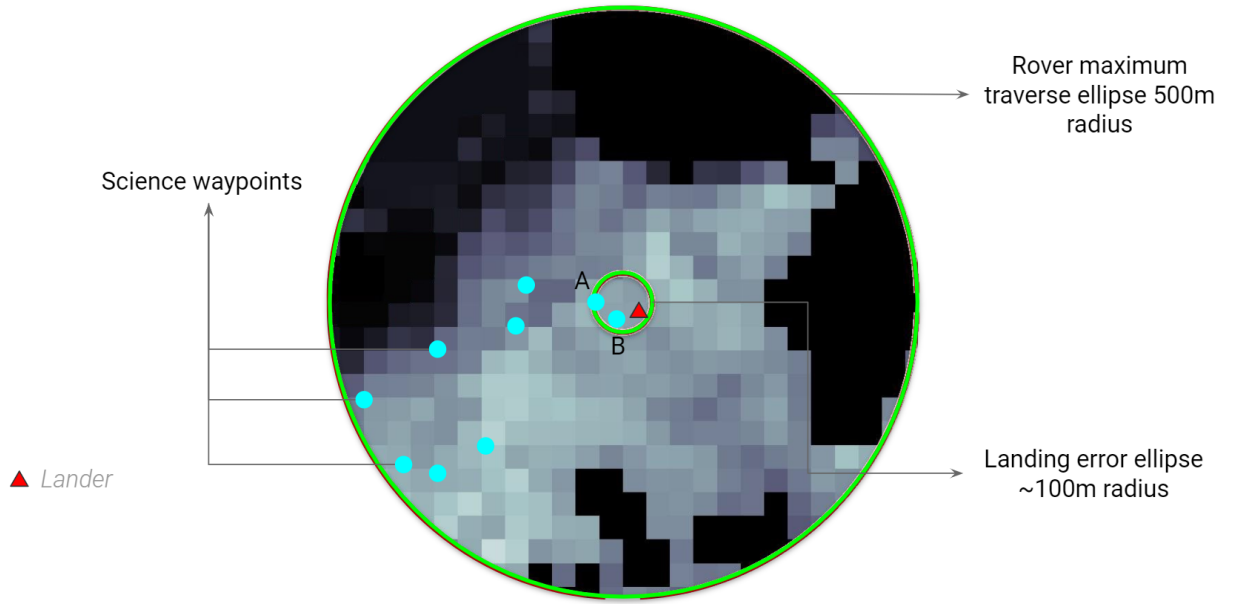


Figure 40. Step 3, evaluate VTM within Rover Maximum Traverse Ellipse (RMTE). Own work.

Step 4 -- Sequence of science waypoints selected

Selected waypoints determine sequence of science investigation traverses. This sequence is defined based on distance, timing for rover traversal, and level of interest (fig. 41).

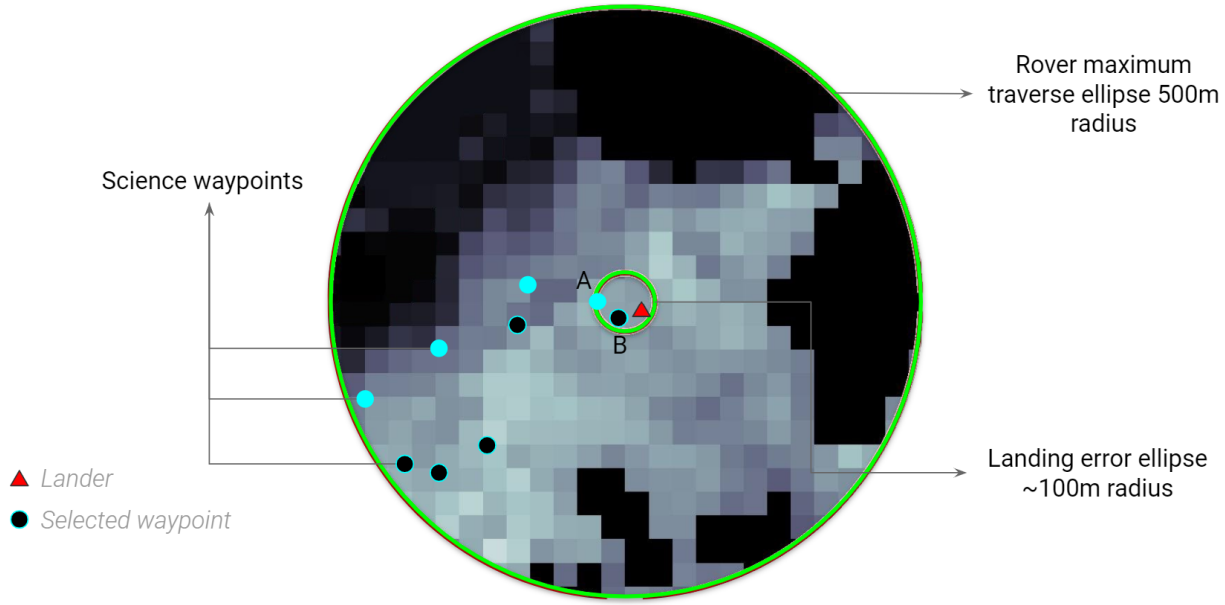


Figure 41. Step 4, select science waypoints desired for the rover's traverses within the RMTE. Own work.

Step 5 -- Navigation waypoints are defined with imagery + viable maps

In order for the rover to successfully traverse at a local level between the selected science waypoints, some additional waypoints may need to be determined. These waypoints do not have any specific scientific interest necessarily but they help the rover navigate around any areas that are hazardous for the mobility, power, perception, or thermal systems (figure 42).

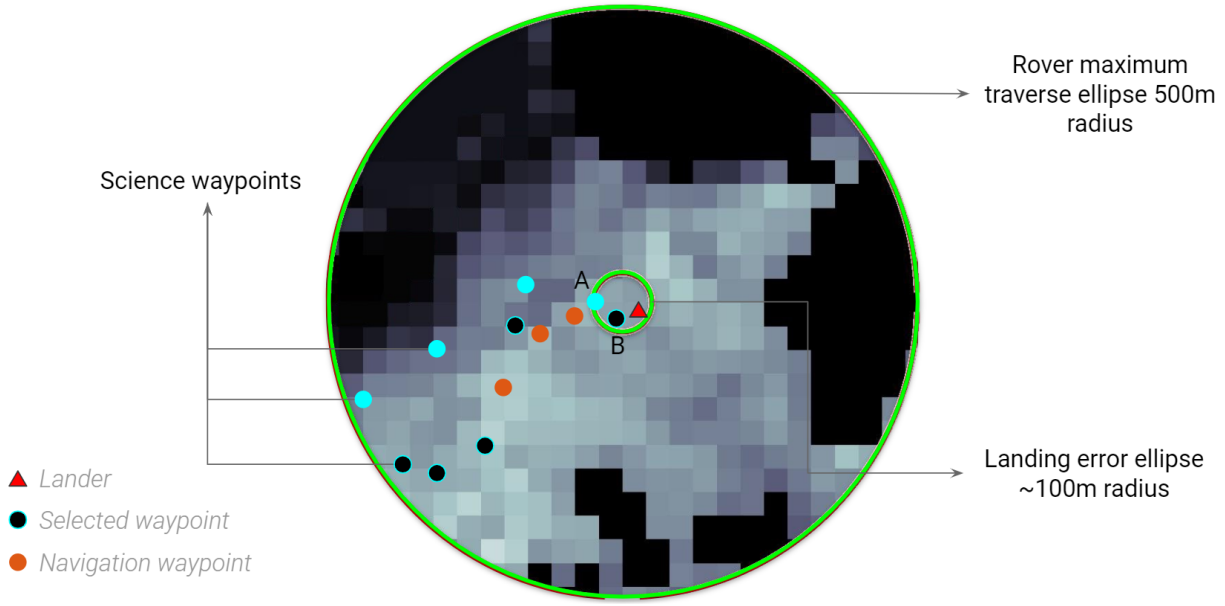


Figure 42. Step 5, define navigational waypoints to direct the rover around hazardous areas. Own work.

Step 6 -- Path between waypoints is computed

Once the science waypoints are selected and the navigational waypoints are defined a path at a high level can be planned between all these waypoints. This path is computed by an algorithm which plans for the most optimal route for slope, illumination, and to some extent, energy (figure 43).

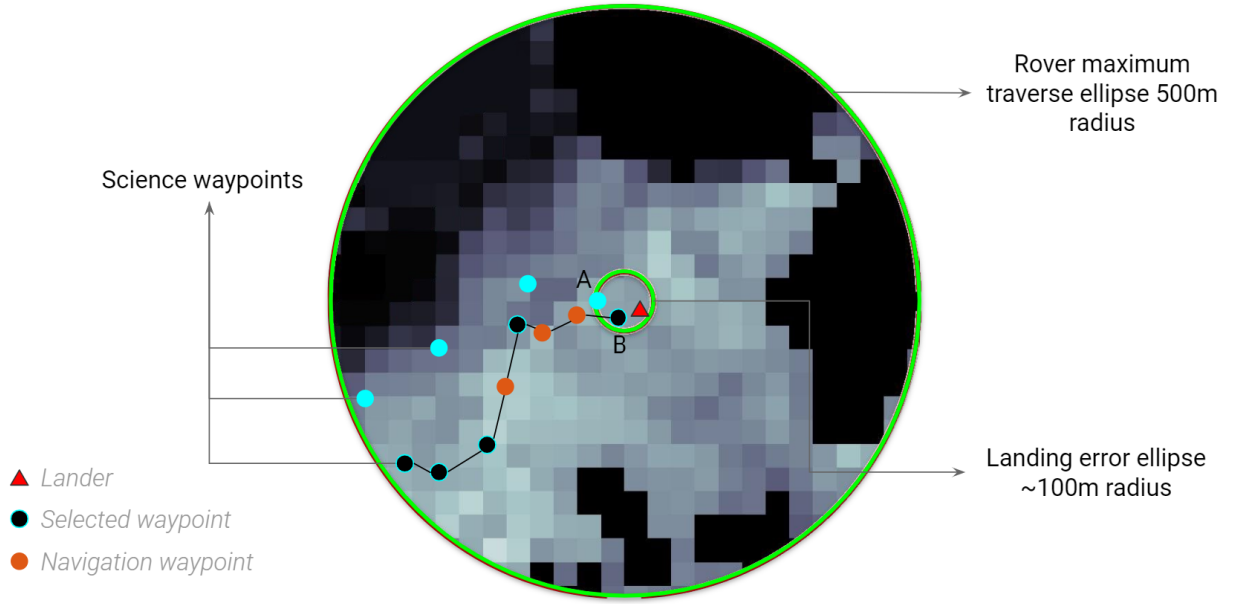


Figure 43. Step 6, compute the global path between a sequence of both navigational waypoints and science waypoints. Own work.

Step 7 -- Tuned distance margin of safety applied

The rover is autonomous, so this path is helpful but what is most helpful is also a margin of safety. Refining this margin of safety between paths depending on the risk associated with the path is important. Figure 44 shows an example of a distance margin tuned to the specific risk between waypoints. Ultimately both margin for distance as well as time are applied to each path. This tells the local planner aboard the rover what the minimum and maximum amount of time it should take between waypoints in order to make sure that its power system is supported and that the rover can traverse back to the lander when it needs to align with the DTE communication windows (figure 44).

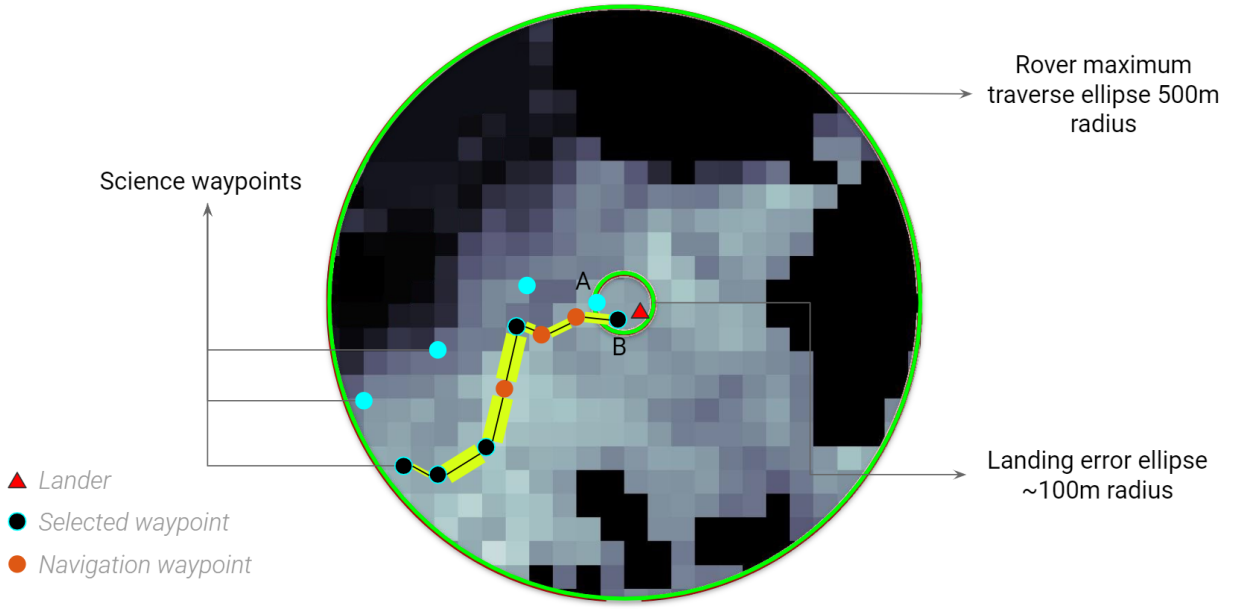


Figure 44. Step 7, compute tuned distance margin of safety along each path between waypoints. Own work.

Science waypoints will look different for different science missions, but all should focus on the core environmental analysis considerations mentioned in section 5.5.. These are again rover capabilities, science initiative, and environmental conditions. MoonRanger's science waypoints are defined to meet the following criteria:

1. Proximity to one or more permadark or shallow ice locations, hereafter "ice targets"
MoonRanger's core mission purpose is to characterize and identify hydrogenous volatiles at the lunar pole. In order to successfully characterize hydrogenous volatiles over distance, MoonRanger's landing site must accommodate this. Locations of ice-stability are dependent on the over-time light exposure at the pole. The NSS instrument can detect hydrogenous volatiles and related data within ~1 meters of the lunar surface. Successful landing sites are ones that are within range and bearing such that our trek will lead to a location of ice stability within this depth. It is important to avoid permadark locations, and regions with shallow ice stability may not provide sufficient illumination on the lander for the full mission duration, so instead the paradigm is to choose landing sites that allow MoonRanger to rove from the lander to regions of shallow ice stability. A permadark location would not provide sun exposure for sufficient power during the mission. PSRs or micro-cold traps also have potential for stable ice and are much closer in range to the landing location, hence a reduction in operation risk. Initial operations will plan around these PSRs and longer range operations will plan towards far range ice targets.

2. Range within 500m of at least one ice target
As a micro-rover with less mobility and battery capacity than a primary rover, MoonRanger cannot guarantee the speed exceeding 1km per 24hr period. Since MoonRanger lacks a direct-to-Earth radio it must return to its lander to download data and receive information from Earth such as traverse plans, so that means double-distance and double-time to and from ice targets. Hence, even a baseline ice target might require a 1 day trek with a total traversal distance of ~1km.

3. Bearing to ice target 90° +/- 20° to average sun azimuth

MoonRanger's solar array is fixed to point 90° relative to the rover heading. Therefore to facilitate charging while driving without significant trajectory changes, sun-to-rover direction should be close to 90° or -90° relative to the rover's heading. MoonRanger's solar array is one-sided, but this direction is specified as perpendicular either way to the rover's heading due to the rover's ability to drive both forward or backward. Because of MoonRanger's power system, the sun angle and direction relative to its solar configuration needs to be as perpendicular as possible to ensure its adequate power and survival. The scheduled ~12 day mission duration starting December 7th 2022 exhibits a sun bearing traveling approximately from ~105° to ~332°, and should be considered when evaluating the location of a potential ice target and the rover's direction of travel to such an ice target (figure 45).

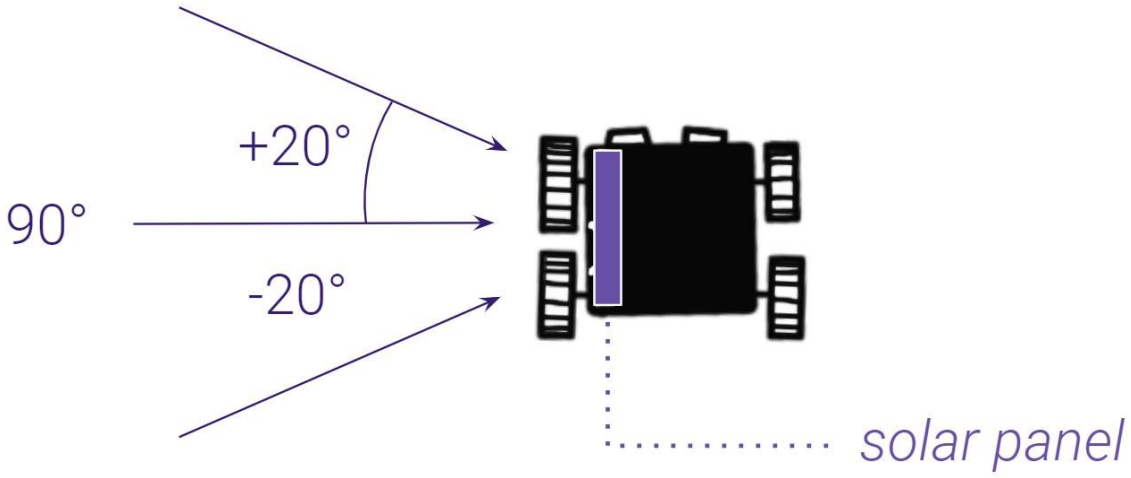


Figure 45. The above describes the criteria stating the bearing to a primary Ice target should be 90° +/-20° average sun azimuth[8]. This bearing to an Ice target will be parallel to the rover's solar panel. To maximize power to the rover, the sun should be as perpendicular to the rover's solar panel as is possible during the entire mission's surface operations. Own work.

4. Slope along route to ice target not to exceed 10° (limit of rover pitch)

MoonRanger's mobility configuration limits its overall path slope to be ≦ 10°. The landing site example exhibits a ~500 m trek with an achievable slope that does not exceed 10°.

Evaluation

The waypoint and path planning process was presented at MoonRanger's first NASA standard review, the Critical Design Review (CDR). Two categories of external attendees were in attendance. NASA assigned the mission five formal reviewers, most from Marshall Space Flight Center, to review the mission development formally and submit feedback the mission must track and on which to carefully follow up. Another category included ~60 invited but informal observers, members of NASA facilities, experts in space or robotic related fields at other universities or otherwise. The feedback for the Mission Operations team from the formal NASA

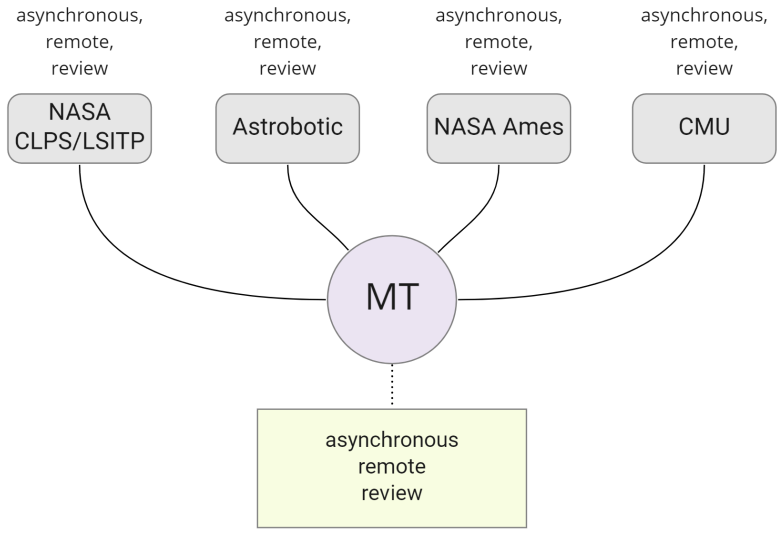
[8] 90° +/- 20° is a condition used during early site analysis. Large angle ranges such as 90° +/- 45° are used during later planning in the global path planning process to allow for "tacking" which allows the rover to adjust its trajectory to maintain an optimal power system along treks.

review committee was positive and complimented the team for a thorough understanding of operations. Minor feedback was as been submitted from the informal observer personnel, none is critical not relates to the planning approach taken by MR's Mission Operations team. Some feedback related to operator training and shifts. This topic is definitely related. Testing and training operators is paramount to mission success, which hinges on the concept of testing like you fly and flying (or roving) like you have tested. Some further questions arise. Who would use this software? What training would be required? What level of experience is necessary for use? What is the use? This comes back to the original discussion of the audience. This process, while primarily related to teams embedded within an autonomous, micro-rover, lunar exploration mission, is also relevant as a higher level conceptual framework for operations construction overall. Understanding goals, whether they be for an individual, project, or organization, are at the core of development. Considering constraints is equally important in order to scope the development and operations accordingly. Within the environment, whether that be physical or conceptual, selecting specific goal points in sequence and then defining any additional steps that help achieve those goals could be a very beneficial step to take.

6. Prototypes

This section describes the design, functionality, and associated purpose for a mission planning tool ideal for surface operations planning and landing site analysis through a series of prototypes I configured and designed over the course of my research. Each prototype described addresses a specific unique function subset of mission planning, described inline with each. Each Prototype development involved varying degrees of interfacing with existing software platforms or interfaces. Limitations and capabilities of each will be described as well as the kinds of interactions each experienced. Prototypes which were used to a great extent within the mission include an interface diagram showing interactions between the tool and stakeholders as well as an evaluation of the success of said prototype.

6.1. Map Interface 1 (MT)



Initial analysis began by defining MoonRanger's specific criteria for site selection, considering the three core environmental analysis factors -- rover capabilities, scientific initiative, and environmental constraints. These specifications are detailed in section 5.2. At the time of initial analysis, no exact landing site had been proposed or selected, so all polar regions were examined using the terrain imagery, ice stability at depth and slope data available on

MoonTrek (Lunar and Planetary Mapping and Modeling Project, 2017), shown in figure 46, to identify potential sites and communicate requirements to NASA. Notice that this preliminary planning did not have access to illumination data. This analysis took place with an already existing CONOPs[9].

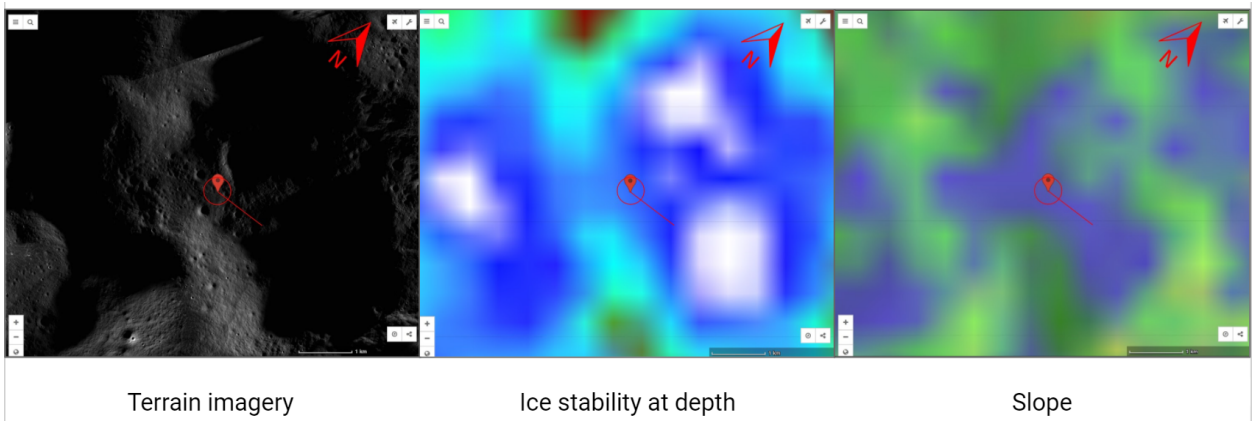
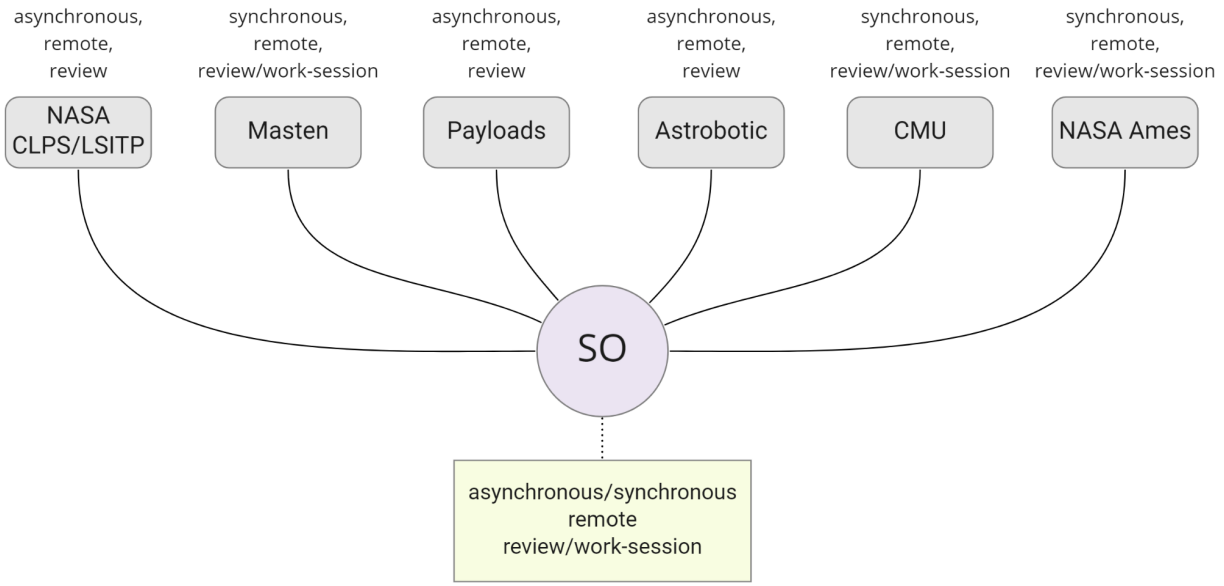


Figure 46. Initial analysis using MoonTrek (Lunar and Planetary Mapping and Modeling Project, 2017). Own work using MoonTrek.

6.2. Surface Operations (SO)



Concurrently alongside this analysis, a detailed operations plan was developed in spreadsheet form to articulate timing, distances traveled, and required maneuvers during the surface operations (figure 47). This spreadsheet defined operations which the initial CONOPs had yet to cover. While useful for defining details of the surface operations, this spreadsheet didn't provide a way to visualize the timing of communication windows down to Earth in a way that showed relationships to the entire mission timeline.

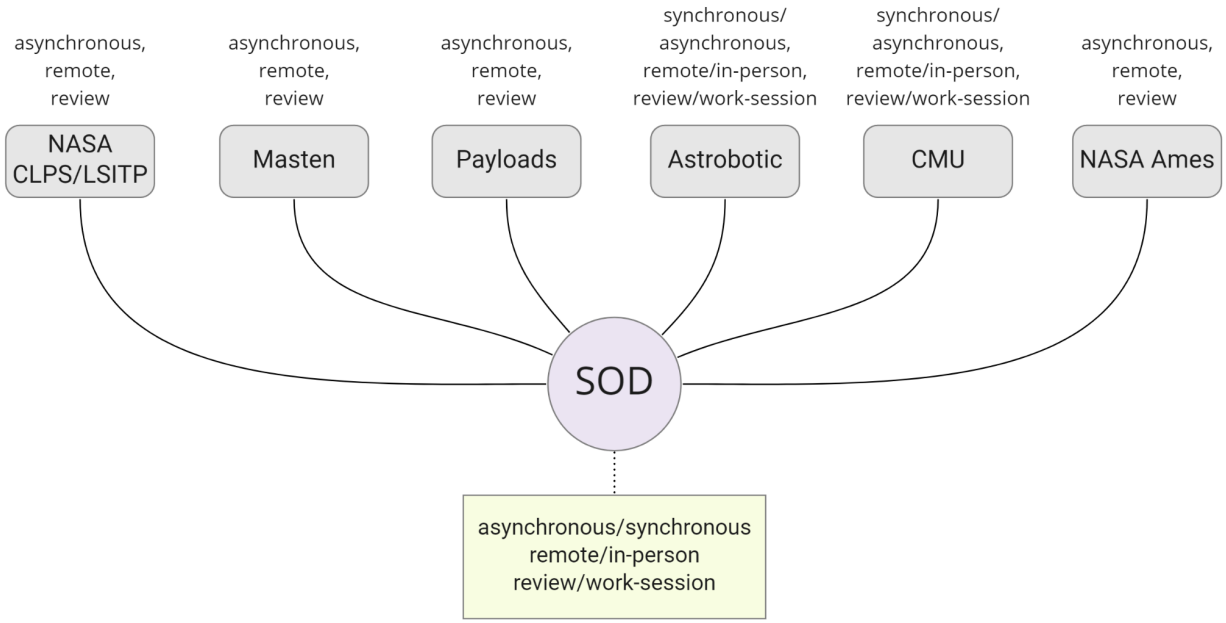
[9] First iteration of the CONOPs developed by Dan Myers, member of the MoonRanger Systems team, 2020

MoonRanger Surface Operations

		distance traveled during the trek - includes out and back travel (m)	total distance from lander at the end of the trek (m)	margin	phase time duration (hrs:min)	total comm time with margin for checked comm events	total time of each comm window with margin (hrs:min); each box represents a different comm window
01. Land					03:00		
a.	Retain temperature > -30°C					☐	no rover-specified comm
b.	No power					☐	
c.	Locked down					☐	
d.	No communication with lander					☐	
e.	Landing location confirmed by Masten					☐	
f.	Landing descent imagery if available					☐	
g.	Margin			---	☐	☐	
02. Warmup and wireless test					03:28	03:28	*comm window 1*
a.	Warmup				01:00	☑	
b.	Rover status				00:05	☑	
c.	Capture local images				00:10	☑	
d.	Establish network				00:10	☑	
e.	Wireless test				00:05	☑	
f.	Actuator test				00:10	☑	
g.	NSS data collection checkout				00:30	☑	
h.	Load global map				00:30	☑	
i.	Margin			0.3	☑	☑	
03. Deployment					01:42	01:42	
a.	Deployment preparation & analysis of local images				00:45	☑	06:01
b.	Upload exit route				00:05	☑	
c.	Deploy				00:10	☑	

Figure 47. Surface operations detailed using google sheets organization structure. Own work.

6.3. Surface Operations Diagram (SOD)



To make sense of surface operations in a spreadsheet, a diagram is particularly useful. This diagram in figure 48 organizes operations by color, showing a rover/lander WiFi communication range as a blue circle around a lander (center red object) and longer range conceptual ice targets. White stars distinguish which treks have a science-focus.

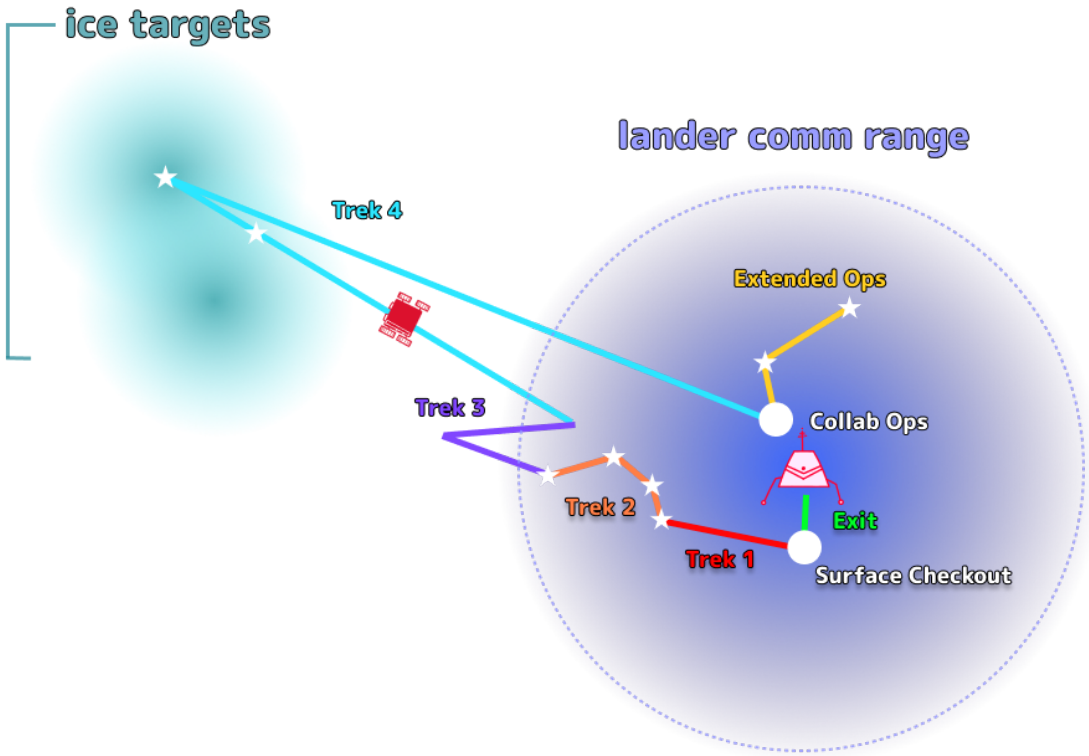
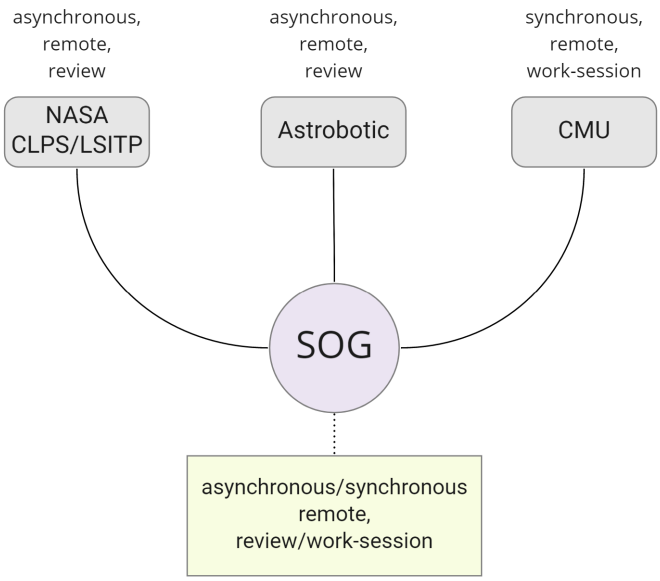


Figure 48. Diagram of MoonRanger's surface operations. Own work.

This diagram is very useful for communicating MoonRanger's surface operations at a very high level to stakeholders and to the public. For the internal development team, the diagram is a quick reference tool relevant to many subsystems, but for detailed mission planning it doesn't provide alignment with communication windows, detailed operations, and mission time.

6.4. Surface Ops Gantt (SOG)



A next iteration of the surface operations spreadsheet and surface operations diagram (figures 47 and 48) integrates this visualization of the mission timeline, developed in Figma and led by Griffin Tang, former lead of the mission operations team for MoonRanger (figure 49).

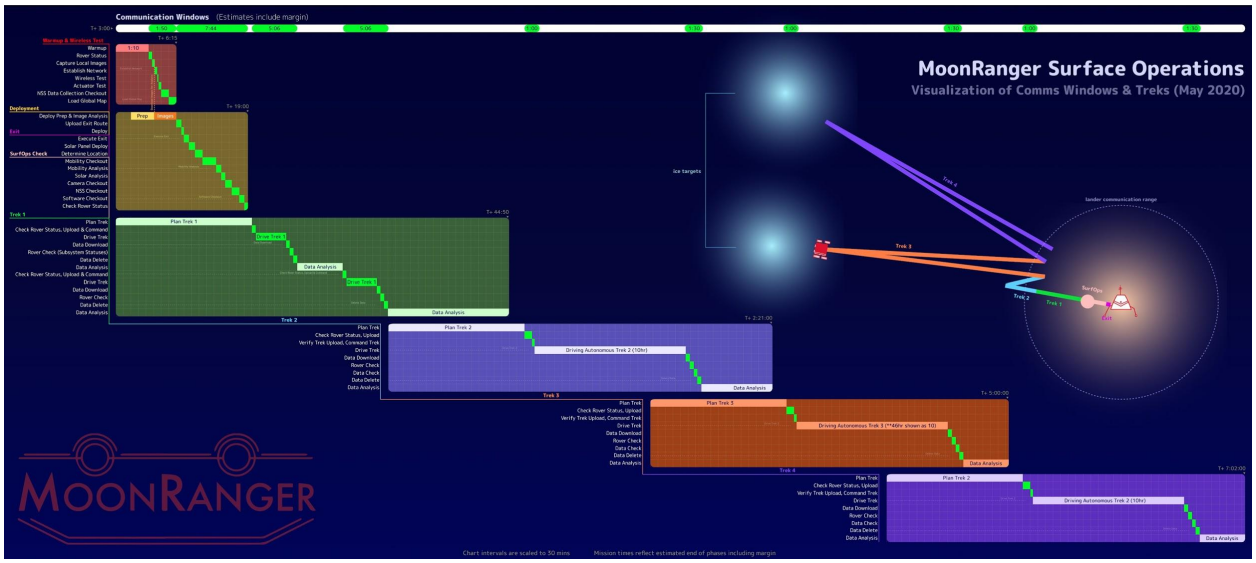
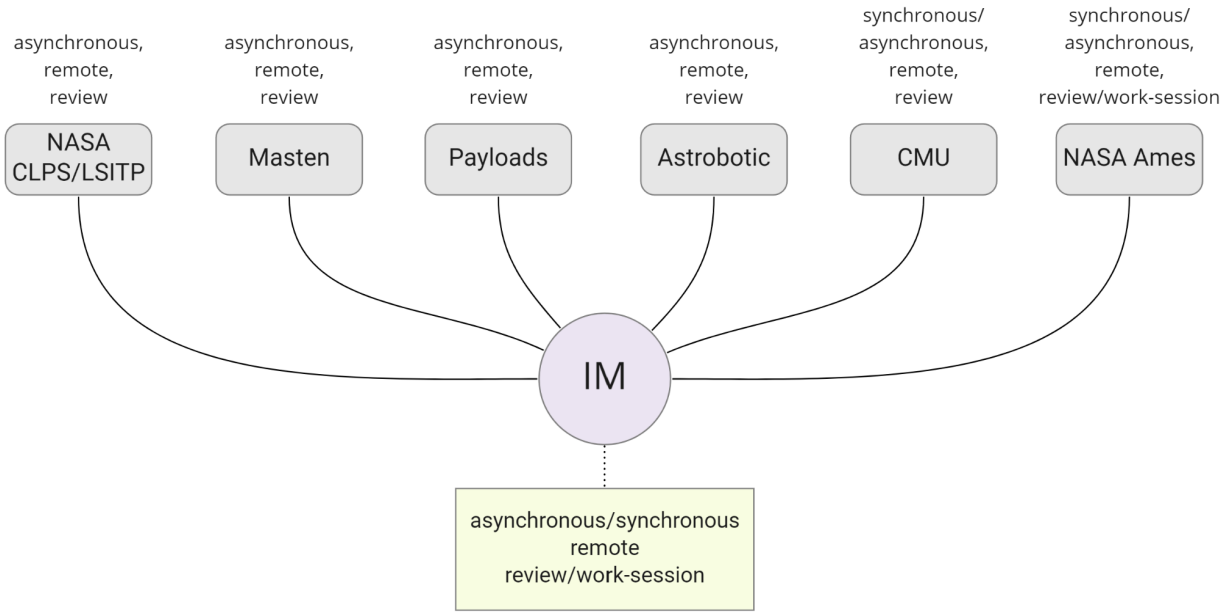
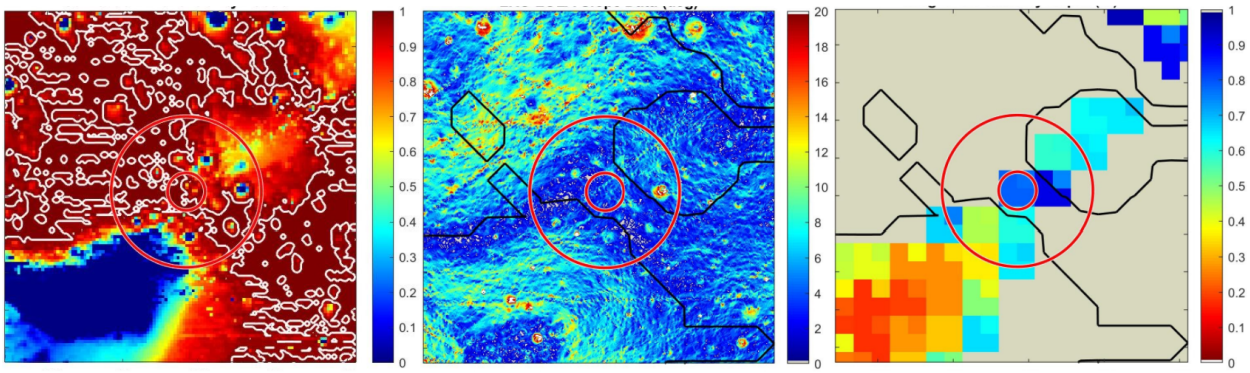


Figure 49. Initial analysis using MoonTrek. Work in collaboration with Griffin Tang.

6.4. Map Interface 2 (IM)



Map and environmental analysis progressed, with helpful mentorship from Rick Elphic, science Principal Investigator for the Neutron Spectrometry System (NSS) at NASA Ames. Data used during this analysis accounted for illumination and higher resolution slope and ice stability at depth data. This analysis used Matlab (figure 50). This landing site, with visualizations of the rover traverse ellipse, landing error ellipse, and written definitions of conditions was presented to NASA to advocate for the site shown in the figure as well as one near Haworth Crater at the lunar south pole. This analysis integrates contouring, to designate regions of 99% fraction illumination and above across all maps. Notice the horizontal/striated contoured regions in the illumination over time map on the left. These striated areas indicate regions of potential multipath interference (Kuroda, n.d.), leaving this site not the most ideal for rover exploration and data communication back to Earth.



Illumination over time Slope Ice stability at depth

Figure 50. Intermediate analysis using Matlab. Own work.

The next planning iteration involved the construction of this viable map shown in figure 51, allowing for representation of traversable rover slopes and viable illumination percentage throughout the ~12 day surface mission.

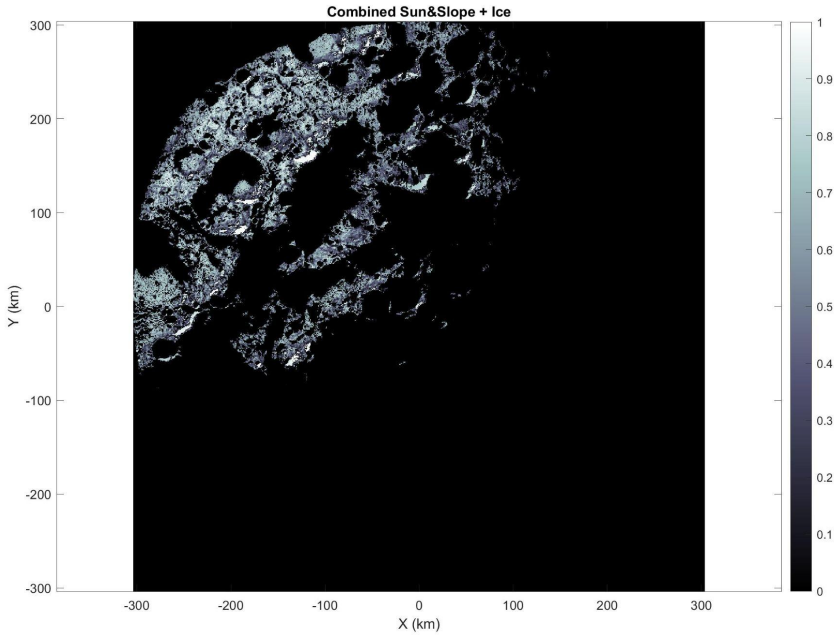
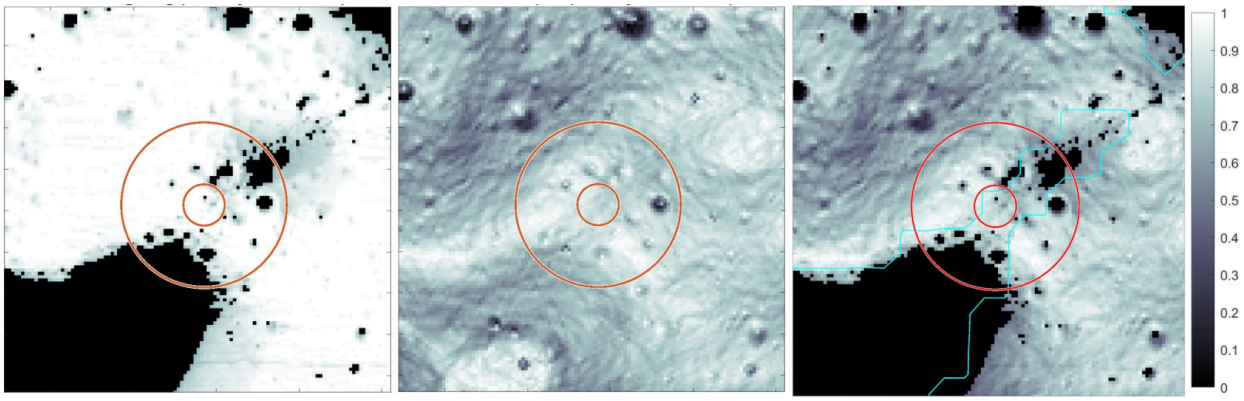


Figure 51. Viable map generated and shown for global south pole reaching out to ~80 deg latitude. Own work.

Analysis next evaluated the proposed sites using all three viable maps. These viable maps didn't present the easiest mechanism for visualizing the science-oriented dataset, only the slope and illumination datasets (figure 52).



Viable illumination | Viable slopes | Combined + ice stability at depth

Figure 52. Viable maps for illumination, slope, and combined zoomed to one of the two advocated sites. The contouring on the right most image shows a region with possible stable ice. Own work.

Once the final site was selected in December of 2020, the immediate step was to evaluate each individual map in as quick a way as possible to begin defining the specifics of operations. Figure 53 shows illumination, slope, and ice stability at depth maps both at higher resolution, with new specifications for landing error and rover traverse ellipses, and specified to the selected site near Haworth crater.

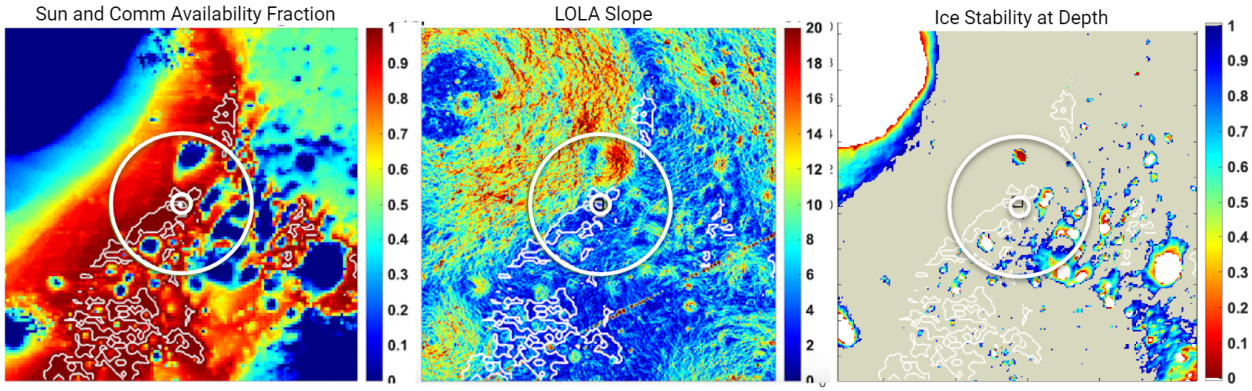
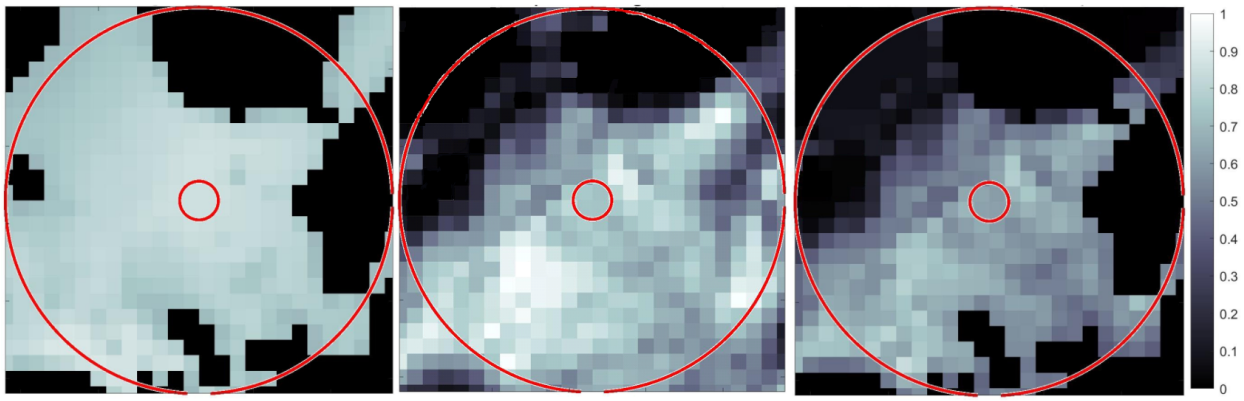


Figure 53. Initial analysis using MoonTrek. Work in collaboration with Rick Elphic.

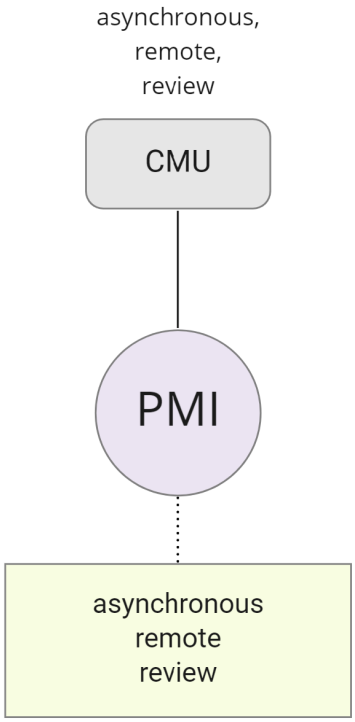
Viable maps, also zoomed to this site would allow for operators to select specific waypoints and begin final stages of planning (figure 54).



Viable illumination | Viable slopes | Combined + ice stability at depth

Figure 54. Viable Traverse Maps showing traversable well illuminated, well sloped, and a combination of the two from left to right. Own work.

6.5. Paper Mission Interface (PMI)



For the second Paper Mission (see section 4.4), an initial global planning pipeline was developed and the waypoint selection process was tested using Miro (Rojanarata, 2020). The Miro Board interface was a place where all relevant mission information could live for operators to view, navigate and reference during operations. This interface, however, was static, didn't actually interface with datasets or data manipulation and other than the ability to zoom around the page, was not interactive at all. This interface was the first combined interface and iteration of a mission planning tool.

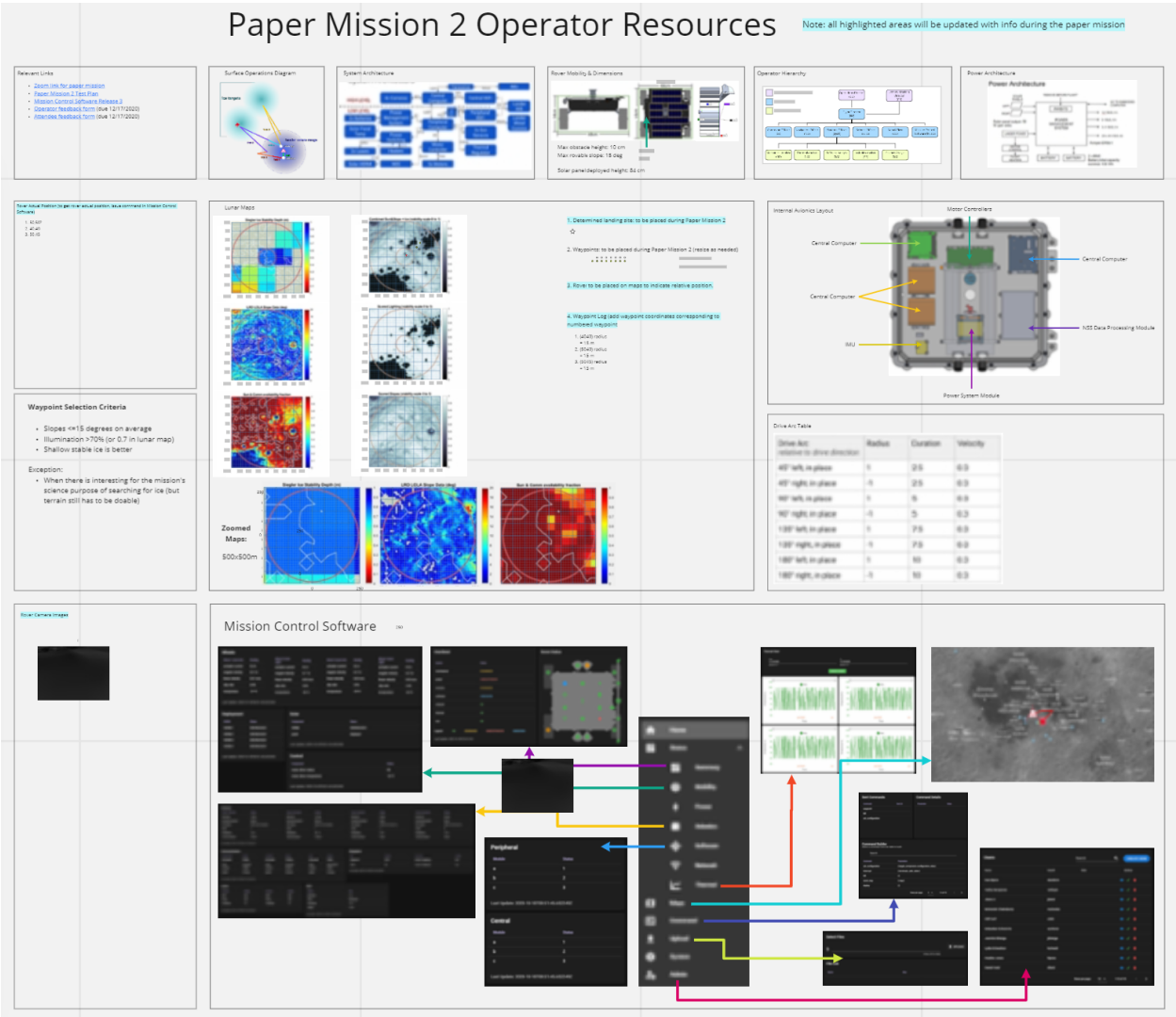


Figure 55. Two-dimensional, non-interactive mission planning interface Prototype 1 constructed for operators for a Paper Mission. Work in collaboration with the MoonRanger Mission Operations team of Fall, 2020.

Evaluation

During MoonRanger's second paper mission, the Miro mission planning interface was developed and used to test initial planning procedures. The Miro interface was used to organize all relevant visuals, diagrams, and quick information for operators. Diagrams included were rover belly clearance, mechanical dimensions, avionics architecture, avionics configuration, lunar maps, operator hierarchy, mission control software user guide, surface operations diagram, drive arc table, and relevant links to associated documents. During the paper mission, operators used the Miro board along with other interfaces (including mission control software and Paper Mission 2 Test Plan) to navigate the paper mission event. From a Mission Operations internal perspective, this was very useful to operators, especially for those stepping into operator roles with limited operational experience or domain knowledge.

One observer submitted feedback with no comment on interfaces.

All twelve operators/participants submitted feedback on interfaces. 50% rated the interfaces as “Successful,” while the other 50% rated as “Somewhat Successful.” It is important to note that these reviews were in response to all paper mission interfaces (both mission control software and Miro board), so some reviews may not reflect sentiment towards the Miro board specifically.

Successful reviews describing the interfaces are summarized as follows:

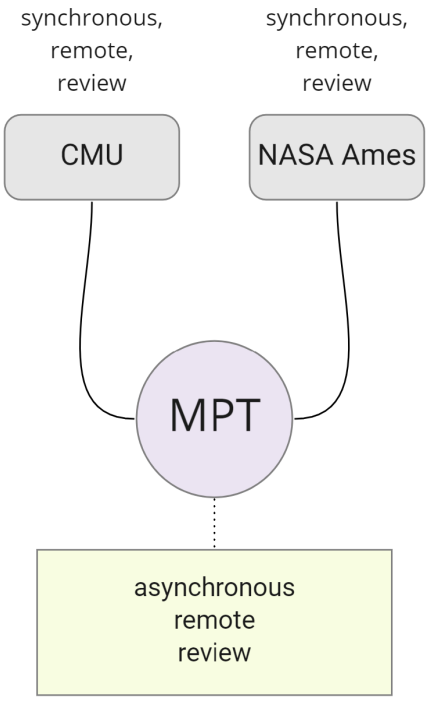
- Much better than the previous paper mission
- A solid stand-in for anything not yet implemented
- A way to follow what was going on
- Very clear and easy to understand quickly, providing all the information essential to this operators specific roles (Data Officer, Mechanical Analyst)

Somewhat successful reviews describe the interfaces as follows:

- Waypoints on Miro board could have been smaller and were too large in comparison to the lunar maps used for global planning waypoint selection
- Content of the board was helpful, but the layout was a bit difficult to follow. Something with separate tabs could be used to organize information
- Because a virtual environment (Zoom) is a difficult environment to work with for a paper mission, the careful design of interfaces could be used to maximize communication and decision making

6.6. Mission Planning Tool (MPT)

The next iteration developed extensively upon all core ideas and mission planning capabilities described in the previous section. While not used heavily within the MoonRanger team, this prototype is meant to provide an example of critical functionalities essential to CAS planning. The core purpose of this application was to provide a platform for those conducting mission development procedures to use as an interactive tool for preliminary surface operations design and environmental analysis. Goals are as follows:



1. To facilitate the understanding of lunar datasets individually, their significance, and how they were collected in some capacity.
2. To present a mechanism for global planning, the process of identifying viable or traversable terrain at a given site and understanding how risk levels and design implications could affect the resulting viability.
3. To allow mission planners to identify areas of interest within datasets interactively in a hands-on manner and to design surface operations around the parameters specific to each map.

In order to achieve these goals, careful choice of datasets is imperative.
The primary considerations of site analysis for a lunar rover mission are (a) mobility, or how well a rover can drive on terrain of various slopes and over obstacles of varying heights, (b) power and thermal, both very closely tied, specifically solar power and component or rover system temperature limits, and (c) scientific initiative. Three datasets fit each of these considerations. Elevation data (in the form of slopes) provides a context for analyzing rover mobility (a). This dataset, from the Planetary Data Sciences Node (Earth and Planetary Remote Sensing Laboratory, n.d.), is interpolated for slopes using Matlab. The same dataset is combined with a model of solar and Earth elevation with respect to the lunar south pole for a 12 day mission at a given time (Dec 2022). The resulting illumination over time dataset allows users to understand which areas support a mission's given thermal and power systems (b). Water is considered one of the most valuable resources of the solar system, being a substance which can provide oxygen for breathing, water for hydrating humans, plants, or otherwise, and hydrogen for fuel into the rest of space. Therefore, Siegler Ice Stability at Depth data, from MoonTrek, is the third dataset. This data is manually produced by Matt Siegler at the Planetary Science Institute, also a collaborator with NASA's VIPER rover mission.NASA Ames Research Center. The ice stability depth calculation is a model based on the thermodynamics of sunlight hitting the topography. The model calculates how heat propagates into the subsurface when it is sunlit, but also flows back out and radiates away during times of darkness. Siegler's model uses realistic thermal conductivity and includes the effects of re-radiation by nearby sunlit terrain. The calculation results in a predicted temperature profile whose maximum decreases with depth. At the point where that profile crosses the ice stability criterion, that becomes the ice stability depth. It is important to note that this approach is a model, not a measurement. No ground truth data proving the existence of ice at the lunar south pole yet exists, so this dataset is one of the best models.

Datasets are preprocessed in Matlab, which excels at manipulating very large datasets (up to 36000x36000 pixels). Elevation data was interpolated for slope. Illumination data was pre-constructed. Ice Stability at Depth data was filtered to only show stable ice within 1m of the lunar surface, according to the capabilities of existing hydrogenous volatile measuring scientific instruments. Images of each individual dataset are stored as JPEG files from a global and local perspective. The global perspective allows users to understand data implications at a high level and local maps allow users to zero in on an example landing site to analyze in further detail. Data processing was attempted in Python to avoid the use of purely displayed images in streamlit, but the size of the data resulted in very high processing times (~15 min) and streamlit's process for viewing a map dataset such as this (`streamlit.plot()` function) creates an image of the map first before displaying, which kills the point of processing in Python altogether. It also errored with such a large dataset during this process.

Viable maps for slope and illumination are constructed also in Matlab by setting a threshold limit, treating all values above (or below in the case of the dataset) as viable and all those below as completely not-viable. Values within the viable range are scaled from 0 to 1, where 0 is least desirable and 1 is most desirable. A combined viable map is generated by multiplying each of the viable slope and illumination maps together.

`streamlit_drawable_canvas` played a valuable role in a tab dedicated to surface operations development.

The resulting application consists of four tabs.

Tab 1: Intro to Site Analysis
This tab explains site analysis - what it is, how it's done and how it benefits mission development. This tab also introduces the other tabs and their individual functionality.

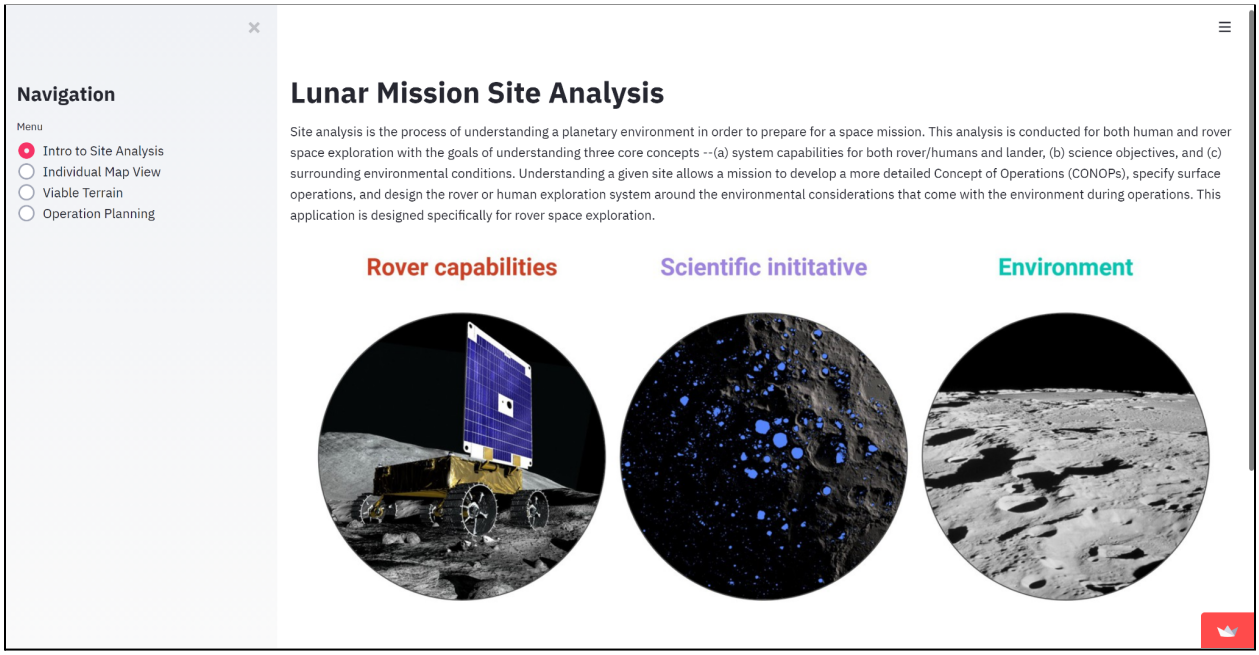


Figure 56. Tab 1, "Lunar Mission Site Analysis," gives an introduction to lunar mission site analysis, describing three core ideas. Own work.

Tab 2: Individual Map View
This tab allows users to view side-by-side maps or layered maps either local or global. The side-by-side view displays maps individually. Users can interactively click on each map in the sidebar and view an enlarged version. A description pops up in the sidebar describing the dataset - it's resolution, what it means, and in some cases how it was collected. The layered view allows users to layer each map and adjust the opacity between each to begin drawing parallels between various map parameters and conditions.

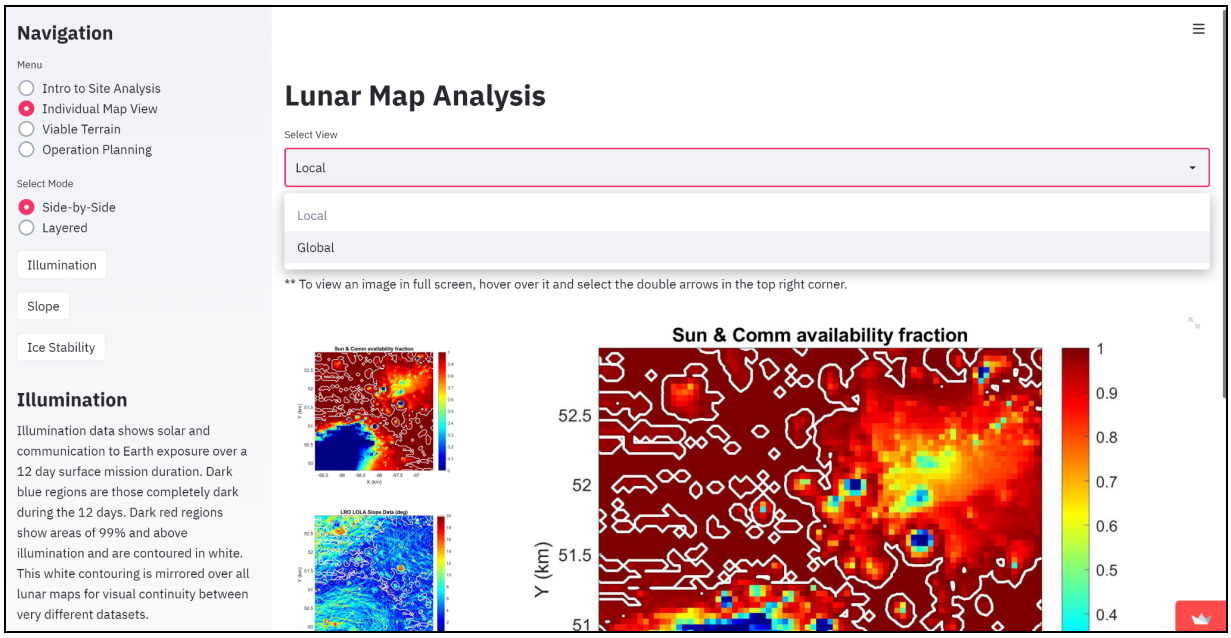


Figure 57. Tab 2, "Lunar Map Analysis." Side-by-side view allowing users to view terrain data at a local or global scale. Users can view datasets side by side (shown in image) or in a layered view, where the opacity and order can be adjusted. Upon selecting a specific dataset to view primarily (Sun & Comm availability fraction is the selected dataset here), information about the data appears on the panel on the left. Own work.

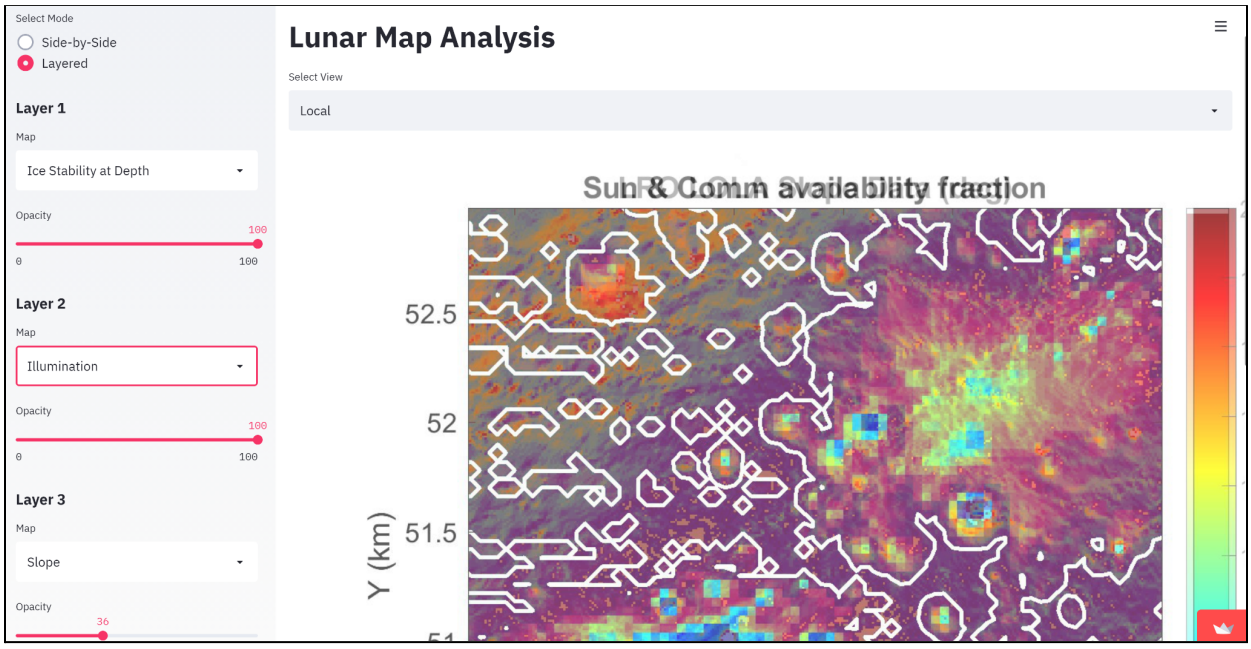


Figure 58. Tab 2, "Lunar Map Analysis." Layered view allows the user to assign layers, order layers, and adjust opacity. Own work.

Tab 3: Viable Terrain

This tab lets users identify regions which are rovable and those which are not rovable, given their mission's specific parameters specific to slope and illumination maps. Users can select

different degrees of risk for each map and observe the local and global implications of viable terrain.

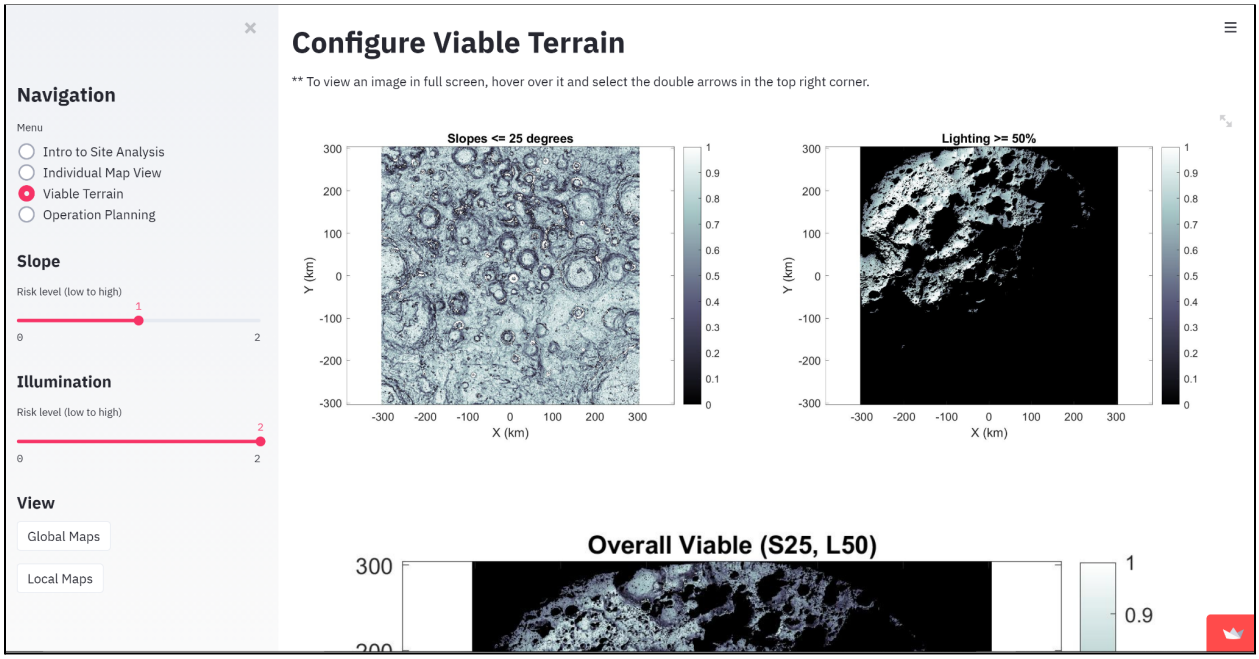


Figure 59. Tab 3, "Configure Viable Terrain," allows users to adjust three Viable Terrain Maps -- Slope, Lighting, and Combined ("Overall Viable"). Users can adjust the level of risk they are willing to take with regards to illumination and slope (i.e. a rover may accept more risk when traversing larger slopes if it has a more robust mobility system). As the user adjusts the risk level on the left hand side, the Viable Terrain maps update to show the resulting traversable terrain. The Combined Viable Terrain map "and's" both slope and illumination, showing combined traversable terrain. Own work.

Tab 4: Operation Planning

This tab leverages each local individual map as a canvas, selectable by a user, on which to draw. Users can select waypoints of interest for their science purpose and evaluate whether or not those waypoints fit their illumination and slope capabilities. Users can draw on landing ellipses using the circle tool, outline regions of interest with the rectangle tool, indicate rover traverse paths using the line tool, or freedraw as they like. Each object drawn can be resized and moved around within the canvas. Users can also adjust the opacity of the background map to focus more on the map or more on their diagrams. Diagrams are shown below the canvas on their own and can be saved by right clicking.

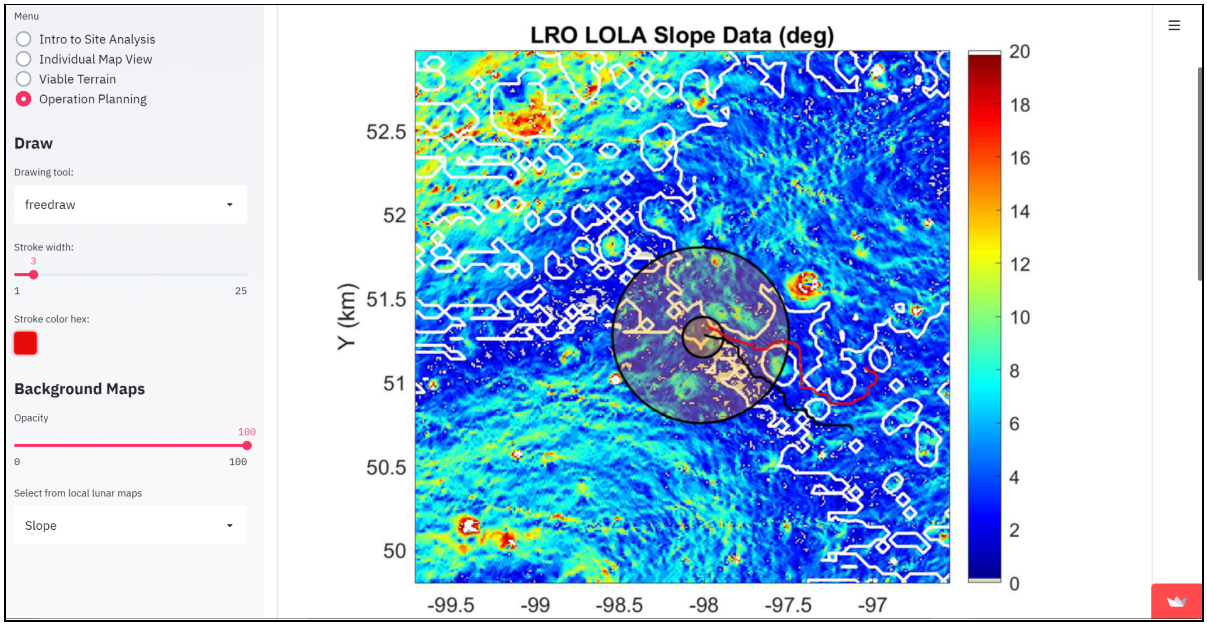


Figure 60. Tab 4, "Operation Planning," allows users to sketch and plan out surface operations at a local scale. Users can add landing error and Rover Maximum Traverse ellipses, color code waypoints and traverses, and view their operations diagram on illumination, slope, and Ice Stability at Depth maps. Own work.

This application can be viewed on Streamlit here and the Github repository is available here.

Evaluation

Through the use of this application, users learn about the site analysis process, the criteria for evaluation - rover capabilities, environmental constraints, and scientific initiative, and how site analysis benefits mission development. They learn about three key maps used for such site analysis, the resolution of the data, and what instruments were used for data collection.

This system has enabled intuitive user configuration of viable terrain maps, a feature which can also be used to understand how increasing the fidelity of aspects of the rover system design can affect the scope of rovable terrain. Such a capability can be used both in early on mission development before a solidified rover configuration has been defined as well as later on during, say, the global planning process.

The system also provides a platform for dataset-and-drawing-integrated surface operations development, something lacking in all existing site analysis tools.

The future of this work could involve the integration of more datasets, for instance datasets of permanently shadowed regions or temperature profiles at the south pole. It could allow users to all lunar regions (south pole, north pole, and equatorial regions) or could even be extended to include different planets, prioritized by those most within the reach of current space exploration trends and technological capabilities for rover exploration. It could investigate further the means by which users could interact directly with the datasets themselves versus images. The Viable Terrain tab could include more variable risk levels for both slope and illumination and could

include some way to overlay science specific datasets. The Operation Planning tab could allow users to number or label the marks they make, save multiple diagrams, and view other maps as background images.

7. Findings & Discussion

This section identifies key findings which emerged throughout the system and prototyping phases of research. Findings include the criticality of visualization to planning, language that emerges from planning, implications of viable maps on rover design decisions, and broader implications of each. The chapter culminates in a section describing features and characteristics integral to an ideal mission planning tool for CAS micro-rovers.

7.1. Visualizations are Critical to Planning

During this research process, I learned very quickly that missions already involve very many visualization interfaces (see Chpt 4). Technical visualizations are methods of choice for mission development support. They support design, analysis, understanding, and communication within and among teams.

Thermal Desktop, as utilized in MoonRanger's thermal analysis, is a case in point. Thermal Desktop produces numerical time-histories of temperatures at hundreds of points on the robot for every variation of sun angle, driving direction, shadowing and computer loading experienced during the mission. This matters because electronic components can't be too hot or too cold despite polar thermal conditions varying immensely due to sun and shadow. Aspects of the rover's geometry, surface coatings, insulation, and the characteristics of heat-generating components like batteries, computers and motors are varied within the tool as design evolves. The point of describing the tool and the process to this level of detail is that visualizations are the quantitative, illustrative and intuitive means for consuming, mastering and socializing the results. The dimensionality of the analysis and the combinatorics of the process are such that the sea of numbers defies intuition and understanding. Counterpart examples are utilized for mechanical vibrational analysis and software planning simulation. In the same way that technology has developed, allowing autonomous rovers to exist in the way that MoonRanger does, visualization tools have developed to make some of that functionality possible.

This however is merely a discussion of visualization or lack thereof. The next part to the conversation is -- what about visualization tools which already exist? Are they lacking in some way in a visualization-specific context? Absolutely. During my prototyping process I expected that there would be certain clear answers to a problem. You have this problem, use a graph, this problem, use a heat map. It didn't turn out to be that simple. These decisions were relatively easy to make for me, but the real challenge came down to what color do I make this specific map in order to communicate the information in a meaningful way? In what way do I organize a detailed surface operations spreadsheet to best distinguish DTE communication windows, science operations, and autonomous operations? Ultimately these questions revolve around design decisions to make in order to assign specific meaning intuitively to an incredibly complex planning problem. This is not just as simple as visualizating for complex information systems,

but is complex in another sense -- design decisions can be catered to a specific mission with specific initiatives, capabilities, and constraints, as seen in the discussion of existing planning tools in Chpt 2. Tailoring a planning interface to the specific datasets a mission must evaluate for planning is critical.

Though not the best solution to the planning problem, my prototyping process was especially helpful in allowing me to identify a need, understand the scope, iterate, evaluate, and jump around certain hurdles that just were not worth the time given my own limitations and constraints with time and people-power. Throughout the mission, my development process consisted of the following:

1. Investigating an unknown domain or subject area
2. Developing a prototype for a specific function I saw in the mission operations focus area
3. Using that prototype until limitations were observed
4. Repeat

This process meant not only that I began to notice the depth of a certain domain, but I was able to test and investigate many existing tools in an attempt to solve a problem at hand in the midst of a fast-paced mission environment.

Out of this visualization exploration research came a couple additional findings addressed in the next two sections.

7.2. Planning Language

When my mission planning began, through the visualization and prototyping process, it became clear that certain considerations were particularly relevant. These considerations didn't necessarily have precedence in the planning domain, especially considering that MoonRanger's mission was unique, and that the explorer was a first-ever lunar polar CAS micro-rover. Over time I distinguished and defined new terms and language to assist planning. These were embraced within and beyond the team. This has become common language within the community. Terms include:

Ice Target
Red Whittaker coined this term when we first sat down to write and review a document for NASA CLPS/LSITP detailing the considerations for a landing site. This term refers to a location with possible stable ice within 1m of the lunar surface, exhibiting a traverse to that location with slopes $\leqq 15°$ on average, with the sun azimuth at $90° \pm 20°$ relative to the rover's traverse direction, illuminated enough at the site for rover survival, all within a maximum distance of a lander location. What a mouthful. This term became integral to describing these exact characteristics when presenting documentation and conduction conversations among relevant stakeholders. This term was defined about 6 months into the mission.

Rover Maximum Traverse Ellipse (RMTE)

There is a similar term assigned with a lander, called a “landing error ellipse.” You can map a landing error ellipse on a map to show how far in any direction from a targeted landing location a lander may be off, worst case scenario. This is a very helpful term for early planning because it helps you specify better landing sites over others, if the terrain is favorable over the entire landing error ellipse. Similarly, conversations kept coming up about the MoonRanger rover’s capabilities of going far away from a lander over here, or over there. Before the final landing site was selected, but after I had sent along our mission’s criteria for an ideal site, I received a list of 10 potential sites from NASA asking for an evaluation of their feasibility for MoonRanger. I was slightly surprised to see that almost 80% of these sites were not doable for us for a few reasons, one being the proximity to possible stable ice. Almost all the sites had a possibility of stable ice, but these ice regions were well out of our rover’s maximum range from a lander. I began mapping a second ellipse, in addition to the landing error ellipse, on maps to show very explicitly how far our rover could traverse away from the lander’s location. I gave this ellipse the term Rover Maximum Traverse Ellipse (RMTE). It too became an integral part of planning conversations. Can we go there? No, it’s not in our RMTE. Or…. This site is a great landing location because there are Ice Targets in the RMTE!

Viable Traverse Map

Viewing maps alone is helpful, but it doesn’t give an individual a clear-as-day picture of what is actually doable for the rover and to what extent. Usually maps have many different colors, but seeing all these colors can get distracting and exciting, thinking of all the possibilities for X kind of exploration, when in reality not all those possibilities are an option. A solution to easy understanding of rover capabilities and constraints is a map that filters out all the no-go regions, keeps the go-regions, but scores them on a gradient so preferable areas are more visible or bright than regions towards the no-go end of the spectrum.[10] After producing a few of these maps, using them in conversation, and using them as a case and point for how feasible a site was or was not, I attached the term Viable Traverse Map (VTM). This term was most heavily used within the MoonRanger team around discussions of global path planning and waypoint selection.

Waypoint of Interest (WOI) & Navigation Waypoint

As MoonRanger’s surface operations expanded to involve detailed maneuvers targeting the three science goals[11] I designed, “Ice Target" was no longer the only science-purpose waypoint MoonRanger would traverse towards. New waypoints included micro coldtrap-targeted locations within the rover/lander WiFi range (another ellipse which should be added to a map and termed). Having two distinctions to science waypoints can be a little confusing when having a conversation with someone not as deep in the surface operations planning process. What is most valuable to communicate is whether a waypoint is science-focused or not. When planning waypoints, apart from those targeting areas, there will be other waypoints defined. These waypoints are meant not just to direct the rover between science-areas, but to help the rover avoid large obstacles

[10] See Chpt 5.5. Planning Around Constraints & Capabilities for more information
[11] Chpt 3.3. Operations

at a global scale. Hence, my definition of Waypoint of Interest (WOI), which refers to any science-target, and Navigation Waypoint, which directs the rover along an intended global path. As the surface operations planning process has continued to develop and I'm beginning to define more concrete waypoints, these must be communicated to the global path planning team. Many communications among the global planning team overall have involved these two terms.

In each of these situations, a visualization existed, meaning was articulated around the visualization, and a term was produced. What emerges from this terminology development is the power a visualization tool has to produce new domain language. The patterns that solidify through a visual planning and communication process can result in language which eases communication, provides new affordances, and has a way of shaping the conversations around planning.

7.3. Viable Maps and Mission Design

The concept of Viable Maps for MoonRanger's mission developed well into the rover development timeline. Key features of the rover had already been designed and were contributing to the list of rover capabilities and constraints. Of course this is valuable for the aforementioned reasons, but what about a different context?

In response to RQ3, asking *Could an interface structure influence the decision making process of a team?*, I would respond, yes. This viable map was only used in the later stages of planning for MoonRanger's mission, but it could also be used in the very early planning stages, well before key rover capabilities and constraints were set in stone. A team could investigate a potential landing region and play around, iterating through varying degrees of acceptable risk for datasets that are or *could be* relevant to their mission. They could use this visualization capability and the resulting information to make design decisions related to their rover itself. For instance -- they really want to explore a certain kind of terrain feature but they don't quite know how that feature manifests or what capabilities their rover would need to have to achieve such an objective. Playing around with risk tolerances on a viable map, they can weigh their options -- does a better mobility system get us there (steeper slopes), does a better power system get us there (worse illumination), etc., until they can determine a happy medium between a few sets of capabilities. Ultimately the rover's own design could result from this visualization interaction.

This kind of interaction deduces a very critical and powerful role visualizations could play in early mission planning, not just once rover designs are above 25% maturity[12]. Similar visualization functionality could immensely benefit CAS micro-rover missions specifically, as time and resources are huge constraints on design and development. Such a functionality could speed up the development process and offer insight and direction for future design decisions and implications for a rover.

[12] Percent mature is a metric sometimes used to describe the fidelity of design. A rover at 90% maturity is close to complete, whereas a rover at 25% maturity is still in the stage of early concept design.

7.3. The Ideal Mission Planning Tool

The final development of this thesis culminated in the requirement definition. Requirements are a tool typically used within the context of systems engineering to identify core features organized hierarchically to achieve a goal. Requirement hierarchy refers to top level goals (usually termed Objectives) which feed into lower levels of requirements (Level 1, Level 2, Level 3, etc.) where the higher the number of the level, the lower the level. Lower levels of requirements describe the most detailed functionalities or features. Requirements involve a formal statement that goes like so, “Subject (shall/should) do/be (this capability).” The word “shall” denotes a requirement which is non-negotiable or absolutely necessary and “should” denotes a requirement which is desired but not necessary. (see Appx B and C for further detail)

Where most requirements start at the highest level as Objectives, the requirements for this Mission Planning Interface begin at a Level 2. The reason for this is because these requirements will likely be a part of a larger mission system and would draw from higher level requirements. The highest level MPI-L2 requirements include the four subsets shown in figure 61.

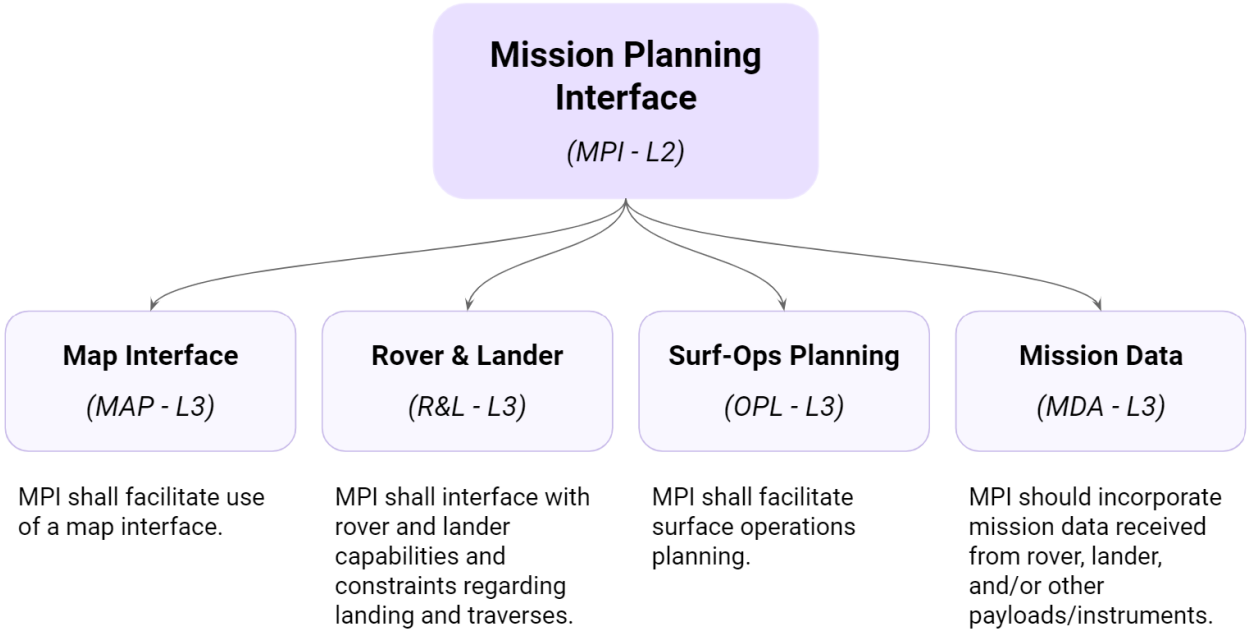


Figure 61. Mission Planning Interface requirement hierarchy. Own work.

Each of these four lower Level 3 requirements each contain their own defined requirements. All Level 3 requirements within each category include an ID, title, description, are prioritized as “shall” or “should”, are defined with a rationale with reasons for why each requirement is defined, and are tracked with notes. Any requirement which needs to be removed is crossed off with a date of removal and reason for removal.

8. Future Work

Ongoing Mission Work

Mission operations, responsible for some of the core mission design considerations such as the CONOPS, objectives, and constraints, needs to be a part of early mission development, even for smaller-scale micro-rover missions. There are of course several constraints for these and all missions such as not knowing what part of the Moon will be the mission target, not knowing the exact landing site. However, identifying core objectives and defining capabilities/constraints inform operations, which can iterate over time with development and new information. The operations in turn feed the rover design, which is critical for fast paced development timelines. The other two characteristics that should be considered when designing operations are the culture of the team and stakeholder expectations.

Improve Visual Interfaces

Regarding a mission planning interface, this research was limited by time and resources and resulted in partially developed prototypes. Future work in this context could take three approaches. The most basic level would be to take the capabilities and methodologies mentioned in this research, tune, pick and choose, and apply bare minimum to a mission. This would be most useful for missions with heavily limited budget, personnel, resources, and time. At a second level, a mission could begin with the requirements mentioned in Chpt 7, tune to their specific needs, capabilities, and constraints, and develop a software tool around that customization. The ideal approach would be to design a software tool configurable mission by mission, integrating instead core mission planning capabilities stemming from requirements noted as likely universal. This would allow a specific mission, especially a micro-rover mission with limited personnel and time, to use the software, analyze the environment, plan surface operations, organize information, and play around with rover design choices, allowing a team to weigh options to find the best system solution. Definitely no small task, but one which has not yet manifested anywhere within the space planning domain and could result in creatively explored mission design solutions that involve an experience of exploration.

Exploring Immersive Technologies

With rover, and remote operations in general, only growing with future missions, mission operation teams tools need to consider human experience. In this context, experience does not just refer to interface design, usability, or aesthetics, but instead the experience of human exploration. With rovers exploring a remote environment, human operators explore from Earth vicariously through their rovers. A more immersive human remote-experience environment could be incredibly meaningful for individuals during and before the surface mission, but also provide an environment to explore the data collected during operations for years after the fact, allowing operators to revisit the explored terrain and analyze layers of information and new insights into the future. A more immersive and tangible remote-exploration experience could also offer incredible scientific and operational advantage, with the potential to improve decision making and information analysis. Furthermore, this approach could also reach the community external to missions, the public, providing an environment to learn about space and operations and appreciate the exploration and planetary environment.

The design field has begun to expand within the mission operations context, but there is still room to grow. Future tools might include or improve upon immersive VR/AR pre-launch and operational planning allowing operators to move and explore in a virtual space with the capability to layer datasets, toggle and organize information, design operations diagrams and solutions, and collaborate with collaborating but dispersed teams. Newer and increasingly accessible technologies such as VR and AR mean that the memories and experiences humans create of a mission can move beyond a screen.

Understanding Missions

Finally, I would like to touch on my experience throughout this research. I am privileged and lucky to have had the opportunity to participate in one of the first university lead missions, a mission of many other firsts -- first rover to the south pole of the Moon, first autonomous micro-rover, first rover to profile lunar ice. This is an experience not available to many and for it, I am incredibly grateful. MoonRanger's mission was and is a very interdisciplinary effort, involving individuals of all backgrounds and levels of experience. I felt very at home with the project and my background as a designer and mathematician as well as my design approach to operations was welcomed, celebrated, and supported. The experiences I have with my background proved very useful during the development of my work and I feel gave me a unique perspective and advantage in many ways. Taking an embedded role, developing directly within the mission, was a continuation of Vertesi's work (2016 & 2020), but in a new context. This approach allowed for deeper and more complex analysis of visualization tools and their effect. Design research allowed me to produce and introduce new visualization concepts directly within the mission and with an embedded role, I was able to directly observe the culture and needs of a focus area directly.

9. Summary, Contributions, and Conclusion

9.1. Summary

This thesis investigates the role that visualization tools and methodologies can play within the development and operation of unprecedented rover space exploration missions. MoonRanger, an autonomous micro-rover bound for the lunar south pole in 2022 to explore for hydrogenous volatiles, serves as the specific context for the research. MoonRanger is first-of-class Commercial, Autonomous, Science (CAS) micro-rover. CAS rovers present vastly different capabilities and constraints in comparison to their predecessors. Their mission planning and operations are correspondingly unique. With an embedded position aboard MoonRanger this thesis researches what interactions, experiences, and mission operations approaches apply directly to this class of rover. The work is uniquely generated and calibrated from the unique perspective of researcher immersion as an active developer within the mission and bringing the power of visualization to that pursuit. Methods employ iterative system and prototype development, identifying gaps in functionality and addressing each with agility to make the case for an ideal planning tool. Results include a series of visualization-based methodologies and planning considerations for CAS micro rovers, deployed within the case study, MoonRanger.

Findings confirm visualizations play a critical role not only in mission planning, but for rover design itself and communication at large.

9.2. Contribution

Through the development of methodology for surface operations design, landing site selection criteria, environmental analysis, mission success criteria, and global planning, the work is directly significant to the space exploration field. The research sets precedence at a high level by contributing to the first commercial, autonomous, lunar polar micro-rover to explore for water-ice, resulting in methodologies that can be applied to similar missions of the near and long term future. Visualization mechanisms play a critical role in planning with the ability to communicate complex problemselts by layering, tailoring, prioritizing, and allowing interaction and immersion within a planning and decision making space. Insights regarding the effectiveness of these visualization tools suggest visualizations organically produce language within a planning environment, play a role in guiding planning conversation, and can directly influence the direction a mission may take.

Direct contributions are defined as follows:

- Language expressing distinctions of exploration for polar lunar ice
- Detailed surface operation scenario for MoonRanger mission
- Analysis resulting in determination of destination of MoonRanger's landing site
- Global planning pipeline for MoonRanger mission
- Methodology for waypoint definition of a CAS rover
- Scientific goals defined for completion of core scientific objective
- Importance of Viable Map for preliminary rover design
- Requirements for an ideal mission planning tool
- Visualization and interaction techniques necessary for mission planning

9.3. Conclusions

9.3.1. Visualization for Rover Space Exploration

Visualization technology is growing to include multidimensional capabilities of Augmented Reality (AR) and Virtual Reality (VR), leaving an opportunity to provide a deeply rich, insightful, and valuable exploration environment for remote-explorers. As rovers take the lead, always exploring extreme and far away environments before humans, the approach to mission operations needs to consider human experience as a mechanism for production of memories, curiosity, and meaning which could benefit the planning success for rover missions. Mission operations tools have progressed in functionality over the years, very few address the human factor of remote-exploration.

9.3.2. Visualization as Ultimate Space Mission Qualification

The highest unanticipated outcome of this experience is that the power of visualization is so significant that, done well, it is regarded internally and externally as the means to fulfill the goals and convey results and vision to the world. Qualifications for space missions are commonly presumed to be engineering, science, craft, testing, or management focussed. Although

necessary and universal, these are also common and, to some extent, pedestrian. When a similar approach of pure functionality is taken within the context of mission planning, human experience is lacking. In reality, human experience itself can result in functionality by providing a more tangible connection to an environment (Norris, 2016).

Any and all of these without visualization come up short in the rich and cross-disciplinary communication essential to success. Alternately, good visualization is worth a thousand data points or a million words. Done well, visualization can be the most powerful tool in the evolution, implementation, operation, and ultimately communication of a mission.

References

[1] Abercrombie, S. P., Menzies, A., Winter, A., Clausen, M., Duran, B., Jorritsma, M., Goddard, C., & Lidawer, A. (2017). OnSight: Multi-platform Visualization of the Surface of Mars. AGU Fall Meeting Abstracts, 11. http://adsabs.harvard.edu/abs/2017AGUFMED11C0134A

[2] Allan, M., Wong, U., Furlong, P. M., Rogg, A., McMichael, S., Welsh, T., Chen, I., Peters, S., Gerkey, B., Quigley, M., Shirley, M., Deans, M., Cannon, H., & Fong, T. (2019). Planetary Rover Simulation for Lunar Exploration Missions. 2019 IEEE Aerospace Conference, 1–19. https://doi.org/10.1109/AERO.2019.8741780

[3] Andrienko, G. L., & Andrienko, N. V. (2010). Interactive maps for visual data exploration: International Journal of Geographical Information Science: Vol 13, No 4. International Journal of Geographical Information Science, 13(4), 355–374.

[4] Arizona State University. (2020). QuickMap [Web]. https://quickmap.lroc.asu.edu/

[5] Brewer, J. D. (2000). Ethnography. McGraw-Hill Education (UK).

[6] Bussey, D. B. J., Spudis, P. D., & Robinson, M. S. (1999). Illumination conditions at the lunar South Pole. Geophysical Research Letters, 26(9), 1187–1190. https://doi.org/10.1029/1999GL900213

[7] Camera, Narrow Angle, LROC | National Air and Space Museum. (n.d.). Retrieved May 5, 2021, from https://airandspace.si.edu/collection-objects/camera-narrow-angle-lroc/nasm_A20160054000

[8] Cecchinato, M. E., Cox, A. L., & Bird, J. (2017). Always On(line)?: User Experience of Smartwatches and their Role within Multi-Device Ecologies. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, 3557–3568. https://doi.org/10.1145/3025453.3025538

[9] Colen, J. (2015, March 2). NASA's Ames Research Center [Text]. NASA. http://www.nasa.gov/ames

[10] Crawford, C. (1982). The Art of Computer Game Design. 89.

[11] DiBiase, D., MacEachren, A. M., Krygier, J. B., & Reeves, C. (1992). Animation and the Role of Map Design in Scientific Visualization. Cartography and Geographic Information Systems, 19(4), 201–214. https://doi.org/10.1559/152304092783721295

[12] Dunbar, B. (2019, November 18). Commercial Lunar Payload Services Overview [Text]. NASA. http://www.nasa.gov/content/commercial-lunar-payload-services-overview

[13] Earth and Planetary Remote Sensing Laboratory. (n.d.). PDS Geosciences Node, Washington University, St. Louis, Missouri. Pds-Geosciences Washington University in St. Louis. Retrieved May 3, 2021, from https://pds-geosciences.wustl.edu/

[14] Ellis, C., Adams, T. E., & Bochner, A. P. (2011). Autoethnography: An Overview. Forum : Qualitative Social Research, 12(1), n/a.

[15] Elphic, R. C. (2017). The Resource Prospector Neutron Spectrometer System: RP's Bloodhound. Annual NASA Exploration Science Forum (NESF).

[16] Elphic, R. C. (2020). MoonRanger Fraction Illumination [Lunar South Pole].

[17] Fisch, P. (2020). Thermal Modeling and Design of a Micro-Rover for Lunar Polar Exploration. International Symposium on Artificial Intelligence, Robotics and Automation in Space.

[18] Greicius, T. (2019, January 23). NASA's Opportunity Rover Logs 15 Years on Mars [Text]. NASA. http://www.nasa.gov/feature/jpl/nasas-opportunity-rover-logs-15-years-on-mars

[19] Hayne, P. O., Aharonson, O., & Schörghofer, N. (2021). Micro cold traps on the Moon. Nature Astronomy, 5(2), 169–175. https://doi.org/10.1038/s41550-020-1198-9

[20] Home | Astrobotic. (n.d.). Retrieved May 3, 2021, from https://www.astrobotic.com/

[21] Höök, K. (2010). Transferring qualities from horseback riding to design. Proceedings of the 6th Nordic Conference on Human-Computer Interaction Extending Boundaries - NordiCHI '10, 226. https://doi.org/10.1145/1868914.1868943

[22] Khera, N. (2020). MoonRanger Roving.

[23] Koenig, N., & Howard, A. (2004). Design and use paradigms for Gazebo, an open-source multi-robot simulator. 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (IEEE Cat. No.04CH37566), 3, 2149–2154 vol.3. https://doi.org/10.1109/IROS.2004.1389727

[24] Kumar, V. (2020). Formulation of Micro-Rover Autonomy Software for Lunar Exploration. International Symposium for Artificial Intelligence, Robotics and Automation in Space.

[25] Kuroda, V., Allard, M., Lewis, B., & Lindsay, M. (n.d.). Comm for Small Sats: The Lunar Atmosphere and Dust Environment Explorer (LADEE) Communications Subsystem. 11.

[26] Lakdawalla, E. (2008). Landing ellipses. The Planetary Society. https://www.planetary.org/articles/1425

[27] Lakdawalla, E. (2018). The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job. Springer.

[28] Lorenz, R. D., & Clarke, E. S. (2020). Influence of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) on the local atmospheric environment. Planetary and Space Science, 193, 105075. https://doi.org/10.1016/j.pss.2020.105075

[29] Lucero, A. (2018). Living Without a Mobile Phone: An Autoethnography. Proceedings of the 2018 Designing Interactive Systems Conference, 765–776. https://doi.org/10.1145/3196709.3196731

[30] Lucero, A., Desjardins, A., Neustaedter, C., Höök, K., Hassenzahl, M., & Cecchinato, M. E. (2019). A Sample of One: First-Person Research Methods in HCI. Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion, 385–388. https://doi.org/10.1145/3301019.3319996

[31] Lunar and Planetary Mapping and Modeling Project. (2017). Moon Trek [Web]. https://moontrek.jpl.nasa.gov

[32] Lunar Reconnaissance Orbiter. (n.d.). Lunar Reconnaissance Orbiter. Retrieved May 5, 2021, from https://lunar.gsfc.nasa.gov/

[33] Marirrodriga, C. G., Van Winnendael, M., & Putz, M. (1997). Micro-Rovers for Scientific Applications in Mars or Moon Missions. https://www.esa.int/esapub/pff/pffv7n2/garcv7n2.htm

[34] McCarthy, N. (2021). How The Cost Of Perseverance Compares To Other Mars Missions [Infographic]. Forbes. https://www.forbes.com/sites/niallmccarthy/2021/02/19/how-the-cost-of-perseverance-compares-to-other-mars-missions-infographic/

[35] Multilayer Insulation. (n.d.). Aerospace Fabrication & Materials. Retrieved May 5, 2021, from https://www.aerospacefab.com/product/mli/

[36] NASA JPL. (2003). Catalog Page for PIA04413. Photo Journal. https://photojournal.jpl.nasa.gov/catalog/PIA04413

[37] NASA JSFC. (n.d.). South Pole Landing Site LOLA DEMs. NASA Johnson Space Flight Center (JSFC). Retrieved May 3, 2021, from https://core2.gsfc.nasa.gov/PGDA/LOLA_5mpp/Haworth/

[38] NASA Mars. (n.d.). Mars Exploration Rovers Overview. Mars.Nasa.Gov. Retrieved April 29, 2021, from https://mars.nasa.gov/mer/mission/overview/

[39] NASA. (1969). APOLLO 11 ALDRIN. AP Images. http://www.apimages.com/metadata/Index/Associated-Press-International-News-In-Space-AP-/e0e37d0c13e4da11af9f0014c2589dfb/27/1

[40] Norris, J. (2016). Immersed on Mars. Dr. Jeff Norris. http://drjeffnorris.com/project/benefits-of-immersion

[41] Northon, K. (2019, July 1). NASA Selects 12 New Lunar Science, Technology Investigations [Text]. NASA. http://www.nasa.gov/press-release/nasa-selects-12-new-lunar-science-technology-investigations

[42] Orlova, A., Nogueira, R., & Chimenti, P. (2020). The Present and Future of the Space Sector: A Business Ecosystem Approach. Space Policy, 52, 101374. https://doi.org/10.1016/j.spacepol.2020.101374

[43] Pant, A. (2021). Space Technologies at California. https://stac.berkeley.edu/project/rover

[44] Potter, S. (2020, April 8). NASA Awards Contract to Deliver Science, Tech to Moon [Text]. NASA. http://www.nasa.gov/press-release/nasa-awards-contract-to-deliver-science-tech-to-moon-ahead-of-human-missions

[45] Robinson, M. S., Speyerer, E. J., Boyd, A., Waller, D., Wagner, R. V., & Burns, K. N. (2012). EXPLORING THE MOON WITH THE LUNAR RECONNAISSANCE ORBITER CAMERA. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIX-B4, 501–504. https://doi.org/10.5194/isprsarchives-XXXIX-B4-501-2012

[46] Rojanarata, T. (2020). How Online Whiteboard Promotes Students' Collaborative Skills in Laboratory Learning. Proceedings of the 2020 8th International Conference on Information and Education Technology, 68–72. https://doi.org/10.1145/3395245.3396433

[47] Samuelson, A. (2018, October 10). Mars Virtual Reality Software Wins NASA Award. NASA Jet Propulsion Laboratory (JPL). Retrieved May 1, 2021, from https://www.jpl.nasa.gov/news/mars-virtual-reality-software-wins-nasa-award

[48] Schell, J. (2008). The Art of Game Design: A book of lenses. CRC Press.

[49] Schorghofer, N., & Taylor, G. J. (2007). Subsurface migration of H2O at lunar cold traps. Journal of Geophysical Research: Planets, 112(E2). https://doi.org/10.1029/2006JE002779

[50] Schweitzer, L., Jamal, H., Jones, H., Wettergreen, D., & Whittaker, W. L. "Red." (2020). Micro Rover Mission for Measuring Lunar Polar Ice. IEEE Aerospace Conference.

[51] Shea, G. (2017, June 20). NASA Systems Engineering Handbook Revision 2 [Text]. NASA. http://www.nasa.gov/connect/ebooks/nasa-systems-engineering-handbook

[52] Shea, G. (2019, October 18). Appendix S: Concept of Operations Annotated Outline [Text]. NASA. http://www.nasa.gov/seh/appendix-s-concept-of-operations

[53] Siddiqi, A. A. (2000). Challenge to Apollo: The Soviet Union and the Space Race, 1945-1974. National Aeronautics and Space Administration, NASA History Division, Office of Policy and Plans.

[54] Siegler, M., Paige, D., Williams, J.-P., & Bills, B. (2015). Evolution of lunar polar ice stability. Icarus, 255, 78–87. https://doi.org/10.1016/j.icarus.2014.09.037

[55] Sinclair, D., & Dyer, J. (2013). Radiation effects and COTS parts in SmallSats. paper SSC13-IV-3.

[56] Smith, D. E. (2015). LRO-L-LOLA-4-GDR-V1.0, LDEM_80S_40M [Lunar South Pole]. NASA Goddard Space Flight Center, MD: Goddard Space Flight Center.

[57] Thompson, C. M., & Shure, L. (1995). Image Processing Toolbox: For Use with MATLAB. The Math Works.

[58] Tufte, E. (1983). The Visual Display of Quantitative Information.

[59] Tukey, J. W. (1977). Exploratory Data Analysis. Addison-Wesley Publishing Company.

Appendix A: Key Acronyms

This section defines any key acronyms used throughout the thesis document.

ANSYS	Analysis System
AR	Augmented Reality
ARC	Ames Research Center, NASA center
CAD	Computer Aided Design
CAS	Commercial, Autonomous, Science, missions
CD	Computational Design
CDR	Critical Design Review
CLPS	Commercial Lander Payload Services
CMU	Carnegie Mellon University
Co-I	Co-Investigator
CONOPS	Concept of Operations
COTS	Careful Off The Shelf Component
DTE	Down to Earth communication
EDA	Exploratory Data Analysis
HDRM	Hold Down Release Mechanism
IM	Map Interface 2 (thesis prototype)
IMU	Inertial Measurement Unit
iOBC	ISIS On Board Computer
JSFC	Johnson Space Flight Center
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LSITP	Lunar Surface Instrument and Technology Payloads
MC	Mission Control
MCS	Mission Control Software
MER	Mars Exploration Rover
MLI	Multi-Layer Insulation
MOP	Mission Operations
MPT	Mission Planning Tool (thesis prototype)
MR	MoonRanger
MT	Map Interface 1 (thesis prototype)
NAC	Narrow Angle Camera
NASA	National Aeronautics and Space Administration

NSS	Neutron Spectrometer System
OBJ	Objective
PDR	Preliminary Design Review
PI	Principal Investigator
PMI	Paper Mission Interface (thesis prototype)
PSR	Permanently Shadowed Region
RMTE	Rover Maximum Traverse Ellipse
RTG	Radioisotope Thermoelectric Generator
SIM	Simulation
SIR	System Integration Review
SO	Surface Operations (thesis prototype)
SOD	Surface Operations Diagram (thesis prototype)
SOG	Surface Ops Gantt (thesis prototype)
SRR	System Requirements Review
TLI	Trans Lunar Injection
TVAC	Thermal Vacuum (usually referring to testing)
VIPER	Volatiles Investigating Polar Exploration Rover
VR	Virtual Reality
VTM	Viable Traverse Map
WOI	Waypoint of Interest

Appendix B: Glossary / Key Terms

This section defines any key terms used throughout the thesis document.

Chassis
When referring to a rover, the main body structure, which usually houses internal components.

Commercial Lander Payload Services
An "initiative (which) allows rapid acquisition of lunar delivery services from American companies for payloads that advance capabilities for science, exploration or commercial development of the Moon." (Dunbar, 2019)

Concept of Operations (CONOPs)
A term describing all phases of a mission and the details of each phase as relevant to all subsystems; usually presented in order of occurrence; phases could include integration, launch, transit, land, deploy, surface operations, post processing, and analysis. (Shea, 2019)

Critical Design Review (CDR)
One of a series of NASA standard reviews a mission must pass. These reviews involve a mission team presenting work to a board of NASA reviewers who formally evaluate the mission progress. CDR reviews are heavily centered around mission requirements and the steps taken to satisfy these or progress the mission in a direction which will. Reviews can sometimes last more than one day. MoonRanger's CDR was two days long, 5 hours of presentation on each day. The committee submits feedback and Requests for Action (RFAs) following the presentation which the mission team is required to address and resolve.

Environmental testing for Space
Environmental testing refers to a series of tests which make sure an instrument will survive all expected environments experienced to enter or exist in space. These include testing vibration, shock, radiation, thermal, and vacuum, among others.

Hydrogenous Volatiles
"The MoonRanger rover will host a NSS, developed by NASA ARC. The NSS measures changes in the leakage flux of low energy neutrons out of the regolith. Soil with hydrogen content results in reduced leakage fluxes of neutrons within a 0.5 eV to 500 keV energy range, as these neutrons are thermalized by the hydrogen. Leakage flux of thermal neutrons can either increase or decrease depending on the abundance of hydrogen and the depth at which hydrogen exists. The NSS is able to detect both thermal and epithermal neutrons via two helium-3 gas proportional counters. One is covered in cadmium and detects only epithermal neutrons above ~0.5 eV and the other, which is uncovered, detects both thermal (<0.5 eV) and epithermal neutrons (>0.5 eV). When a neutron enters the detector tube it interacts with the helium-3 and electrons are produced [9]. These produced electrons are drawn towards an anode wire in the detector, which is held at a high voltage, and are amplified in the process. The number of electrons produced initially and those as a result of this amplification, is proportional to the

energy of the two ions produced in the nuclear reaction. The total charge is converted to a step voltage output by a charge-sensitive amplifier and then shaped to a unipolar waveform by a shaper amplifier. The area of the shaped waveform is then measured. A histogram then is constructed to record the count rate for various neutron energy levels. This histogram for each detector is the primary output of the system. Aboard the MoonRanger rover, the NSS will detect and profile hydrogen content within the upper meter of the lunar surface." (Schweitzer, 2020)

Ice Stability at Depth
Refers to the depth at which lunar environmental conditions are conducive to stable ice.

Landing Error Ellipse
Landers plan to land at exact coordinates but may be off. This error ellipse provides a radius around a goal landing site which defines how much error a lander expects during landing.

Lunar Reconnaissance Orbiter
"The Lunar Reconnaissance Orbiter is a NASA robotic spacecraft currently orbiting the Moon in an eccentric polar mapping orbit. LRO data is essential for planning NASA's future human and robotic missions to the Moon." (Lunar Reconnaissance Orbiter, n.d.)

Lunar Surface Instrument and Technology Payloads
A call put out by NASA in search of rovers, surface instruments, or technology to fund and send to the Moon's surface for commercial research and exploration.

Multi Layer Insulation (MLI)
"Multilayer Insulation (MLI) blankets provide passive thermal control to a variety of spacecraft, launch vehicles, and instruments in vacuum. They work by limiting the amount of radiative heat transfer through multiple layers of thin reflectors and spacer materials." (Multilayer Insulation, n.d.)

Narrow Angle Camera
"The Narrow Angle Camera (NAC) from the Lunar Reconnaissance Orbiter (LRO) is a CCD camera attached to a powerful telescope with a 700mm focal length. It can take black and white images of the Moon with a resolution of less than a meter. This flight spare instrument is identical to the flown instrument built by Malin Space Science Systems. NASA transferred the camera to the Museum in 2016." (Camera, Narrow Angle, n.d.)

Near-teleoperation
Operations which occur in as real time as possible but are limited by factors such as latency (the lag between Earth and lander communication) or by autonomous rovers, which cannot necessarily be teleoperated as directly as non-autonomous rovers.

Neutron Spectrometer System
Science instrument carried aboard MR rover.

Payload
In the context of space exploration missions, an instrument, rover, or object carried aboard another instrument/rover/lander into space.

Permanently Shadowed Region
Regions of the lunar poles which receive no light at all. This occurs because the sunlight which hits the lunar poles is so low elevation all year round that any dips in terrain, such as valleys or crater floors, never see the light. These regions are especially cold and could harbor lunar ice.

Position Estimation
The act of determining the location of an object within a space from images and sometimes other data such as orientation (from an IMU).

Requirements
A list of hierarchical goals and objectives which define functionality for a mission and rover.

Solar Influx Angle
The angle of the sun with respect to an object or body.

Speed made good
Average speed of a rover over total distance traveled.

Waypoint of Interest (WOI)
Term defined through mission planning for MoonRanger. Refers to a location with possible surface ice or stable ice within 1 m of the lunar surface. Must be along a traverse with an average bearing of + or - 20 deg of the sun azimuth, average slopes not exceeding 10 deg, and within 500 m of a lander location.

Appendix C: Supplementary Material

Stakeholder Roles

Stakeholder	**Role**
SpaceX	Rocket launching lander and payloads to space
NASA CLPS/LSITP	Responsible for overseeing lander and payload development on the collective mission between all
Masten	Lander for MoonRanger and seven other payloads
Payloads	Seven other instruments also aboard the same lander as MoonRanger rover
Astrobotic	Key actor on MoonRanger contract
CMU	Responsible for MoonRanger rover and mission design and development
NASA Ames	Responsible for science instrument (NSS) development

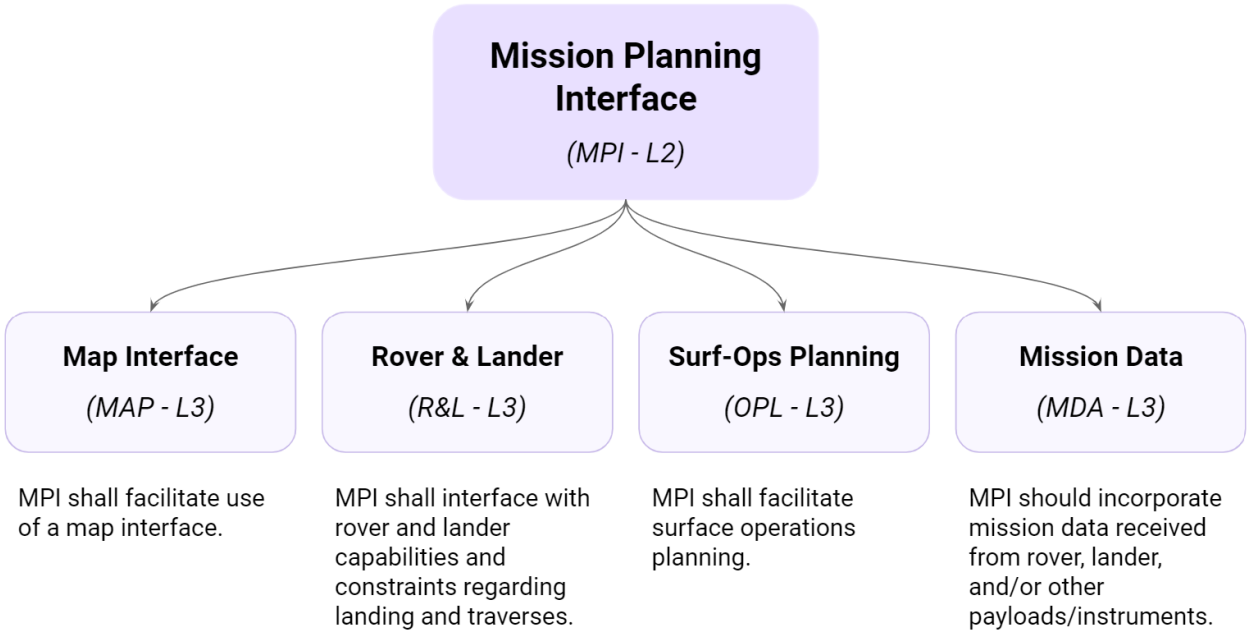
Prototype Interactions

	NASA CLPS/LSITP	Masten	Payloads	Astrobotic	CMU	NASA Ames
MT	Asynchronous Remote review			Asynchronous Remote review	Synchronous In-person worksession	Synchronous Remote worksession/review
PMI					Synchronous remote	
SO (surface ops spreadsheet)	Asynchronous Remote review	Synchronous Remote review/worksession	Asynchronous Remote review	Asynchronous Remote review	Synchronous Remote worksession/review	Synchronous Remote worksession/review
SOD (surface ops diagram)	Asynchronous Remote review	Asynchronous Remote review	Asynchronous Remote review	synchronous/ Asynchronous remote/in-person review/worksession	synchronous/ Asynchronous remote/in-person worksession/review	Asynchronous Remote review
SOG	Asynchronous Remote review			Asynchronous Remote review	Synchronous Remote worksession	

IM	Asynchronous Remote review	Asynchronous Remote review	Asynchronous Remote review	Asynchronous Remote review	synchronous/ Asynchronous Remote review	synchronous/ Asynchronous Remote worksession
MPT					Synchronous Remote review	Synchronous Remote review

Global Planning Requirements

Requirements (see App. B), are a term generally used within the systems engineering context of a mission. Because a mission is likely already equipped with a set of requirements, starting from an Objective (OBJ) level and feeding into Level 1, Level 2, etc. requirements, these Global Planning requirements begin at a Level 2. This is because they are meant to live within an existing set of mission requirements. The requirement hierarchy of these Global Planning requirements is shown below.



Each set of requirements is defined with a **Title** and acronym **ID**. The **Priority** is either shall, referring to a requirement which must be put in place, or should, which denotes a requirement which is desired but not essential. If the requirement contains no information marked as To Be Determined (TBD) or To Be Revised (TBR), its **Status** is OK. Each associated **Description** includes a requirement statement, referencing the priority of the requirement and articulating its purpose and intention. All children requirements include reference to their **Parent**. Child requirements also include a **Verification Method**, which is either test, inspection, demonstration, or analysis, indicating which approach is used to confirm the correct implementation of the requirement once complete.

MPI Level 2 Requirements

Mission Planning Interface (MPI)				
ID	Title	Priority	Status	Description
MPI-1	Map Interface	Shall	OK	MPI shall facilitate use of a map interface.
MPI-2	Rover & Lander	Shall	OK	MPI shall interface with rover and lander capabilities and constraints regarding landing and traverses.
MPI-3	Surface Ops Planning	Shall	OK	MPI shall facilitate surface operations planning.
MPI-4	Mission Data	Should	OK	MPI should incorporate mission data received from rover, lander, and/or other payloads/instruments.

MAP Level 3 Requirements

Map Interface (MAP)						
ID	Title	Priority	Status	Description	Verification Method	Parent
MAP-01	Layer Toggle	Shall	OK	The Map Interface shall facilitate toggling between baseline maps	Demonstration	MPI-1
MAP-02	Global View	Should	OK	The Map Interface should exhibit a global view	Inspection	MPI-1
MAP-03	Local View	Shall	OK	The Map Interface shall exhibit a local view of the landing site	Inspection	MPI-1
MAP-04	Opacity Adjustment	Shall	OK	The Map Interface shall allow opacity adjustment between baseline maps	Demonstration	MPI-1
MAP-05	Viability	Shall	OK	The Map Interface shall facilitate the construction of viable maps for rover traversal analysis	Demonstration	MPI-1
MAP-06	Layer Order	Should	OK	The Map Interface should allow layers to be ordered by the user.	Demonstration	MPI-1
MAP-07	Multiple Maps	Shall	OK	The Map Interface shall allow for the display and interaction with multiple maps and/or datasets.	Demonstration	MPI-1
MAP-08	Merit Map	Should	OK	The Map Interface should provide a merit map, or a way of evaluating the value of a planned traverse. This could indicate a value score for mobility, science return, power survivability, thermal survivability, etc.	Demonstration	MPI-1

R&L Level 3 Requirements

Rover & Lander (R&L)						
ID	Title	Priority	Status	Description	Verification Method	Parent
R&L-01	Landing Error Ellipse	Shall	OK	The MPI shall display the landing error ellipse	Inspection	MPI-2
R&L-02	Rover Max Traverse Ellipse	Shall	OK	The MPI shall display the rover's maximum traverse ellipse	Inspection	MPI-2
R&L-03	Operations Traverse Limit	Should	OK	The MPI should display all other operations traverse limits	Demonstration	MPI-2

OPL Level 3 Requirements

Surface Operations Planning (OPL)						
ID	Title	Priority	Status	Description	Verification Method	Parent
OPL-01	Waypoint Planning	Shall	OK	The MPI shall facilitate waypoint planning	Demonstration	MPI-3
OPL-02	Regions of Significance	Should	OK	The MPI should facilitate definition of regions of interest	Demonstration	MPI-3
OPL-03	Path	Shall	OK	The MPI shall interface with rover paths	Demonstration	MPI-3
OPL-04	Communication to Earth	Should	OK	The MPI should exhibit communication to Earth windows	Inspection	MPI-3
OPL-05	Mission Time Sweep	Should	OK	The MPI should facilitate a sweep through mission time	Demonstration	MPI-3

MDA Level 3 Requirements

Mission Data (MDA)						
ID	Title	Priority	Status	Description	Verification Method	Parent
MDA-01	Rover executed Path	Should	OK	The MPI should display the rover's executed path	Demonstration	MPI-4
MDA-02	Science Data Collection	Should	OK	The MPI should interface with science data collection during surface operations	Demonstration	MPI-4
MDA-03	Communication Status	Should	OK	The MPI should display communication status	Inspection	MPI-4
MDA-04	Rover coordinates	Shall	OK	The MPI shall display the rover-post-trek coordinates	Demonstration	MPI-4