A Case Study of the MER Cape Verde Approach: Challenges for Planning and Scheduling Systems*

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Abstract

The Mars Exploration Rover Opportunity has recently completed a two year campaign studying Victoria Crater. The campaign culminated in a close approach of Cape Verde in order to acquire high resolution imagery of the exposed stratigraphy in the cliff face. We believe the Cape Verde campaign provides an informative case study for developers of planning and scheduling systems. The close approach to Cape Verde provided significant challenges for every subsystem of the rover as the rover needed to traverse difficult, uncharacterised terrain and approach a cliff face with the potential of blocking out solar energy and communications with Earth. In this paper we describe the strategic analyses performed by the science and engineering teams so that we could successfully achieve the science objectives while keeping the rover safe. We discuss implications and challenges that this study raises for the developers of planning and scheduling systems.

Introduction

The Mars Exploration Rover Opportunity has spent nearly two years exploring the bays and capes of Victoria Crater. Using a rover to explore Victoria provides an unprecedented ability to peer back in time through Martian history by studying the layered sedimentary rocks and outcrop exposed by the impact. Cape Verde (Figure 1), in particular, provides a stunning example with nearly 6 meters of exposed stratigraphy. A primary goal of the Victoria Crater campaign has been to perform a close approach to Cape Verde in order to acquire high resolution panoramic imagery of the promontory.

Cape Verde proved to be an extremely challenging scientific objective for every subsystem of the rover. A close approach of the cape required the rover to traverse unknown, treacherous terrain as it moved into the shadow of the cliff with the potential of blocking sunlight from the solar powered vehicle in the middle of winter along with the potential to block out communications with Earth preventing the team from communicating with the rover if something should go wrong. The campaign required that the team perform careful analysis of every vehicle subsystem and interactions among subsystems in order to ensure that the highest quality science was achieved while keeping the rover safe. In this paper we

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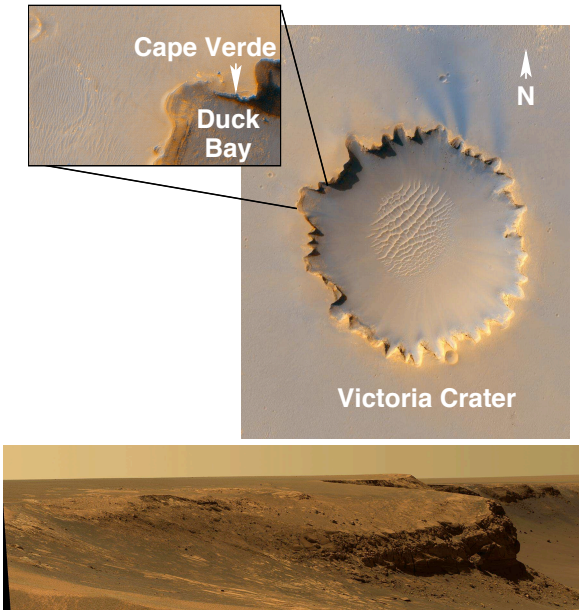

Figure 1: Cape Verde (images from MRO/HiRISE and Opportunity Rover).

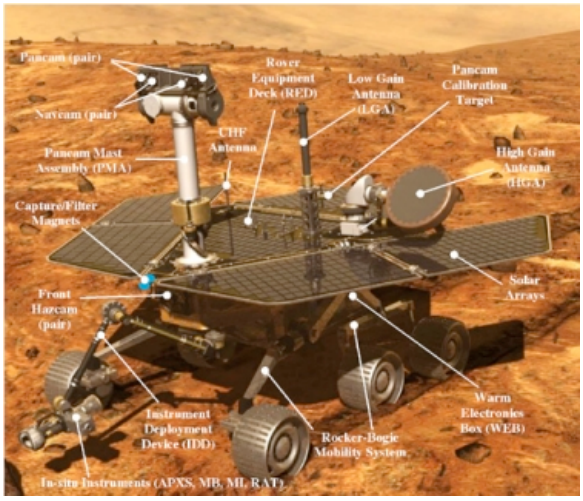

Figure 2: A Mars Exploration Rover.

recount the challenges faced by each subsystem and review the analysis that was performed in support of the approach.

The campaign provides an interesting case study for those developing planning and scheduling tools to support this type of analysis. The wide-ranging scope of the analysis combined with the high levels of uncertainty provide significant challenges for support tools. We begin with a description of the analysis performed followed by a discussion of the implications and challenges for planning and scheduling systems.

The most immediate challenge faced in the Cape Verde campaign was getting the vehicle close to the cape without getting trapped in the uncharacterized soil and slopes along the way. We describe the traversability analysis that was performed in order to identify a safe route to the cape.

One of the most sobering prospects of the operation was the fact that we were moving a solar powered rover toward the shadow of a south-facing cliff in the middle of winter with the sun low in the Northern sky. Power models that take into account occlusions of the sun from terrain had never been developed for the mission as no one had considered taking a solar powered vehicle close to a cliff. A miscalculation here could result in leaving the rover stranded in a location where it could not take in enough solar energy to heat itself through the night which could result in loss of the spacecraft. We describe how a new power model was developed to enable the team to make decisions about where we could take the rover. Additional analyses were performed on the thermal subsystem to determine how much additional system heating may be required if the rover moved into shadows.

Occlusions of the sun were not the only dangers posed by the cape wall. The wall also had the potential to block Earth as the team tries to upload new commands to the rover, and to block the rover's view of the Odyssey orbiter as it tries to send data to Odyssey to downlink to Earth. Analyses were performed to assess the impact the cape would have on the telecommunications subsystem.

The following describes in more detail the analyses that were performed by each subsystem to ensure the success of the mission and safety of the rover.

Science Objectives and Analysis

The primary goal of the Cape Verde imaging campaign was to correlate the stratigraphy at the Duck Bay ingress section with the stratigraphy observed in cliff faces during the traverse of Victoria Crater's rim. While other cliff faces were observed at typical ranges of 60 m or greater, the Opportunity rover was able to navigate to a stand-off distance of ˜10 m from Cape Verde, providing native resolutions of up to 3 mm/pixel. In addition to standard image acquisition, super-resolution sequences were employed on five high-priority science targets that were identified based on a previous imaging of Cape Verde from sol 1342 (Figure 3). Super-Resolution sequences combine information from multiple images taken from slightly different pointing geometries in order to extrapolate a new image at higher than native resolution (Bell *et al.* 2006).

Each of the five super-resolution targets were chosen to answer a specific questions regarding the unique nature of the bedding at Cape Verde (see Figures 3 & 14). Target A was intended to analyze a distinct boundary that appeared to be an erosional contact at the base of the cliff face. Target B aimed to understand dark and light bands (which appeared to be multiple diagenetic horizons) superimposed on bedding. Target C consisted of a unique erosional ridge, also superimposed on bedding. Target D was intended to capture what appeared to be grainflow strata transitioning into finer scale bedding below a possible contact. Target E was chosen to study a possible erosional contact or set boundary at the base of the cliff face, likely a longer exposure of the same surface as seen in Target A.

Cape Verde is an East-West trending promontory with a vertical exposure of ˜7 m, length of ˜25 m, and average slope of ˜$60°$ (see Figure 3). The stand-off distance to the Cape was chosen based on safety constraints and a desire to keep the camera bore-sight within $45°$ of the cliff's surface normal. Time of day was critical to successful imaging as solar illumination originated from the northern portion of the sky and commonly resulted in glinting off facets in the cliff face. This problem was exacerbated by the rover's proximity to Cape Verde, requiring the camera mast to angle up towards the sky in order to keep the cliff in its field-of-view. Optimal lighting under these conditions consisted of diffuse illumination during times when the solar incidence angle was far enough away from the angle between the target's surface normal and the camera bore-sight.

Mobility Analysis

The first challenge we faced in the Cape Verde approach campaign was identifying a safe path the rover could follow across Duck Bay to get close to the cape. Details on the MER mobility system and an overview of mobility operations with Opportunity can be found in (Biesiadicki & Maimone 2005; Biesiadecki, J. et al. 2005; Cheng, Maimone, & Matthies 2005). The general approach we took to the Cape Verde approach analysis was to first identify the closest point we could safely get the rover to Cape Verde considering traversability analysis alone. We would then use the path to get to that point as a basis for the analysis of the other subsystems. If necessary, we could back off from that closest point if it turned out it would not be safe from some subsystem perspective.

The highest concern in the traversability analysis was to avoid getting the rover stuck. Getting close to the cape was a major science objective, but we did not want to pay the price of not being able to get back out of the crater and continue exploration. The major criteria in finding a safe path were to take advantage of outcrop when possible, avoid areas that appeared to consist of deep, loose soil and favor paths that minimized the slopes the rover encountered. We also wanted to delay as long as feasible putting the rover on slopes that would tilt it away from the sun so that we could maximize the solar input to the rover during the campaign.

Much of the traversability analysis was based on slope maps which are derived from the stereo images acquired by the rover's cameras. Figure 4 shows an example slope map

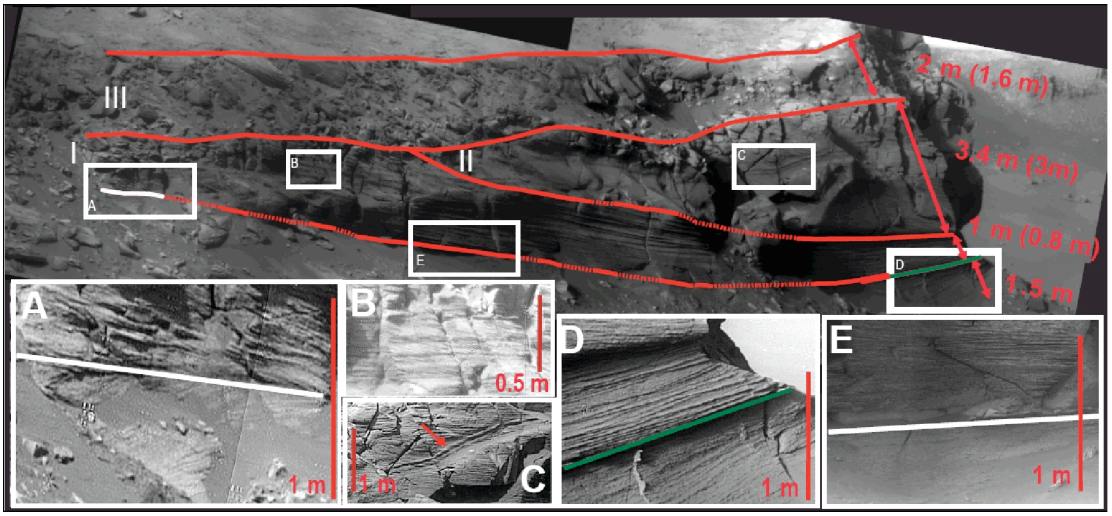

Figure 3: Cape Verde cliff face as observed on MERB sol 1371. Targets A through E represent high priority science targets that were imaged using super-resolution techniques. Please see text for a description of each target. Labels I, II, and III distinguish large-scale variations in observed stratigraphy; I. Thickly bedded dune toeset laminae (grainflow) II. Dune foreset cross-stratifications formed of climbing translatent strata with evidence for superimposed wind ripples. III. Impact breccia.

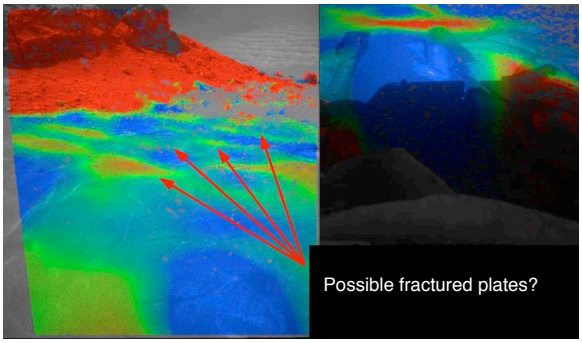

Figure 4: Slope analysis of terrain leading to Cape Verde: blue indicates slopes $< 15°$, red indicates slopes $> 20°$.

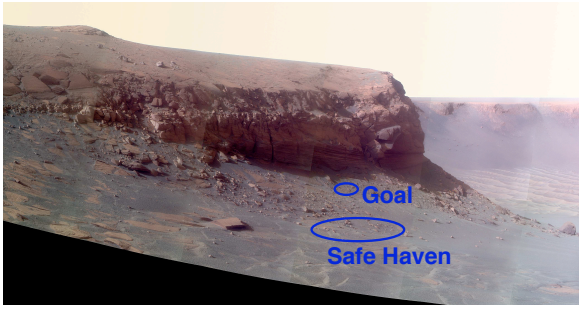

Figure 5: Key locations in analysis.

of the area in from of Cape Verde. Colors are used to indicate the severity of the slopes. In this map, blue is used for slopes less than $15°$ and red for slopes greater than $20°$. Note that close to the cape face the slopes start to increase rapidly. These slopes are also facing South, so that when the rover encounters them it would be tilted away from the sun, which in the Winter season for Opportunity was in the North.

Two key locations were identified for the campaign and are shown in Figure 5. The location labeled "Goal" was identified as the closest point we could safely get the rover taking into account traversability concerns alone. "Safe Haven" was selected as a sort of "base camp" for the final approach. This is the last area where the rover would have favorable tilts relative to the sun before climbing up the steeper, South-facing slope of the cape face. It was also our retreat location in case our power predictions were not on target and we found ourselves with too little power. We could quickly retreat back to Safe Haven and recharge the vehicle.

At the time we began this analysis, we had been exploring the interior of Cape Verde for several months and had learned some of the challenges and surprises the terrain held. The most important discovery for traversability analysis was that the terrain leading toward Cape Verde had a series of step-like features resulting in relatively sharp drops in the slope. These "steps" show up as small red regions in the slope map of Figure 4. One hypothesis to explain these features is that this area of Duck Bay consists of a series of fractured plates and the steps are the transition from one plate to the next with sand filling in the gap. In fact, we had a difficult time with one of these steps, taking several sols to extract the rover over the lip. Figure 6 is a front hazcam image taken on Sol 1557 after the rover successfully backed up over a step.

The final path we used is shown in Figure 7. After extracting the rover from the step on sol 1557, we deviated from the originally planned path and went back up-slope and toward

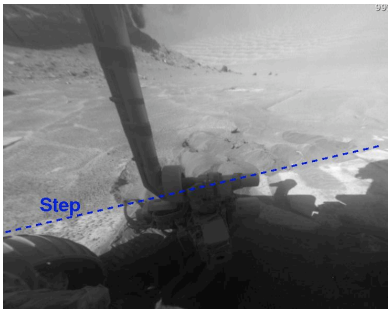

Figure 6: Sol 1557 front hazcam showing a step feature.

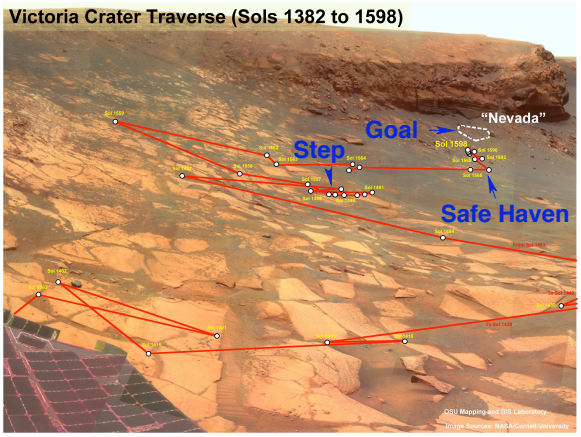

Figure 7: Actual path taken to approach Cape Verde.

the cape. This allowed us to take a route that avoided the larger of the step features that we saw in Figure 4.

Horizon Masks

A topographic map of Victoria Crater was created from a pair of images collected by the Mars Reconnaissance Orbiters High Resolution Imaging Science Experiment (HiRISE) instrument. (McEwen, A. et al. 2007; Kirk, R. L. et al. 2008). Using this topographic data, a series of horizon masks were generated. A horizon mask is a 360 degree sweep in azimuth, from a single location, showing the vertical angle to the horizon (intersection of surface and sky). For example, Figure 8 contains the horizon mask centered at Safe Haven and positioned 1 meter off the ground (the height of Opportunitys solar panels). The X-axis in the graph represents azimuth with 0 directly north and 90 directly east. The Y-axis corresponds to the vertical angle which intersects the horizon in that azimuth direction. Figure 8 indicates that, at Safe Haven, the terrain directly north of the Rovers deck (i.e. toward the cape face) is at an angle of about 23°.

For comparison, the horizon mask for the Goal location is in Figure 9. Here, the elevation due North is higher, with an elevation of about 25°. This of course make sense as the Goal location is closer to the cape face which lies to the North of the rover. In contrast, the elevations in the horizon mask in the East, South and West do not change as much

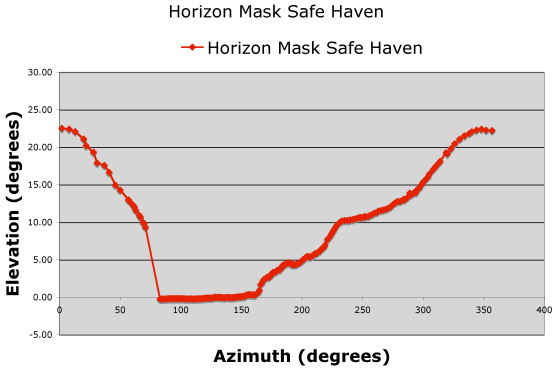

Figure 8: Horizon mask at Safe Haven (data obtained from MRO/HiRISE and USGS).

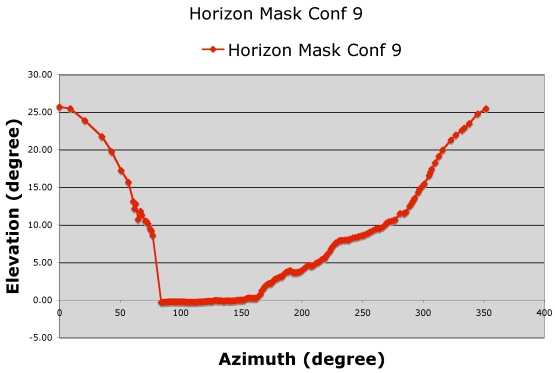

Figure 9: Horizon mask at Goal location (data obtained from MRO/HiRISE and USGS).

between these two locations.

The horizon mask played an important role in many of the analyses we will see in the upcoming sections. For example, knowing the elevation of the horizon at a given location allowed the power engineer to determine how much the terrain will block out solar energy.

Power Analysis

The Mars Exploration Rovers are powered by solar panels and two rechargeable Lithium-ion batteries which store up power when sunlight is not available or the power draw on the rover exceeds the solar input. The batteries are charged in turn when the solar input to the solar panels exceeds the power current needs of the vehicle.

Like Earth, Mars is axially tilted and, as such, the amount of solar energy varies with the seasons. Situated to the South of the equator, Opportunity and Spirit experience winter when the sun is to the North. Opportunity is near the equator so it does not have the larger fluctuations in power experienced by the Spirit rover position further South, but the variance between winter and summer can still be significant for the rover.

We had originally planned to complete the exploration of Duck Bay, including the approach of Cape Verde well before Winter Solstice on Mars when the sun is lowest in the sky and the days are shortest. However, we ended up spending extra time exploring the crater, including responding to the loss of one of the actuators in Opportunity's arm, that the actual approach to Cape Verde was to happen exactly at Winter Solstice.

To make the campaign more challenging from the power subsystem perspective, Cape Verde is a South facing cape and would potentially block out significant amounts of what little winter solar energy there was. If power levels go too low, there would be insufficient energy in the batteries to allow the rover to run heaters during the night that are critical for its survival. Thus, we needed to be extremely careful in our modeling of predicted power to ensure that we would not take the vehicle into an area where it could not get sufficient energy to stay alive.

Going into the Cape Verde analysis, the mission already had sophisticated power models that provide high-fidelity predictions of the amount of power expected for future sols taking into account a vast array of information including the time of year, the tilt of the rover, measures of the amount of dust in the atmosphere, estimates of the amount of dust on the solar panels, expected temperatures throughout the day and night, and the starting state of the batteries and the planned activities on the rover. The operations team uses these power predicts every day to evaluate the developing command sequences and verify that the planned activities are compatible with the power subsystem.

As sophisticated as the power models were, they did not take into account loss of solar energy due to varying terrain as no one had ever seriously considered driving a solar powered vehicle into the shadow of a cliff. Thus, as part of the Cape Verde analysis, a revised power model was developed that takes into account terrain occlusions.

The power model breaks the solar input into three types of solar energy: direct, direct diffuse and isotropic. Direct solar energy accounts for the majority of the solar input and is modeled as a ray from the sun to the vehicle. The horizon masks from Section along with ephemeris data to predict the azimuth and elevation of the sun over the course of a Martian day were used to determine when the terrain of the crater would occlude the direct energy of the sun. This type of occlusion corresponds to the rover being in shadow. Direct diffuse energy results from the energy from the sun being scattered by the atmosphere. It is modeled as a cylinder from the sun to the rover. As the sun changes elevation in the sky, it cuts through different amounts of atmosphere and, as a result, the diameter of the cylinder changes. Thus, the new power model tracks the diameter of the cylinder over time and again consults the horizon masks to determine how much of the cylinder gets occluded by the crater terrain. Finally, isotropic energy is energy reflected from surrounding terrain. The presence of the South facing Cape Verde while the sun is in the North means a reduction in the amount of isotropic energy from that direction.

With the revised power model, we performed a series of predictions using the horizon masks from different locations in the path from Safe Haven toward the cape face. At each location, we projected forward in time through the sols that would be required for the rover to approach the cape and return, adding in padding to account for unexpected issues. We were originally hoping to take the vehicle within 2 meters of the cape face, but our power predictions indicated that we would likely not have sufficient power during middle of winter to support such a close approach. However, the models indicated that an approach of about 4 meters would be possible.

Of course, before basing our final decisions on these brand new power models, we wanted to validate them with empirical data from Mars. Thus, during the implementation of the Cape Verde approach, we used the predictions of the power models as a guide for day to day planning and proceeded conservatively. One strategy that was used was to make use of autonomous behavior of the mobility system to stop the drive if the tilt of the rover exceeded a certain limit or if the vehicle progressed within a certain distance of the cape face. We set these limits to be sure that we kept the rover in locations where we knew it would have sufficient power even with the loss of solar energy due to the cape face. We could then look at the data that came from the rover the following day and compare it with the energy levels predicted by the new power models.

Thermal Analysis

One of the many issues that had to be addressed before going into Victoria crater was the effect that being in the crater and approaching the cliffs at Cape Verde, which would place us in the shade of the cliffs for a rather lengthy time of each Sol, would have on the temperatures of the components. In order to determine the effect it was necessary to exercise the Rover Thermal Math Model (TMM) with conditions that would be representative of those to be encountered in the crater.

The major concern was the internal electronic components. They have very narrow Allowable Flight Temperature (AFT) limits. Most of the electronics have minimum AFT limits of about -40°C. There was no concern for the external hardware since they had rather wide AFT limits. The majority of the external hardware has minimum AFT limits of $-105°$C and none of the components have shown that they were near this temperature in the past while going through the Martian winters except for the Solar Panels.

To exercise the TMM model and have it be representative of a worst case condition a sol was chosen that had low power dissipation for the activities that it was to perform throughout that sol. When the rovers drive in a given sol the drive control boards in the electronics dissipate much greater power than when science is performed. An attempt to find a sol that would have low power dissipation was desired. The one that was chosen had a Mossbauer spectrometer integration in it and therefore the Rover could actually be napping through most of the sol. And finally we performed a worst case analysis by modeling as if there were no Sun so that there was no solar insolation on the rover.

Using the power dissipation profile from the model sol the TMM was run four times in an attempt to achieve a quasi steady-state condition. The final temperatures from each run

Component	Initial Temp °C	No-Sun Temp °C	Delta Temp °C
Battery	-16	-20	-4
SSPA	-28	-35	-7
SDST	-28	-35	-7
UHF	-28	-34	-6
REM	-27	-34	-7
MTest	-60	-65	-5

SSPA =Solid State Power Amplifier
SDST=Small Deep Space Transponder
UHF =Ultra High Frequency Electronics
REM =Rover Electronics Module
MTest=Mini Test Electronics

Table 1: Conservative thermal modeling for Cape Verde approach.

were made the initial temperatures for each succeeding run and four runs made. The results turned out to be rather benign and indicated that there was no item that would experience any temperature close to its minimum AFT limit. Table 1 shows the nominal minimum temperatures for the model sol and the resulting temperatures for the runs that were made with no solar input to the model.

Telecommunications Analysis

The objective of the telecommunications analysis is to ensure that we have reliable communications with the rover during the Cape Verde approach. There are two modes of communication between the rover and Earth (Hilland, Bhanji, & Estabrook 2004). We have a direct line of communication with the rover by transmitting between the Deep Space Network and the rover's High Gain Antenna (HGA) or Low Gain Antenna (LGA) (Figure 2). This is typically referred as an X-band pass as it uses frequencies in the X-band range to transmit data. The use of the HGA is preferred over the LGA as it provides higher data transfer rates.

We can also communicate indirectly with the rover using a relay through the Odyssey orbiter. In these cases, when the rover sends data to Earth, it first sends the data to Odyssey, which in turn, sends the data to the Deep Station Network on Earth. During our extended missions, the nominal communication path is to use X-band to send command sequences to the rover and Odyssey relay to send data from the rover back to Earth.

In order to ensure reliable communications, we needed to analyze the impact of the approach to the cape on both X-band and Odyssey relay communications.

X-Band Communication

For reliable X-band communications, the rover needs an unobstructed line between Earth and the HGA of the rover (see Figure 2) during the time of the pass. There are three objects that could occlude the rover's view of Earth: 1) the rover's Pancam Mast Assembly (PMA), 2) the rover's solar panels, and 3) the terrain.

The PMA, as shown in Figure 2, includes a masthead housing the panoramic and navigation cameras. It is possible that the masthead can be positioned in such a way that

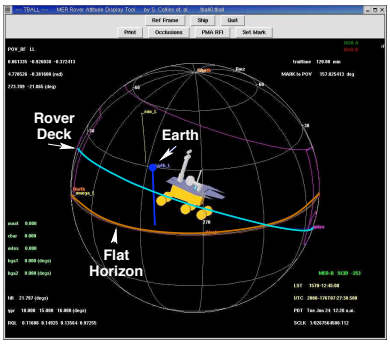

Figure 10: Using the TBall tool to check for rover deck occlusions for X-band pass on Sol 1570.

it could block the line between Earth and the HGA. Fortunately, the HGA can actuate and, in these situations, the rover can re-position the antenna to avoid the PMA occlusion. Onboard software handles these cases automatically.

Depending on the tilt of the rover and the location of Earth in the Martian sky, the rover deck can also act as an occlusion during an X-band pass. The position of the Earth in the Martian sky depends on the time of year and time of day. Thus, we had to check for occlusions for the range of sols in which we would be conducting the approach and at the times of day we would be attempting to communicate with the rover. X-band passes are usually scheduled in the late morning but, depending on Deep Space Network scheduling, can occur earlier or later.

We have a tool called TBall which helps us check for these PMA and rover deck occlusions. TBall allows the user to specify a sol and time of day on that sol along with a rover attitude (roll, pitch and yaw). It then plots the plane representing the rover deck relative to a flat horizon. It also shows the position of the Earth relative to the rover deck and plots the path the Earth will follow. It is then a simple matter of determining at what time the path of the Earth crosses below the plane of the rover deck. An example TBall plot is show in Figure 10. This is for the X-band pass on sol 1570. This was a relatively late pass starting at 12:45. By the time the pass is over, at 13:05, the Earth is still well above the rover deck.

In preparing for the Cape Verde approach, we ran TBall for several uplink windows within the range of sols in which we would be performing the approach. In particular, we made sure we picked sols when we had X-band passes later in the day, as the Earth would be lower in the horizon at those times. We used the rover's attitude for the Goal configuration as this had the highest amount of tilt, and thus, the greatest chance of the deck interfering with communications. Fortunately, we found that the deck would not be in danger of occluding Earth during our planned X-band passes.

The final analysis with respect to X-band communication was to determine if the cape itself would occlude Earth during an X-band pass. Again, we looked at several of the X-band passes that would occur during the sols of the approach

to see how the Earth trended toward the terrain. We used ephemeris data to predict the azimuth and elevation of the Earth with respect to the rover in the mid-morning (the earliest time for an X-band pass) and mid-afternoon (the latest time for an X-band pass). We compared the Earth azimuth and elevation with the elevation of the terrain at that azimuth as reported in the horizon masks (Section). We found cases where, if there were a mid-afternoon X-band pass, we would be in risk of the terrain occluding Earth, but fortunately, we did not have X-band passes during those times.

In the end, it was determined that neither the tilt of the vehicle nor the proximity to the cape would pose a problem for our X-band communications.

Odyssey Communication

Both the Opportunity and Spirit rovers use the Odyssey (ODY) orbiter regularly for returning both rover engineering and science data. Using the UHF link instead of X-band is less power intensive for the rover and yields much higher data returns because the Orbiters are able to continually track and downlink data to Earth at higher return data rates. Over 90% of MER rover data has been sent through Odyssey. Odyssey is considered the prime nominal downlink source for planning in the MER extended mission.

The rover can see the Odyssey orbiter on an average of 4 times per sol, the orbiter passes are distributed between midnight and sunrise (a.k.a. AM passes), and from midday to late afternoon (a.k.a. PM Passes). The project generally only uses ODY overflights that are above 10° in max elevation. Passes above 10° in max elevation can range in duration from 10 to 15 minutes, and the return link data rate from the rover to both orbiters can be up to 256 kbits/s but are usually 128 kbits/s.

Rover azimuth strongly affects link performance. Figure 11 provides an example of Odyssey overflights variability of the data volume returned showing the effects of various rover azimuths. The analysis was done using 3 basic horizon masks, 5°, 10°, and 20° elevation horizon masks. These are simple masks that assume a flat terrain. Even though we are able to apply these horizon masks easily to predict data volumes, we were not able to apply the same global horizon mask while inside Victoria crater and for the approach to Cape Verde because the terrain was highly variable and required a higher fidelity horizon mask.

Using the custom Cape Verde horizon masks obtained using MRO orbiter data along with the general ODY overflight geometry files delivered by the MER Navigation and Strategic teams, we were then able to merge all the provided data together using a MER tool to generate plots for analysis. Figure 12 is an examples of the plot for Sol 1571. The plot has azimuth angles along the X-axis and elevation angle of the terrain or the Odyssey spacecraft along the Y-axis. The horizon mask used for the figures is for the Safe Haven location. The red curve is the same as the curve shown in Figure 8. The plot has the available Odyssey UHF passes that are above 10° in elevation per Sol, labeled with an identification number used by the MER project ground and flight software (i.e. 45740, 45743). The first number, 4, of the 5-digit id is for Odyssey UHF windows only, the next three

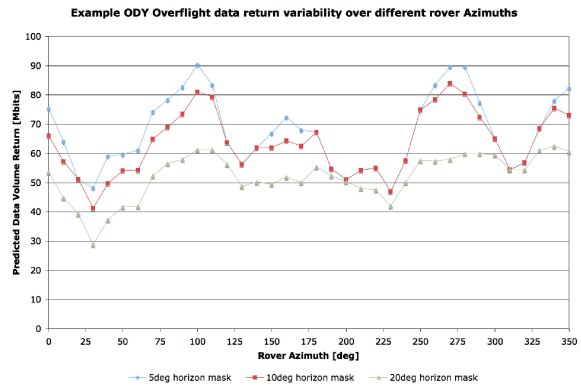

Figure 11: Predicted UHF pass volume versus rover azimuth for 3 different horizons masks applied.

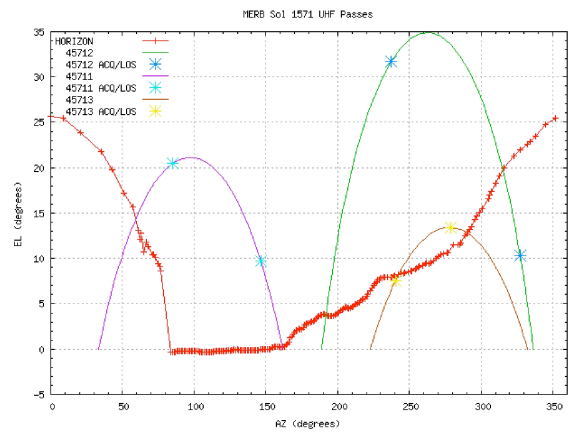

Figure 12: Sol 1571 Odyssey overflight geometry with terrain mask for Safe Haven.

digits represent Sol number and the last digit is for a nighttime or daytime UHF pass. If the last digit is even then its a nighttime pass and if the last digit is odd, it is a daytime pass.

For Sol 1571, the lower elevation pass, the 45713 line, is almost completely obstructed by the terrain. In those cases, we would use the other UHF pass shown, in this case, 45711 (which is the other daytime UHF pass), which is only obstructed at the beginning of the pass. In general the MER ground process picked the higher elevation of the two passes, so this analysis only confirmed that the strategy did not need to change.

Figure 13 illustrates a case where choosing the higher elevation out of the two daytime passes was not optimal. In this case, the higher elevation pass, 45673 is more occluded by the terrain than the lower elevation pass, 45671. In general, this geometry occurred approximately once in every 20 sols, so it would not be a significant impact to rover operations near Cape Verde.

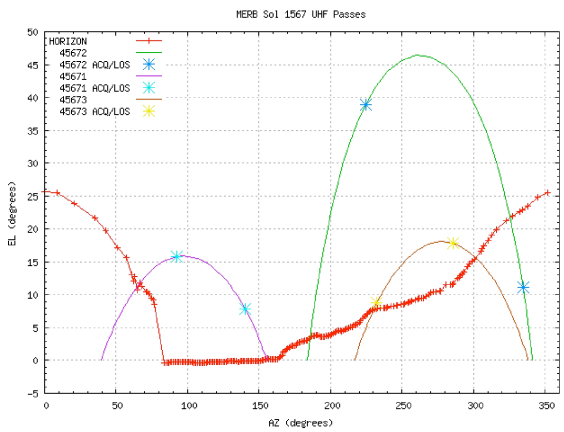

Figure 13: Sol 1567 Odyssey overflight geometry with terrain mask for Safe Haven.

Results

Figure 7 shows the path the rover took to reach its closest point of approach to Cape Verde. As can be seen in the figure, we did not quite get to our intended goal location. Traverses on the steep terrain just South of the goal proved to be extremely challenging. Rover plans had to be crafted very carefully to deal with the high degree of slippage and to avoid running into rocks in the area.

We debated whether or not to re-evaluate our goal location and even considered halting our approach at this location when, on sol 1600, the rover experienced an anomaly with the drive motor on its left front wheel. An unusual current spike was detected by onboard software and the drive was stopped early. The data looked eerily similar to the data observed on the Spirit rover soon before Spirit lost the drive motor on its right front wheel. This caused heightened concern that Opportunity might soon lose its left front drive motor. We had little hope that we could get Opportunity out of Victoria with only 5 functional wheels. As a result, it was decided that it was time to leave the crater and we began the process of driving Opportunity back out of Duck Bay.

Despite not reaching the original goal location, the Cape Verde approach was able to achieve our science objectives. The imaging campaign successfully captured all of the features of interest in the cliff face. A mosaic taken at dusk using the L1 filter (sol 1580) produced a very useful mosaic of the entire promontory. This mosaic revealed that Cape Verde primarily consists of low angle cross-bedding, with a light-toned diagenetic band crosscutting the physical stratigraphy. At the base of the cliff there is an erosional surface that may help to correlate the physical stratigraphy exposed at Cape Verde with stratigraphy seen in the ingress path, and elsewhere in the crater. The east side of the promontory produces a different geometry, revealing trough-like cross-bedding similar to that seen at Cape St. Mary.

In addition to the L1 panorama, super-resolution images of Targets A, E and D provided useful information regarding the erosional surface at the base of Cape Verde, and Targets B and C investigated possible diagenetic horizons

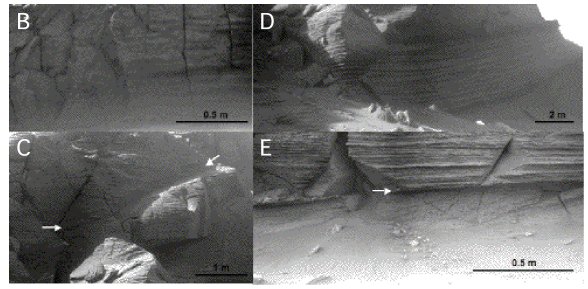

Figure 14: Cape Verde super-resolution science targets. A; Target A (not pictured) was not well exposed in the sol 1575 viewing geometry, but appeared to expose the erosional contact at the base of the Cape from the sol 1342 viewing geometry (Figure 3). B; Target B consists of light and dark bands that at first appeared to be possible multiple diagenetic horizons. However, the super-resolution image suggests that there are not multiple diagenetic horizons, and the bands are simply the result of variations in basaltic sand content, and the weathering style. C; Target C was selected to study the erosional ridge (white arrows). It appears that the ridge might be the result of wind abrasion, as sand built up on the ledge below, and the area just above the ledge was preferentially eroded (the ridge parallels the ledge). D; Initial images of Target D suggested that perhaps there was evidence for grainflow, but the super-resolution images from sol 1575 suggest that this target exposes an oblique cut through a large dune. E; Target E clearly captured the erosional surface at the base of Cape Verde. This surface holds high scientific value in trying to correlate the stratigraphy in the ingress path with the stratigraphy exposed at Cape Verde, and other promontories.

and ridges (Figure 14). The surface at the base of the cliff face (Targets A, D, E) is clearly an erosional surface, separating low-angle cross-beds in the cliff face from higher angle bedding exposed in the scree slope below the cliff. What initially appeared to be evidence for grainflow on the east side of the promontory (Target D), can actually be explained by a change in the cliff face geometry, producing the change to trough-like cross-bedding. Additional clarification was reached regarding the possible multiple diagenetic bands (Target B), which can be explained by variations in the basaltic sand content of individual beds. Details revealed in super-resolution images suggest that the erosional ridge (Target C), might be the result of wind abrasion through preferential erosion, as sand built up on the ledge below the current ridge. These conclusions would not have been possible without the additional detail provide by super-resolution imaging. Additional details are provided in Figure 14.

In addition to improving our geologic understanding of the Victoria crater stratigraphy, this campaign led to improvements in processing super-resolution images and imaging under difficult lighting geometries. Even after four years on Mars, operating the MER spacecraft is still a learning process. Difficult lighting geometries associated with trying to image a south-facing cliff during southern hemisphere

winter, when the sun is mostly behind the cliff face, resulted in initial versions of the super-resolution images producing artifacts such as hot pixels, large lighting gradients, and cat scratches (faint white trails visible in some of the images). Modifications of the super-resolution algorithms have been created to reduce the magnitude of these effects and will be used to process both past and future super-resolution imaging sequences.

Challenges for Planning and Scheduling

The Cape Verde campaign provides many challenges for planning and scheduling systems. The previous sections described a variety of tools that were essential in the formulation of our strategic plan, however, as will be discussed, there is great potential for support tools that can help manage the complexity and scope of this type of analysis. It should be noted that the MER project makes use of planning and scheduling technology on a daily basis. The MAPGEN mixed initiative planner is used as part of tactical planning (i.e. operations planning for a particular day of activities) (Ai-Chang, M. et al. 2004). While MAPGEN is a integral part of tactical planning for MER, the type of long-term, strategic analysis performed for the Cape Verde campaign was beyond the scope of this tool. However, MAPGEN was used as part of the tactical operations that implemented the strategic plan for the actual approach of Cape Verde.

One of the most challenging aspects of the Cape Verde approach analysis was the scope of the planning problem. The approach required careful analysis across every vehicle subsystem including science payload, mobility, power, thermal and telecommunications. Each subsystem was represented by one or more experts who participated in the analysis. Thus, any support tool must be able to coordinate a large set of users with varied backgrounds.

Further, the various subsystems require significantly different domain knowledge to support reasoning. In order to ensure that science objectives are achieved and high quality data products are collected it is necessary to reason about trade-offs between the different times of day, and resulting lighting conditions, for when an image is acquired as well as the relative value of acquiring images at different distance from and angles with respect to targets of interest. Power analysis requires an knowledge of the relation between power loads, battery charge, solar energy production and its relation with atmospheric and terrain conditions. Telecommunications analysis requires reasoning about orbital geometry of relay satellites and the vehicle's attitude with respect to Earth, orbiters and the surrounding topography. Even Mars weather experts were consulted during the analysis to get predictions on wind and dust trends that could be expected.

The tight coordination required across these subsystems provides another significant challenge. Every decision from each subsystem has implications across other subsystems and ultimately affects how well the campaign objectives are achieved and what risks are incurred. The science objective impose requirements on how close the rover must get to the cape which, of course, has direct implications on the mobility subsystem. And conversely, the mobility subsystem feeds back to the science requirements regarding how close the vehicle can feasibly and safely approach the cape. The proximity to the cape has significant impact on the amount of solar input to the rover's solar panels, thus, directly impacting how much power the vehicle will have to accomplish its tasks. The science objectives also impose data volume requirements as the rover has a finite storage for images. This must be taken into consideration with the expected rate at which data can be relayed through orbiters which, again, could be impacted by the proximity to the cape. The lighting requirements for the imaging combined with power predictions and telecommunications constraints for downlinking data combine to determine how many days will be required for completing the imaging campaign. Because power is directly tied to Mars seasons, this planning horizon was an integral part of the planning.

These are just a few of the examples of how interconnected the reasoning becomes. While the team has tools that can support the individual analyses, there is great potential for tools that can help assess the impact decisions in one subsystem have on the others and that can help organize and manage the trade-space.

Many aspects of the analysis had to be performed in the face of limited or highly uncertain information. Perhaps the biggest source of uncertainty was the days during which the campaign would be executed. The analysis was performed while Opportunity was investigating and achieving science objectives within other areas with Duck Bay. The Cape Verde approach was to be completed after these other objectives were accomplished and prior to Opportunity exiting the crater. In addition, since Opportunity would be traveling over uncharacterized terrain it was extremely difficult to predict how long it would take to reach different locations along the way. Since it was difficult to predict how long these activities would take, the timeframe, including the start date and duration, for the Cape Verde campaign was a continually moving target. As we were literally in the middle of the Martian winter, solar energy input was highly dependant on the specific day. Fortunately, the weather was stable for this timeframe, otherwise, the potential for dust storms and elevated atmospheric opacity would have contributed greatly to the uncertainty in the analysis.

Another important source of uncertainty was predictions of the rate at which dust would accumulate on the solar panels. This is an important factor for the power models as the dust on the solar panels directly impacts the ability of the panels to produce energy for the rover. Reasonable estimates were made to support analysis. Later, as the timeframe for the approach changed, new predictions were made based on current conditions and propagated through the analysis. This resulted in revisiting past decisions to re-assess the situation in light of the new information.

Another challenge is the coordination with mobility planning and analysis that needed to be performed (often on a daily basis) to enable Opportunity to approach Cape Verde. Drive paths and conditions can have a large effect on overall rover resources. These effects need to be estimated by a planner when creating or modifying a plan. Even small changes to drive time and power requirements can have sig-

nificant effects on other subsystems. Changes to the drive path, rover attitude and terrain conditions must also be constantly monitored since they have large effects on current rover state. A planner will need to continuously monitor different mobility states so that a future plan can be updated to take any changes into account.

When creating a plan of future activities, the path the rover will take has obvious implications on both power and time requirements. Further various terrain conditions, such as loose soil or high tilt, both of which cause high slip, can also significantly affect the time a drive will require. Since rover attitude is typically directly affected by the drive path, mobility issues can also have a large effect on items such as overall rover power (due to the angle of the solar panels) and communication bandwidth, which as mentioned previously can be largely affected by the rover's attitude during communication passes. Sometimes a change in rover path or attitude can be performed during a drive (such as turning the rover to a particular heading at the end of a drive) to enable a strong line of communication with an orbiter or to place the rover solar panels at a better angle to the sun. However this type of activity also requires time and energy and often such a maneuver was not possible in Victoria Crater due to terrain conditions and other safety concerns. A planner will need to balance these constraints and often make trade-offs about what subsystem requirements need to be high priority. For instance, there are a number of hard constraints for mobility alone that must always be met in order to keep the rover safe and fully operating. There are also a number of soft mobility constraints that may improve the rover's operation conditions but are not required to keep the rover out of danger (e.g., driving a particular path may improve the amount of data that can be sent to Earth at the end of the drive but may not be necessary to send only critical data.).

In order to estimate the effects of a drive path or other mobility concerns on a plan, a planner will likely need to interface with separate subsystems that can help estimate these conditions. For instance the effects of a drive path on rover attitude (e.g., rover tilt) could be provided to the planner through software tools that estimate slope conditions based on stereo imaging. The planner will also need to accept different forms of manual input including the determination of the actual drive path (which for Victoria was done by operators on the ground) and different types of terrain in formation (such as where high slip areas might be found).

Mobility issues can have both short- and long-term effects that must be balanced during planning. For instance the current rover power state might affect the drive path that is chosen for the next day (e.g., a rover may be driven along a certain heading to optimize solar energy), however the path may also be effected by long-term science, communication or thermal concerns. As mentioned previously, driving near a cliff (or other large terrain feature) can affect all of these subsystems. In many cases, drive paths through this type of area would be avoided so that negative effects on these resources would occur. However in the case of Victoria, a drive path that took the rover close to a piece of outcrop was important enough scientifically that it outweighed other concerns.

Conclusions

The Cape Verde approach campaign proved to be an exciting and challenging operation that resulted in the collection of highly valuable science data. The operation required strategic analysis across every rover subsystem to ensure that high quality data could be collected while ensuring the safety of the spacecraft. We have discussed a variety of challenges that planning and scheduling systems will face in order to provide support for this type of analysis. At the same time, there is great potential for tools that can help users manage the scope of reasoning, breadth of knowledge, and uncertainty of information inherent in space exploration.

Opportunity is now out of the crater and embarking on a 12km trek to Endeavour Crater. The journey to Endeavor and the crater itself promise even more exciting science and engineering opportunities and challenges.

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