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Adaptive Situational Awareness for Real-Time Lunar Surface Operations

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Abstract

The Lunar South Pole, the site of future space operations for Artemis missions, presents unique operational challenges. The line of sight to the Earth and Sun are both low over the horizon. The lighting and shadow environment is highly dynamic. Surface operations, unlike trajectory-based operations, are non-deterministic, rendering traditional timeline-based mission operations inaccurate. Given the reactive nature of surface operations in the Lunar Polar Environment, providing timely situational awareness to the operations team is critical to both mission success and spacecraft survival. To meet these needs the VIPER Lunar Rover Mission built an adaptable situational awareness system for surface operations at the Lunar South Pole, designed to evolve with mission experience.

Acronyms/Abbreviations

Deep Space Network (DSN)
Digital Elevation Map (DEM)
Direct to Earth (DTE)
International Space Station (ISS)
Permanently Shadowed Region (PSR)
Situational Awareness (SA)
Volatiles Investigation Polar Exploration Rover (VIPER)

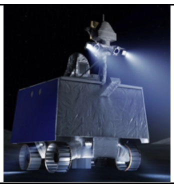
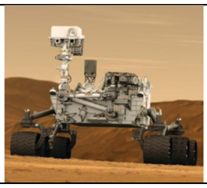
1. Introduction

We define situational awareness (SA) as the ability to perceive and understand the status of mission execution as it relates to the operational decisions that need to be made by the mission team. Here we describe situational awareness as it applies to the design of the VIPER lunar rover for operations at the lunar south pole. Many of these constructs will be applicable for other missions to the lunar south pole as well as other near real time command and control surface missions.

Mission operations processes, and what constitutes situational awareness, vary across a number of factors. A comprehensive list is out of scope here, but we can cover key parameters as they relate to SA. Mission operations are both enabled and constrained by spacecraft design, mission goals and the operational environment of the primary mission. Command and control may be done in real time or near real time from Earth orbit and into Cislunar space. At greater distances round trip light time constrains command and control options, with real-time operations no longer possible. A trajectory driven mission in orbit or doing a fly by is deterministic. Mission controllers know where the vehicle will be, and when. A mobile surface mission does not carry that degree of determinism. The uncertainty is a product of vehicle/surface interactions.

Table 1 shows some example missions and how they vary operationally by key parameters that affect SA.

Table 1- Contrasting Operational Parameters Relevant to SA

	VIPER Moon Rover	Mars Rover	ISS
			
Communications	Continuous to operate	~ One DSN pass per Sol	Continuous
Comm Round Trip Latency	Nominal 6 – 10 seconds	20 – 40 minutes	<= 2 sec
Environment	Unstructured	Unstructured	Engineered
Command & Control	Near Real-Time Continuous	Command Sequences	Direct Operation

2. Conceptual Components of Situational Awareness

For the VIPER mission, SA has both spatial and temporal components, with requirements variable by mission control position. The components of mission execution that are relevant for SA are defined below.

Activities

Activities are pre-defined by Mission System Engineering in an activity dictionary. This is a comprehensive catalogue of all predefined operational activities the rover and the payload can perform. Each entry specifies key parameters such as nominal duration, power consumption and data volume to simulate resource consumption. Examples include payload calibration, instrument checkout, panorama, drill bites of 10cm, and temperature pause. Activities are an atomic unit of composition used to build mission timelines.

Procedures

Procedures govern how mission activities are executed. VIPER's near-real-time human in the loop command and control operations concept has led the team to structure and pace the mission timeline around procedures. Each activity in the timeline is a procedure, with some activities/procedures being higher level procedures that govern the execution of sub-procedures.

Events

Events are significant occurrences or actions that impact mission progress that require monitoring or response. These events can include planned mission operation activities such as deadlines for drill location re-confirmation or system checks or environmental hazards such as shadow or communication loss of signal (LOS) and acquisition of signal (AOS) and markers of earth elevation at one and two degrees. Effective identification and management of these events are crucial for maintaining situational awareness and ensuring the agility of operations across the operations team to make informed decisions in a timely manner.

Constraints

Constraints at the lunar South Pole stem from the region's unique environmental conditions and operational challenges. The Sun remains low on the horizon resulting in long shadows and limited traversable corridors of sunlight. This affects solar generation and necessitates careful planning and replanning to ensure the rover remains in illuminated corridors. Maintaining Thermal management especially in permanently shadowed operations is critical to safeguard rover health. Direct-to-Earth (DTE) line of sight requirements depends on avoiding Earth shadow which can be obstructed by local lunar terrain shadow casters. Safe havens, due to lunar libration there are periods when the Earth is not visible from the South Pole leading to communication blackouts for DTE (direct to Earth) communication. Resource Constraints, periods inside the permanently shadowed regions (PSR) are shaped by battery state of charge and temperature and require efficient energy storage for operation during critical drilling activities in PSR. Addressing these constraints requires robust mission planning and adaptive operational strategies.

Deterministic Elements

Deterministic elements refer to aspects of the mission that behave in a predictable and consistent manner, given initial conditions. Key characteristics of deterministic elements can be forecasted given sun elevation and the percentage of the sun disk available during safe haven. Deep Space Network (DSN) schedules are forecasted to ensure reliable communication coverage. By leveraging deterministic elements mission planners can design robust plans that adapt reliably in the challenging lunar environment.

3. VIPER Operations

As background for understanding the components of SA for VIPER, the basic mission operations concepts are explained below. Figure 1 shows a graphic overview of the basic concept of surface operations for VIPER.

Rails

VIPER driving on "rails" is an engineering activity, in which science is conducted, but is not the primary focus. The purpose of a rails drive is to get the rover to the next science station.

Prospecting

Prospecting refers to the localized traverse within a science station dedicated to high resolution characterization of lunar volatiles. Unlike the "Rails" drives, the prospecting traverse proceeds at reduced speed to enable detailed subsurface hydrogen mapping and extended measurements at waypoints. The resulting data drives drill-site placement refinement and builds an evolving three-dimensional map of volatile distribution.

Science Stations

A Science Station is a predefined operational zone. Sites are chosen to provide an area safe from shadow constraints for the entire duration. Dominant thermal regions are selected to sample representative ice stability types for comparative thermal and environmental analysis. Unlike operations on "Rails", science station operations prioritize real-time science decision-making to optimize prospecting data collection to spatially map surficial and sub-surface water distribution and to optimize drill deployment location to characterize water ice distribution down to one meter.

Each science station is allocated a strictly bounded operational window augmented by a small grace period that can be used to recover any accrued temporal debt by executional delay. At the lunar south-pole where illumination and Earth-shadow cycles impose stringent spatial limits, exceeding the nominal window plus its grace period jeopardizes subsequent activity. Failing to reach critical PSR entry and safe haven within prescribed temporal limits threatens the entire mission. Hence, station entry time defines the total science opportunity, and any delay shortens that task list and must be reconciled by rescoping activities from near term science activities to realign to the strategic timeline. Strict tactical schedule discipline remains essential. On-time station exits set the cadence within a small mission allowance. Any overrun beyond the grace allowance converts into irrevocable mission debt.

To resolve mission debt, Planners may invoke a rescope of subsequent tasks or compress prospecting accrual according to a predefined prioritized science task list and if necessary descope low priority tasks to recover lost time, thereby preserving the safe haven arrival buffer and maintaining overall strategic mission integrity.

Science station activities take place within the allocated time for that station. If activities are late or delayed they may be traded against other activities within a 24 hour period to maintain a safe arrival buffer to the staging area before critical destinations such as PSR and safe haven.

Safe Haven

The area near the lunar south pole loses direct line-of-sight communication with Earth due to lunar libration. Even though the Moon and Earth are in phase lock, at the pole, due to the Moon's rotation and orbit, there are periods when the Earth moves out of the rover's direct line of sight. The rover must enter a safe state in a designated location that is carefully selected to ensure maximum sunlight exposure during the two-week loss of communication. The safe haven location is positioned in elevated terrain to maximize exposure to sunlight during the two-week period to power the heater to prevent its components from freezing. Safe havens provide a secure environment for the rover to withstand periods without Earth contact ensuring that it can resume the mission once communication is restored.

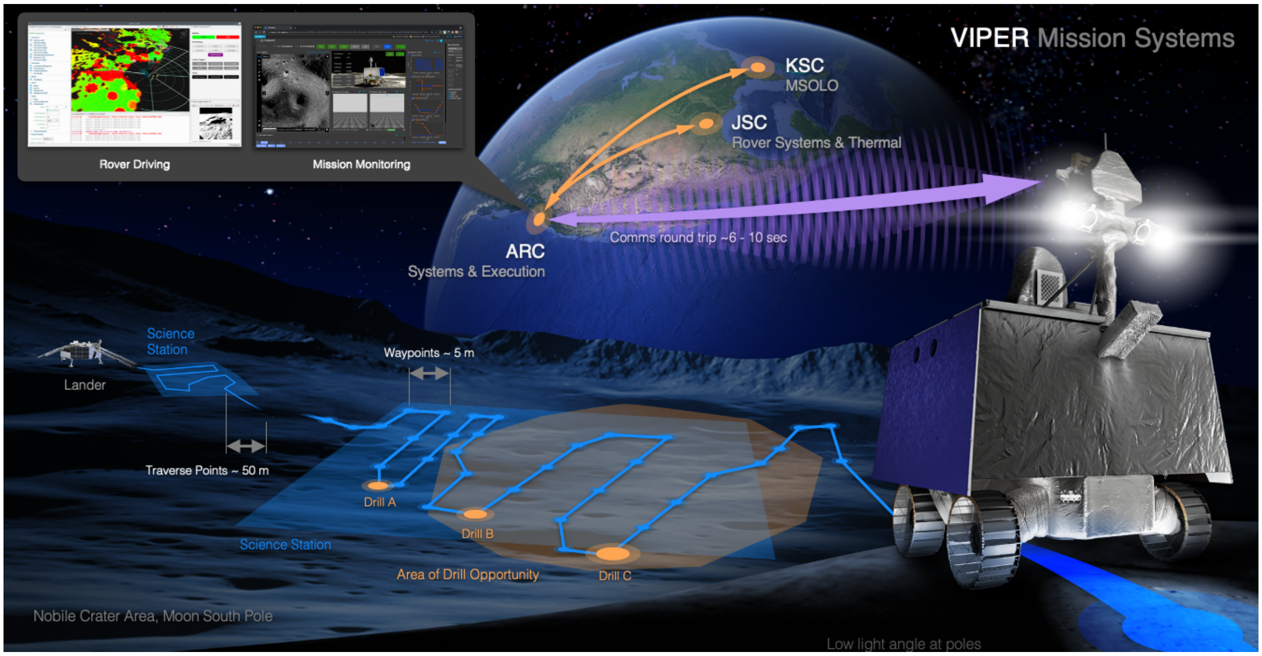


Figure 1 - VIPER Mission Systems Operational Concept

4. Are We on Time?

What it means to be "on time" for VIPER is a complex question. The mission is operationally constrained by lighting and shadows. The rover is solar powered and can operate in shadow for limited periods of time. Extended shadow operations would be mission ending. The mission must have communications to operate, as it is controlled by the mission team on Earth. Within these constraints, science operations are planned in the science station with fixed time allocations, to ensure the ability to reach a safe haven to survive communications and sun shadows.

There are real-time, tactical and strategic components. Mission success depends on tactically adapting to environmental and operational variability in addition to unplanned communication outages. Execution variation introduces potentially serious risk. Tactical re-planning occurs when triggered by an execution variation (ahead/behind value) greater than a nominal noise tolerance. This drift delay triggers a descope of subsequent science station activities in near-term execution, nominally within a 24-hour window, where tasks are compressed or deleted according to a pre-defined science driven priority task list to resynchronize tactical execution to the strategic timeline within the grace period. Guided by structured protocols, this framework can prevent cascading re-planning spirals by enabling strategic cuts rather than reactive triage in high-pressure decision-driven scenarios. By continuously monitoring and visualizing deviations in the SA display, our re-planning framework ensures timely decisions even under limited conditions.

A time-based result of this process is simply summarized as an "ahead/behind" time value that is shown in multiple views in the mission main SA display including the Gantt, Time List and Notebook views.

5. SA and Plan Representations

The monitoring and execution of mission activities over time has been represented as activity timelines, a practice that dates to the early days of spaceflight. In the Apollo era, timelines were used for both trajectory-driven deterministic operations, and non-deterministic roving surface operations.

Timelines may be used, in different ways, across mission types. Figure 2 shows an example timeline from VIPER. This timeline shows mission activities and procedures categorized by swimlanes to indicate dependencies across lanes highlighting inter-team collaborations. Figure 3 shows an example of a tactical build schedule from the Mars Exploration Rover Missions. This represents the flow of activities from receipt of data from the rover on Mars, to uplink of the next command sequence. Note that timeline representations are the common means of communicating activity execution across different types of missions.

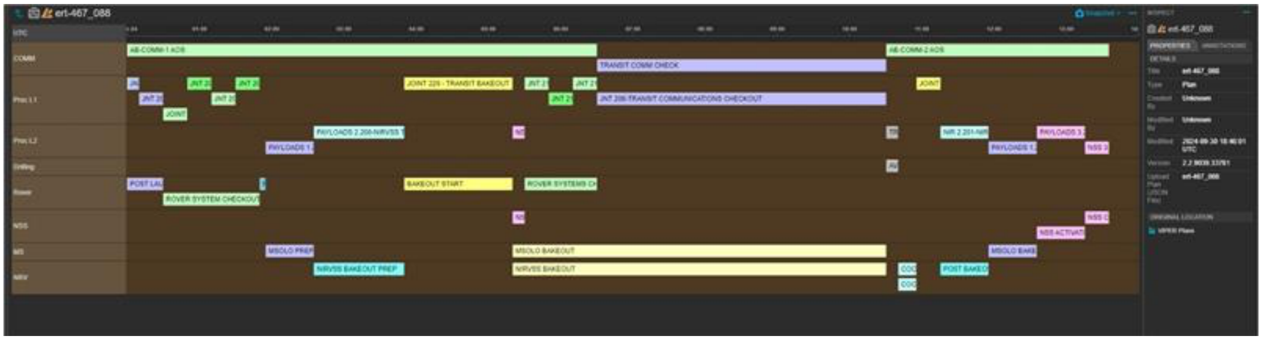


Figure 2 – VIPER Timeline Example

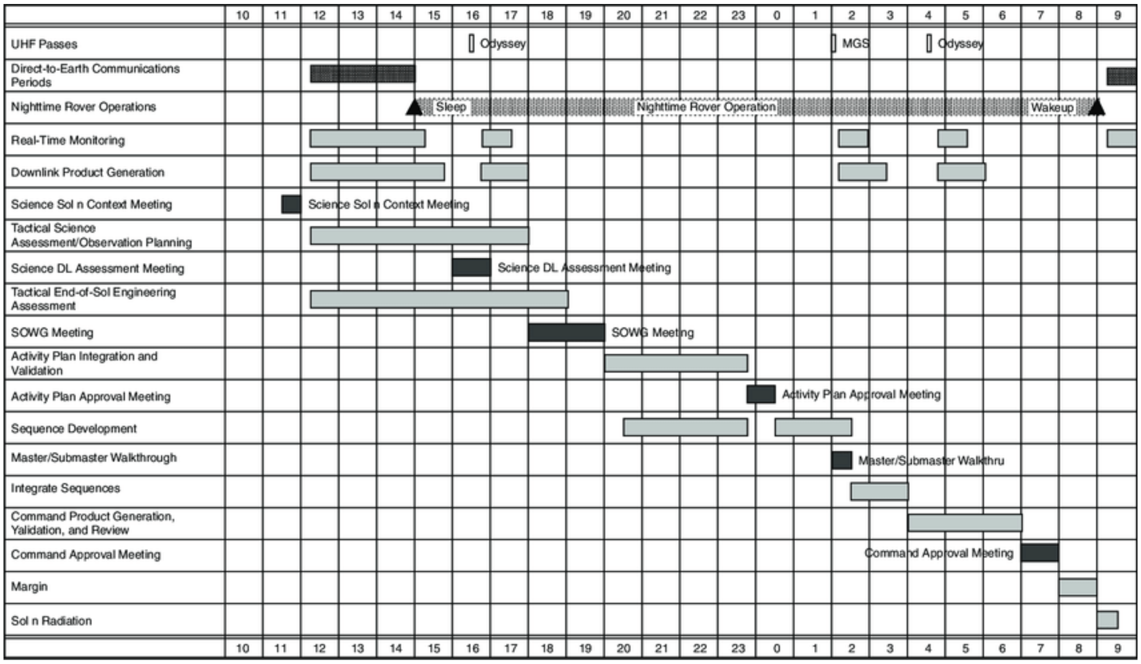


Figure 3 – Example Generic Timeline for the MER Tactical Operations Process

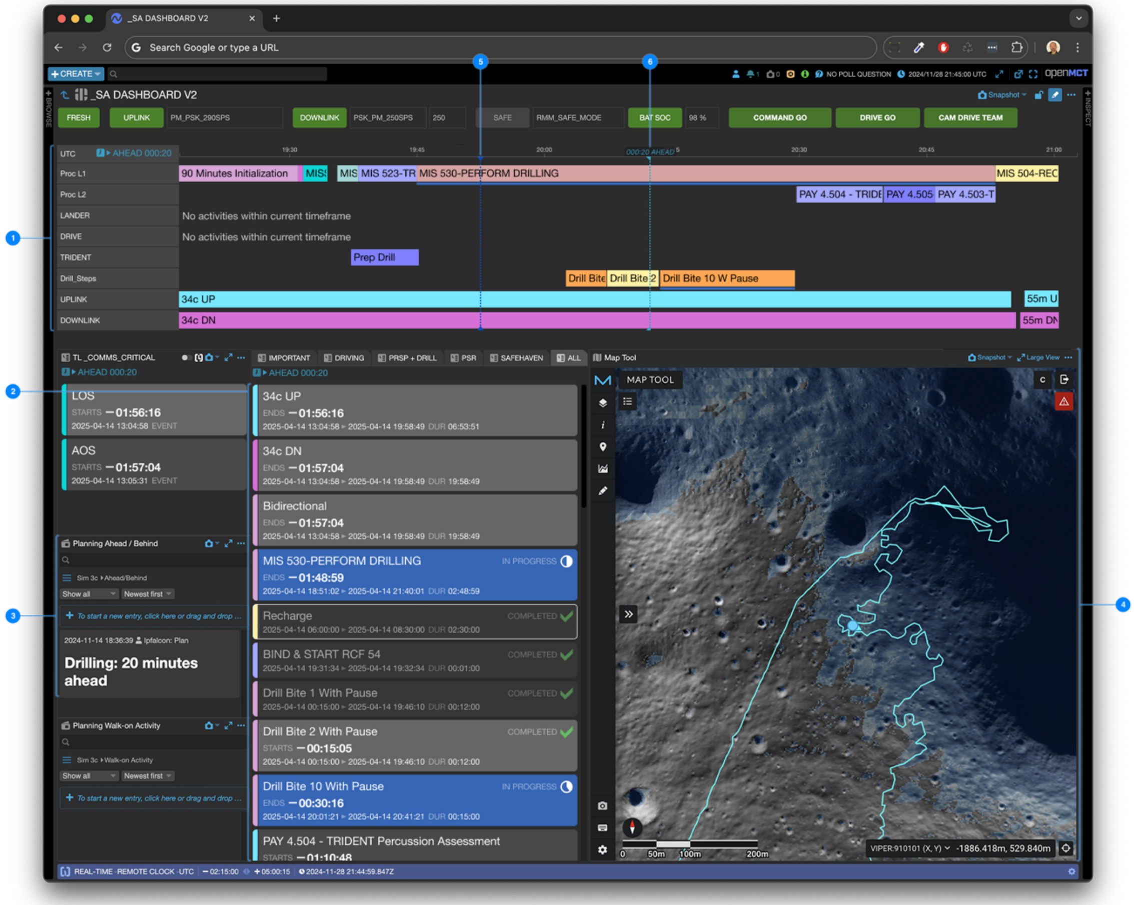


Figure 4 - VIPER Primary SA Display

Figure 4 shows the primary situational awareness display used in the VIPER mission. The VIPER primary SA display is used to provide common SA information to all members of the flight control team. It is built from composable elements that may be adapted to lessons learned in test and training. The display contains a timeline view (1), and time ordered list (TOL) views (2), with modifications to support near real-time robotic surface operations.

For VIPER, activities and procedures have a one-to-one correspondence. Therefore the state of procedure execution represents activity progress in procedure steps, though not necessarily in time. To support this structure, the primary modification to the TOL view is the addition of the capability for an operator to set current status to each activity/procedure. Status may be set to “In Progress,” “Completed” or “Skipped.” Other values may be inserted based on need. The timeline representations are based on the plan. Due to the non-deterministic nature of surface operations, the actuals will vary from the plan. The capability to set execution status in real-time enables an operator to see actual status.

Note that there are two TOL views. On the left is the AOS/LOS view. These elements are not executed procedures, they are deterministic states. Hence they are separated from the TOL view of procedures. As these elements are composable, they may be changed if test and training shows a benefit.

The timeline shows “when” we are in mission execution. The map view (4) shows where the rover is on the surface. Ahead or behind status relative to specific mission criteria is shown in a note on the left. We used a repurposed notebook view composed into the SA display to allow the planners to note ahead/behind status.

A detailed breakdown of the elements in this view is given below:

A. This is a mission timeline representation showing the plan. Activities are shown as coloured bars that visually articulate start, end and duration. To accommodate the reality that events will seldom start and end at the planned times, we have added the capability for operators to set the current status of activities as "In Progress", "Completed", "Skipped" and other values; this is visually reflected in the view. The current time (callout 5) and the "ahead/behind" line (where in time the mission is from an executional perspective, callout 6) are visually represented in the view as well.

B. The same mission plan is also displayed as a time-ordered Time List view. Shown here is the "All" list which shows all activities and events from the mission plan; Time List views can also be filtered by name and category. Activities in this view provide additional detail not available in the timeline/Gantt view and are visually differentiated to indicate if they ended in the past, span the current time, or start in the future. Users have the same affordances to set current status on Activities as noted in the timeline view.

C. A Notebook component is used by the Planning team to articulate the "ahead/behind" context of current operations. This component can contain formatted text content, is easily edited and is asynchronously updated in all views that include it.

D. An embedded Map View component shows operators the current location of the rover and includes the ability to visually overlay information such as the planned traverse path and ice stability maps (shown above) in addition to live instrument data heat maps and pre-computed terrain and time-based data such as sun and comm shadows.

6. Adaptability

The SA display shown in figure 4, as mentioned, is built from composable elements using Open Mission Control Technologies (Open MCT) software, https://github.com/nasa/openmct. The team put together a set of building blocks that may evolve based on test and training lessons learned. Figure 5 shows a display canvas on the right and directory tree on the left. The composable elements are assembled in the canvas from elements in the directory. We see two primary uses for this capability in SA. The main SA display may be modified, including content and arrangement. We also expect position-specific SA displays with levels of details required by position. For example the science team will need accrual statistics and detailed information on science station time available. The systems position will require more detailed data on vehicle status.

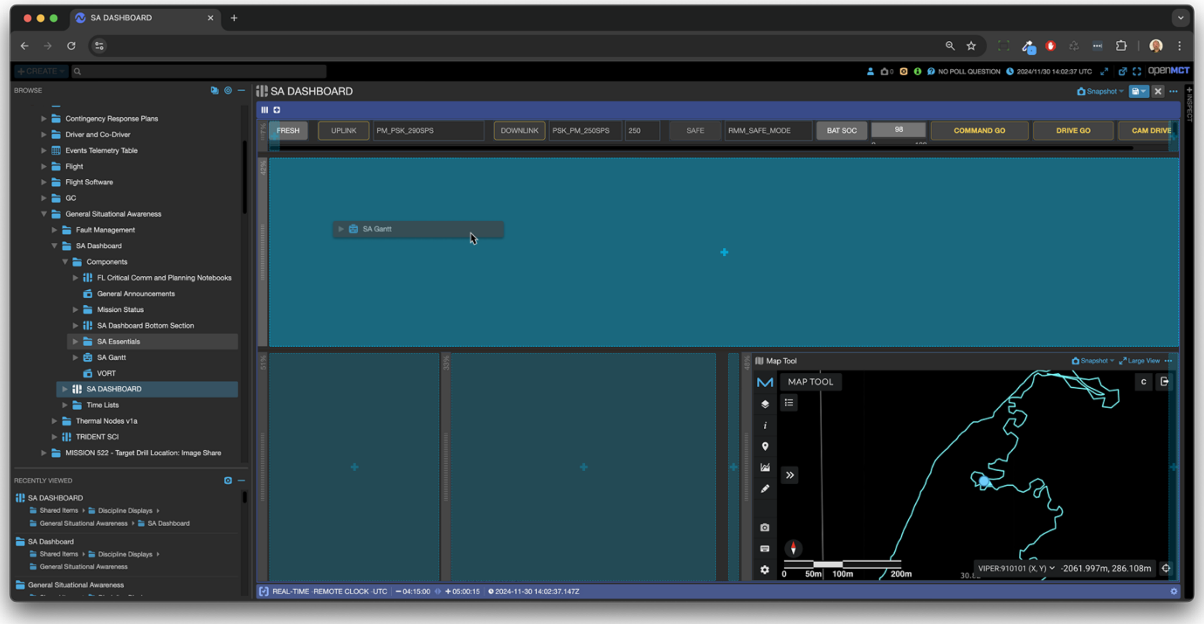


Figure 5 - Open MCT Composable SA display editing canvas

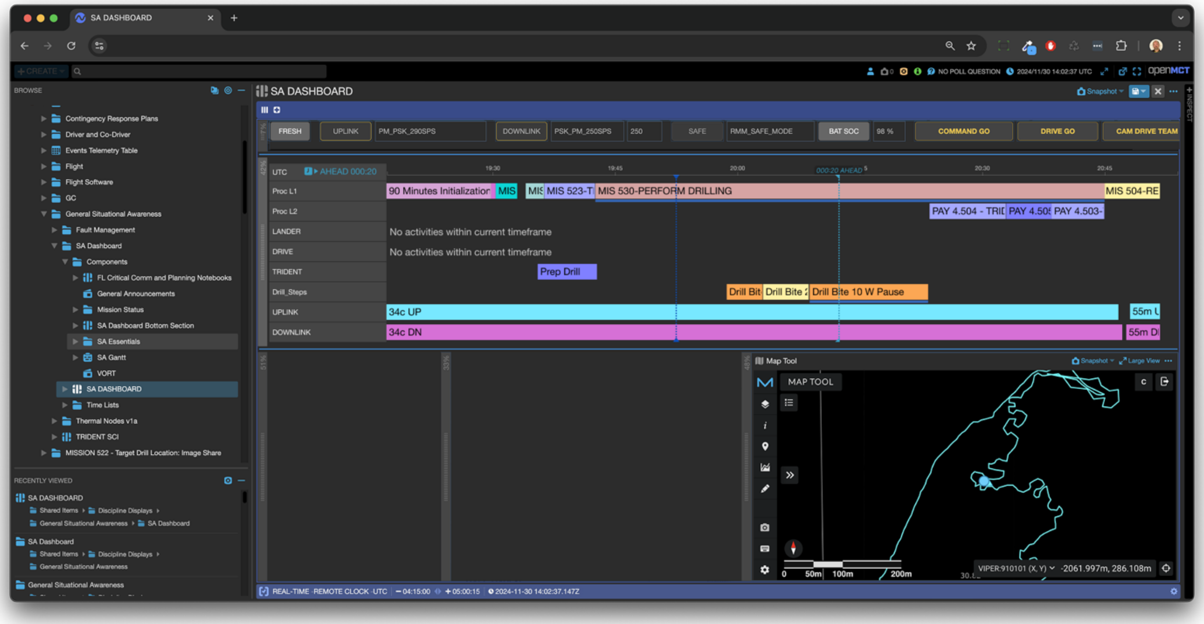


Figure 6 - Composable SA display, having added a timeline component

7. Conclusion

Operations at the lunar South-Pole present mission teams with a uniquely dynamic environment, low sun and Earth elevations, rapidly shifting shadows, unforeseen hazards and non-deterministic execution that challenges conventional timeline planning. To address these challenges, the VIPER situational awareness system decomposes mission execution into visualized components within an integrated display, providing both the strategic context and the tactical granularity required to adapt in near real-time. By enabling real-time decision making, the system enhances risk mitigation by promptly visualizing changing conditions. Its adaptable display architecture, hosted in OpenMCT, can evolve to incorporate new metrics and user driven layouts offering a template for future Artemis lunar surface assets. The high-level lessons learned are applicable to other near real-time command and control surface missions with mobility. While some of the mission elements are specific to VIPER, future Artemis missions to the surface of the lunar south pole should benefit from techniques developed here.

References

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