VIPER Mission Traverse Planning – Design, Strategies, and Dynamics.

K. Ennico-Smith[1], A. Colaprete[1], M. Shirley[1], E. Balaban[1], R. Beyer[1,2], K. Bradner[1], J. Coyan[3], R.C. Elphic[1], L. Falcone[4], C. Fassett[5], D. Lees[1], D.S.S. Lim[1], Z. Mirmalek[1,6], A. Nefian[1], M. Siegler[7]. [1]NASA Ames Research Center, Moffett Field, CA 94043 (Kimberly.Ennico@nasa.gov), [2]SETI, [3]USGS, [4]KBR Wyle Services, [5]APL, [6]BAERI, [7]Planetary Science Institute.

Introduction: The Volatiles Investigation Polar Exploration Rover (VIPER) is a lunar polar volatiles prospecting mission developed through NASA's Science Mission Directorate (SMD) Planetary Science Division [1]. VIPER is scheduled to land on Mons Mouton near the lunar South Pole in late 2024. VIPER's primary mission goal is to characterize the distribution of water and volatiles across a range of thermal environments. This characterization aims to assist in understanding the origin of lunar polar volatiles and also help evaluate the In-Situ Resource Utilization (ISRU) potential of the lunar poles.

The VIPER rover is a four-wheeled robotic vehicle weighing ~450 kg. It is solar-powered and teleoperated from Earth over a line-of-sight radio link. The rover can move at up to 20 cm/s on flat terrain. Accounting for commanding, localization, navigation, and obstacle-avoidance delays, however, the effective speed is closer to 1 cm/s. This effective speed is known as "Speed Made Good" (SMG), adopted from maritime culture, and kept as a key performance metric for VIPER operations planning, execution, and evaluation.

The mission duration is anticipated to be more than 90 Earth days and involves up to 20 km of driving. VIPER's prospecting payload consists of spectrometers to detect volatiles and assess concentrations, context imagers, and a drill for sub-surface measurements down to one meter depth [2]. Mobility, combined with the prospecting and drill instrument suite, makes VIPER an analytically powerful resource mapper.

Traverse Plan Structure: The VIPER traverse, or ground path that the rover takes, must meet the science measurement goals (Table 1) and not violate engineering constraints (Table 2). At its most basic structure, the traverse is made up of legs. A leg is one lunar day. A leg starts at the landing site or at a Safe Haven (SH). SHs are locations with periods of sustained sunlight (and shadow periods <50 hrs) where the rover can remain powered while it is stationary, waiting for the next Earthrise to resume moving. During a leg the rover encounters several Science Stations including Permanently Shadow Region (PSR)-entry types. Science Stations are areas of specific science interest. They are classified by their spatially-dominant-Ice Stability Region (ISR) type [3] and have specific areal coverage requirements to meet the measurement mapping needs [4].

Strategic Planning: The VIPER team has invoked multiple automated route-planning approaches for lunar polar conditions. Strategic Plans cover the Full Mission, specifying the overall route and timing. They are designed to optimize mission productivity and minimize risk. Example of a multi-day Strategic Plan is shown in Figure 1. Metrics such as number of visited Science Stations and PSR entries, odometry, time to Sun Shadow, time to DSN shadow, ISR accrual, etc. are captured. Strategic traverses are built on initial 20 m/pixel map products based on LOLA Digital Elevation Models (DEMs) and updated for 4 m/pixel thermal maps [5].

Traverses are evaluated for their robustness against delays and rover faults. Examples of deliberate uncertainties introduced include time of landing, initial battery change, power draw, SMG, and duration of Science Station activities. DSN failures and Solar Energetic Proton (SEP) events are also injected. Most contingencies cause delays, which can introduce cascading effects on the traverse due to tight Sun or communication windows later.

Strategic Plans are baselined at Launch minus one year. After launch, updates are planned once per month during hibernation or when contingency branches are triggered. They provide a mechanism to compare options to select the optimal one going forward.

Table 1. Traverse Requirements come from Measurement Goals

Measurement Goal	Traverse Requirement
Coverage Density: Determine water distribution and form across defined Ice Stability Regions (ISR) with an uncertainty of <50%.	Visit at least one 3800-m^2 region (Science Station) from all four thermal environments (defined by their dominant ISR type).
Length Scales: To account for possible scales of spatial variability, measure at scales of <1 meter and as large as 1000 m.	Minimum of two additional ISR repeat measurements separated by at least 100 meters for a total of six ISRs.
Vertical Coverage & Sampling: Subsurface measurements sample across depths from surface to 100 cm deep w/ sampling interval of 10 cm.	Minimum of three subsurface characterizations per Science Station separated by tens of meters.
Sensitivity: Measure physical state and abundance of hydrogen-bearing volatiles, including H_2O when present at concentrations >2 wt%, H_2, H_2S, NH_3, and other non-hydrogen-bearing volatiles including CO_2 and CO when present at concentrations >5 wt%.	Rover payload instruments are continuously taking data within Science Stations and at Drill Sites.

Table 2. Traverse Requirements adhere to Engineering Constraints

Engineering Constraint	Traverse Requirement
Solar Powered Rover	Endurance in min. power mode 50 hrs Working endurance in shadow (w/drill) 9.5 hrs
Tele-operated from ground	Line-of-sight to Earth for radio comms while driving
Slopes	15° slope limit
Hazards	Negotiate 10 cm obstacles
Distance	20 km
Speed	10-20 cm/s when moving; 1 cm/s effective speed

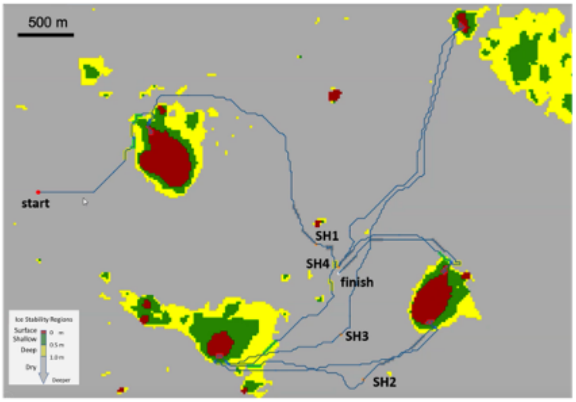

Figure 1. Example of Strategic Traverse. Start (landing) and finish points indicated. Safe Havens (SH) are where the rover is stationary with sufficient solar power when the Earth is below the lunar horizon. This traverse visits all four ISR types (i.e., thermal environments) as indicated by the color legend.

Tactical Planning: After a family of Strategic Plans has been designed, the planning team designs routes inside small areas to optimize information gain (Figure 2). Geostatistical analysis techniques (e.g., trend analysis, kriging, linear regression) are applied to react and respond to prior measurements while maintaining the required coverage density. Another example is the third drill site in a Science Station is not *a priori* fixed. The VIPER Science Team advises drill placement and subsequent sample analysis activities which is, in turn, folded back into the Tactical Plan.

Tactical Plans use the latest 1 m/pixel products based on a Shape-from-Shading (SfS) DEM [6] generated by the NASA Ames Stereo Pipeline [7]. The plans cover the current Lunar Day (~10–14 Earth days) and contain full detail such as DSN comm passes/handovers, selected ground team activities, etc. Updates are planned up to one release per shift.

During the mission, several Tactical Plans are autogenerated. They are ranked against the mission science goals and validated against the mission timeline before being committed to the configuration-managed mission timeline. Tactical Plans remain responsive to changes due to anomalies or opportunities. As an example of an opportunity, the VIPER surface mission timeline includes discrete “flex time” during which the Science and Engineering Teams can request specific activities (e.g., extra images, special rover positioning). It is possible that rover drivers improve on their SMG metrics as they learn how to better navigate the terrain, leading to additional opportunity. Equally, SMG might be hindered due to driver response that might slow rover progression such as navigating small craters or rocks or sunward-driving. Tactical Plans can provide a look ahead to where we might need to exit and rejoin the traverse to get back on the timeline dictated by the Strategic Plan.

Dynamic Science Operations Paradigm: By design, VIPER Science Operations is integrated with the Strategic and Tactical Planning process. Unlike Mars rover missions, VIPER’s operations demand real-time decision support in order to make progress in a challenging and dynamic lighting and communications environment. Operators and scientists have access to up-to-the-minute measurements and rover and instrument status. A team in VIPER’s Mission Science Center (MSC) advises and supports real-time operations in order to maximize science return. Prior to launch, the VIPER Science Team reviews and prioritizes Strategic and Tactical Plans as they are developed. Secondly, during multiple operational sims and readiness tests, the teams test and evaluate tools to facilitate traverse change communication. During the mission, the Tactical Planner is present in the MSC, working side by side with the scientists, as the team lays down the best science path forward while staying within the engineering constraints.

Conclusions: The lunar polar regions provide an environment where the lighting and shadows change at the VIPER’s effective 1 cm/s speed (SMG). For a solar-powered rover, planning a traverse with these constraints makes for a fascinating trade of time and position. This is particularly critical for decision-making if and when the rover needs to change its path. Getting ahead or behind has implications.

References [1] Colaprete, A. et al. (2019), AGU Abstract P34B-03. [2] Ennico-Smith, K. et al. (2020) LPSC #2898. [3] Siegler, M. et al. (2019) LPSC #6038. [4] Colaprete, A. et al. (2023) LPSC #2910. [5] Shirley, M. et al. (2022) LPSC #2874. [6] Beyer, R. et al. (2023) LPSC #2377. [7] O. Alexandrov and R. Beyer. ESS 5.10 (2018), pp. 652–666.

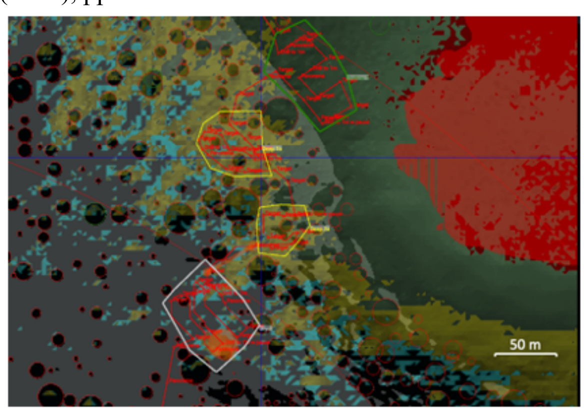

Figure 2. Example of a Tactical Traverse. Four Science Stations, outlined by colored polygonal shapes, are shown. Each are at least 3800 m^2 in size. The rover’s path is shown in red and covers both a required minimal distance per Station plus a mapping pattern. Underlain is the ISR map. Red circles denote craters to avoid. The Science Team iterates with the Planning Team to adapt the traverse and drill sites within the polygonal shapes to optimize the science return from prioritized science goals and objectives.