VIPER TRAVERSE PLANNING M. Shirley[1], E. Balaban[1], A. Colaprete[1], R. C. Elphic[1], H. Sanchez[1], L. Falcone[1], R. Beyer[1,2], S. Banerjee[3], and K. Bradner[1]. [1]NASA Ames Research Center, Moffet Field, CA (mark.h.shirley@nasa.gov), [2]SETI Institute, [3]Stanford University

The NASA Volatiles Investigating Polar Exploration Rover (VIPER) [1] will land in the vicinity of the Nobile crater near the lunar South Pole in late 2023. The mission's primary objective is to study the composition and distribution of hydrogen-bearing and other volatiles. The rover and its operational plan are still being designed. Given that, this abstract summarizes the mission's measurement goals, its environmental and engineering constraints, and the current state of traverse planning.

Mission Overview: The VIPER rover is a four-wheeled robotic vehicle weighing $\sim 450\,\mathrm{kg}$. It is solar-powered and teleoperated from Earth over a line-of-sight radio link. The rover can move at up to $20\,\mathrm{cm/s}$ on flat terrain. Accounting for commanding, localization, navigation, and obstacle-avoidance delays, however, the effective speed is closer to $1\,\mathrm{cm/s}$. The mission will last up to 100 Earth days and involve up to $20\,\mathrm{km}$ of driving.

The rover carries nine cameras including a stereo pair on a rotating mast and a downward facing camera with LEDs for wavelength discrimination. All cameras are used for science as well as for navigation or evaluation of driving hazards. Also carried are a neutron spectrometer, mounted at the front, and near-infrared and mass spectrometers mounted underneath [2]. All the spectrometers will normally operate continuously, whether the rover is driving or stationary. An augering rotary percussive drill can bring material up from a depth of $1\,\mathrm{m}$ in $10\,\mathrm{cm}$ "bites" and put that material on the surface within the fields of view of the belly-mounted instruments. The drill also contains two temperature sensors along its length.

The mission is expected to produce extensive data sets from the instruments and cameras, as well as a wide variety of derived products following the mission. These should help to answer questions about the origin and distribution of lunar polar water and other volatiles in cold traps and regolith, as well to provide data needed by NASA to assess the potential for in-situ resource utilization in lunar polar regions.

Goals and preferences for planning VIPER's traverse arise mainly from scientific considerations, while most constraints and limitations stem from rover engineering and operations as described next.

Data Collection Approach: The VIPER data collection approach is based on visiting distinct thermal environments characterized by their ice stability depth[3]. At this depth, which varies with topography, ice sublimes less than $1\,\mathrm{mm/Ga}$, making it effectively stable over geologic time periods. By discretizing depth, we produce maps containing many instances of four kinds of Ice Stability Region (ISR): *surficial* at $0\,\mathrm{m}$; *shallow*: $(0, 0.5]\,\mathrm{m}$; *deep*: $(0.5, 1]\,\mathrm{m}$; and *dry*: $(1, \infty]\,\mathrm{m}$.

A region to be surveyed is called a *science station* and must be at least $3800\,\mathrm{m}^2$. The survey takes $\sim$ 24 hours and involves driving over 224–335 m of terrain with the spectrometers active and drilling to a depth of 1 m in three locations, with one including a pause for a subsurface temperature measurement. The path driven and the drill sites will be chosen to sample different horizontal length scales (5–1000 m) and relationships to morphological features. Science stations in permanent shadow (surfical ISR type) involve drilling only once but the same distance driven.

More broadly, VIPER's traverse plan must include one science station of each type, plus two repeats at least 100 m from the earlier ones, and these stations must span a distance of 1 km. Also, the landing site must be at least 800 m from any large permanently shadowed regions (PSRs) that are visited in order to reduce the risk of contamination from the lander's exhaust.

Environmental and Operational Constraints: The rover's 1 cm/s sustained average speed is roughly the same speed with which the long shadows move around the Moon's pole. For a solar-powered rover, planning a traverse, therefore, is a little like playing pacman with the shadows as ghosts. Since VIPER will be teleoperated, it must maintain line-of-sight to radio antennas on Earth and stay out of radio shadows cast by terrain as well. Since PSRs tend to be lower than surrounding terrain, they must be visited when Earth is near its maximum elevation, which limits the available times. Also, we require a $2°$ safety margin above terrain for the radio link but allow the sun to go down to the horizon or to be slightly occluded except when driving intentionally into shadow to conduct science.

For the half of each month when Earth is below the horizon, the rover must be parked at a "safe haven" location while waiting for the Earth to rise again. These locations are safe in the sense they do not exceed the rover's ability to survive darkness because the rover cannot maneuver autonomously to stay in sun. VIPER's design is a compromise between battery capacity, the total weight of battery, mobility system, structure and instruments, and the carrying capacity of the lander. This compromise has yielded 50 hours of survival endurance in a special hibernation mode. It also allows 9 hours of normal operations in shadow, including drilling once to 1 m.

Many operational factors do not constrain the traverse path but do introduce delays that need to be accomodated within the mission schedule. Examples include calibrating the hazard cameras and absorbing Deep Space Network (DSN) coverage gaps, which may vary from 1–40 minutes nominally.

Traverse Plan Structure: Finding a traverse plan that works boils down to choosing a sequence of science stations that can be surveyed within the lighting and comm constraints near the pole.

A traverse is divided into *legs* encompassing the rover's movement and activities within one lunar day. The first leg starts at the landing site and ends at a safe haven. Last lunar day leg starts at a safe haven and may end at a disposal location or a hard-to-reach point of scientific interest, e.g., too deep in a PSR to drive back out. All other legs start and end at safe havens. We are aiming for four legs (lunar days), with a chance of going longer.

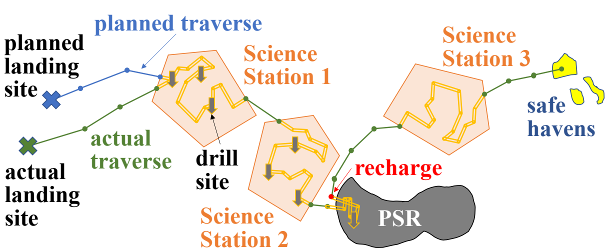

Figure 1: Example of a VIPER traverse leg.

PSRs are at lower elevation than the surrounding terrain, thus opportunities to enter a PSR occur when the Earth is near its highest elevation. Solar azimuth (and elevation slightly), controls the amount of temporary shadow the rover must cross to reach permanent shadow, and this factor further limits which PSRs can be entered during one of these opportunities. As a consequence, a leg is defined by which PSR(s) are visited during that lunar day and where in space and time the PSR entry point(s) are. The time before and after PSR entries can be used to explore the science stations along the thermal gradient between PSRs and Safe Havens. A typical leg may include several dry, deep, and shallow stations before or after one or two PSR entries.

Traverse Generation and Optimization: The number of options for planning each leg is large but not intractably large, and we have both stocastic and deterministic algorithms to generate candidate traverses. The overall goal in constructing legs and linking them together is to maximize science return while minimizing operational risk. Clearly plans that visit more PSRs and science stations are preferred as are plans that include time for the inevitable delays and disruptions. Note these factors are in opposition.

Evaluating candidate traverses on their scientific return involves estimating the number of science stations (or partially surveyed science stations) that the traverse can accomplish, which includes accounting for prospecting distances and the number of drill operations done. A more difficult task is evaluating how robust a candidate traverse is to things going wrong and how much scientific data would be returned. We do this using Monte-Carlo simulations.

We introduce uncertainties in the following quantities: time of landing, initial battery charge, power draw, SMG, and duration of science station activities. Additionally, DSN failures and Solar Energetic Proton (SEP) events are also injected. SEP events can temporarily degrade some rover capabilities like the neutron spectrometer. Most contingencies cause delays which can introduce cascading effects on the traverse due to tight sun and comm windows later.

Traverse simulations also model some responses by the flight control team on the ground. For instance, if the rover is running late, pre-planned battery recharge periods are shortened or eliminated. This can work because the rover recharges slowly while driving, but may increase risk later if another problem occurs when the battery is low. The science team can also agree to drill to a shallower depth to save time. These simulations produce probability distributions on the outcome of executing a given traverse, including critical outcomes like reaching full mission success, as well as distributions on metrics such as total distance driven.

The actual flight control team will, of course, adapt to problems and opportunities as they arise. In particular, the mission science team will fine-tune its goals frequently in response to real-time scientific findings and give new goals and preferences to the mission planners to replan a portion of the traverse.

Next Steps: Our planning to date has used $20\,\mathrm{m/pixel}$ map products based on LOLA Digital Elevation Models (DEMs), but we are moving to $1\,\mathrm{m/pixel}$ products based on a Shape-from-Shading (SfS) DEM generated by the NASA Ames Stereo Pipeline [4]. This DEM also uses LOLA as a foundation but adds a lot of detail. We don't expect to finalize the traverse until spring of 2023, when imagery from ShadowCam aboard Korea Pathfinder Lunar Orbiter [5] is available to plan the PSR entries, but the VIPER project expects to release another status report and a candidate traverse before then.

References: **[1]** A. Colaprete et al. In: *LPSC*. 2021, p. 1523. **[2]** K. Ennico-Smith et al. In: *LPSC*. 2020, p. 2898. **[3]** M. A. Siegler et al. In: *Nature* 531 (2016), pp. 480–484. **[4]** O. Alexandrov and R. Beyer. In: *ESS* 5.10 (2018), pp. 652–666. **[5]** M. S. Robinson et al. In: *EPSC*. 2017, p. 506.