Lunar science operations visualization and mapping tools on NASA's VIPER mission

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Abstract

The National Aeronautics and Space Administration (NASA) Volatiles Investigating Polar Exploration Rover (VIPER) mission presents a unique opportunity to develop new tools and confirm the usefulness of existing tools for a collaborating team of scientists to recognize, annotate and synthesize important data from disparate sources. Apollo era lunar science and exploration included humans on the Moon to make real-time data collection and sampling decisions, operate instruments and assimilate observational inputs in real-time. VIPER requires scientists to make the same decisions that were delegated to Apollo astronauts, on the same time scales (minutes), remotely from earth. The VIPER Science Team (VST) is tasked with providing mission enhancing scientific input to guide rover traverse planning and drill site confirmation and selection throughout surface operations. The VST input will be of vital importance to the mission's ability to maximize science return and to meet broader NASA objectives for future lunar in-situ resource utilization (ISRU) and exploration activities. To meet these new challenges, both the work practices of the science team and their tools and data management practices need to be adapted to support real-time, integrated decision-making. This paper provides an account of the VIPER-specific development of two support tools, Open MCT (NASA Ames), a mission control application and framework, and MMGIS/Map Tool (NASA JPL), used for data visualization and mapping. The VIPER Science Operations team employed the following criteria to guide the development of the visualization and mapping tools that would be adopted for use across the mission: 1) Equal access to data and tools for all team members; 2) Fluid, interactive exploration of data in real-time; and, 3) Efficient export, using pre-defined data packages and minimal mouse clicking, of relevant data in a format readable by popular tools (e.g., common to the lunar and planetary science community - MATLAB, ArcGIS, JMP, Excel). In collaboration with MMGIS's development team at JPL, they adapted MMGIS, which was originally developed for Mars mapping and data visualization, for lunar mapping and real-time geolocated data visualization to support VIPER and integrated it into the Open MCT framework. This paper presents the resulting tools and features such as real-time map visualization and identification and export of data selected from time-series plots.
Keywords: mission operations tools, science operations, software architecture, tele-operated rover, lunar mission, systems integration

Acronyms/Abbreviations

Open Mission Control Tools (Open MCT)
Multi-Mission Geographic Information System (MMGIS)
Mission Systems (MS)
Mission Science Center (MSC)
Mission Operations Center (MOC)
Mission Operations Systems (MOS)
Ground Data Systems (GDS)
Mass Spectrometer for Observing Lunar Operations (MSOLO)
Near Infrared Volatile Spectrometer System (NIRVSS)
Ames Imaging Module (AIM)
Web Mapping Service (WMS)
VIPER Science Team (VST)

1. Introduction

The National Aeronautics and Space Administration (NASA) Volatiles Investigating Polar Exploration Rover (VIPER) mission [1] presents a unique opportunity to develop new tools and confirm the usefulness of existing tools for a collaborating team of scientists to identify (recognize and annotate) and synthesize important data from disparate sources. Apollo era lunar science and exploration included humans on the Moon to make real-time data collection and sampling decisions, operate instruments and assimilate observational inputs in real-time. Lunar orbital missions have worked to operational timescales, e.g., decisional timelines and communication exchanges, that were weeks in length. NASA rover missions on Mars have worked to operational timescales that were on the order of ten to twelve hours, multiple days, and weeks. For the VIPER mission, however, operational decisions for rover driving and instrument commanding will be compressed to minute-scale timeframes. VIPER requires scientists to make the decisions that were delegated to Apollo astronauts, on the same time scales, remotely from earth. The VIPER Science Team (VST) is tasked with providing mission enhancing scientific input to guide rover traverse planning and drill site confirmation and selection throughout surface operations. The VST input will be of vital importance to the mission's ability to maximize science return and to meet broader NASA objectives for future lunar in-situ resource utilization (ISRU) and exploration activities. The VST works in the Mission Science Center (MSC) which is co-located in the same facility with the Mission Operations Center (MOC) and shares a common computing and network infrastructure. To meet these new challenges, both the work practices of the science team and their tools and data management practices need to be adapted to support real-time, integrated decision-making.

In this paper, the authors provide an account of the VIPER-specific development of two support tools, Open MCT (OMCT) (NASA Ames) [2] and MMGIS/Map Tool (NASA JPL) [3], for data visualization and mapping. MMGIS (Multi-Mission Geographic Information Tool), which was originally developed for Mars mapping and data visualization, was adapted for lunar mapping and real-time geolocated data visualization to support VIPER, and integrated into the OMCT framework which was the selected mission control application.

Development followed a series of steps, beginning with an assessment of science work needs for lunar science operations in real-time and off-line [4,5,6]. VIPER's Science Operations team employed the following criteria to guide the development of the visualization and mapping tools used by the Science and MOS teams:

1) Equal access to data and tools for all team members
2) Fluid, interactive exploration of data in real-time (as it is collected)
3) Efficient export, using pre-defined data export packages and minimal mouse clicking of relevant data by mission members co-located in the MSC and MOC.

This paper provides some examples of the resulting developments to address VIPER's science operations needs such as real-time map visualization and identification and export of data selected from time-series plots. Note that all references to data and data analysis in this paper refer to simulated lunar data that was used for VIPER training.

2. Development Process

The development process for adapting both Open MCT and MMGIS to support the VIPER science system within the mission system was based in user-centered design principles. VIPER's Science Operations team engaged all stakeholders early in the development process, working with both the VST and MS teams as both groups developed their tools and processes for VIPER operations.

A key aspect of the process was to work with VST members to identify realistic lunar science operations use cases, e.g. interpretation of data from multiple instruments to select a drill site. The VIPER Science Operations (SciOps) & Integration team would work with both the VST and MOS (mission operations systems) to iteratively design solutions to meet these requirements. The design process incorporated not only traditional discussions and brainstorming with focused testing of specific tools and capabilities, but also larger scale simulations of VIPER operations which included both tools and processes.

VIPER SciOps & Integration conducted initial assessments of each tool, Open MCT and MMGIS, to understand its capabilities. This assessment included understanding the use of each tool within the context of supporting real-time remote science with a tele-operated rover on the Moon. Open MCT was focused on telemetry monitoring for flight mission operations and shift logs for MS operators. MMGIS was focused on off-line analysis of Mars data, in contrast with VIPER's real-time data analysis needs. MMGIS was designed to focus on the geographic area, equatorial, on Mars that was (is) the subject of Mars missions, whereas the VIPER mission's site on the Moon would be in the south pole region (Mons Mouton). For the tool itself, this change in geographic location is not simply a matter of changing the map area that is displayed. Appropriate map projections must be selected and user interaction tools tuned to those selections to work properly in polar regions.

2.1 Training

VIPER Science Operations organized a series of training modules for VST which also provided user-feedback directly to the OMCT team who participated. The training modules were focused on use cases that were relevant to the portion of the VST team doing the training (e.g. NIRVSS instrument team) but with a focus on understanding the OMCT capabilities available to address needs specific to their process, e.g., data analysis, image visualization. While engaging in the training process, improvements were identified that fed back to OMCT development and resulted in improvements benefiting Science and MOS workgroups.

2.2 Simulations

The full-team mission simulations were also part of the overall approach to developing science operations support tools and carrying out integrated testing with the broader MOS team. These simulations were essential to refining the detailed capabilities needed to operate VIPER and helped identify missing or incomplete capabilities in a way that more component or instrument-focused tests could not. Testing science operations tools in concert with operations procedures and the broader mission operations teams helped to clarify the tradeoffs and benefits between devoting additional resources to software tool development vs. making changes or additions to procedures performed manually by the VST or MOS team members.

3. Results

The outcome of the design, training and simulation processes resulted in newly designed Open MCT displays and map products, updates to OMCT's data export formats and MMGIS's user interface and implementation of new MMGIS and OMCT capabilities to support real-time data visualization for VIPER.

3.1 Equal Access to Data

Equal access to data and tools by all mission members is a guiding principle that cannot be taken for granted. As tools are developed for specific users it cannot be assumed that the same tools can be easily used by similar users. The VIPER mission's multiple workgroups were working on the same goal of acquiring lunar science data from a tele-operated robot and instrument payload, however, they had variable needs that shaped their data display and analysis features.

Open MCT provided data displays for all who were enabled to use the software. VIPER SciOps & Integration sought to bring Open MCT into the MSC for use by the VST. Two examples of data displays developed show an integrated view (on a common time base) of data from several sources, including NIRVSS and MSOLO spectrometers, rover mobility status and imagery. These displays were designed by VIPER's Instrument Scientists whose work during surface operations would take place from within the MSC [4]. The displays can be viewed from any VIPER operations console to provide shared context for collaboration. The upper image (Fig 1) is a detail of simulated instrument data showing a real-time display of NIRVSS spectrometer water band-depth overplotted with MSOLO water partial pressure data over a synchronized display of drill data which indicated when sub-surface material will be exposed to the spectrometers.

Figure 2 is an integrated display that shows rover mobility status (i.e. moving or sitting still), images from both the NIRVSS AIM camera and rover, NIRVSS and MSOLO water data and an observation notebook all synchronized on a common time-base (blue footer at bottom of image). Note that both the compass rose in the image display and several improvements to the plots (e.g. more compact layout to see more integrated data) resulted from design discussions and testing with the Science Operations team and broader VST.

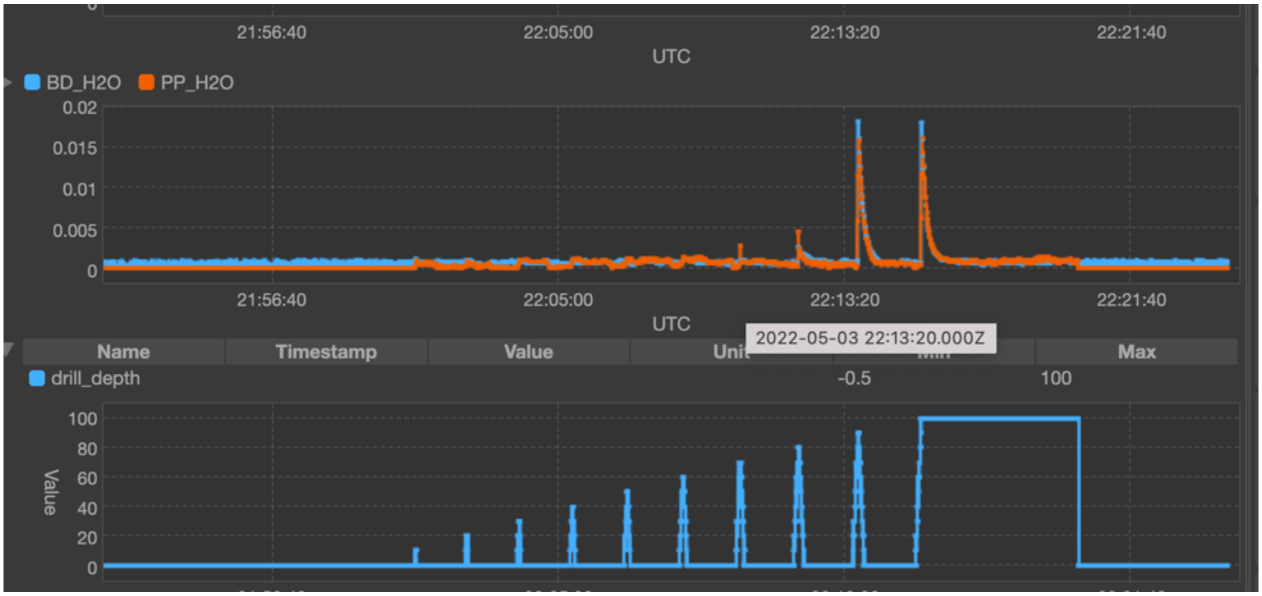


Figure 1 Simulated instrument data for NIRVSS shown in Open MCT

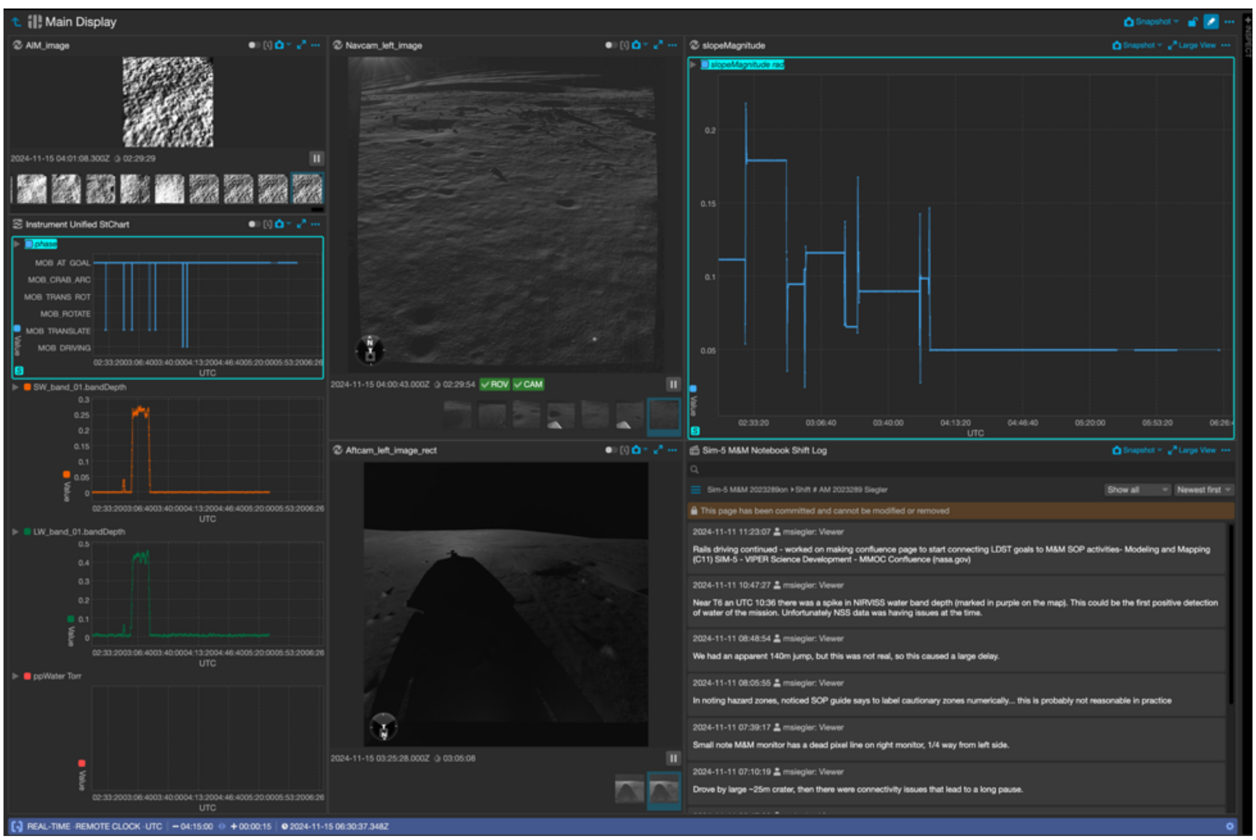


Figure 2 Open MCT display

3.2 Fluid Interactive Exploration of Data in Real-Time

A critical part of real-time high-tempo data analysis is supporting users' ability to understand the data that they are reviewing in context with other important events and activities happening simultaneously. For the VST this means being able to understand and correlate data from multiple instruments, rover imagery and rover location in the context of the surrounding terrain. Knowledge of the overall mission timeline is also important to understand the deadline for making a decision. To support this process effectively, the science operations tools need to facilitate flexible viewing and comparison of data from multiple sources.

Figure 3 shows an example of an MMGIS display as it was deployed for displaying the location and data from the Mars 2020 (Perseverance) rover. Figure 4 shows an example of an MMGIS display used for VIPER.

Mars data is collected approximately twice daily when communication windows are available to Mars and downloaded as static files to a server (this includes twice daily updates to rover position) where the data can be viewed in MMGIS. The VIPER SciOps and GDS workgroups worked with the MMGIS development team to add support for dynamic real-time data updates in MMGIS.

The VIPER map in Fig. 4 shows live rover position and uncertainty as the rover moves across the Lunar surface. Instrument data is also updated live as it is collected. The update rate depends on the instrument and varies from about once per second to once every 30 seconds. E.g. NSS predicted ice burial depth is shown by the purple “heat map” dots in Fig. 4. Rover imagery of the Lunar surface is ortho-projected and drawn on the map as it arrives from the rover (approx. every five minutes). The MMGIS display was integrated within Open MCT (the combined system is called “Map Tool”) so that all data products can be turned on and off in the map display and time-bounded dynamically by any user on the VST or MOS teams during mission operations.

Several architectural updates were made to the MMGIS backend and capabilities were added to the VIPER Map Server application in response to needs identified in the design and testing sessions. Figure 5 shows the data flow architecture for Mars data on the left side and for VIPER on the right.

Improved WMS capabilities were captured by the VIPER SciOps & Integration team and subsequently implemented by the MMGIS team to display large, dynamically updated map data consistently. Live rover position and instrument data updates were also implemented. New API support was added to support integration of MMGIS with Open MCT, and for dynamic map layer management (e.g. to update the map layer display when updated traverse plans were published). These new capabilities implemented for VIPER science operations are now distributed with the public open-source version of MMGIS.

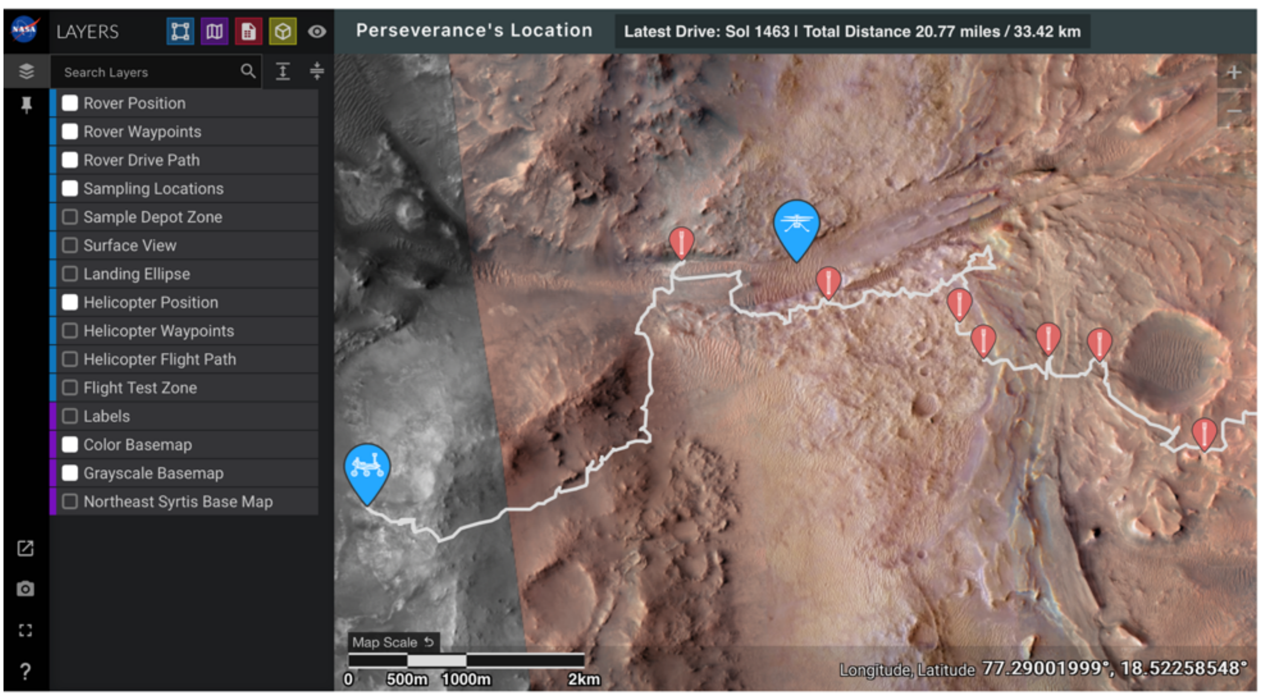


Figure 3: Example of MMGIS map display for Mars 2020.

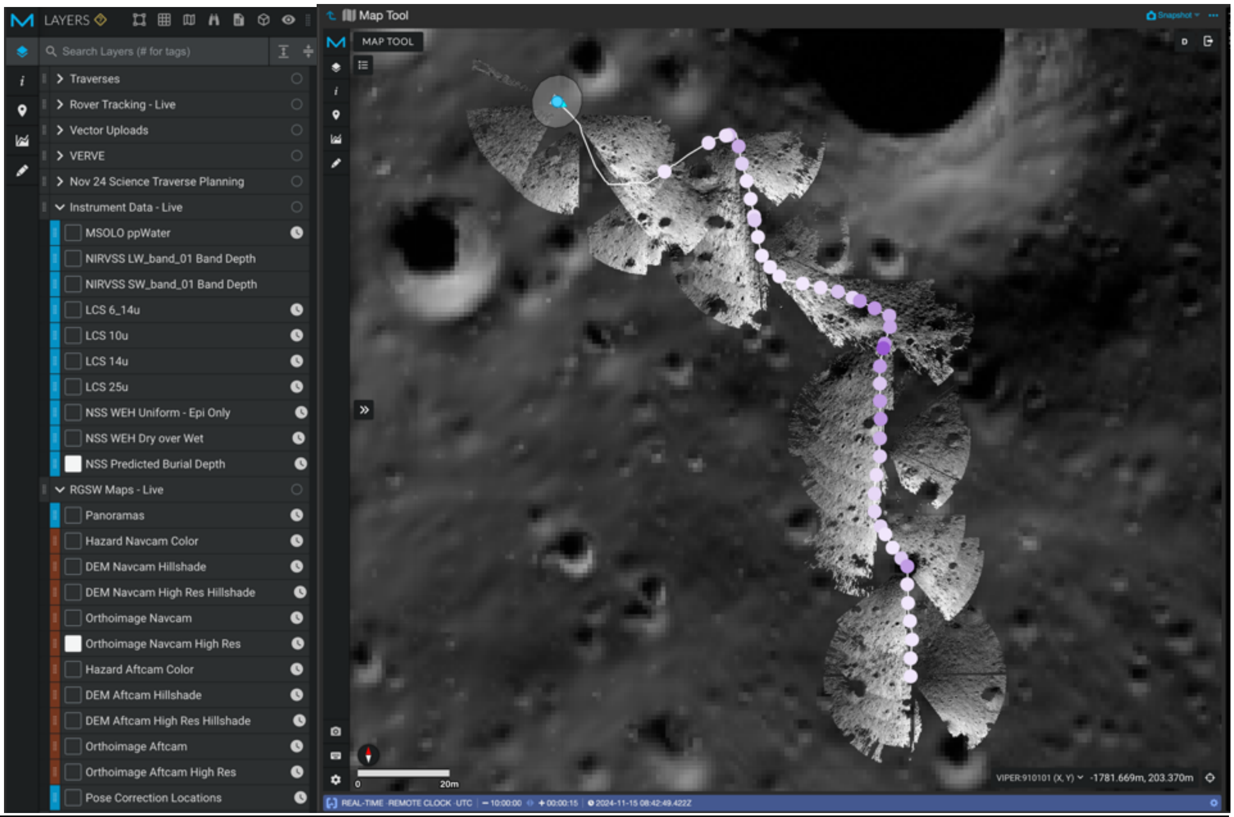


Figure 4 MMGIS map display for VIPER with live instrument data and rover imagery

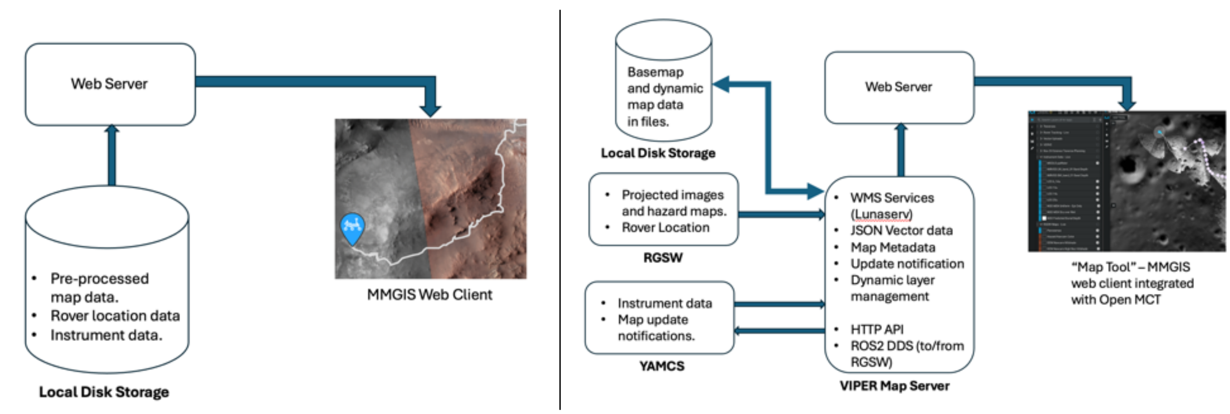


Figure 5: Left side shows MMGIS with data architecture used for Mars 2020. Right side show MMGIS as integrated with Open MCT and dynamic data updates to support VIPER.

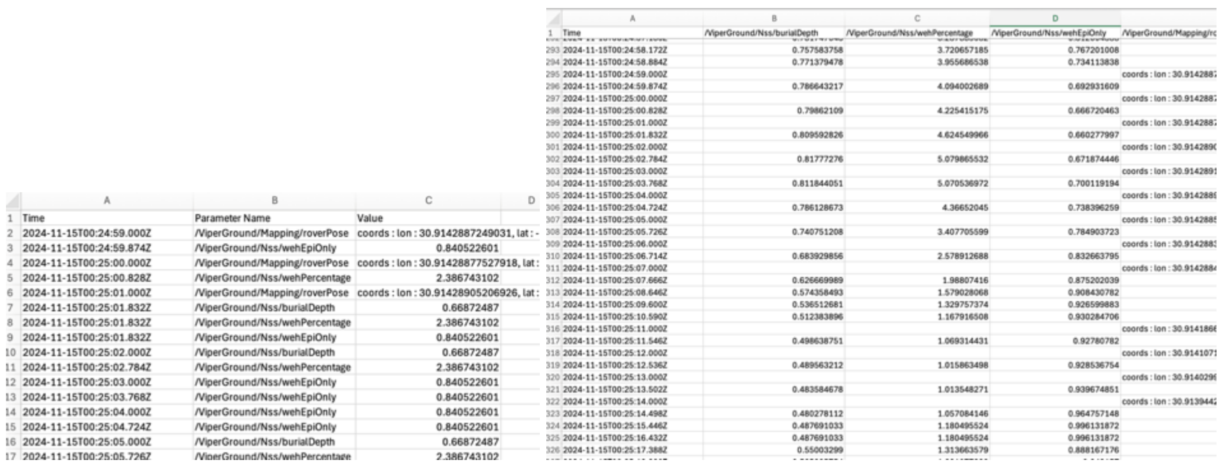
3.3 Efficient Export of Data in a common, usable format

The data export capability focused on exporting data in usable formats readable by popular tools (e.g., common to the planetary science community), for example MATLAB, ArcGIS, JMP, Excel. Most popular data analysis tools provide a flexible, general capability for importing external data with the assumption that even unconventional data formats can be imported eventually with enough preparation of the incoming data. To meet the real-time decisioning requirements for VIPER's mission and science operations, it was important to ensure that data export and analysis was part of an integrated and pre-designed workflow so that data could be identified, exported and analyzed with enough time to influence mission operations.

The implementation of data export from Open MCT evolved in response to design sessions and simulation testing with the VST (Figure 6). The original export format on the left interleaves parameters by time. Testing with this version revealed difficulty importing data into other tools which typically expect a tabular format. It also requires some potentially complex inference when importing data (e.g. is a data point missing in the export, or was it just not reported during the exported data window). The structured tabular format on right side of Fig 6 was developed after testing and design iteration with the VST, implemented in OMCT by the GDS team and is now used for VST data analysis.

Open MCT allows users to create an "alias" or "shortcut" to a telemetry data point. Figure 7 shows a data export package of telemetry points that were assembled from various rover and instrument systems and aggregated into a Geostatistics focused collection for rapid export during VIPER operations. Figure 8 shows architecture of the processing pipeline that was run by the VST following the data export to generate derived geostatistics data and updated maps.

Figure 9 shows an example of a completed data product produced by this process. The image on the left side shows a prospectivity map computed from orbital data (blue-green areas indicate an increased likelihood of water being present near the surface). The image on the right is an updated version of the prospectivity map that integrates simulated data collected during a mission simulation session. The data was collected and processed on a schedule that would allow it to influence the selection of a drill site for the rover during ongoing VIPER operations.



	A	B	C
1	Time	Parameter Name	Value
2	2024-11-15T00:24:59.000Z	/ViperGround/Mapping/roverPose	coords : lon : 30.9142887249031, lat : -
3	2024-11-15T00:24:59.874Z	/ViperGround/Nss/wehEpiOnly	0.840522601
4	2024-11-15T00:25:00.000Z	/ViperGround/Mapping/roverPose	coords : lon : 30.91428877527918, lat :
5	2024-11-15T00:25:00.828Z	/ViperGround/Nss/wehPercentage	2.386743102
6	2024-11-15T00:25:01.000Z	/ViperGround/Mapping/roverPose	coords : lon : 30.91428905206926, lat :
7	2024-11-15T00:25:01.832Z	/ViperGround/Nss/burialDepth	0.66872487
8	2024-11-15T00:25:01.832Z	/ViperGround/Nss/wehPercentage	2.386743102
9	2024-11-15T00:25:01.832Z	/ViperGround/Nss/wehEpiOnly	0.840522601
10	2024-11-15T00:25:02.000Z	/ViperGround/Nss/burialDepth	0.66872487
11	2024-11-15T00:25:02.784Z	/ViperGround/Nss/wehPercentage	2.386743102
12	2024-11-15T00:25:03.000Z	/ViperGround/Nss/wehEpiOnly	0.840522601
13	2024-11-15T00:25:03.768Z	/ViperGround/Nss/wehEpiOnly	0.840522601
14	2024-11-15T00:25:04.000Z	/ViperGround/Nss/wehEpiOnly	0.840522601
15	2024-11-15T00:25:04.724Z	/ViperGround/Nss/wehEpiOnly	0.840522601
16	2024-11-15T00:25:05.000Z	/ViperGround/Nss/burialDepth	0.66872487
17	2024-11-15T00:25:05.726Z	/ViperGround/Nss/wehPercentage	2.386743102

	A	B	C	D	
1	Time	/ViperGround/Nss/burialDepth	/ViperGround/Nss/wehPercentage	/ViperGround/Nss/wehEpiOnly	/ViperGround/Mapping/ro
293	2024-11-15T00:24:58.172Z	0.757583758	3.720657185	0.767201008	
294	2024-11-15T00:24:58.884Z	0.771379478	3.955686538	0.734113838	
295	2024-11-15T00:24:59.000Z				coords : lon : 30.9142887
296	2024-11-15T00:24:59.874Z	0.786643217	4.094002689	0.692931609	
297	2024-11-15T00:25:00.000Z				coords : lon : 30.9142887
298	2024-11-15T00:25:00.828Z	0.79862109	4.225415175	0.666720463	
299	2024-11-15T00:25:01.000Z				coords : lon : 30.9142887
300	2024-11-15T00:25:01.832Z	0.809592826	4.624549966	0.660277997	
301	2024-11-15T00:25:02.000Z				coords : lon : 30.9142890
302	2024-11-15T00:25:02.784Z	0.81777276	5.079865532	0.671874446	
303	2024-11-15T00:25:03.000Z				coords : lon : 30.9142891
304	2024-11-15T00:25:03.768Z	0.811844051	5.070536972	0.700119194	
305	2024-11-15T00:25:04.000Z				coords : lon : 30.9142889
306	2024-11-15T00:25:04.724Z	0.786128673	4.36652045	0.738396259	
307	2024-11-15T00:25:05.000Z				coords : lon : 30.9142885
308	2024-11-15T00:25:05.726Z	0.740751208	3.407705599	0.784903723	
309	2024-11-15T00:25:06.000Z				coords : lon : 30.9142883
310	2024-11-15T00:25:06.714Z	0.683929856	2.578912688	0.832663795	
311	2024-11-15T00:25:07.000Z				coords : lon : 30.9142884
312	2024-11-15T00:25:07.666Z	0.626669989	1.98807416	0.875202039	
313	2024-11-15T00:25:08.646Z	0.574358493	1.579028068	0.908430782	
314	2024-11-15T00:25:09.600Z	0.536512681	1.329757374	0.926599883	
315	2024-11-15T00:25:10.590Z	0.512383896	1.167916508	0.930284706	
316	2024-11-15T00:25:11.000Z				coords : lon : 30.9141866
317	2024-11-15T00:25:11.546Z	0.498638751	1.069314431	0.92780782	
318	2024-11-15T00:25:12.000Z				coords : lon : 30.9141071
319	2024-11-15T00:25:12.536Z	0.489563212	1.015863498	0.928536754	
320	2024-11-15T00:25:13.000Z				coords : lon : 30.9140296
321	2024-11-15T00:25:13.502Z	0.483584678	1.013548271	0.939674851	
322	2024-11-15T00:25:14.000Z				coords : lon : 30.9139442
323	2024-11-15T00:25:14.498Z	0.480278112	1.057084146	0.964757148	
324	2024-11-15T00:25:15.446Z	0.487691033	1.180495524	0.996131872	
325	2024-11-15T00:25:16.432Z	0.487691033	1.180495524	0.996131872	
326	2024-11-15T00:25:17.388Z	0.55003299	1.313663579	0.888167176	

Figure 6: Open MCT data export evolution in response to design sessions and simulation testing. Table on the left shows the original data export and on the right is the improved data export.

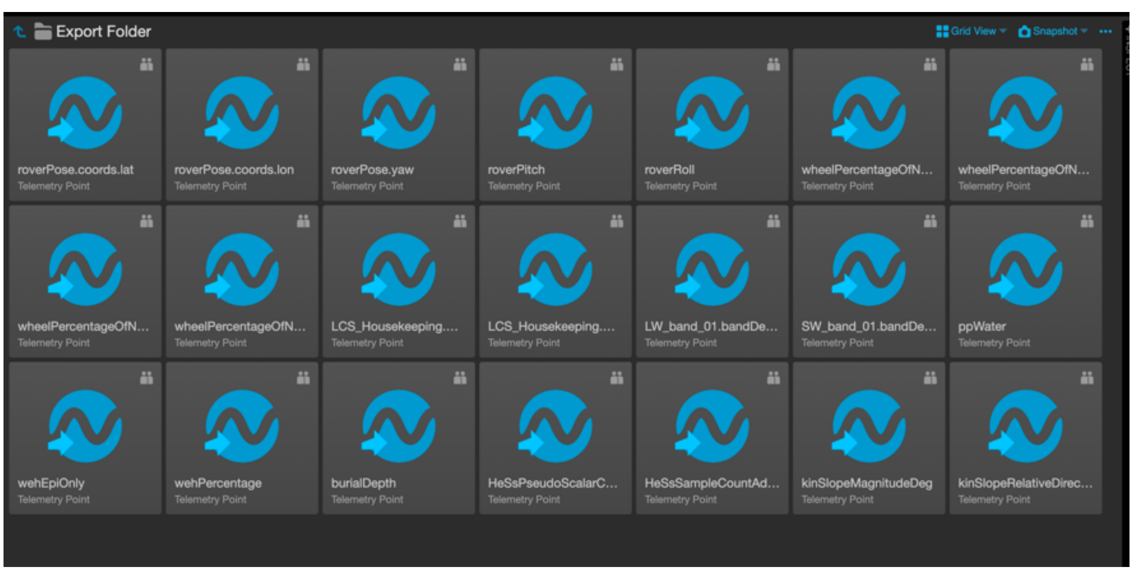


Figure 7: Open MCT display of a selected telemetry collection, specific to VST Geostatistics, for export.

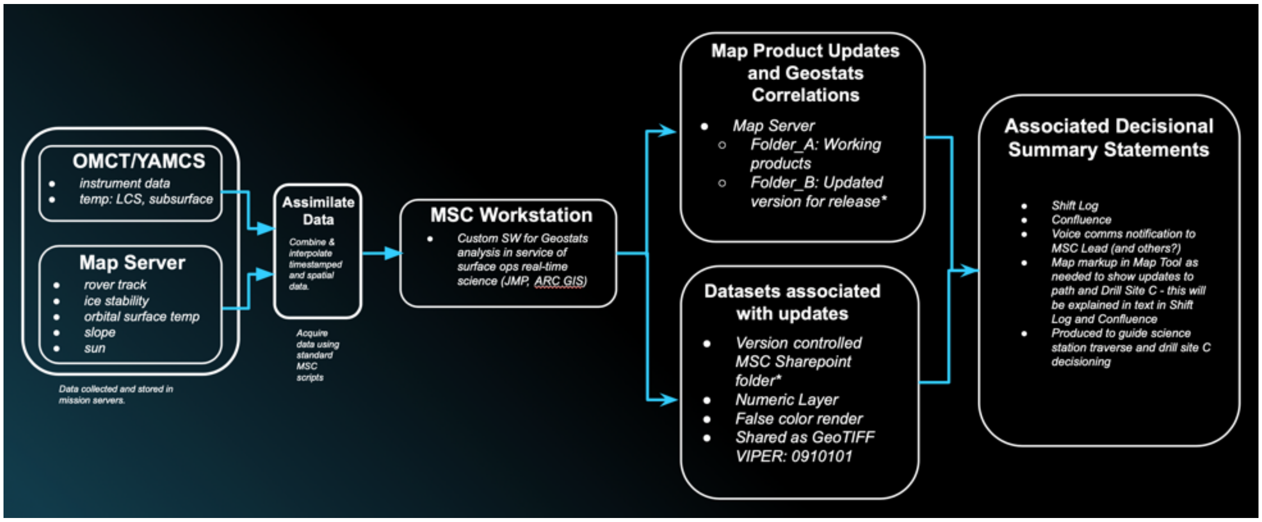


Figure 8: VIPER Science Geostatistics data analysis process workflow.

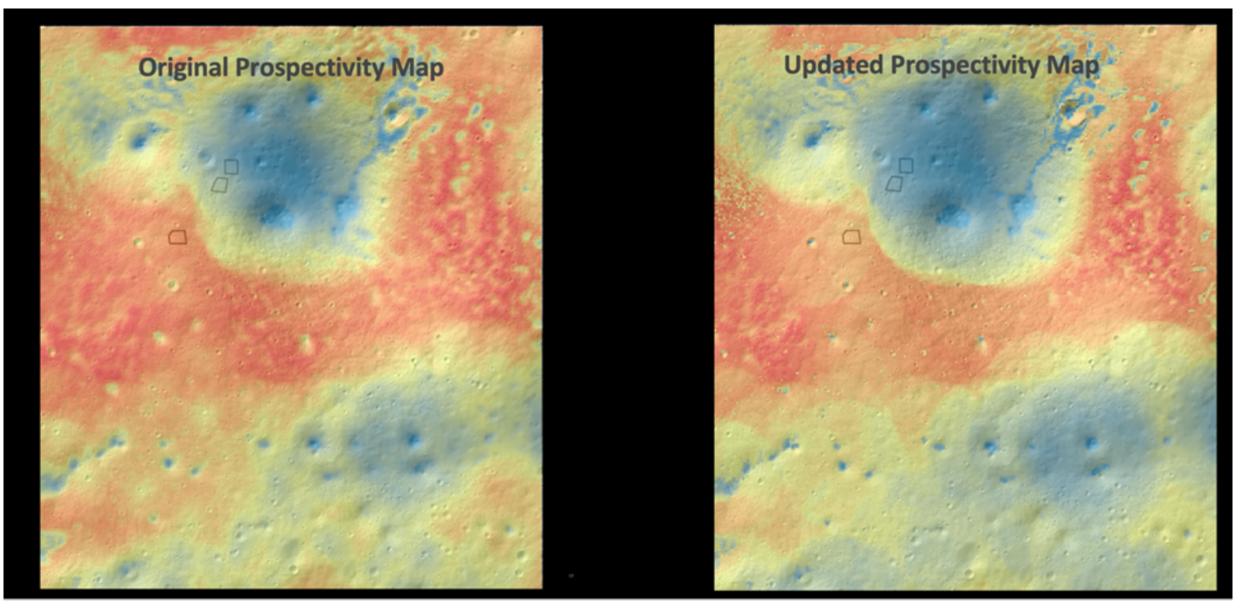


Figure 9: Example of a Prospectivity Map displayed in MMGIS generated from the data analysis procedure shown in Fig 8.

4. Conclusion

The purpose of this work has been to be able to identify and analyze data in time to influence real time operations. Robust tools for high-tempo data analysis and decisional applications must be developed with scheduled time to train and simulate use, in order to iteratively refine them for their intended use. VIPER SciOps & Integration used early integration and a development approaches [6] guided by the principles of equal access, fluid real-time data flow, and efficient data export.

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