System Models to Reduce Mission Design Time and Manage Risk: The Mars Microprobe Mission Case Study

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Abstract. New approaches to modelling spacecraft system are being tested at the Jet Propulsion Laboratory in order to better understand and quantify the interactions among spacecraft subsystems and mission variables and thereby understand and manage mission risk. Ultimately the goal is to enable the design of lower cost missions and to reduce the time between system concept and launch. This paper will present the New Millennium Deep Space 2 system model developed using NuThena's Foresight program. The system tool models the physical and media access control layers of the telecom relay link, the capacity and temperature of the batteries, and the data generated by the science payload. The event driven simulation is activated by a sequence of events file, an instrument requirements file and a set of environmental inputs. The model described has been used to select subsystem components, perform system trades, and visualize data return scenarios.

Introduction

NASA foresees designing and launching a greater number of robotic missions per year than at any other time in its history. In support of this effort, JPL is establishing sets of tools that can reduce the time between concept development and product readiness. Over the past two years, system and subsystem models pertaining to different aspects of deep space mission design have been created in order to compare the utility of various commercial design tools and to understand how to efficiently pass information between tools. In particular, several model-based system design tools are being evaluated through close collaboration between the model developers and the mission team.

In this paper, we describe the system model developed for the Deep Space 2 (DS2) mission using NuThena's Foresight tool. DS2 is the second mission in the New Millennium Program.[1] The goal of this Program is to demonstrate the performance of new technologies in space. DS2 was selected because mission success depends to a greater extent than typical on understanding the interdependence of various subsystems over a wide range of conditions. In addition, the relative simplicity and short duration of the DS2 mission meant that all of its subsystems could be simulated in a single, reasonably sized, model. Lastly, the short timeframe from design to flight meant that the mission team were eager to test tools that could help them quantify the impact of different mission scenarios on the mission lifetime and the data return.

System Modelling

Model-driven approaches to system design are key to enabling JPL to support the development of multiple, fast paced, projects. System models permit the performance of multiple subsystems to be assessed in the early phases of a mission. Virtual system level testbeds can precede the fabrication and test of flight hardware. Then system trade studies can be performed, allowing the impact of new technologies or capabilities to be assessed at a time when the cost to modify the design is still low.

Several commercial vendors, including NuThena Systems, are developing system modelling tools. NuThena's Foresight supports the development of system models through the definition of executable process models. Dynamic analysis of the system model is accomplished through a simulation engine which allows alternate process paths to be evaluated. The data flow of each model is specified through a graphical tool. Foresight uses a proprietary language, similar to C, and state transition diagrams in order to describe the process within each model. In addition the user can create generic, reusable, subsystems which can be used as building blocks in the model. Foresight runs on UNIX and PC platforms. The system model can be translated into C, compiled and run in a batch mode.[2]

The DS2 Mission

The DS2 mission consists of two microprobes, each weighing less than 2 kg in mass, that will impact the Martian soil at high speeds and will perform in situ science. The microprobes will be transported to Mars by the Mars'98 Polar Lander mission. They will separate from the spacecraft prior to its atmospheric entry in December, 1999. The main objective of the DS2 mission is to validate microprobe technology. At impact the probes will separate into a forebody and an aftbody system as shown in Figure 1. The aftbody, in which the telecommunications subsystem resides, is designed to decelerate instantly thus absorbing an 80,000 g impact, whereas the forebody, with the instruments payload and a microcontroller, may reach a depth of about 1 meter and must sustain a impact of 30,000 g's.

The two main scientific experiments are carried out in the prime phase of the mission which lasts two Martian days (or sols[*]). The first consists of a soil sample analysis experiment designed to detect the presence of water ice. The second centers on the collection of data from the deceleration of the fore body; this data is expected to provide clues on the geological stratification of Mars. The probe will also collect temperature and pressure measurements until the batteries are depleted. Depending on the number of batteries that survive impact and their performance over temperature, the extended mission may last up to 12 sols.

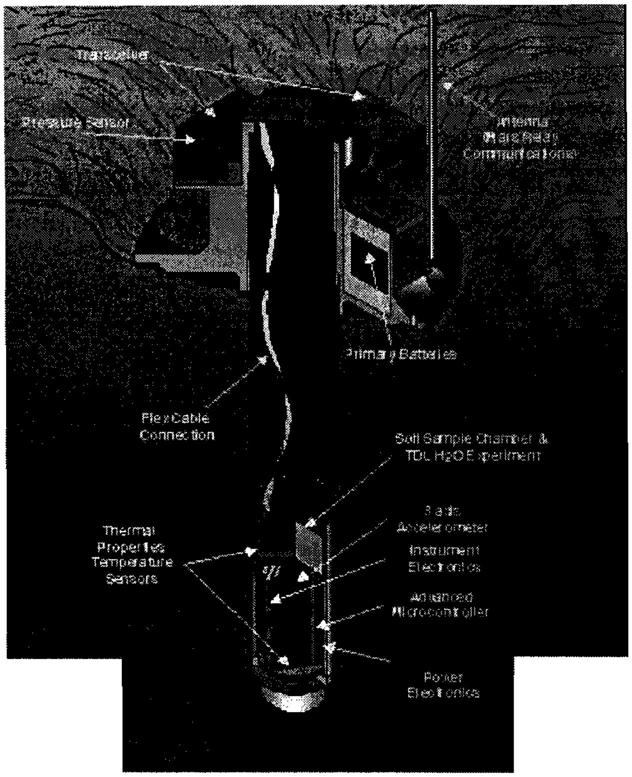

Figure 1. The DS2 Microprobe.

The scientific data generated in the fore body is relayed via an umbilical cord to the telecom system in the aft body and stored in the telecom buffer. The data is relayed to the Mars Global Surveyor (MGS) spacecraft whenever the microprobe receives its unique polling tone. Figure 2 depicts MGS in a 400 km polar orbit and the landing site for the microprobes and the Mars'98 Lander. Due to the southern landing site chosen for the microprobes and MGS' polar orbit, MGS will pass over the microprobe landing site multiple times per sol.

Figure 3 shows a typical pattern for the elevation angle to MGS as seen by a microprobe at 75° South latitude over 100 Earth hours or approximately 4 sols. In fact, the landing target for the microprobes is an ellipse centered at 75° South latitude and 148° East longitude. As can be seen in the figure, MGS appears above 10°

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[*] A sol is 24 hours and 37 minutes.

elevation angle about 13 times per sol. Although the landing site is thought to be sandy and free of large boulders, the project does not wish to depend on being able to transmit successfully at elevation angles less than 20°. There are 7 passes/sol where the MGS ascends above 20° elevation angle and 3 passes/sol where MGS ascends to above 45° elevation angle.

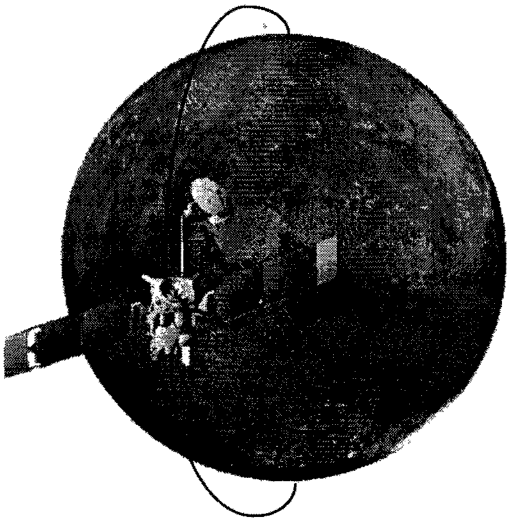

Figure 2. Targeted Landing Site for the DS2 Microprobes and the Mars Global Surveyor in its Polar Orbit.

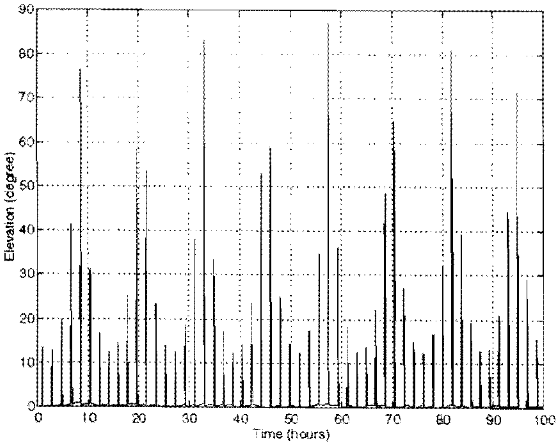

Figure 3. Typical Elevation Pattern.

Both microprobes are expected to land in close proximity to one another and to the Mars'98 Polar Lander. Both probes desire 1 or possibly 2 passes/sol. The Mars'98 Lander will use the Mars'98 Orbiter as prime for its communication with Earth, MGS will serve as a backup only. Although the rise and set times for MGS will not vary significantly between the two nearby microprobes, they do depend on the actual latitude and longitude at the landing site.

At each communication opportunity, the microprobe will attempt to transmit as much of the data in its buffer as possible. The buffer has a capacity of 55 kBytes. This data can be formatted into 8 Balloon Telemetry Time Slot (BTTS) packets. The primary mission will generate the first few BTTS packets worth of scientific data which will be stored permanently in the buffer. The telecom system will transmit these packets at each communication opportunity. The remaining packets will contain atmospheric and engineering data gathered in the extended phase of the mission. They will be updated as new data arrives.

The return of scientific data will prove the new microprobe technologies used in DS2. A range of low power miniaturized components are being developed to operate over a wide temperature range (-80° C to -20° C) and withstand the high force impact. The key components enabling mission success are Lithium batteries, a micro-telecommunications system, an Advanced Micro Controller (AMC), and advanced sensors.

Initially, the goal of the system modelling effort was to verify that the telecom system could return the required 8 BTTS under a variety of conditions, e.g.

- antenna pattern
- downlink threshold power (used to trigger data transmission to MGS)
- probe inclination angle
- minimum elevation angle for transmission
- probe location
- MGS location at the time of landing

Engineers also wished to visualize the impact of different data return scenarios. The program was also thought to be useful in the mission operations phase of the project in order to determine the timing of the optimum passes for each microprobe.

Subsequently, additional subsystems were modelled when it was recognized that the power of the transmitting amplifier, which is the main determinant in ensuring data return, was tightly coupled to the battery capacity. The system tool was then used to assess mission lifetime under several worst-case scenarios.

The system tool generates the following main observables versus time:

- battery capacity
- data return
- data generation

System Model of DS2

Figure 4 shows the block diagram of the system model implemented. The shaded area represents the part programmed with the NuThena's Foresight tool. The only MGS system required for the DS2 model is that of the telecom subsystem. In the following sections each block shown will be described.

MGS and Probe Telecom

The modelling of the MGS telecommunications subsystem was limited to the quadrifilar helix antenna and to the performance of the telecom system. Both the physical layer and the media access layer of the microprobes' telecom system were modelled.

The MGS Mars Balloon Relay Protocol will operate in a half duplex mode with DS2 at UHF frequencies. Data transmission from each probe is initiated upon receipt of the proper interrogation signal. BTTS packets are 16 sec long and continuously transmitted by MGS with a specific tone addressing one of up to four different landed elements. Once the probe recognizes its own tone and judges the received power to noise ratio in the channel to be above the predetermined threshold, it transmits 13 sec worth of packets at a bit rate of 7 kbps, while turning off the receiver to save power. The data stream is the product of the concatenation of a Reed Solomon (255,223) code and a convolutional code with rate 1/2 and constraint length 7. The RF power transmitted is proportional to the supply voltage ranging from 300 mW to 1200 mW. The received data packet is rejected by the MGS telecom subsystem if the bit Signal to Noise Ratio (SNR) is less than 2.3 dB.

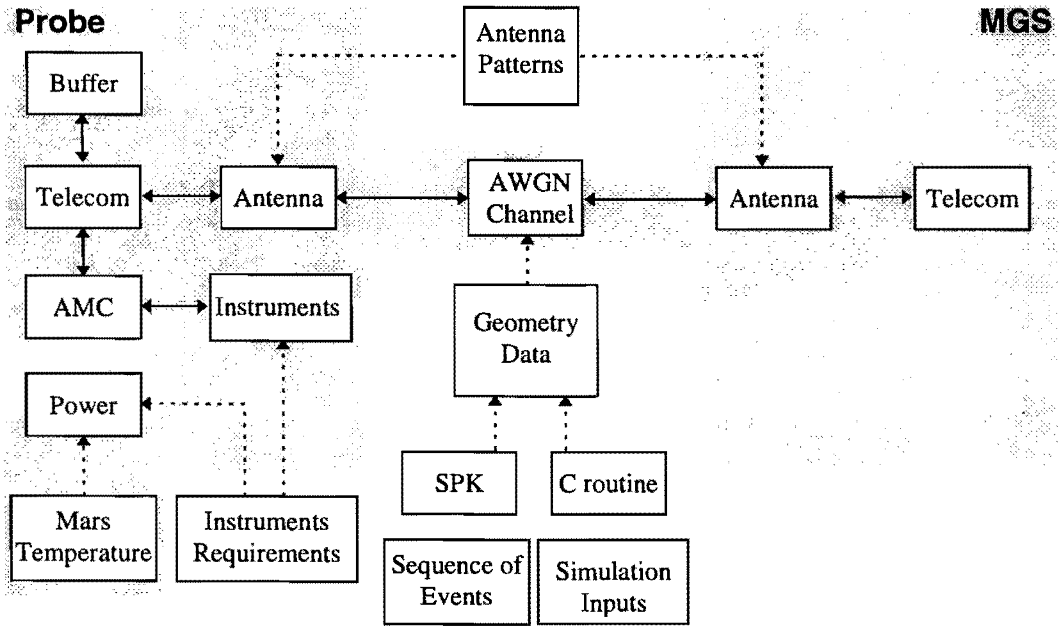

Figure 4. Block Diagram of the System Model.

The channel at UHF frequencies is modelled as an Additive White Gaussian Noise (AWGN) channel. The link budget and the protocol analysis were developed with Foresight while an interface to Matlab, via a C subroutine, allowed the simulation results from the tone detector algorithms to be linked into the telecom model.

Power Model

The power subsystem consists of two batteries connected in parallel. Each battery was composed of 4 cells. Mission success was required with the operation of one battery only. Battery capacity, nominally 550 mA hours per battery at the beginning of the simulation, depends on the Mars temperature, which was simply modelled as a sine wave varying in one sol between -80° C and -20° C.

Advanced Micro Controller

AMC modelling was limited to control the activation of the other subsystems and instruments based on the Sequence Of Events (SOE) defining the scenario being analyzed.

Instruments

Each instrument in the model was characterized by its power requirement and by the amount of scientific or engineering data generated. Foresight supports "reusable" processes that can be used to define multiple elements, allowing a special purpose file to create differences between them. This enabled a complex model - consisting of eleven different instruments in addition to the telecom and AMC subsystem - to be developed rapidly in conjunction with an instrument requirements file.

Data Buffer

The overall data storage in the memory is limited to 8 BTTS. Five of these are reserved for the water experiments with the remaining used for engineering and weather data. The basic protocol model transmits BTTS 1 through 8 and then restarts again with BTTS 1. In this way there are several opportunities to transmit the primary science results, with the last three BTTS providing temperature and pressure measurements as a function of time.

External to the Foresight environment shown in Figure 4 are the following blocks.

Geometry Data

The geometry data (MGS position versus time) are generated by either a C subroutine or through the use of an SPK (Spacecraft Planet Kernel, a type of data file commonly use to describe spacecraft ephemeris) file.

Antenna Patterns

Antenna patterns are described in an ASCII file with gain given as a function of off boresight angles.

Sequence of Events

This file contains the sequence of events (SOE) versus time. An example of SOE file follows:

```
"POWER",0.0,0.0,3600000.0
"AMC",60.0,0.0,20.0
"CALIBRATION",60.0,0.0,60.0
"AFT",250.0,0.0,369.96
"FORE",250.0,0.0,369.97
"DA",250.0,0.0,369.98
"AMC",251.0,0.0,369.0
"IA",510.0,0.0,109.99
"LANDED",620.0,0.0,1.0
"FORE",621.0,1800.0,5.0
"AFT",621.0,1800.0,5.0
"TEMP",646.0,30.0,1.0
"WATER",730.0,0.0,150.0
"AMC",730.0,0.0,510.0
"SOIL",730.0,0.0,120.0
"SAMPLE",880.1,0.0,360.0
"TELECOM",1240.0,0.0,3600000.0
"WATER",18000.0,0.0,563.0
"AMC",18000.0,0.0,614.0
"SOIL",18000.0,0.0,250.0
"SOIL",18350.0,0.0,200.0
"WATER",23040.0,0.0,630.0
"SOIL",23040.0,0.0,630.0
"AMC",23040.0,0.0,631.0
"PRESSURE",31220.0,0.0,300.0
```

For example the line:

```
"TEMP",646.0,30.0,1.0
```

indicates the beginning of temperature measurements at the time t=646 s from the beginning of the simulation, with duration 1 sec and with a periodicity of 30 sec.

Instrument Requirement

A file, with power and data generation specifications. An example follows:

```
"Temp_sensors",55.0,0.0,55.0,0.40,48,1
"Acc_Descent",50.0,0.0,50.0,0.68,12,20
"Acc_Impact",60.0,0.0,60.0,0.40,16,7
"RCVR",21.9,0.365,21.9,1.0,0,0
"XMTR",888.0,0.0,1200.0,1.0,0,0
"AMC",42.76,0.6,103.0,0.40,0,0
"Power_system",0.049,0.049,0.049,1.0,0,0
"Water_exp",1250.0,0.0,1250.0,0.8,146,1
"Soil_heater",3000.0,0.0,3000.0,1.0,0,0
"Door_pyro",1695.0,0.0,1695.0,1.0,0,0
"Sample_motor",6000.0,0.0,6000.0,1.0,12,0.2
"Calibration",400.0,0.0,400.0,1.0,149,0.0167
"Fore_engineering",55.0,0.0,55.0,0.40,132,0.2
"Aft_engineering",50.3,0.03,50.3,0.68,160,0.2
"Pressure_Sensor",50.0,0.0,50.0,0.68,32,0.2
```

For example the line:

```
"Water_exp",1250.0,0.0,1250.0,0.8,146,1
```

indicates that the water experiment consumes 1250 mW of DC power in the peak and normal power mode and 0 mW in the quiescent mode. The instrument efficiency is 80%. It produces 146 bit per sample at a rate of 1 sample per second.

Simulation Inputs

The inputs to the system model are stored in a file containing information such as the probe location and the antenna inclination. An example follows:

```
(event    0.0    0   (probe_lat -77.0))
(event    0.0    1   (probe_lon -150.0))
(event    0.0    2   (start_time "17 dec 1999
00:00:00"))
(event    0.0    3   (end_time "20 dec 1999
00:00:00"))
(event    0.0    4   (orbit_flag 0))
(event    0.0    5   (sched_com 0))
(event    0.0    6   (mult_factor 1.0))
(event    0.0    7   (min_elev 15.0))
(event    0.0    8   (Antenna_pat 0))
(event    0.0    9   (Inclined_at 0.0))
(event      0.0      10    (BEACON_POWER_TH
47.75)
```

Model Performance

The Foresight simulation engine allowed the user to run, monitor and visualize different mission scenarios. Typical execution time is on the order of hours when the Foresight code is run in real time on a Sun Sparc 20, but on the order of minutes when translated to C and compiled via the coder provided with the tool. The size of the model was about 11 Mbytes for the initial telecom program and 30 Mbytes for the final system model.

Simulation Results

In this section the performance of the baseline DS2 mission will be given as well as results of three types of trade studies. As mentioned earlier, a simple model was constructed first to assess the feasibility of returning 8 BTTS in one MGS pass under a variety of probe conditions. Next, a more complete model of the microprobes was built. It was used to evaluate the baseline DS2 scenario. Next results obtained on the impact on data return of perturbations in the monopole antenna pattern and the mission lifetime with full battery capability are described.

Data Return versus Probe Conditions

The number of successfully transmitted BTTS in a single MGS pass was studied under a number of conditions. The baseline case assumed that the probe landing at exactly 75° S latitude, perpendicular to the terrain, and that line of sight communications to MGS were possible at 0° elevation angle. Deviations from this baseline were studied in the following manner:

- probe inclination angle (0, ±15°, ±30°) where only North and South inclination of the probe were calculated
- elevation mask angle (0° to 30°)
- probe latitude (73° South to 77° South)

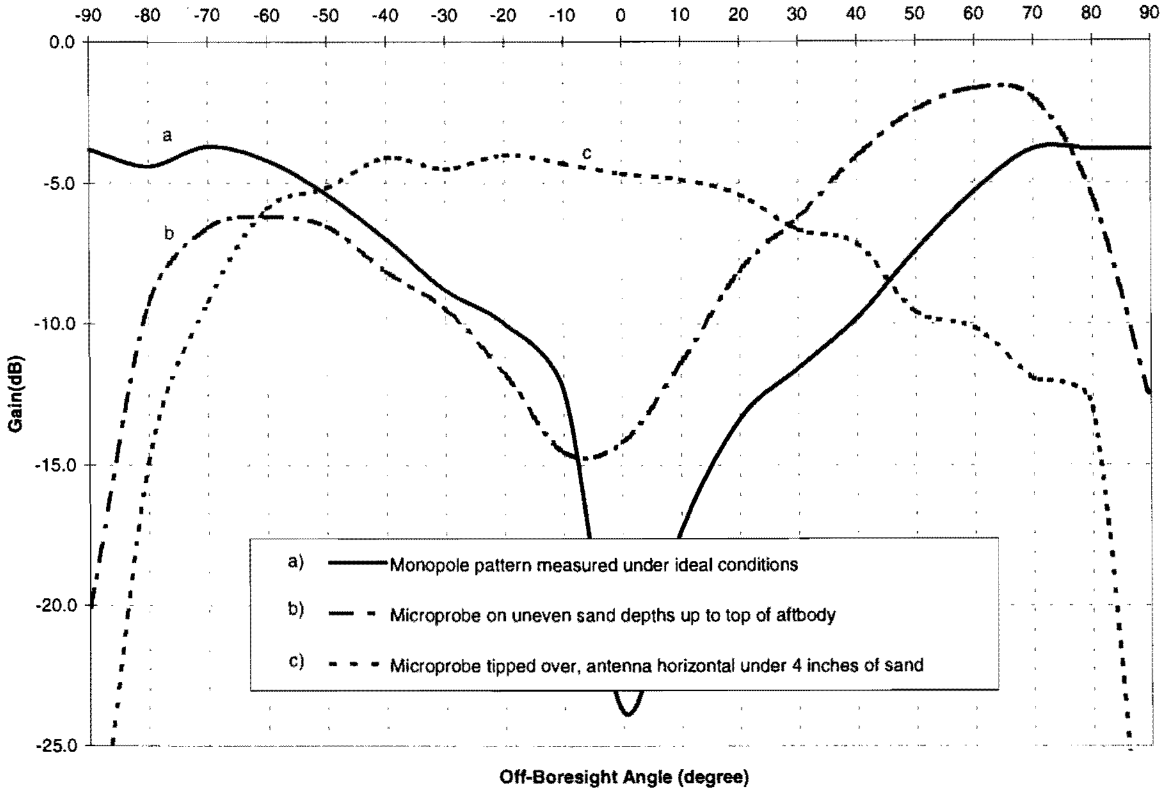

Figure 5. Measured Antenna Patterns During Testing.

All cases were run assuming the use of a monopole antenna on the microprobe. This antenna was chosen not for its gain characteristic which has a deep null at zenith, but for its low mass and its ability to survive the high impact landing. Figure 5 shows the monopole pattern measured under various conditions. In this analysis the ideal monopole pattern, pattern a, is used. In addition, the lowest value of 300mW was used for the RF power of the microprobe's transmitting amplifier.

Figure 6 gives the number of BTTS transmitted during one sol for the baseline case. Positive BTTS are those successfully received by MGS, i.e. with a SNR of greater than 2.3 dB; negative BTTS are received in error. The tag over each bin represents the maximum elevation angle at which transmission occurred. It can be seen that the microprobe can successfully transmit 8 BTTS in any pass.

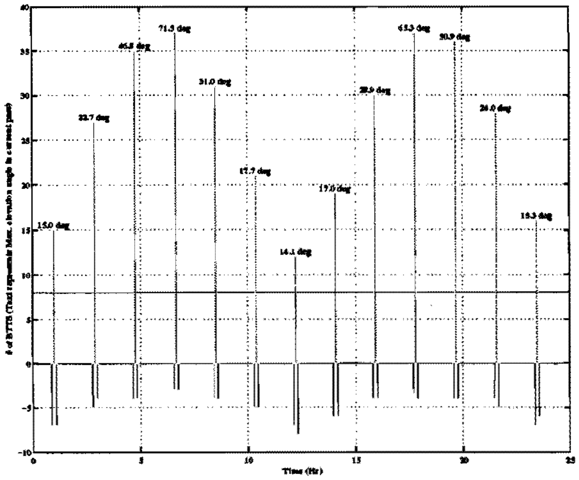

Figure 6. Data Return.
(Inclination=0°, Mask=0°, 75° South)

Figure 7 shows the results obtained in a worst-case scenario where the probe is assumed to land at 73° S, with an inclination angle of -30° with respect to local terrain. Boulders at the landing site assumed to preclude communications until MGS reaches an elevation of greater than 30°. Two types of positive BTTS' are shown: those in green represents transmissions at elevation angles greater than 30°; those in orange represent BTTS' potentially lost due to transmission at elevation angles below 30°. In this case, successful transmission of 8 BTTS can be assured for four passes / sol (the 2nd, 3rd, 8th and 9th pass only).

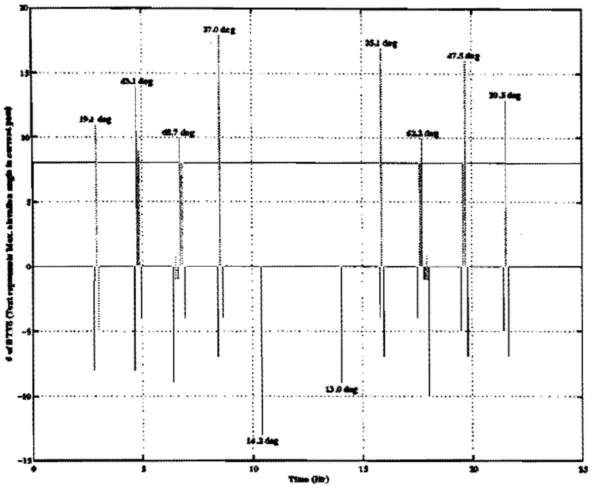

Figure 7. Data Return.
(Inclination=-30°, Mask =30°, 73° South)

DS2 Baseline Scenario

The DS2 microprobe possesses two batteries. The baseline scenario adopted by the mission assumed that one battery would fail at impact and that only two communications with MGS would be possible per sol. The following figures give the number of BTTS created by the microprobe under the baseline SOE file, the battery capacity (Amp sec), the number of BTTS transmitted to MGS and the number of times each BTTS was received at MGS over 10 sols. Antenna pattern b is used for the monopole and the probe is assumed to land at exactly 75° S latitude, with an inclination angle and mask angle of 0°.

Figure 8 shows the number of BTTS written in the memory in this scenario. Only 5 BTTS were generated during the first 10 sols - not the 8 BTTS originally anticipated - suggesting the possibility of adding more experiments in the first sols.

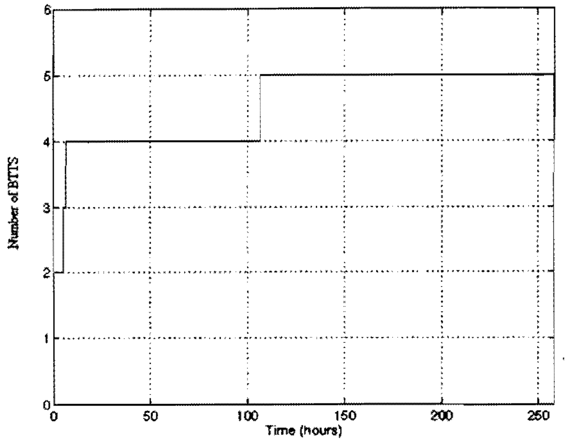

Figure 8. BTTS Written in Memory vs. Time.

Figure 9 illustrates the battery discharge. After the major science experiments are concluded part way into the first sol, the telecom transmitter becomes the major drain on battery capacity. . Even with one battery left the mission lifetime is about 10 sols.

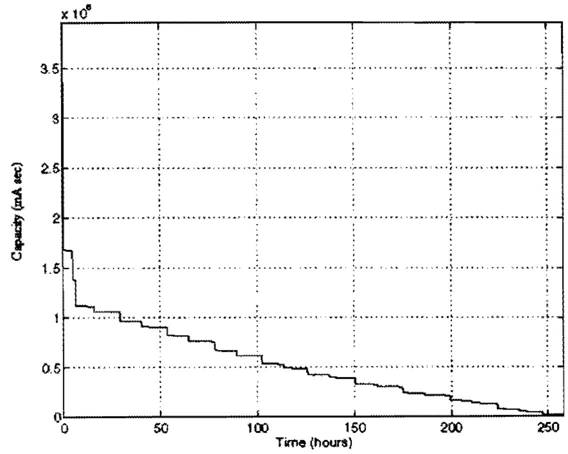

Figure 9. Battery Capacity vs. Time.

The number of BTTS successfully received by MGS is shown in Figure 10 for each of the available two MGS passes / sol.

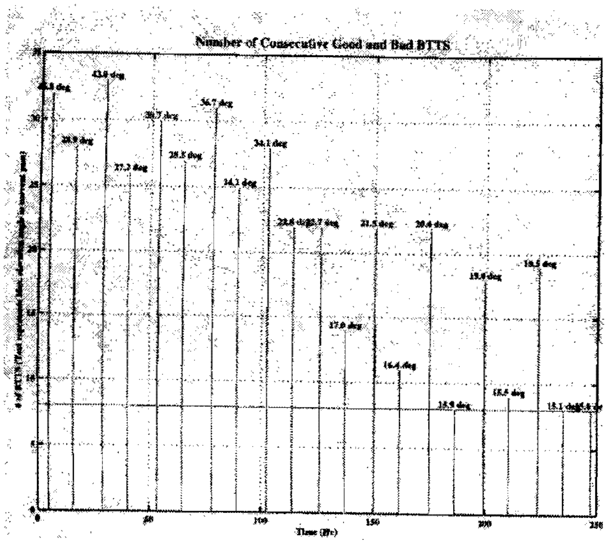

Figure 10. Data Return.

Figure 11 details the number of times each BTTS is received. All versions of BTTS 1,2 and 3 contain the primary scientific data acquired in the first sol whereas the information stored in BTTS 4 and 5, representing engineering and scientific data, is continuously updated.

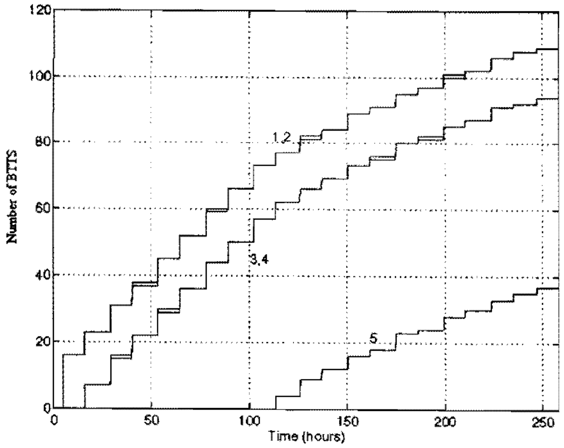

Figure 11. BTTS Successfully Received by MGS.

Impact on Data Return of Antenna Pattern

Once a mock-up of the microprobe aftbody was constructed, it was possible to measure the monopole's antenna pattern with the microprobe in various configurations. These antenna patterns are shown in Figure 5 where pattern b was measured when uneven sand depths up to the top of the aftbody were placed on the microprobe and pattern c is obtained when the microprobe is tipped over with the antenna horizontal under four inches of sand.

The effect of these two antenna patterns on the number of BTTS packets received by MGS is illustrated in Figure 12.

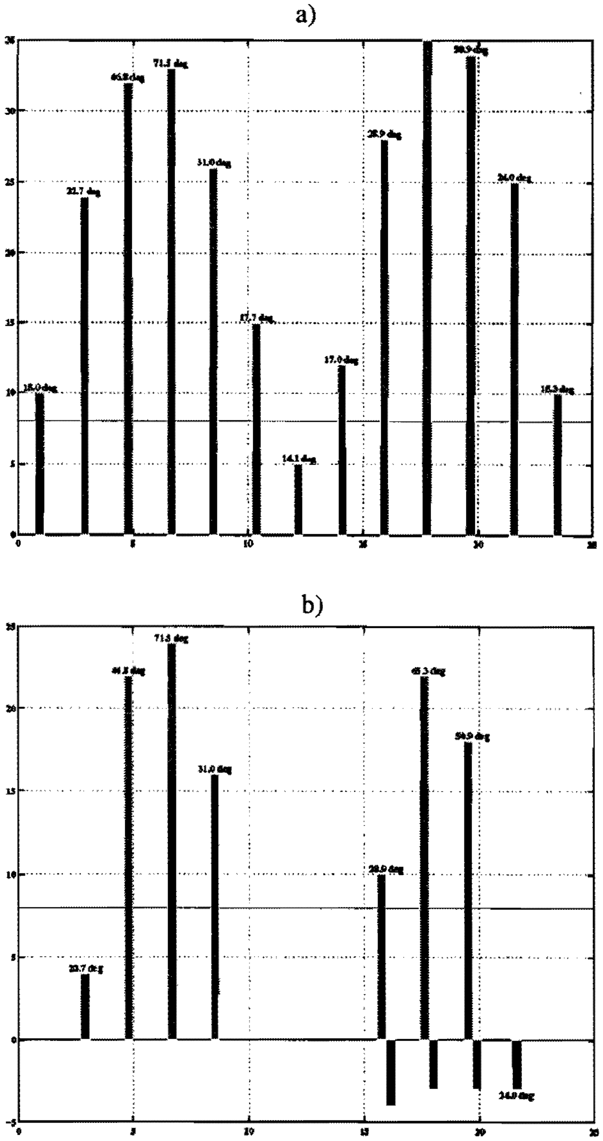

Figure 12. Effects of Antenna Patterns on the Data Return: a) Monopole pattern b is assumed; b) Monopole pattern c is used.

Although antenna pattern c does not possess a null at zenith, its gain rolls off at off-boresight angles of greater than 50° (corresponding to elevation angles of 40°), consequently fewer BTTS are returned. Note that many packets are received in error during the second half of the sol (night-time). This is due to the dependency of the RF power on the supply voltage, which as explained before is temperature dependent, ranging from 1.2 W at -20° C to 0.3 W at -80° C. In both cases, most MGS passes can support data returns of greater than 8 BTTS.

Mission Lifetime with Full Battery Capability

Figure 13 illustrates one of the mission lifetime scenarios analyzed with the tool: operation with one or two batteries in the microprobe. In addition, the microprobe is assumed to transmit to MGS at each pass, thus reducing the battery capacity far more rapidly than in the baseline case.

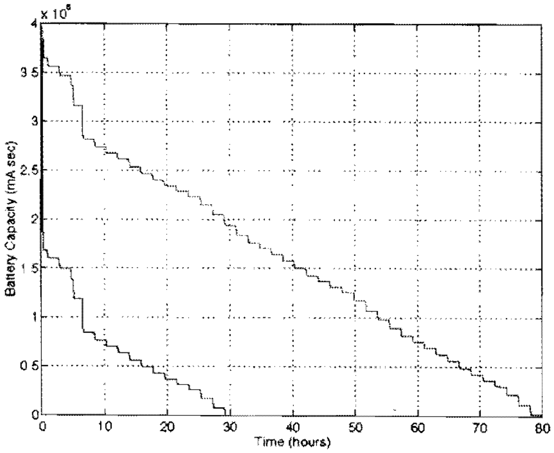

Figure 13. Effects of a Battery Loss on Mission Lifetime.

In this mode, the mission lifetime is reduced from 250 hours, as shown in Figure 9, to 30 hours. If both batteries survive impact, mission lifetime increases to 80 hours. Nonetheless the single battery scenario will allow the return of two water experiment data sets, with a longer lifetime providing more weather measurements.

The Direct to Earth Link Model

In September 1997, damage to one of the solar panels required the MGS project to re-evaluate its aerobraking strategy with the possible consequence that the final orbit would not be suitable for relaying data from the DS2 probes. The DS2 project assembled a team to quickly analyze the possibility of using a Direct To Earth (DTE) link at S band.

The Foresight system model was used to assess the overall feasibility of this option. While changes had to be made to substitute the MGS model with Deep Space Network (DSN) performance data and to modify the telecom system, quantitative data was obtained within a few weeks.

Figure 14 illustrates the power to noise ratio at the DSN for the case of: 1 W of RF transmit power with the probe vertical to the Mars surface. Pt/No's of 10 dB-Hz were possible with the use of the 70 m Canberra DSN; reception at Goldstone was predicted to be 5 dB higher. In the best possible geometrical configuration of the microprobe, the mission was predicted to last slightly more than 7 hours with a power to noise ratio allowing the return of only few bits per second.

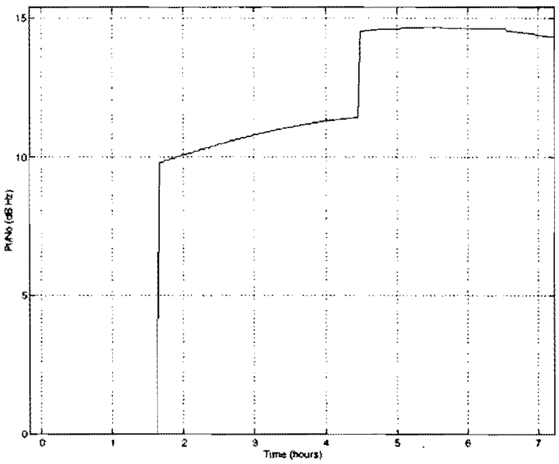

Figure 14. Power to Noise Ratio at the DSN Receivers.

Ultimately this approach was dropped due, in large part, to the results obtained with this model. In November a strategy was identified that should allow the spacecraft to reach a circular polar orbit in January 1999.

Conclusions

In this paper we described the system model developed for the DS2 mission, highlighting the possible results and trades that can be performed with such a tool.

Our experience with NuThena's Foresight software was positive. Foresight's reusable process and the state transition diagrams allow fast behavioral modelling of the subsystems based on a sequence of events. The first system model was running within a month, compiled easily, and was useful in supporting multiple trade studies. The more sophisticated system model took over 6 months to write and debug. The 30 Mbyte file was ultimately very unwieldy and, because it never compiled, was not useful in running large trade studies.

We have found that model-driven approaches to system design are powerful tools to quantify the interaction of multiple subsystems. The question remains whether the benefits of less comprehensive, more simplistic models will outweigh the promises of complex, detailed, models.

Acknowledgments

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Biographies

Andrea J. Barbieri received his diploma degree in Electrical Engineering from University of Padua, Italy, in 1995. Since 1997 he has been a member of technical staff in the Communications Systems and Research section at Jet Propulsion Laboratory. His present interests include telecom design for future deep space missions and for mobile-satellite communications systems.

Dr. Polly Estabrook is the Technical Group Supervisor for the Advanced Communications Concepts Group in the Communications Systems and Research Section at the Jet Propulsion Laboratory. Dr. Estabrook received the Ph.D. degree in Electrical Engineering from Stanford University in 1989. Her current interests are in the area of deep space communications, in-situ communications, and satellite and terrestrial network interoperability. Dr. Estabrook was the technical co-chair for the International Mobile Satellite Conference in 1995 and for the Satellite Communications in the Global Information Infrastructure Workshop in 1997.