Space Mission Scenario Development and Performance Analysis Tool

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Abstract—This paper discusses a new and innovative approach for a rapid spacecraft multi-disciplinary performance analysis using a tool called the Mission Scenario Development Workbench (MSDW). To meet the needs of new classes of space missions, analysis tools with proven models were developed and integrated into a framework to enable rapid trades and analyses between spacecraft designs and operational scenarios during the formulation phase of a mission. Generally speaking, spacecraft resources are highly constrained on deep space missions and this approach makes it possible to maximize the use of existing resources to attain the best possible science return. This approach also has the potential benefit of reducing the risk of costly design changes made later in the design cycle necessary to meet the mission requirements by understanding system design sensitivities early and adding appropriate margins. This paper will describe the approach used by the Mars Science Laboratory Project to accomplish this result.

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1. INTRODUCTION

The objective of the MSL mission is to measure the potential habitability of life on the surface of Mars. The enhanced MSL rover, as compared to the existing Mars Exploration Rovers, is planned to launch in 2009 and have a lengthy surface lifetime of one Mars year (approximately 2 Earth years) or more. As such, the project management was primarily interested in analyzing the Mars rover and its surface operations. For the purposes of brevity, this paper will only address Mars surface operations, however the approach presented and the tool can be used in other mission phases and mission types as well.

At the Jet Propulsion Laboratory (JPL) the life cycle of a deep space mission normally goes through six phases, each culminating with a review by project management and its funding agencies [1]:

- **Pre-Phase A:** Advanced Studies
- **Phase A:** Mission & System Definition
- **Phase B:** Preliminary Design
- **Phase C:** Design & Build
- **Phase D:** Assembly Test & Launch Ops
- **Phase E:** Operations

Generally speaking, once a JPL mission concept is accepted, the project moves into Phase A where the formulation phase begins with more formality and systems are defined in greater detail. The mission requirements and concept are refined to establish a more optimal design rather than just a feasible one. The product of this process is a mission architecture characterized such that its effectiveness in achieving mission objectives can be properly evaluated. Two important aspects of the mission architecture are the flight system and the mission activity plan. The Mission Scenario Development Workbench (MSDW) was used during this formulation phase to help refine and optimize the flight system design and mission timeline.

The purpose of the space vehicle flight system is to transport the payload safely to its destination and enable the

[2] IEEEAC paper #1613, Version 3, Updated December 20, 2004

return of science data to Earth. Typically the flight system is composed of several subsystems [1]:

- Power Subsystem
- Command & Data Handling Subsystem
- Telecommunications Subsystem
- Propulsion Subsystem
- Mechanical Subsystem
- Thermal Subsystem
- Guidance Navigation and Control Subsystem
- Spacecraft Flight Software

Each subsystem is responsible for a particular function, such as electrical power distribution, and has design characteristics like solar array size, solar cell technology, secondary battery size and battery cell technology. Designing these subsystems to meet payload, trajectory, communication and activity requirements within the mass, cost and performance constraints of the project is vital for achieving mission success.

The mission activity plan is a time ordered sequence of events that establishes how the space vehicle flight system and its instruments will be used during the course of the mission. To develop this plan, mission planners perform a series of analyses to better estimate subsystem performance and determine how effective the proposed design is at achieving mission objectives. Often, these analyses use worst case estimates with large margins subject to the best judgment of the analyst. The effectiveness of the mission can be better and more consistently assessed earlier in the lifecycle if the activity plan can be integrated with higher fidelity models that can provide the anticipated performance of the subsystem, thus reducing the chance of errors later in the lifecycle and ultimately reducing mission cost and enhancing effectiveness.

This paper discusses how mission planning and system design specification spreadsheets were integrated with higher fidelity multi-mission simulation models to create a spacecraft multi-disciplinary performance analysis tool called the Mission Scenario Development Workbench (MSDW) for the MSL Mission. Our goal in developing this tool was to enable rapid mission planning and flight system/instrument hardware trades and provide a means to accurately evaluate the system's performance early in the project lifecycle.

We begin with a brief overview of the surface mission planning process. The paper then discusses the MSDW framework. It goes on to describe models used in this framework, and concludes with the results of this effort and outlines areas for future work.

2. Surface Mission Planning Process

The Mars surface mission planning process begins with the development of an equipment list and a baseline scenario. The equipment list is the flight system engineer's best estimate of the space vehicle design. It is composed of several spreadsheets that describe the design parameters of assemblies and instruments on the spacecraft. Many of these items are consumers of resources that can be described as having discrete states. In general, these assemblies are grouped by the resource they consume. For example, the power equipment list (PEL) records assemblies that consume power by operating state.

Consumers of other resources such as computer bus or data bandwidth are maintained in other spreadsheets. Sheets for describing assemblies that produce resources or whose behaviors cannot be described with discrete states, like batteries and solar arrays, also exist. Since the interaction of all these devices within the system can be highly complex, their behavior cannot be captured accurately in a spreadsheet. Instead they are simulated with separate computer programs written in a high-level language as will be described later in the paper.

The mission baseline scenario is the mission planner's best estimate of how the space vehicle will be used in operations. It consists of a time ordered sequence of events as well as estimates for total data returned to Earth and system power/energy consumption. The level of fidelity in the mission plan matches the level of fidelity of the equipment lists.

The process for developing a baseline scenario is shown in figure 1. It begins with an activity template that outlines the commands necessary to meet high-level mission objectives. Generally one command specifies all the activities required to carry out one day's worth of activities (a Mars day is referred to as a "sol", short for solar day). On MSL the activity template consisted of:

- 6 sols of Reconnaissance (where the rover is looking for potential targets to analyze)
- 50 sols of Science (sample and rock analysis)
- 15 sols of Traverse (driving to a new location)
- and possibly some Recharge sols (minimum energy day required to recharge the batteries typically after driving)

Next, a list of data relay orbiter passes was developed. The list includes orbit start and end times, as well as estimates of data volume throughput. These are used to model the transmission of data from the MSL rover on the surface, via an orbiting relay asset, to the Deep Space Network antennas and finally to the ground processing team at JPL. A model of the ground process is used to estimate the total time required to analyze rover data, and generate the command set for the next sol. The set of times produced by these models is combined into an activity timeline. Once this is completed the timeline can be used to analyze the effectiveness of various mission trades.

The MSL mission has many choices of where and when to land so the mission planner develops a scenario for each of these sites by requesting actual orbiter view times and orbiter transmission rates at a variety of plausible landing times, latitudes and longitudes from the telecommunications system engineer. They then choose the best relay orbiter for each of these sites and incorporate actual view times and available data volumes for relay in the activity plan.

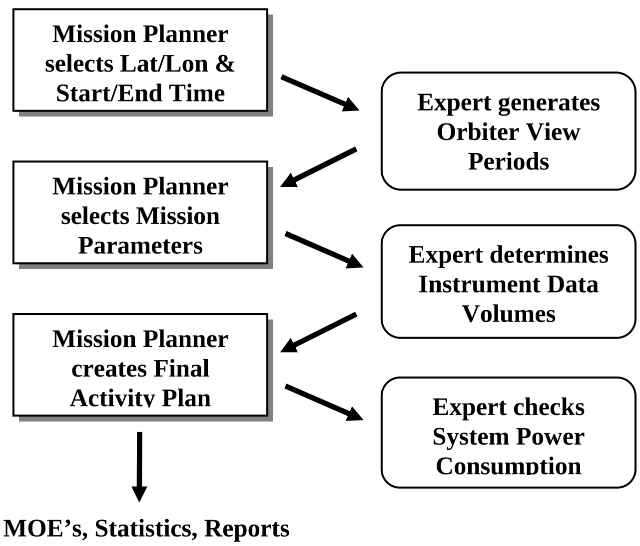

Figure 1 –Mars Surface Mission Planning Process

Of course science instruments and cameras generate the data that must be transmitted to Earth. To get a better estimate of these data volumes, the mission planner consults the Command & Data Handling (C&DH) system engineer. In this case because of the complexity of the C&DH subsystem, the engineer uses their best judgment along with sufficient margins to determine the available data volumes. The same is true for the space vehicle power consumption – the power subsystem is also rather complex so the domain experts traditionally add up the loads and include sufficient margin to determine whether the mission has adequate operational and survival power.

3. MULTI-MISSION MODELS

The main objectives of MSDW were to decrease the amount of time required to perform subsystem performance analyses and improve the accuracy of the mission plan by using the anticipated performance of the subsystems rather than worst case estimates. To accomplish this, we developed credible simulation models of the power, telecom and C&DH subsystems. More specifically, the simulations required a multiplatform library deployment with all of its design characteristics and state variables parameterized, and accessible through an Application Programming Interface (API). The API also allowed the user to enter an activity plan and trajectory. Moreover, the simulations would need to use actual flight project data to quickly predict the resources and performance of the subsystem over the mission timeline, and would need to run in a closed loop manner with environment models that were, preferably, already integrated. Lastly, while not specifically required for this task, we wanted the simulation to be able to respond dynamically to inputs from other subsystems for compatibility with future research efforts. Given these requirements we choose to use the Multi-Mission Analysis Tool suite.

The Multi-Mission (MM) Analysis Tools are a suite of proven subsystem simulation models used at JPL [2]. They are multiplatform software simulators currently used in Mars Exploration Rover (MER) operations team to predict the performance and resources of space vehicle before a sequence of activities is uploaded. The simulations can provide variable fidelity and produces dynamic time and sequence dependent results rather than static point solutions. As such, they model the behavior of devices as they respond to spacecraft events/commands and the environment over a mission timeline at a level of detail appropriate to each stage of the project lifecycle, which in MER's case was operations. The models in MM suite currently include:

- Power/Thermal (MMPAT)
- Command & Data Handling (MMCAT)
- Telecommunications (MMTAT)
- Propulsion (MMPROP)

It is anticipated that additional models for Structural (MMSTRUC) and Guidance Navigation and Control (MMGNC) subsystems will be developed in the next year.

All of the models were developed by subsystem experts or adapted from validated heritage models. The tool itself comes with models for many of the most commonly used assemblies used on space vehicles today. All of these models have been validated using previous or current missions, such as Pathfinder and MER, and give an accurate prediction of the system performance and resources.

The parameterized interface allows the user to apply the tool to other types of missions and other mission phases of the same mission. It can support planetary orbiters, heliocentric orbiters in various phases like cruise, landed and orbiting and can also support critical events such as flyby, TCM and EDL. This is possible because the simulations are controlled by model parameters and were designed to be data-driven, modular and multiplatform. This also means the models can be expanded to include additional hardware types. Moreover, the application can be deployed stand-alone or as

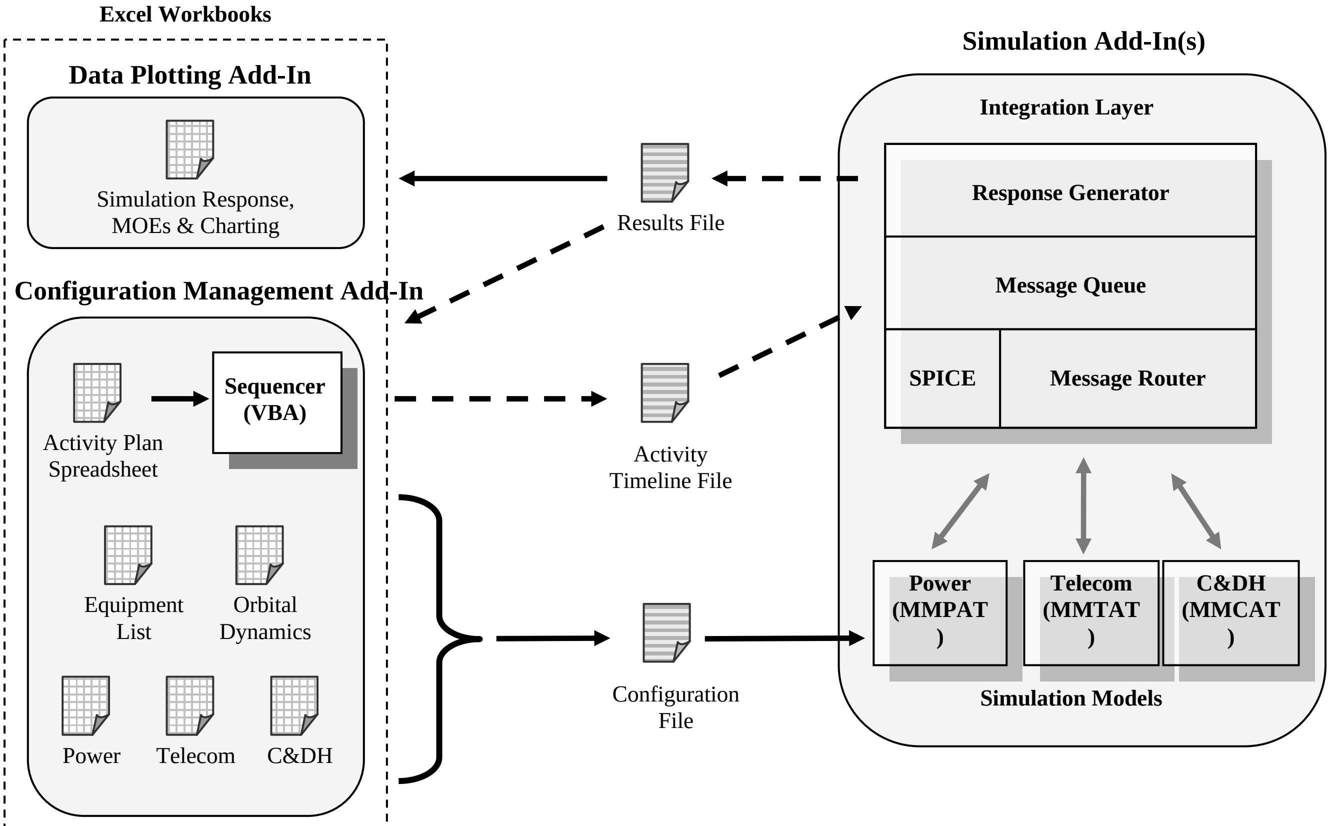

Figure 2 –Mission Scenario Development Workbench (MSDW) Architecture

a library in another application. In our case the tool was integrated with mission activity planning spreadsheets.

4. MSDW FRAMEWORK

Having specified the spacecraft equipment list and baseline activity plan in spreadsheets, our next task was to create a framework that would allow the mission planner to incorporate the subsystem model libraries into the mission planning process. The MSDW architecture is shown in figure 2. The software was deployed as Excel add-ins since mission planners traditionally use Excel for their activity plan development. There are five add-ins in the workbench: a Configuration Management add-in, three simulation add-ins and a Data Plotting add-in.

The Configuration Management add-in consists of the mission's equipment list and activity plan spreadsheets as well as some VBA code to generate the data files needed to drive the simulation. The activity plan spreadsheet is used by the mission planner to describe the activities the space vehicle will perform. When the plan is completed the user generates an activity timeline file through the Configuration Management GUI. This file is simply an ASCII text file with a time-ordered sequence of events that is read into the simulations integration layer message queue and executed when the simulation begins.

The equipment list spreadsheets are used to express the space vehicle design. When a design is specified, the user uses the Configuration Management GUI to generate a configuration file. This file is another ASCII text file that describes the space vehicle design in way the simulation models understand.

There are three simulation add-ins one for each analysis that the mission planner needs as shown in figure 1. The first add-in is an Orbiter View Times Generator that reads in the start time and latitude/longitude of the mission and generates relay orbiter view times based on the telecom subsystem configuration and relay orbits. The second add-in is a Data Volume Generator that determines the data stored in the system based on the usage and configuration of space vehicle instruments and command & data handling subsystem configuration. The last simulation add-in is the Power Simulation which executes the activity plan and checks to see if it violates any power subsystem constraints, such as running out of secondary battery energy.

Although there are three simulation add-ins, the simulation models are complied into a single C++ library. This greatly simplifies the software deployment and calling sequence. Essentially, the mission planner follows the same process as before except instead of referring to domain experts the simulators are called. From a software point of view the calling sequence is just a loop as shown by the dashed arrows in figure 2.

5. MSL MSDW RESULTS

MSDW was used to evaluate various MSL mission scenarios. The mission planner stepped through a variety of design parameters, and used the tool to review the effect each choice had on various mission performance statistics including mission duration, number of science goals achieved, and power profiles. A detailed activity timeline was produced for each scenario showing the timing associated with science activities on board the rover, Mars relay orbiter passes, and sequence generation processing on Earth. The activity plan tracked events in both UTC and local Mars time.

Each simulation run resulted in a set of tables and graphs that depict the relationship between major surface mission activities, return of critical data to Earth, generation of sequences, and uplink of commands to Mars and the flight system performance and resources. The user can change key design parameters while viewing these charts, and evaluate the effect on major mission goals in real time. A sample set is shown below in figures 3 – 8.

Time (UTC)	Time (LMST)	Duration (sec)	Data Volume (Mbits)	Orbiter
	0:00:00			
2010-12-09T21:53:08.999	3:11:18	578	261.448	MRO
2010-12-09T22:14:25.999	3:32:01	4897	84.224	MTO
2010-12-09T23:05:12.999	4:21:27	674	149.184	ODY
2010-12-10T01:02:52.999	6:15:58	687	11.424	ODY
2010-12-10T08:42:55.999	13:43:42	447	155.632	MRO
2010-12-10T10:33:56.999	15:31:45	502	136.012	MRO
2010-12-10T11:23:24.999	16:19:54	532	121.212	ODY
2010-12-10T12:05:20.999	17:00:42	1268		MTO
2010-12-10T13:20:01.999	18:13:23	749	516.48	ODY
2010-12-10T17:43:17.999	22:29:37	2173	4.808	MTO

Figure 3 –Relay orbiter view periods and estimated data volume throughput

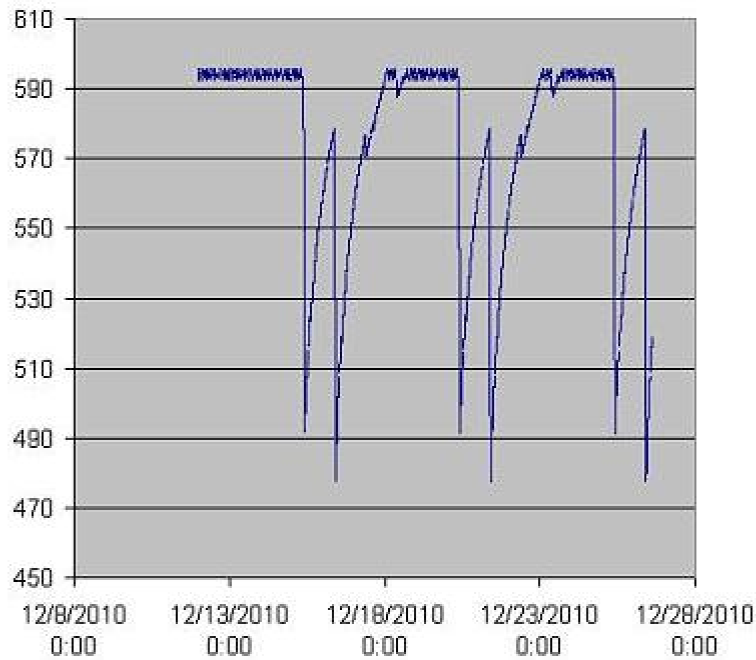

Figure 4 – Secondary battery state of charge in watt-hours

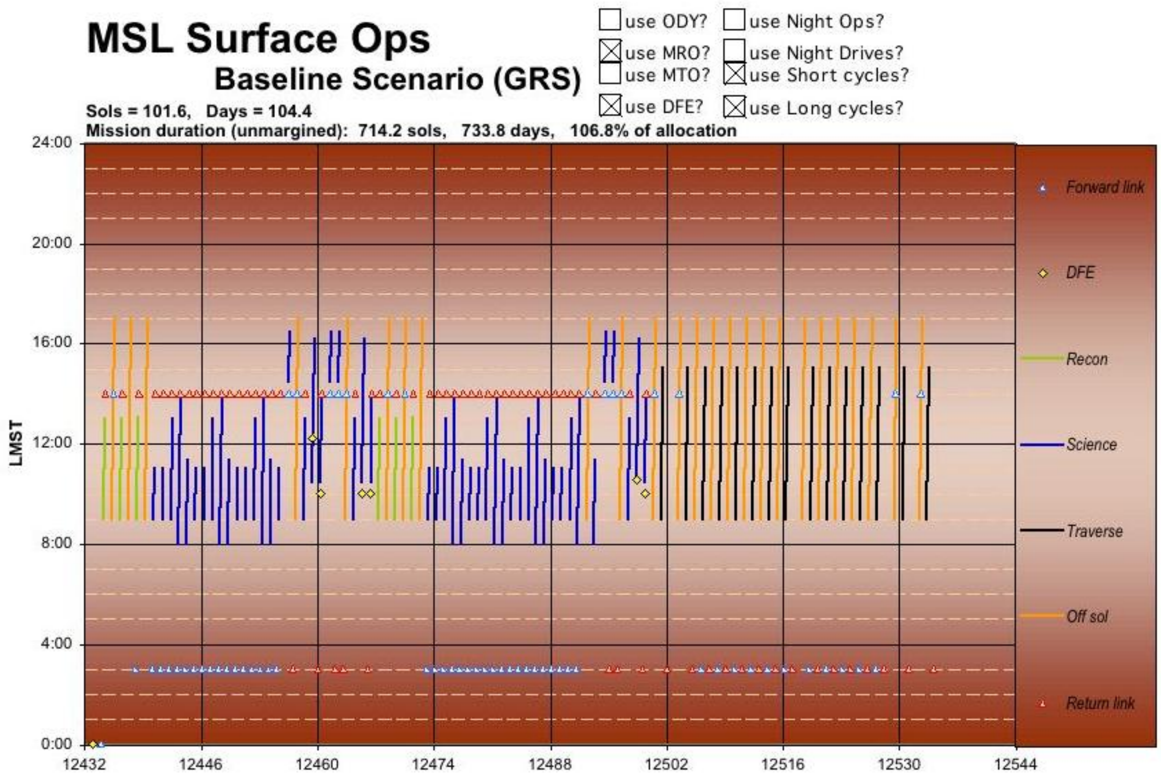

Figure 5 –Graph of MSL surface operations on a sol-by-sol basis

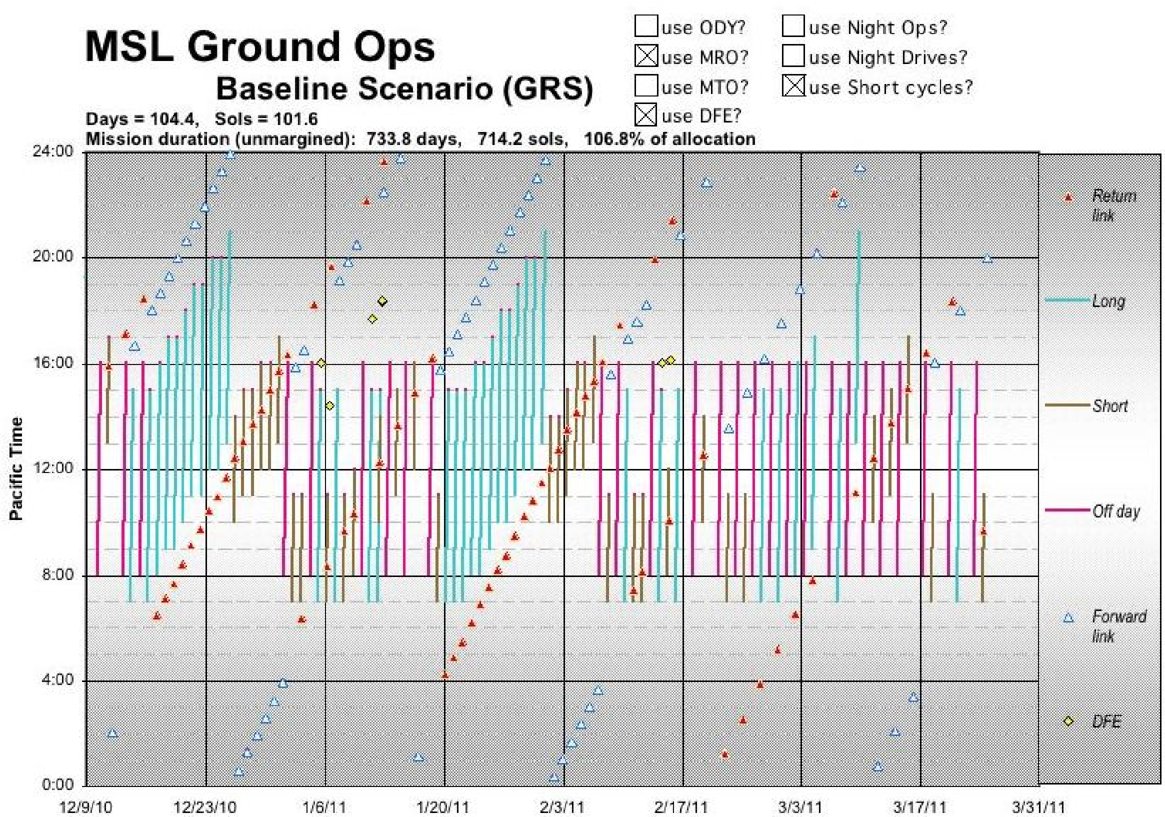

Figure 6 –Graph of MSL ground operations on a day-by-day basis

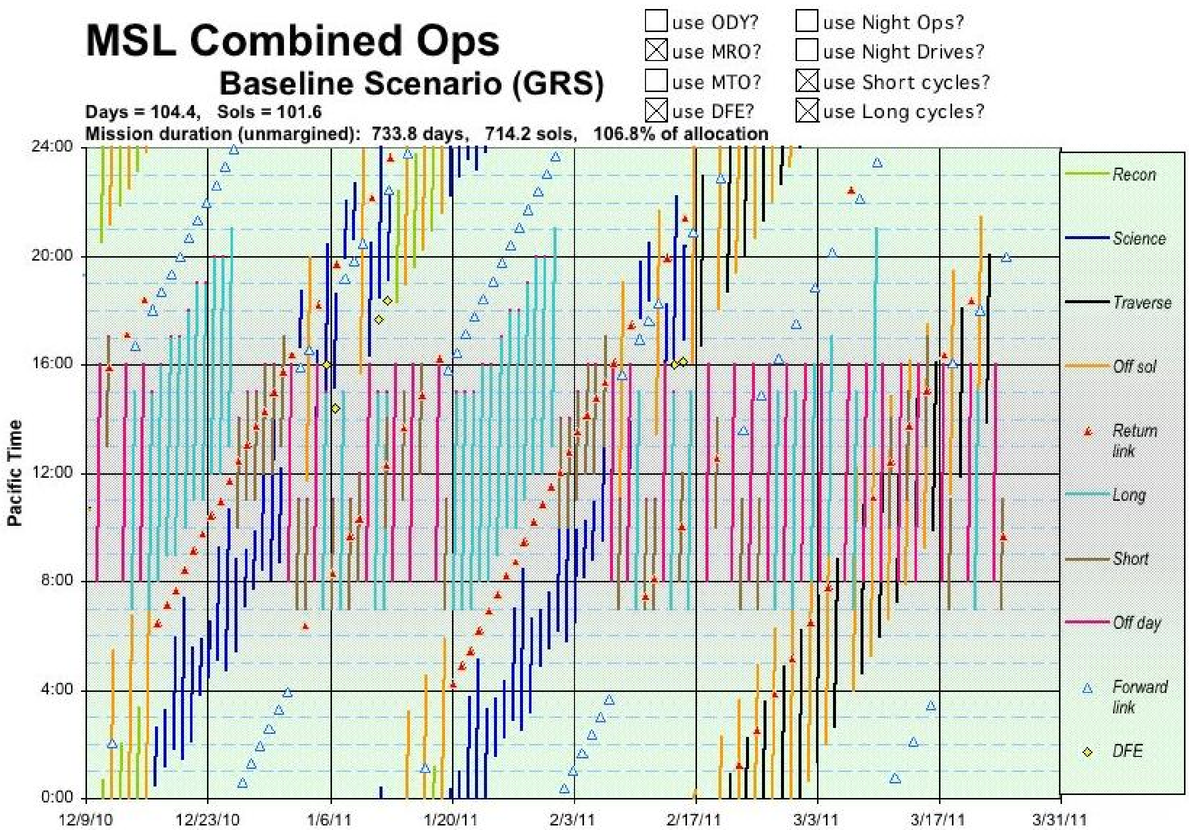

Figure 7 –Graph of combined MSL ground operations and surface operations

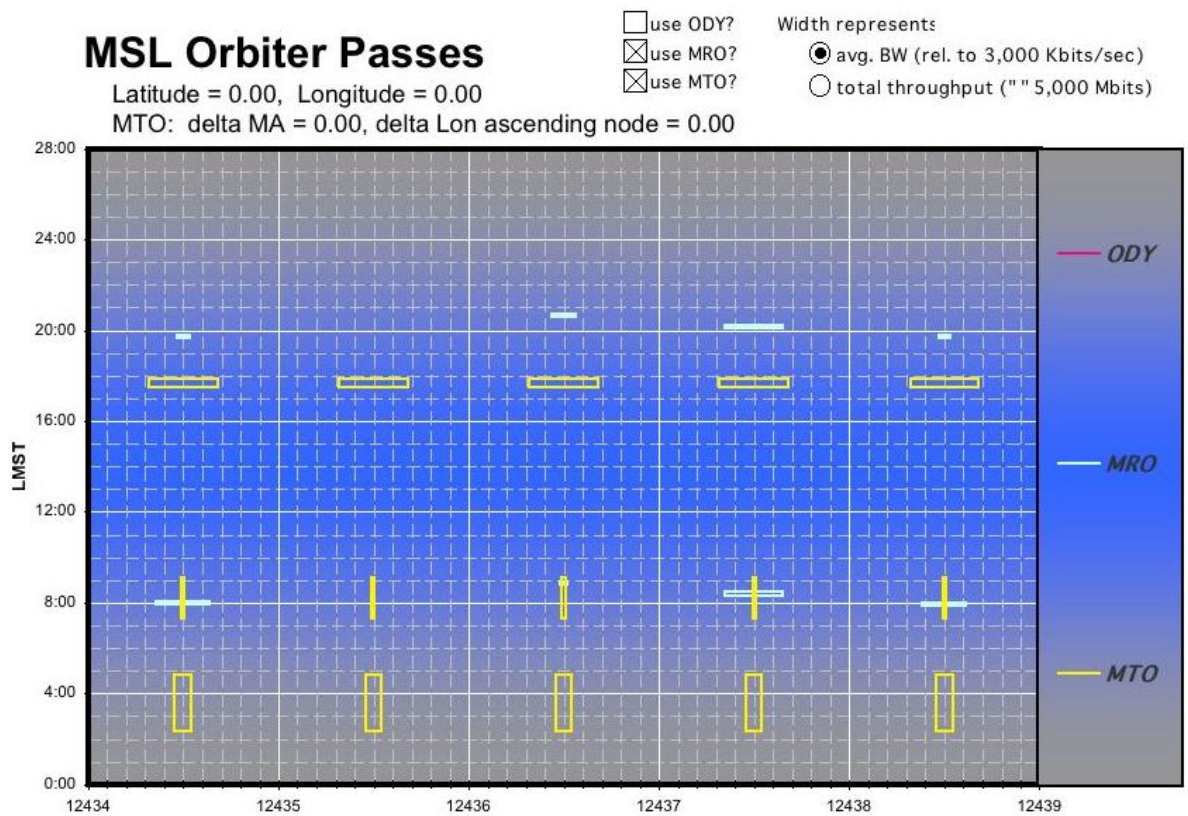

Figure 8 –Graph of MSL Orbiter Passes

Figure 3 shows a table of Mars relay orbiter view periods and data bandwidth estimates for various relay orbiters on a single day.

Figure 4 provides feedback on the secondary battery state of charge. This profile tells the mission planner if the proposed plan is feasible from a power standpoint, and allows the planner to insert battery recharge events as necessary.

Figure 5 depicts MSL surface operations. This provides the mission planner with an automatically-generated schedule showing all the main Mars rover activities on a daily basis (actually per "sol", the name for the Mars day, which lasts 24 hours and 37 minutes). The units along the X axis are Mars sols, and the units along the Y axis are local time of day on Mars, where a day is divided into 24 equal "Mars hours". "LMST" stands for Local Mean Solar Time. This is determined by the longitude of the rover in comparison to the Mars prime meridian, and is similar to Pacific Time or other time zones here on Earth.

Using this chart the user can see at a glance when the different types of sequences are to be run: green for reconnaissance, blue for science activities, and black for traversing to a new investigation site. The orange bars tell us when the Earth-Mars link (relay orbiters and ground processing) was unable to turn around the previous sol's data fast enough to generate a new sequence in time for the next sol.

The red and blue triangles indicate the start of each relay orbiter pass which is used by the mission. There are several passes to choose from, and the software picks the one with the earliest pass end time, which is usually the one with the highest bandwidth. High bandwidth passes are valuable in a Mars environment where power is usually a limiting factor on operations. Blue represents a transmission from Mars to Earth, know as the "forward link". Red is a new sequence coming from Earth to Mars, know as the "return link".

The yellow diamonds indicate that the rover will be receiving the sequence in a direct transmission from Earth, without the intervention of a relay orbiter. This is known as a "Direct From Earth" or DFE link. The bandwidth on these links is very small, and they are only used to uplink small tweak sequences in support of Science sols 4 and 5. Sol numbers refer to our 5-sol model of the Science process.

Underneath the title is a summary of the key mission performance parameter: the mission duration required to complete all the science goals in terms of both days and sols. It also shows what percent this duration represents of the time allocated to the project to achieve our goals. Using this we can readily compare the likelihood of completing our mission within the time budgeted.

There are also set of check boxes along the top which allow the user to change the main input parameters and see the results in terms of a new chart in near-real time (~10 seconds per change). These parameters allow us to evaluate the effects of mission optional behaviors in terms of the mission duration goal.

Figure 6 depicts MSL ground operations. This provides the mission planner with a schedule showing the main Earth ground processing activities on a daily basis. The units along the X axis are Earth days, and the units along the Y axis are local time of day at JPL with daylight savings time taken into account.

Using this chart the user can see which days will involve the standard ground process ("long" days in blue), and which use the compressed process ("short" days in brown). Days off are shown in pink, and are a result of the mechanics of the Earth-Mars link timing (similar to the orange bars in figure 5). Again, forward links (Earth-to-Mars) are blue triangles, and reverse links (Mars-to-Earth) are red triangles. The yellow diamonds are DFE passes, and correspond to the ones shown in figure 5. This chart also provides the same sort of summary information across the top as in figure 5. It also provides identical controls so the user can see the effect of key parameter changes in real time.

Figure 6 depicts combined MSL ground and surface operations giving a combined view of the interaction between Mars rover events, and JPL ground processing activities. The chart displays data in terms of Earth days and Pacific Time, so that we can see at a glance when events on Mars should be happening in terms of local JPL time.

This is especially useful for tracing the chain of actions between uplink (forward link) and downlink (return link) events, and helps explain visually why the relay or link turnaround was unable to provide a new sequence to the rover in time to be executed during the next sol -- i.e., why there are "Off" days.

Figure 8 depicts MSL Orbiter Passes. Much of the mission depends on the type and timing of relay orbits as seen from the MSL rover's landing site. This chart allows the mission planner to see the schedule of relay passes in terms of local Mars time (LMST). Three orbiters are modeled in the software, and the chart can depict any combination of them.

The key outputs are pass bandwidth, which gives the amount of data that can be transmitted per second; and the total data throughput of a pass. The user can switch back and forth between these two views, and evaluate the effects of changes to orbiter parameters and orbiter selection. The X axis is used both to indicate sols, and within sols to

indicate 1/10th of the total output being depicted (3,000 Kbits/sec bandwidth, or 5,000 Mbits total throughput).
The software includes Keplerians of each orbiter, and these can be modified to help determine the impact of timing, nodes, etc. on mission operations. Since orbits are difficult to change, the main use of this chart is to help explain the timing of the forward and reverse links, but it can be used to identify phasing which would be beneficial, and this information can be passed on to the projects responsible for orbiter operations.

6. CONCLUSIONS

The MSL Project has successfully used this capability to perform multi-disciplinary performance analyses and develop a robust mission plan early in the Formulation phase of the Project. Using anticipated spacecraft performance with proven models instead of worst-case estimates has allowed system designers to appropriately size elements of the system to meet the mission requirements. Integrating activity planning spreadsheets with reusable, higher fidelity models has also made it possible for the MSL Mission Planning team to demonstrate a more credible set of system performance scenarios which execute 500 – 700 times faster than previous methods.

We anticipate that this capability will allow for MSL system designers and mission planners to design a more robust spacecraft and mission operations plan resulting in additional opportunities for scientific discoveries on the surface of Mars. We also expect that this capability will provide value to other space missions once completed and deployed.

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REFERENCES

[1] Robert Shishko, Robert G. Chamberlain, *NASA Systems Engineering Handbook*, NASA Publication SP-6105, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, second printing April 1996.

[2] Kordon, M., and E. Wood, "Multi-Mission Space Vehicle Subsystem Analysis Tools," IEEE Aerospace Conference Proceedings, Big Sky, MT., March 2003.

BIOGRAPHY

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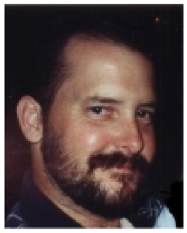

David Hanks *is a member of the technical staff in the Modeling and Simulation Technologies Group at the Jet Propulsion Laboratory. David was responsible for developing the software that allowed Excel to interface to the subsystem models. He received his Bachelor of Arts in Mathematics and Bachelor of Science in Physics from the California State University, Fullerton.*