Lunar science real-time operations and mission systems integration definitions and practices from NASA's VIPER mission

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Abstract

Mission system design for the National Aeronautics and Space Administration (NASA) Volatiles Investigating Polar Exploration Rover (VIPER) mission began with focusing on building key components including a solar-powered rover and the ground data system for operating it on the Moon for 100-Earth-days. The VIPER mission would be designed to support teams of people on Earth and a robot on the Moon carrying out a scientifically planned search for water ice, over a distance of 20 km. Initially, within the mission system design the involvement of VIPER's science team (VST) was noted as "the science customer" - a designation and acknowledgement of a key workgroup in the mission. The VST's work support needs, for a science work system, however, had not yet been defined by the VST in terms of systems and architecture. As the VST's Science Operations team conducted research to develop a science operations system and architecture for VIPER's science mission activities they found the science system needs for supporting real-time lunar science were greater than that which was designated in the mission system for the science customer. They decided to focus on developing the science operations system via ongoing integration rather than establishing a separate science component that later would be adjoined to the mission system. VIPER Science Operations enacted integration as an ongoing work practice; integration was a carried out as a regular activity that required schedule and agenda planning to be carried out on a daily and weekly basis, and adjustments in accordance with other workgroups' activities. The work of integrating requires including and maintaining a greater number of considerations in the short-term work plan such as scheduling and product considerations (e.g., goals, interface features, networks, workspace build, mission simulations) and human relationships. In the long-term, ongoing integration approach can yield benefits that include fewer system conflicts, which can be avoided by learning of conflicts during development when they can be addressed. In addition to lunar science operations development and training with the VIPER Science team, integration included working with VIPER Mission system's operating software workgroup, as well as the workgroups for rover drivers, planning and timelining, mission systems engineering, testing and training, and mission workspace preparation. This paper shows the work of integration as a process during the pre-surface operations development stage and highlights some examples of mission enhancing decisions that resulted from this integrated approach.

Keywords: science operations, mission operations, tele-operated rover, lunar mission, systems integration

Acronyms/Abbreviations

Ames Research Center (ARC)
Ground Data System (GDS)
Johnson Space Center (JSC)
Kennedy Space Center (KSC)
Mass Spectrometer observing lunar operations (MSolo)
Mission System (MS)
Mission Operations Center (MOC)
Mission Operations System (MOS)
Mission Science Center (MSC)
Multi-Mission Operations Center (MMOC)
National Aeronautics and Space Administration (NASA)
Near InfraRed Volatiles Spectrometer System (NIRVSS)
Neutron Spectrometer System (NSS)
The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT)

1. Introduction

Conducting science with a tele-operated multi-instrument-equipped rover on the Moon is a space exploration activity that is the subject of development across many projects and organizations including the National Aeronautics and Space Administration (NASA). One of NASA's recent projects is the Volatiles Investigating Polar Exploration Rover (VIPER) mission.

The VIPER mission is designed for 100-days (four lunar days) of nominal surface operations during which its rover would be tele-operated to drive along a traverse planned in the Moon's south pole region [1,2,3]. Each lunar day (twenty-eight Earth days) the solar-powered robot would operate for fourteen-days in sunlight and would be dormant for fourteen-days in darkness. Mission activities during the fourteen-days of sunlight include driving the rover and using instruments onboard to identify and characterize the distribution of water ice and other volatiles across a range of thermal environments, within a traverse planned for 20 km in the Moon's south pole region (landing site: Mons Mouton [4]).

VIPER's multiple instruments include tools that are science-specific and tools that enable rover driving and science investigations. The instrument suite is comprised of the Mass Spectrometer observing lunar operations (MSolo), the Near InfraRed Volatiles Spectrometer System (NIRVSS), the Neutron Spectrometer System (NSS), and The Regolith and Ice Drill for Exploration of New Terrains (TRIDENT) [5]. Technologies such as the rover's four wheels, eight cameras, and "headlights" support rover driving while also factoring into scientists' abilities to investigate the lunar terrain.

Conducting and coordinating the work of tele-operating a rover in near-real time and carrying out mission science activities requires a robust mission system. VIPER's mission system (MS) is defined [6] as "the combined mission operations system (MOS) and ground data system (GDS). The MOS is the team, operational products and processes needed to operate the mission. The GDS is the hardware, software and facilities used by the MOS to operate the spacecraft." Two key communication conditions that the MS must support, see figure 1, are: 1) the short round-trip communication time – about 6 to 10 seconds – that that elapses from when information is sent from Earth to the Moon and responding information is received on Earth; and 2) on Earth there are multiple workgroups at three NASA Centers – Ames Research Center (ARC), Johnson Space Center (JSC), and Kennedy Space Center (KSC) – that need to be supported and across which there is no discernible time delay for human communication. Figure 1 also shows a representation of the rover's traverse path prepared by VIPER Science [7,8,9] is shown as a blue line with repeating small blue circles and three larger orange circles marked with three drill sites (A, B, C). Each of the small blue circles represents a point at which the rover's drive team sends it a command for its next actions. As the rover is driven, its instruments are operational (except for the TRIDENT drill) and sending data to Earth. At each drill site, the rover is positioned for a period of time during which TRIDENT and other instruments are used to examine the lunar subsurface.

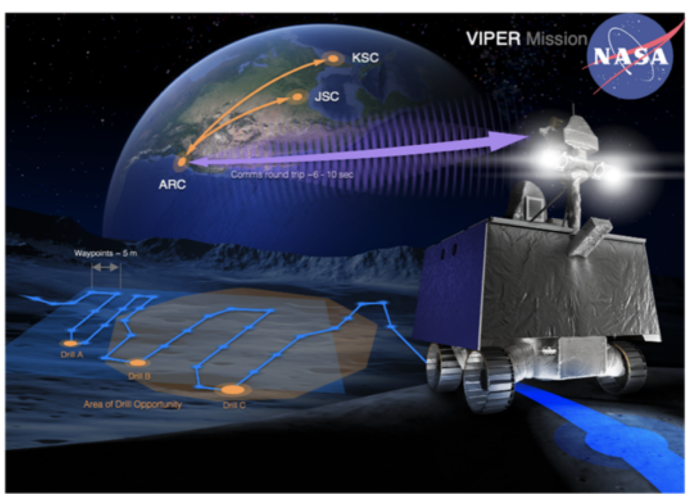

Fig. 1. Some of the VIPER mission's system details.

2. Adjoining mission and science operations systems through early integration

The MS design phase preceded the start of the design of the science system, and for mission activities known as those that would involve VIPER's Science team there was a designation for "the science customer." This designation, a user-profile, was in use prior to being fleshed out with respect to the actual VIPER Science Team (VST) members and how they would conduct remote lunar science. In late fall 2019, the VST's Science Operations workgroup was initiated, and they were responsible for creating a science operations system to be adjoined to the MOS.

As the VIPER Science Operations team conducted research to develop the system and architecture design for VIPER Science [9,10,11] they found that the science work system needs for supporting real-time lunar science were greater than that which were designated for the science customer. With MOS and GDS already developing, Science needed to work against assumptions that the science operations systems could be developed independently and later added to the key systems (MOS and GDS). They discerned that pursuing a traditional integration path could yield an operational outcome, i.e., science mission activities would be enabled. However, considered within the context of a space mission timeline, which requires prescribed periods for development and refinement up to locking down the system (no more changes allowed), this integration approach could lead to conflicts for which there would be little time to address or to plan and make adjustments. To address this issue, they decided to begin integration work with the key MS workgroups while they worked on developing science operations system.

Thusly, VIPER Science Operations enacted integration as an ongoing work practice from the initial design stage. Integration was approached as a regular activity that would need to be included and scheduled in their work timeline, carried out on a daily and weekly basis, and routinely adjusted in accordance with other workgroups' activities. The work of actively integrating required significant time and communication. The resulting integrated mission and science system for VIPER shows the benefit of the early integration approach. One example draws from tools whose development was coordinated with the MOS team – the Open Mission Control Tool (OpenMCT) provided time series data displays and real-time maps of data collected by the rover that enabled multiple workgroups across the MS to simultaneously receive data from the rover and view it with software that supported identification of regions of interest for drill sites and data correlations between different instruments (see Lees et. al. [12] for this discussion). Another example, described in this paper, is seen in the development of the work system by which VIPER's rover drivers interact with the science team in real-time during surface operations.

By February 2023, when VIPER Mission Systems began their Integrated Simulations, VIPER Science was not only an integrated work system within mission operations system but was also tightly coupled with communication infrastructure and software architectures.

3. Science operations integration work practices

VIPER Science Operations began designing and developing the science operations system within the existing mission system. Their methods were based in social science (work ethnography and applied research) [7] and expert knowledge in work systems for remote operations in extreme environments [9,13,14]. The workgroup size was small (2 - 4) and included disciplinary expertise in (listed alphabetically) biology, chemistry, computer, instrument, planetary and social sciences.

3.1. Integration as a re-occurring activity constantly subject to assessment

To consider the fit of their science system design as it developed with the MS plan [1,6] while the MS was also in development, they increased their workload by identifying, requesting, and participating in MOS and GDS meetings. The objectives were to learn how the systems were defined, build relationships with the workgroups, provide science objectives and VST context, and continue to be informed on development of task directions and accomplishments. Identifying mission workgroups' tasks and timelines was followed by contacting and requesting admittance to meetings.

Even with existing membership on the VIPER mission, as within any culture, Science Operations workgroup members needed to learn and follow the sub-cultural aspects for each workgroup in order to gain and maintain ongoing inclusion. Examples of these aspects include conversation turn-taking habits (Do people speak when something comes up that they can speak to or is there a hierarchy to who speaks in what order?), acceptability of interrupting (Is it acceptable to interrupt?), and requests to address information gaps (Should these be made when the needs arises, at the end of the meeting, or in a follow-up communication?).

The Science Operations group size was large enough to allow them to continue participating in VIPER Science work sessions and meetings and to add activities (e.g., meetings, informal conversations) that required coordinating separation as a team and re-connecting to exchange information. A successful VIPER MS was the shared goal across all workgroups. Sustaining a regular presence allowed for a growing knowledge base on MOS and GDS, including relations existed (in terms of infrastructure) to support VIPER Science, and what existed but was not extended to support VIPER Science. With consistent participation and respect for the existing manner in which workgroups were conducting their work, relationships developed that allowed for a gradual decrease in the work of identifying and gaining access.

Actively integrating required continuous assessment because it was a not pre-planned activity (i.e., it was not an assigned task for any workgroup in the early stages). An integration activity with another workgroup could be established and function well for weeks but then drop-off (e.g., a missing email address in a workgroup email to disseminate information or a meeting invite can easily lead one to miss important meeting or receiving materials). The tight schedule of mission preparations does not typically provide time for knowledge recovery. VIPER Science Operations, and some mission members with an awareness on the benefits of early integration, would take extra steps to review email meeting invites and email-sent materials, checking for that persons were included and if not adding them (which sometimes required additional step of getting permission to add). This integration work required multiple persons across several groups – in other words, Science Operations would not have been able to adopt their early integration approach without the support and assistance of mission members across workgroups. It also needs to be acknowledged that not all integration actions will be successful. There are material and cultural conditions which can prohibit uptake of some integration

4. Integration example: Science roles in the Mission Operations Center

As the first NASA mission utilizing a tele-operated robot on the Moon, VIPER required the development of dedicated operations spaces for mission systems, payload commanding, and science operations at ARC. This brought an opportunity to define and organize some of the mission roles in the three MS workspaces at ARC: 1) Mission Operations Center (MOC), 2) Payload Operations Command Center (POCC), 3) Mission Science Center (MSC). VIPER's Science Operations developed a science work system with distinct roles and responsibilities for a team of twelve (the number of scientists that would be on-shift during the twenty-four hour and fourteen-day period of surface operations). The development of workspaces 1 (MOC) and 3 (MSC) was connected to the placement of the science roles in the MS workspaces at Ames. Science Operations would find that their early integration activities made possible the construction of work systems to support science roles in the MOC and the MSC.

Early construction of the MOC supported four positions at a row of consoles set up for the "rover drive team". This setup is visible in an image, see figure 2, shared in the 17th International Conference on Space Operations paper by MS Manager Jay Trimble [7]. The rover drive team is responsible for driving the rover and maintaining its safety while carrying out mission science activities. As the rover is driven along the planned traverse (see fig. 1 for representation), seeking to arrive at locations designated as science stations where the drilling activities will occur, the rover driver sends a new command typically every ~ 2-8 meters. While it is only the rover driver that sends a command, the driver assesses the terrain in concert with the other members of the drive team. The rover's drive team is composed of four roles: 1) Driver, 2) Co-Driver, 3) Navigation, 4) Real-time Science (Real-time Scientist). In figure 2, the consoles for the four roles can be seen at the long workstation at the front of room.

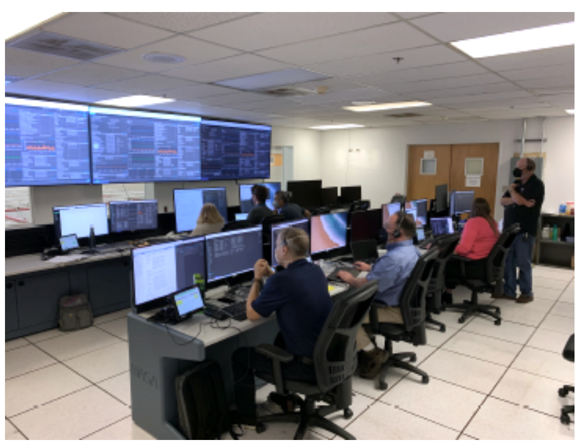

Fig. 2: The VIPER Mission Operations Center, as it appeared in during a pre-2023 mission simulation [7].

The role of Real-time Science is held by one of several designated VIPER scientists. As a member of the drive team, they must be immediately responsive to the other drive team members. Assessments made by the drive team during rover driving and mission science activities occur in timeframes that can vary from seconds to minutes. Expectations for response time are sometimes unspoken and sometimes included in the question or asked for in response to a question. The physical proximity between drive team roles is underpinned by the need to communicate verbally and non-verbally with shared content (e.g., digital content on displays) and metacommunication (e.g., context signals) [15,16].

The Real-time Scientist needs to draw not only from their own knowledge but also from that of their co-investigators, the scientists that are seated in the MSC, see figure 3, in an adjacent building within ARC's Multi-Mission Operations Center (MMOC). Together, the VST provide mission-enhancing scientific input to guide traverse planning and drill site confirmation/selection throughout surface operations. Their input is of vital importance to the mission's ability to maximize science return and to meet broader objectives for future lunar ISRU and exploration activities. The VST would enable the characterization of the distribution (lateral and vertical extent, concentration, variability), form (chemical/physical state of these reservoirs of lunar water and key isotopes), and context (e.g., accessibility/overburden environment, soil mechanics, trafficability, and temperatures) of lunar polar volatiles and water content for the VIPER mission. During surface operations, the VST would be enabled to provide science-driven, consensus-based, timely input and decision-making to enhance mission operations and mission science return [17].

Fig. 3: VIPER scientists seated at twelve assigned console positions in the MSC.

The science operations system for the VST in the MSC includes a specific set of protocols for two-way communication with the Real-time Science in the MOC. VIPER's Science Operations workgroup examined the workload that this represented for the Real-time Scientist and determined that two science roles were needed in the MOC [18]. Figure 4 shows the role of Science Lead seated next to the Real-time Science role. The role of Science Lead was developed to support mission science activities in the MOC, working in collaboratively with the scientist in the Real-time Science role and the scientists in the MSC. Real-time Science role was thus enabled to maintain attention and participation with the drive team without risk of losing contact with their science team counterparts.

Fig. 4: Inside the VIPER Mission Operations Center, a view of the front row consoles supporting the roles of (from left to right) Science Lead, Real-time Science, Rover Driver, Co-Driver, Navigation.

Without early integration, it is highly unlikely the role of Science Lead could have been positioned in the MOC. Even before VIPER Science Operations' assessments led to the creation of the role and identified locating it in the MOC, they had started integration activities with MOS and GDS. Had they identified the role and its location without interaction activities already happening, the addition could have been too late to integrate if MOS and GDS reached a stage of no longer being able to support (data and communication) additional roles. For the Science Lead role to become an integrated role in the MS, there were changes that had to be made to material conditions and relationships and communication interactions which required additional effort from all workgroups (and was received). Subsequently, as the VIPER mission proceeded with simulations of mission surface operations, the role of Science Lead was found to effectively provide a key communication role between the VST in the MSC and Real-time Science during rover driving and mission science activities.

5. Conclusion

Being resilient to forces that would work against operational cohesion is key to enabling integration in a complex and dynamic mission system. Part of that resilience stems from having a team that is committed to the process of being curious and open to dialectic exchange. Actively integrating does increase workloads in the short-term work plan as it requires seeking and maintaining a greater number of considerations such as the scheduling, task progress, and communication exchanges with a greater number of workgroups. In the long-term, it yields benefits that may include reaching system conflicts during stages when there is time to address them which entails understanding the conflict, potential solution creation, and solution adoption. VIPER Science Operations early integration work was, fundamentally, similar to that which can be enacted in any organization composed of multiple workgroups working on different aspects towards shared goals. The process description highlighted here was critical to integrating real-time remote science systems needs into the mission system.

Acknowledgements

NASA VIPER Project Manager Dan Andrews, VIPER MS lead Jay Trimble, VIPER Science, MOS, GDS, and MMOC workgroups

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