Lunar instrument data integration into the Virtual Reality Mission Simulation System for Decision Communication and Situational Awareness

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In situ resource utilization (ISRU) technologies are a key advancement required to enable a sustained human presence on the Moon and Mars. NASA's upcoming Volatiles Investigating Polar Exploration Rover (VIPER) mission to the Moon will provide crucial correlations between volatiles and the lunar geology and environment to characterize these resources as potential reserves for future ISRU on the Moon. VIPER, slated to launch in 2023, will require the coordination of multi-disciplinary teams across the country making real time operational decisions based on rover instrument data. The virtual reality Mission Simulation System (vMSS) is a virtual reality platform designed at MIT by the Resource Exploration and Science of our Cosmic Environment (RESOURCE) team to provide teams with a collaboration interface for similar future planetary missions which will increasingly rely on real-time tactical operations. Herein we determine the integration pathway for analog based datasets that are case studies of VIPER's two main instruments, the near-infrared volatile spectrometer subsystem (NIRVSS) and the neutron spectrometer subsystem (NSS), into vMSS to provide the most valuable visualization tools. Focusing on improving situational awareness, decision making and reducing task load as well as incorporating comments from scientists and engineers working previous analogs and on the current VIPER mission, we recommend the most critical elements to implement into vMSS and the best approaches for data visualization. We present a review of relevant analogs and state of the art mission software. We have developed a design concept and path to flight of analysed instrument data integrated with data maps that allow for virtual manipulation and annotation between non-co-located team members which can be applicable to multiple future planetary missions. We focus on pre-mission mapping of *a priori* data for improved situational awareness, layering of analysed instrument data, correlative mapping and interactive capabilities for in-mission decision making, as well as archiving and annotation tools for post-mission analysis. Finally, we lay out the roadmap for the future development of immersive sample site visualization capabilities and the use of integrated instrument data in vMSS with automated temporal and geospatial planning.

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Nomenclature

AR = augmented reality
BASALT = biological analog science associated with lava terrains
EVA = extravehicular activity
ISRU = in situ resource utilization
IVA = intravehicular activity
MCC = mission control centre
MSC = mission support centre
MVP = Mojave volatiles prospector
NIRVSS = near-infrared and visible spectrometry system
NSS = neutron spectrometry system
RESOURCE = resource exploration and science of our cosmic environment
SSERVI = solar system exploration research Virtual Institute
SSR = science support room
VIPER = volatiles investigating polar exploration rover
vMSS = virtual mission simulation system
VR = virtual reality

I. Introduction

The future of space exploration requires a paradigm shift. Mission complexity is increasing and with the advent of heavy lift launch capabilities and an increased cadence of funded lunar orbital and surface missions, mission frequency can expect to gain momentum as well. In order to ensure we are achieving the most science possible within these missions, human-computer interaction must take a front-seat in mission planning. By treating machines as collaboration tools, we can improve cross-discipline communication, improve real-time decision-making processes, reduce task loads and provide flexibility in both temporal and spatial planning. Science and exploration missions in particular will stand to benefit given the specificity of the knowledge required to make decisions around geological and environmental data. Providing naturalistic visualisation tools in which multiple team members can analyse, discuss and interpret real-time data, has the potential to improve the scientific return on both rover prospecting missions, and later human exploration missions.

The Resource Exploration and Science of our Cosmic Environment (RESOURCE) team, funded by NASA's SSERVI (Solar System Exploration Research Virtual Institute) addresses in-situ resource utilization (ISRU) needs through a structured program directly linking science and exploration. The goal of RESOURCE is to characterize potential resources on SSERVI Target Bodies through scientific investigation and develop corresponding technologies and concepts of operations to enable resource exploration and ISRU. The MIT-led component of RESOURCE focuses on the optimization of the robotic and human interactions for missions to prospect for resources and conduct lunar ISRU as well as future crewed missions to planetary surfaces.

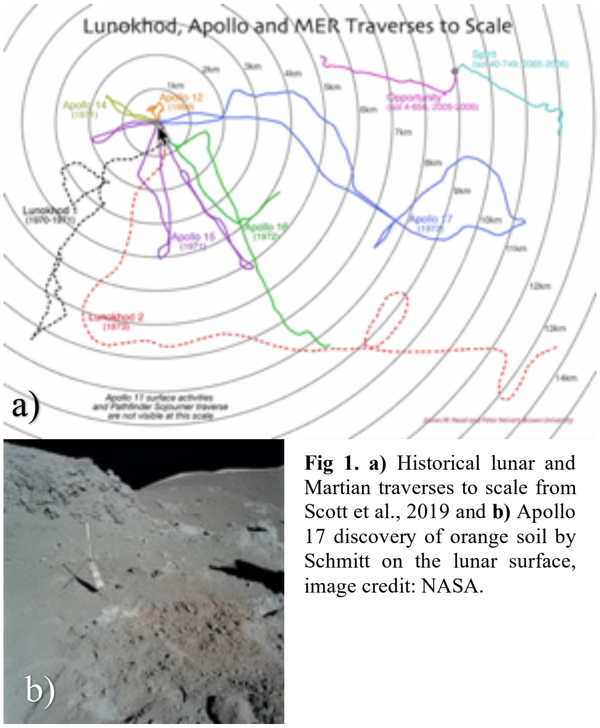

Fig 1. a) Historical lunar and Martian traverses to scale from Scott et al., 2019 and **b)** Apollo 17 discovery of orange soil by Schmitt on the lunar surface, image credit: NASA.

Lunar field explorations during the Apollo missions provided some of the first understanding of lunar geology and history as well as early identification of resources that will be critical in establishing a permanent presence on the Moon[1]. Based on historical ground-based exploration missions, it is clear that traverses can be expected to increase in length and complexity over time, exemplified by the increase from the <1 km Apollo 11 traverse to the Apollo 17 traverse of 35 km (Fig. 1[2]). Because of the greater distances that we can expect to cover, we need to be able to have the flexibility to stop, change direction and look more closely at unexpected discoveries. Field geology relies not only on extensive pre-trip traverse planning, using all available mapping and sensing data, but must also be prepared for unforeseen discoveries that necessitate quick decisions based on observational data and deductions of relationships between rock units and instrument data that may impact the entire planned traverse[1], for example the discovery of orange soil during Apollo 17[3] (Fig. 1). During the Apollo missions, this required astronauts to be trained in geological field work and to be able to easily communicate in-field findings to the Mission Control Center (MCC) and allow the Science Support Room (SSR) to alter objectives in real-time and rapidly reprioritize and communicate changes to the astronauts[2]. From the astronaut side, the identification of points of interest and need for rapid decision making would sometimes result in challenging communications with MCC and from a SSR perspective, rapid changes in scheduling without a full view of the impact to operations would result in an astronaut having nothing to do, a loss in science return potential.

Historically, exploration missions have their console positions set up such that the mission operations team is separate from the SSR team. Logistically, this allows for the SSR team to focus on detailed analyses to advise the operations team potential new points of interest while the operations team can focus on the execution of the traverse. However, this physical separation can challenge communication of priorities and may become a detriment to maximizing science return. More efficient communication methods are needed to ensure this next phase of exploration provides every advantage to scientific exploration. We propose a virtual reality simulation system (vMSS) to provide visualisation tools that can drive real-time science analysis of instrument data in easily digestible displays to allow monitoring of the rover traverse by the science analysis team, and rapid communication of recommendations to the operations team in a collaborative environment.

A. Virtual Reality for decision making and communication

Due to both the dramatic increase in power and resolution of commercially available systems as well as the significant decrease in price of these systems the use of virtual reality (VR) systems in industry and academic contexts for research, design and training have demonstrated a broad applicability of the platforms[4]. In particular, VR has proven useful for storytelling, abstract data visualisation and multi-modal communication across disciplines; three key components of lunar rover missions. Among the industries which have begun to use VR in practice is the aerospace industry for the design decision making process, including Boeing and Lockheed Martin. NASA has also been using VR systems for astronaut training at the Virtual Reality Training Lab (VRL) at the NASA Johnson Space Center (JSC) for decades[5].

In order to have effective VR platforms for such complex use cases as space exploration, it is critical for the VR support staff to understand the goals of the mission to support decision making as well as to design for decision support and enable efficient decision communication. Designing a platform using a naturalistic decision making framework, as described by Klein (2008)[6], emphasizes the role of experience to enable a user to rapidly evaluate a situation under difficult conditions and plan quickly without losing plan quality[6]. VR can be used as a recognition-primed decision making tool by displaying complex instrument data in a recognizable format allowing for intuitive assessments and thus decreasing the time required to make actionable decisions[7]. Examples of this capability will be described in Section IV.

Decision-making capabilities are also enabled by improving situational awareness (SA). SA, as described by Endsley (1995)[8], encompasses three levels: 1) perception of elements in the current situation, 2) comprehension of the current situation and 3) projection of the future status. The 3D immersive nature of VR, when designed correctly, can enhance these three levels of SA feeding into improved decision making. For example, providing prominent cues in the VR environment to draw attention to salient data points would aid in guiding which components of the environment would be initially attended to, forming the first level of SA[8].

From a VR framework standpoint, the development requires the design team to work closely with both scientist and mission controllers to fully understand mission requirements before proceeding. This follows the recognition-planning model approach[7]. Additionally, the system needs to be flexible and adaptable such that any changing demands of the mission can be incorporated into the system to provide real-time support. Finally research has shown that VR is most comfortably used in <1 hour increments [4], thus the in-mission use cases need to be tailored to specific decision checkpoints or on-demand scenarios.

VR and augmented reality (AR) systems have already shown their potential in space robotics analogs missions[9–11], such as the CanMoon field campaign, a lunar sample return analogue mission on the volcanic island of Lanzarote, Spain, in the Canary Island group in 2019[10]. From this analog activity the CanMoon team determined that VR proved to be an ‘incredibly advantageous tool for orientation and interpretation of the terrain’. Preliminary work in the Biological Analog Science Associated with Lava Terrains (BASALT) field campaign, discussed in detail below, also provided guiding insight into AR during EVA. Along with NASA's VRL, and industry use, these early tests provide support for further exploration of VR use for future exploration class missions.

B. VIPER analog missions

Our primary design use case is for analog based datasets that are examples of instrument data onboard the Volatiles Investigating Polar Exploration Rover (VIPER) mission slated for launch in 2023. VIPER uses onboard instruments to detect the presence of volatiles in lunar regolith both during traverses and at depth during drilling. The rover also provides contextual images of the surface including multi-colour spectral imaging for landform identification, porosity, and ice classification. VIPER's onboard instruments include the near-infrared visible spectrometry system (NIRVSS), the neutron spectrometer system (NSS), the mass spectrometer observing lunar operations (MSolo) and the regolith and ice drill for exploring new terrains (TRIDENT). Here we focus on NIRVSS and NSS for which two key analog missions have provided analog telemetry, in-mission analysis methodology and post-mission practices. These are the Mojave Volatiles Prospecting (MVP), which included NIRVSS and NSS and the BASALT mission, which included NIRVSS

The MVP mission was a science-driven field program completed in 2016 focusing on characterizing the form and distribution of lunar volatiles in a lunar mission analog[12]. The mission was conducted at the Ames Science Operations Center (ASOC) at Moffett Field and the Mojave Remote Operations Center (MROC) at the field site. The mission tested the lunar prospecting instruments[13,14] and the concepts of operations required for a successful campaign (Heldmann et al. 2016). The MVP mission provided an assessment of real-time telemetry, traverse planning, operational management, rover operations, instrument configuration management, telemetry flow and traverse plan execution. Complementary to MVP was its precursor Hawaii field campaign in 2012[14].

The BASALT mission was conducted at Hawaii Volcanoes National Park in the Kīlauea and Mauna Loa active volcanoes. The field campaign was completed in November of 2017. Both science and operational elements were studied during the BASALT field campaign, providing results for NIRVSS as well as recommendations for improvements for operational tools[15–17]. The BASALT mission included examination of EVA and IVA procedures along with the mission operations protocols.

We review the software capabilities used on these analog missions (including xGDS, Playbook, holoSEXTANT and Minerva), data analysis techniques, visualization capabilities and uses through the campaigns and the recommendations made for improving cross-team decision communication and situational awareness. We then expand on additional available tools examining additional NASA analog tools and mapping capabilities, such as Lunaserv, a Web Map Service implementation of lunar orbiter data, MoonTrek, part of NASA's Lunar Mapping and Modelling Portal (LMMP), and the Lunar Orbital Data Explorer (LODE)[18]. Using these state-of-the-art tools, the recommendations from the previous analog missions and current recommendations from the VIPER science and mission control teams, we provide a summary of the key elements necessary for a virtual mission simulation system to provide naturalistic data visualisation for improved decision communication capabilities. Given the volatility of new software and technology, we outline a path to flight for the platform to ensure a reliable and effective design.

II. Onboard Instruments

We focus on the NIRVSS and NSS onboard instruments since these are used in MVP, BASALT and planned for VIPER. Additionally, the spectrometry data is visually complex, requiring in-depth knowledge of the instrument functionality to understand, make and communicate real-time decisions based on the graphical representations. A brief summary of the instruments and the necessary comprehension for mission decision making is presented.

A. Near-infrared and visible spectrometry system (NIRVSS)

NIRVSS measures the reflectance spectrum of the lunar regolith using a blackbody lamp to illuminate a view field via a fiber optic cable. A secondary fiber returns the reflected light to a spectrometer which measures the difference between the two spectra. NIRVSS measures spectra between 1.6-3.4 microns, meaning it is sensitive to minerology and volatiles, in particular water, which has diagnostic bands at 1.9 and 3.0 microns. Increasing water content appears as a decrease in reflectance, or a dip in the band depth, as is seen in Fig. 2a. Spectra is taken every 0.5 – 1.0 seconds along a traverse and can also be captured for a depth profile during drilling. The raw spectra are normalized to a reference spectrum for a dry material or known, flat surface. The ratio of the dry spectra to the live spectrum shows water band 'dips'. Measuring an increase in these 'dips' in reflectance demonstrates increasing water content[13].

Raw spectra are first received by the NIRVSS database. This is plotted on the user interface (UI). The saved reference spectrum is passed from the interface to the database and a ratio spectrum is calculated using the spectral calibration. The calibrated spectrum and the ratio spectrum are passed to the UI at which point the user can define the band depth and slope parameters (parameters controlling the band depth measurement). From this the database can calculate band depths and slopes which are plotted with time on the UI and passed to the map server to be plotted along the traverse path, as shown in Fig. 2a.

NIRVSS also provides images of the rover's traverse path. Black and white images are taken every 5-10 s during a traverse and returned as png files, and the drill observation camera multi-spectral png images (peak wavelengths: 410, 540, 640, 740, 905, 940, 1050, and a white broadband LED[19]) are taken every 5 m and may be combined as jpeg files. Every 50 m a panorama is taken generating stereo digital elevation models at each waypoint. The images can have up to 2048 x 2048-pixel resolution but are taken at lower resolution during a traverse due to band width limitations. Image stitching and real-time display were not part of the analog missions.

B. Neutron spectrometry system (NSS)

Galactic cosmic radiation is the continuous, low level, background radiation from sources outside of our solar system. These rays are continuously interacting with the lunar surface. When a cosmic ray strikes the lunar surface, the interaction generates neutrons from the nuclei of the regolith's component particles. The generated neutron flux is moderated by striking hydrogen atoms. Measuring the neutron flux, it is then possible to calculate the abundance of hydrogen on the lunar surface, thus inferring the presence of water[20]. The neutron detectors are sensitive to concentrations of hydrogen in the upper 1 m of the surface. NSS measures neutron albedo at both thermal and epithermal energies. The neutron counts are shown as a function of time in the UI both in a line graph format and with respect to geological location, Fig. 2b. Using the neutron flux in combination with knowledge of the associated surface's albedo and insular properties, neutron flux predictions can then be made of surrounding surfaces. Because neutron flux indicates presence of hydrogen, it is important to understand then that this could represent hydrogen, hydroxyl or water. Without knowing whether the regolith has a uniform geochemistry or its bulk material density, the NSS data needs to be combined with NIRVSS as well as a priori data to provide a more complete picture of the possible regolith water content[21,22].

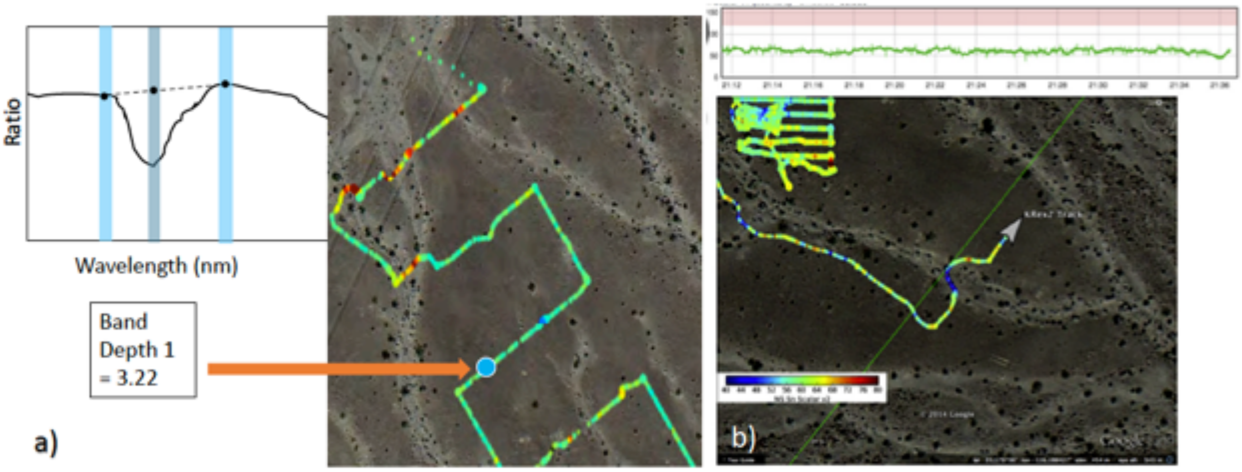

Figure 2. a) Near-infrared and visible spectrometry system data from the Mojave Volatiles Prospecting mission (Heldmann et al., 2016) showing band depth data at a point along a rover traverse, ratio of raw reflectance to reference spectra versus wavelength. **B)** Ground Data System (xGDS) strip chart showing neutron counts as a function of time as detected by the neutron spectrometry system with corresponding raster map showing neutron counts as a function of geographic location.

III. Current software and tool review

First, we will review the software that was used for our two analog missions, MVP and BASALT, followed by the available mapping technologies from NASA that could be used for future lunar resource missions. We highlight user issues and challenges during the field campaigns as well as recommendations made for improving software and operations.

A. The Mojave Volatiles Prospecting (MVP) analog mission

MVP used the Exploration Ground Data System (xGDS) operations software and the Playbook timelining and scheduling software. The xGDS web-based software was developed by NASA to support rapid scientific decision making by synchronizing time and mapped locations of instrument data, observation notes, photos, videos, samples and other data[23–25]. It has been used for multiple NASA Science Operations, including the NASA Extreme Environment Mission Operations (NEEMO), the Pavillion Lake Research Project (PLRP), NASA's RESOLVE rover (ISRU) field tests in Hawaii, NASA's Desert Research and Technology Studies (DRATS) field campaigns[9], and MVP. Table 1 highlights key features of xGDS. Because of the variation in mission goals, onboard instruments and scientific needs, the xGDS software was adapted for each mission. The interface design process followed three stages: (1) a data import stage, converting data from the native format delivered by the field assets into a common format for storage and archiving, (2) a data storage and management stage, taking outputs from stage (1) and archiving the data products and metadata into a database for later use and (3) the web-based data application, providing a web-based search and exploration tool for science and operations teams to access archived data and support analysis [26].

During the MVP mission, xGDS supported four phases of operation: (1) planning, (2) monitoring, (3) archiving, and (4) exploring[12]. The xGDS associated lessons learned from the MVP field campaign are listed in Table 2, highlighting functionality that was critical to the mission and areas that required improvement. Included in these is the future work recommended by the developers and science team working on the map server tools for VIPER.

The Playbook software was a scheduling and planning interface for exploration[27,28]. Like xGDS, it was customized for each mission and provided a web viewer interface that was a separate software tool. Playbook served as a central location for crew to access plan and procedure data and allowed communications with the rest of the team. Playbook provided visual timelines of all activities happening in parallel with the ability to edit schedules, reschedule activities, and provide live updating, or, when not possible, to notify the user that information is out of date. The software allowed for embedded procedures to increase crew efficiency providing procedures and supporting documentation. Although our main goal in this work is not for temporal planning, but is focused on geospatial planning, it is important to consider the link between them.

Table 1: List of key features and their descriptions of the xGDS system.

Feature	Description
Mapping	Can annotate maps
	Raster maps and data - GeoTIFF map data can be imported and viewed as multi-resolution maps
	External Tile Link - can link to maps on external WMS servers
Tracking	Able to collect, manipulate and display vehicle position and track imported GPS data
Planning	The Plan Editor lets users create traverse plans interactively on a map, updating distance, duration and timeline displays in real-time
Instrument Data and Plots	Collects and manages discrete instrument data products, continuously streaming data
	Provides summary information for basic plots for real-time analysis
	Raw data is available for download
Images and Annotation	Manages still images from camera and video capture
	Immage annotation can be turned or or off
Sampling	Can organize metadata about samples, numbers, labels, etc.
Search and Navigation	Post-mission analysis: can explore collected data by day, see summary information and search through based on multiple criteria. Results can be displayed in tabular or map view

B. The Biological Analog Science Associated with Lava Terrains (BASALT) analog mission

The BASALT analog mission used an EVA traverse tool that handled path planning optimization that specially accommodates for the constraints and walking rates of suited crew members walking over natural terrain[29,30], the Surface Exploration Traverse Analysis and Navigation Tool (SEXTANT). This tool allowed for realistic simulations of traverses for training and planning purposes as well as to give astronauts more autonomy on EVA for real-time re-planning[29]. Using lunar orbital elevation maps, SEXTANT planned the most efficient traverse for an astronaut or rover between designated waypoints, along with an emergency return path from the current location. Path efficiency was based on traverse distance, time, and energy consumption requirements, including considerations for solar exposure and shaded regions. The 3D path, obstacles and waypoints were then displayed on an interactive interface, holoSEXTANT. SEXTANT was initially designed for astronaut EVA but had been extended to include multi-vehicle lunar operations[31]. These software tools provided route planning solutions between two points on a map by accounting for the slope information contained within the digital elevation model. During the 2017 BASALT field campaign, holoSEXTANT was deployed as a proof-of-concept augmented reality (AR) system. Additional capabilities during the field campaign included surface-based 360-degree imagery which were processed into panoramas and presented using commercial off-the-shelf Gigapan software; surface-based LiDAR data was processed and combined with multispectral data into 3D terrain models to test real-time zoomed-in mapping capabilities for traverse planning/re-planning; BASALT-OnSight. This was a mixed reality immersive terrain environment custom built by NASA JPL Operations Lab based on the Mars Curiosity Rover OnSight technology and provided 3D terrain models using the HoloLens and JPL and COTS photogrammetry software[17]. Combined, these tools provided terrain familiarization for the EVA crew prior to the campaign, as well as a virtual telepresence for the intravehicular activity (IVA) crew and the mission support centre (MSC) during the campaign.

The overarching software used in BASALT, Minerva, was composed of xGDS, Playbook and SEXTANT. Combining the three tools provided a single interface for geospatial and temporal planning, timeline management, communication management, and science operations management. The Science team used xGDS and SEXTANT for EVA planning, data collection and review as well as for traverse optimization and EVA timelines. The MSC used Playbook for activity scheduling. The Mission Log was used by all members as a communications interface and archiving tool, including for image sharing.

Table 2 highlights lessons learned from the BASALT mission relevant to the vMSS development, in particular focusing on decision-making and situational awareness for instrument data visualization[15–17].

C. Mapping future lunar resource missions

As is exhibited by the analog experiences, missions require a full suite of tools to provide comprehensive decision-making, communication and analysis tools. Following the recommendations of mission planners, we have reviewed several additional available planning and mapping tools in order to assess viability for integration with vMSS as well as to incorporate key design features available in these platforms.

Given one of the primary goals of vMSS is to provide data visualisation, we need to first be able to provide a priori mapping of the lunar surface with the capability of visualising orbital data. Lunaserv[32], the Lunar Orbital Data Explorer (LODE)[33], QuickMap[34], JMoon[35], and MoonTrek[36] are some of the web-based databases of lunar orbital data. These are web map service implementations, with API accessible data downloads. LODE, QuickMap, and MoonTrek provide user interfaces for data exploration, while the Lunaserv database is accessible from GIS programs. Additional functionality is available in MoonTrek and QuickMap, including distance and elevation profile calculations of traverse paths, and surface sun angle calculations.

A priori data maps in VR can provide situational awareness for pre-mission planning, allowing for easier traverse planning, as well as acting as a story telling tool to select landing sites, science stations and drill sites, enhancing cross-team communication. The orbiter data available on these sites will also provide decision-making capabilities. For instance, knowledge of the albedo of a surface combined with orbital neutron spectrometry data can provide preliminary information about the location of high concentrations of hydrogen or water[20,21] feeding into the users first stage of SA[8] and thus providing a basis recognition-primed decision making[7].

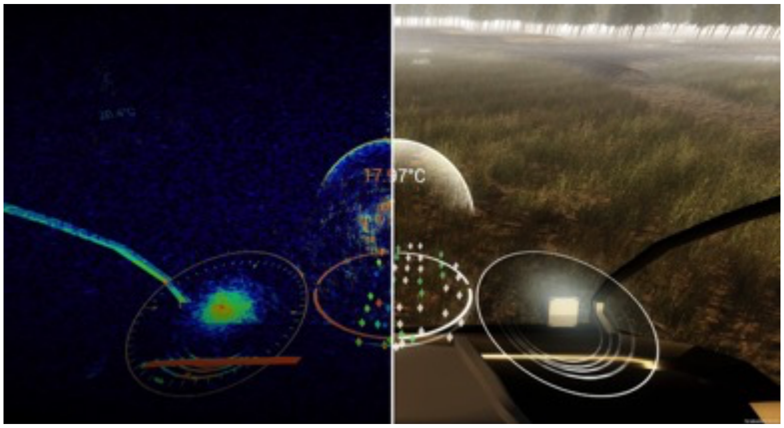

Figure 3. Dopplemarsh data displays in which Different virtual "lenses" highlight various aspects of the sensory world in Dopplemarsh, photo and description from Mayton et la., 2017.

Given the focus of this work on data visualisation, we will also be collaborating with the MIT Media Lab to enable naturalistic displays. Building on work from the MIT Media Lab's Dopplemarsh project[37,38] which integrates real-time data from an environmental sensor network with real-time audio streams and other media from a physical wetland landscape, Fig. 3. They provide data visualisation which does not require more than a top-level understanding of the rendering to interpret, translating sensory information into easily consumable displays.

Table 2. Compilation of key features and recommendations from MVP, BASALT and science specialists from RESOURCE, VIPER, MVP, BASALT, MoonTrek, xGDS and USGS (analog analysis team). Italicised features were features already included and noted as significantly enhancing on the NASA Exploration Analog and Mission Development assessment rating scale in Beaton et al., 2020.

Category	**Software**	**Desired Feature**
Annotation	Playbook	Note-taking with rich media
	xGDS	*Annotatable via integrated, geolocated and time-stamped digital notes*
	HoloSEXTANT	*Use of AR for terrain navigation and annotation were significantly enhancing*
	HoloSEXTANT	Allow ability to virtually translate to other sample/saved locations
	HoloSEXTANT	Incorporate ability to annotate targets of interest within terrain environment (editable, zoomable and draggable)
	HoloSEXTANT	Automatic time-stamping of all scientific data products
	HoloSEXTANT	Searchable data products associated with location of interest
	Overall	Have all instrument data immediately transmitted to xGDS and saved and made accessible - seamlessly broadcast all instrument data
	Overall	Provide pertinent tagging on scientific data products for useful archiving and real-time integration (xGDS used person to tag photos)
	Overall	Reduce task load on IVs - easier note-taking and note-searching capabilities
	Overall	Include voice-to-text transcriptions
Communication	Playbook	multi-media communication (image and video)
	HoloSEXTANT	Need to allow all crew members to work together as a tactical team
	HoloSEXTANT	Allow EV, IV and MSC to be co-located (VR)
	Overall	Software shares and automatically integrates scientific data and information in real-time to allow for concurrent, varied scientific interpretation
Planning	Playbook	Rescheduling support and impacts
	Playbook	Include temporal tracking (currently done by hand for activitiy completion)
	xGDS	Ability to assign activities on traverse path (not just waypoints)
	HoloSEXTANT	*Include overlays of maps for specific science objectives*
	HoloSEXTANT	Improve user interface to include features to help plan and execute EVAs
	HoloSEXTANT	Create a 'super' model with layers of pre-collected data and precursor missions into a geospatially co-registered terrain model
	HoloSEXTANT	Turn on and off data layers
	HoloSEXTANT	Full geospatial and temporal synchronization
	HoloSEXTANT	Add EV traverses, candidate sample locations and hyperlinks to high resolution imagery and instrument data
	HoloSEXTANT	Add ability to measure distance, elevation and heading within maps
	HoloSEXTANT	Add temporal information
	Overall	Temporal and spatial planning integration to support real-time traverse re-planning
	Overall	EVA execution monitoring based on activity progress
	Overall	Include display of current position of rover, completed activities, time remaining on traverse, samples remaining for collection
Situational Awareness	HoloSEXTANT	Increased resolution of 360 degree imagery for sample selection
	HoloSEXTANT	*Verbal descriptions and high resolution contextual close-up images during EVA were significantly enhancing*
	HoloSEXTANT	*VR training and terrain familiarization were significantly enhancing*
	HoloSEXTANT	*Use of LiDAR to enhance 360 stitched panoramas aided in discerning depth and size - significantly enhancing pre-mission for situational awareness*
	HoloSEXTANT	Need DEMs well in advance to ingest informaiton
	HoloSEXTANT	Need to integrate incoming data from the field into the terrain model in real-time
	HoloSEXTANT	Integrate incoming field data to enhance SA
	HoloSEXTANT	Include photogrammetry, thermal data, multispectral, LiDAR, communication coverage maps, surface conditions, known hazards and keep-out zones (slope)
	HoloSEXTANT	Transition between user perspective and birds eye view
	HoloSEXTANT	High resolution panomarma at sample extraction locations
Software	xGDS	Simplified code architecture
	xGDS	Automatitically synchronize with other tools

IV. The virtual reality mission simulation system

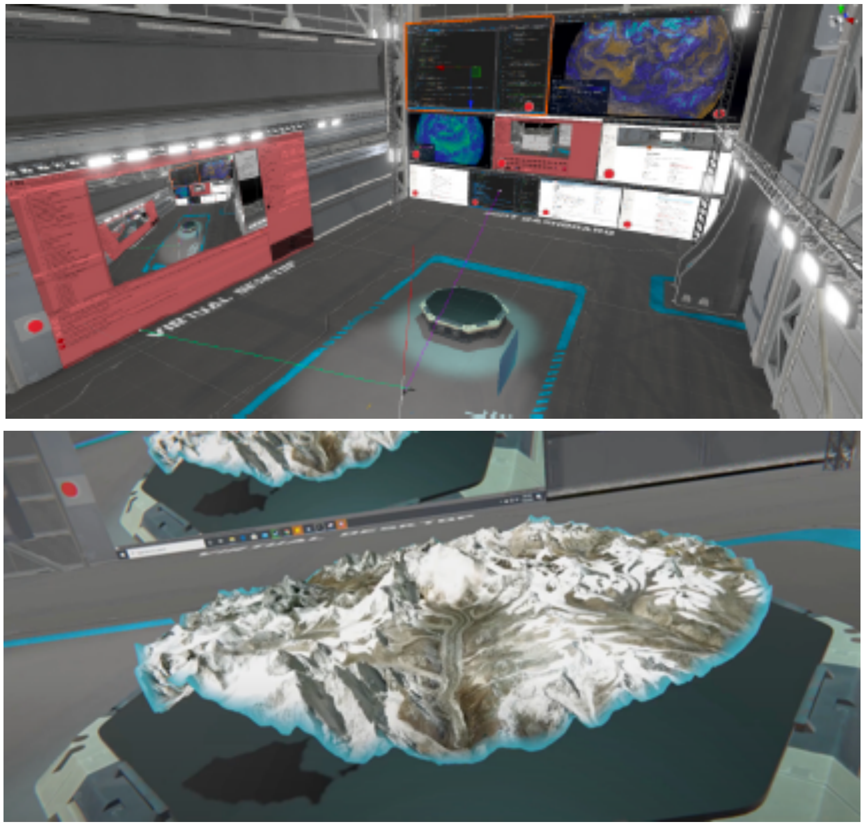

Figure 4. a) vMSS architecture showing central spatial console, virtual desktop (left) and joint dashboard (upper right) and **b)** geo-loader on central console with mountain map displayed.

Using the lessons learned from these precursor analog missions, along with recommendations from the analog mission science teams and the VIPER mission specialists, we propose the following VR platform for use in future lunar rover exploration missions. We focus specifically on ISRU and science missions with NIRVSS and NSS type payloads for this first application, however the methodology used will be applicable for various instrument payloads for future science missions. The platform design considers pre-mission planning and storyboarding, real-time mission decision-making and situational awareness and post-mission data analysis.

A. Baseline platform

The vMSS, initially the virtual mission control center (vMCC), was developed by E. Anandapadmanaban[39] supervised by Dr. Newman at MIT as a VR framework for augmenting mission control operations. vMSS was developed as a hardware agnostic platform in order to accommodate the rapidly advancing hardware capabilities as well as to allow users with varying levels of hardware to use the platform. vMSS was initially developed and tested on the HTC Vive Pro SteamVR headset on the Unity Game Engine and C# but has recently been adapted and migrated to the Occulus Quest (Ward et al., ICES 2021). The Vive is a desktop-dependent head mounted device (HMD), while the Quest is a stand-alone, economical device. The transition was intended to ensure that the platform could provide equally valuable visualisations in a more readily accessible device. This will allow for more users to engage within the platform and will also create a more mobile interface by using a standalone hardware.

The platform, Fig. 4, consists of a central spatial console in which users can pull up 3D data to annotate, discuss and analyse. The spatial console has three data viewer modules: (1) the model-loader, for static, pre-generated models (ex: tools, maps, vehicles) and allows for scaling manipulation of the models, (2) the geo-loader which uses DEM and satellite imagery to automatically create 3D models of terrains with panning and zooming functionality as well as minor annotation capabilities (waypoints, flags) and (3) the data-loader which loads 2D charts from raw data with the ability to view multiple charts simultaneously for comparative analyses. vMSS also includes a virtual desktop, visible only to the individual user, and a joint dashboard on which users can share their displays for all users to view simultaneously. The current platform provides a strong foundation on which to develop our instrument data visualisation capabilities. The geo-loader, however, is only currently capable of displaying maps in the Earth-coordinate reference system.

B. Critical design features for data visualization

Based on the recommendations and lessons learned in Table 2, we have compiled a list of key features to be included in the vMSS development for instrument data visualisation, Table 3. These have been subdivided into two point-of-view (POV) displays. The first is a birds eye view map display (Overview Map) which will enable traverse

Table 3. Summary of key features for vMSS onboard instrument data display integration based on MVP, BASALT and science team recommendations.

Category	Key Features
Software	Synchronize with xGDS, Playbook, Lunaserv, LODE, MoonTrek
	Simplified Architecture for flexible development
Overview Map	Annotatable: via integrated, geolocated and time-stamped digital notes. Include multi-media (images and video and voice-to-text) associating incoming data automatically.
	Scrollable through traverse path accessing data, image projections and notes in real-time
	Selectable data layers overlain on base-layer DEM
	Display instrument data overlayed onto selected map layers in real-time including drill site depth profile data (.csv file formats)
	Traverse planning/re-planning: ability to draw traverse, calculate elevation, distance and sun angle. Display no-go regions with new traverse paths.
	Display real-time execution of traverse path: rover model displays current location, completed vs. planned traverse, completed waypoints/activities (data availble with scrolling function), planned waypoints.
	Toolbox options: including flashlight, highlighting tool, annotation tools, traverse planning tools
	Real-time sensor displays (ex: thermal)
Ground View	Real-time projection of traverse imagery (stitched)
	Real-time layering option of multi-spectral imagery overlaid onto traverse base layer
	Waypoint panorama image display capability.
	Annotatable: via integrated, geolocated and time-stamped digital notes including voice-to-text notes
	Archiving: ability to scroll through imagery via map display or searching for specific waypoints

planning, monitoring and annotation, layering of a priori data and an overview display of rendered instrument data. The user interface will allow for annotation and caching of waypoint data for easy post-mission access. Using web-based storage will ease interaction between vMSS and other planning tools. The second POV will be an immersive ground-based view (Ground View). This will make use of the NIRVSS imagery, stitching the continuous real-time images of the rover's traverse and allowing for layering of multi-colour images and integration of panoramas at waypoints. Images in the ground view will be associated with the map view traverse paths, waypoints and science stations, such that users can jump to previous imagery by selecting points on the map view or scrolling along the traverse path.

Respecting design usability heuristics[40], we focus on matching the system to real world expectations, using recognition rather than recall and allowing for flexibility and efficiency of use with naturalistic affordances. Given our real-world view of what the lunar surface should look like, we can represent the a priori DEM as a gray-scale surface, Fig. 5a. Adding altimetry, we can provide visible layering of the surface to indicate variation in height, Fig. 5b. Intensity of blue, naturally associated with water, will represent regions where orbital data indicate expected water

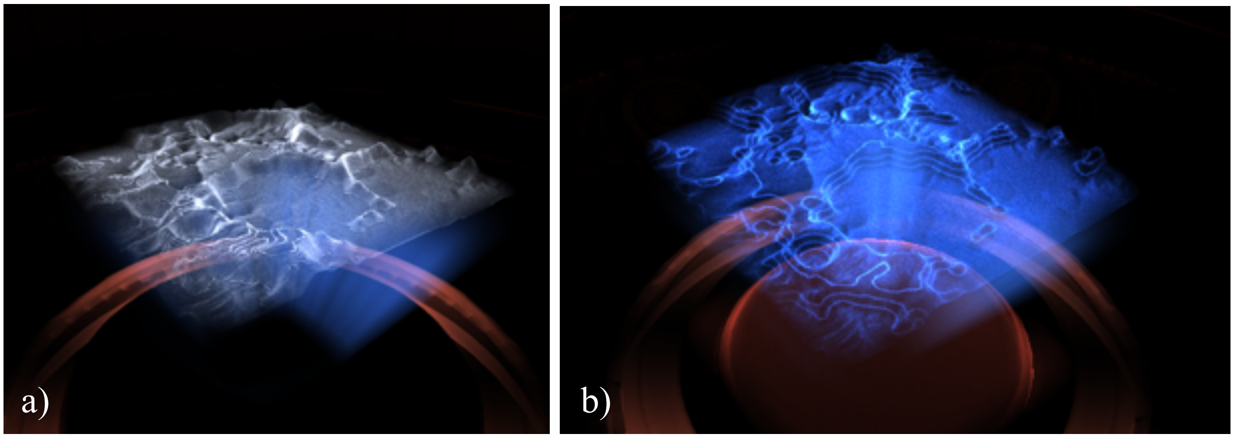

Figure 5. a) Greyscale map view of lunar crater with translucence to indicate orbital data and **b)** visible layering of surface indicating variation in height.

content. Increasing the opacity of the map then will indicate instrument-measured water content, given our expectation that solidity of a surface indicates realness. Pre-planned traverse paths, science stations and drill locations will follow accepted norms for mapping (dashed lines indicate planned traverse, solid indicating completed, etc.). Users will be provided the option of drawing/editing a traverse path, adding waypoints and annotation. The MoonTrek capabilities will allow for the traverse path to be re-planned, providing elevation, and distance as well as no-go regions where slope exceeds rover capabilities. Surface sun angle can be displayed in real-time using light and shadow on the surface. A flashlight tool will be provided to the user to facilitate identification of slope, surface texture and obstacles. By incorporating these capabilities into this multi-user platform, team situational awareness will be enhanced by allowing both the science and operations teams to view decision-critical data collaboratively[8].

The ground view will be visualized from a cockpit-like setting to provide situational awareness to the user of the location of the real-time images being displayed. We use the cockpit display to reduce the effects of motion-sickness often felt with moving displays[37]. Additionally, given the difficulty reported by Apollo astronauts in assessing distance on the lunar surface[1], having a cockpit as a size reference frame and overlayed depth data will enhance geological science return. The focused view of the surface images will allow scientists to more easily assess local geological formations, and correlate data from multi-colour imagery to areas of interest.

At each stage in the VR platform development process NASA's Exploration Analog and Mission Development (EAMD) rating scales will be used for capability, acceptability and simulation quality. These rating scales were developed by the NASA EAMD team at NASA JSC and have been used to develop, refine and evaluate human factors, human performance and ConOps for spaceflight and exploration-class missions[9,15,17,18,41–49].

IV. Path to Flight

The current vMSS platform is assessed as a technology readiness level (TRL) 2 (technology concept and/or application formulated). Our goal is to achieve a TRL 6 (system/subsystem model or prototype demonstration in a relevant environment) with an aim for flight via NASA's continued lunar flight opportunities (CLPS and Payloads and Research Investigations on the Surface of the Moon (PRISM) lunar investigations). Below we present our path to flight.

A. vMSS software development

Working with the current software and data available from MVP and BASALT, we plan to integrate the discussed capabilities into the vMSS platform as follows:

1. Enable lunar reference system
2. Access Lunaserv/LODE data and MoonTrek capabilities
3. Implement MoonTrek elevation, distance and sun angle calculation capabilities
4. Immersive POV projection: stitching images and adding annotation capabilities
5. Add mapping annotation capabilities: enable communication with NASA tools (xGDS, Playbook, etc.)
6. Add 'toolbelt', ex: flashlight
7. Add correlative capabilities across multiple datasets across datasets.

The development will continue on the Unity Game Engine; however, we will upgrade from the current 2019.4.11f1 version to the most recent version of Unity. We will also use the HD Pipeline which will allow for the integration of ArcGIS Maps SDK for Unity. This will ease the use of the Lunaserv content enabling vMSS with GIS capabilities.

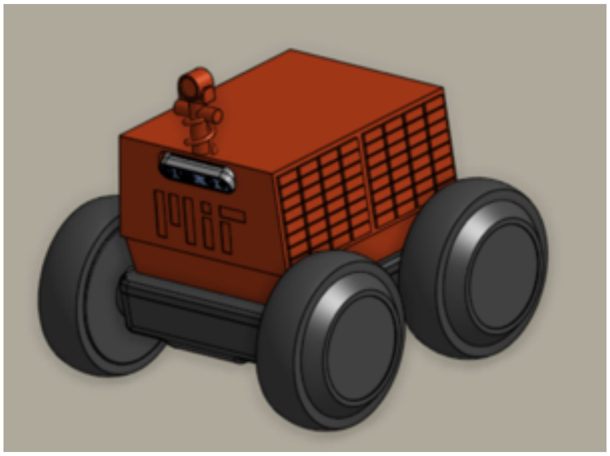

Figure 6: Rover Robotics mini rover design for on-site rover testing, 62 cm x 39 cm x 25.4 cm.

B. On-site rover testing

Preliminary assessment of the vMSS software capabilities will be done using a test rover which will be developed in collaboration with the MIT Media Lab Operations. The rover will be enabled with imaging representative of a VIPER-like rover, Fig. 6. Instrument data transmission will be simulated using assigned MVP NIRVSS traverse data. Initial ConOps will be developed by assessing temporal reduction in decision checkpoints and determining in-mission use-cases for the VR platform by having users complete mission-based tasks with and without the use of VR. This will include an assessment of the ease of communicating decisions to the operations team. The NASA EAMD rating scales will be used to assess the capability, acceptability and simulation quality of the VR platform. Bandwidths, displays and functionality will be assessed for their technical capabilities and address user interface development issues.

C. In-field rover testing

The in-field component of the testing will be comprised of three stages of testing: (1) pre-mission planning, (2) real-time traverse and science station usage and (3) post-mission analysis. This phase of the development will focus on the usability and mission-enhancing capabilities of the software and will build on the on-site rover testing using the in-mission use-cases determined. The first stage will ask mission developers from NASA, JPL and the RESOURCE teams to assess the different a priori visualization capabilities of the software, testing the platform as a story-boarding tool and a tool to provide crew with situational awareness exploring the planned traverse paths. The second stage will require a similar assessment to the on-site rover testing but will instead focus on enhancing decision-making capabilities by reducing task load, to be assessed by the NASA Task Load Index (NASA-TLX). We will also assess improvements in cross-team communication and interpretation of instrument data. The final stage will ask scientists to follow post-mission analysis processes using the VR platform, examining ease of access to stored data, usefulness of visualization capabilities in data analysis and the extensibility of the software.

D. Use cases: CLPS and VIPER

We have focused primarily on the VIPER-analog use-case due to the availability of analog instrument data from the MVP and BASALT missions, however, there are other near-term missions to which this platform has great applicability. Many of the upcoming Commercial Lunar Payload Services (CLPS) missions will require similar planning and real-time assessment tools to which vMSS would be well suited. With this in mind, we will develop the software in a flexible manner which will allow for the implementation of a diverse set of onboard instrument displays and modalities. This can be done by focusing on web-based inputs, using existing display tools, such as ArcGIS Maps for SDK, and keeping a simple display architecture.

V. Conclusion

Establishing a permanent human presence on the Moon and providing a staging ground for Mars will require key ISRU missions, like VIPER, to lay the groundwork. These foundational exploration missions will need to maximize science and exploration return and to do this will need flexible mission planning, and thus optimized communication between operations and science teams. RESOURCE is building capabilities for future lunar exploration missions that will enable human-robotic interactions not only for near-term ISRU missions but eventually for human exploration missions as well. The vMSS platform will enhance decision making capabilities, reduce workload and improve communication pathways needed for these missions. Expanding beyond VR, vMSS can later be adapted for AR to extend these tools to human exploration missions, allowing EVA, IVA and MCC crews to collaborate from the most remote workspaces.

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