Mars Microrover Telecom Subsystem

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This paper details the hardware aspects and 'lessons learned' for the Mars Microrover Telecommunication subsystem. The objective of the Mars Microrover Telecom team is to provide a UHF radio link between the Mars Pathfinder Lander Spacecraft and the robotic Microrover Sojourner. At project inception, the philosophy was to use the best available commercial radio modems with the primary motivations being schedule and budget limitations. Mars Microrover had a three-year hardware delivery schedule, and is a design-to-cost mission, with the Telecom subsystem allocated a fairly small percentage of the total project cost.

The paper will open with a discussion of the trade-off study performed between the 'make' or 'buy' philosophies. We selected the 'buy' philosophy for the radio modems and 'make' for the antennas. We will present a brief review of the industry search for the best available commercial components, which led to these decisions. We will follow, then, the journey from 'commercial' radios to 'space-qualified' hardware. This discussion will include details of environmental issues and tests (radiation effects, shock and vibration, thermal), repackaging issues, software interface tests.
As we chose the 'make' philosophy for the antennas, we will discuss the empirical design methods we employed, to meet electrical and mechanical requirements. In closing, the paper will present some of the lessons learned during the hardware development and test.

In this section, we present the 'make' or 'buy' trade-off study, first for the radio modems then for the antennas. For both components, we include the discussion for the vendor search.
The main factors of consideration in the 'make' or 'buy' trade-off study are, in order of priority: funding level, schedule of hardware delivery, environmental specification. The trade-off study began with the selection of the UHF frequency range to be used for this application. It was determined that 100-450 MHz frequency range should be used for such surface-to-surface RF link. A vendor search for available components at that frequency range was conducted. A list was generated, and attention was first focused on the radios. A pair of commercial radios on the list are actually flying now on board Sojourner and Pathfinder Lander. With this Motorola commercial radio on the 'buy' side, we looked at how we can successfully 'make' our own version of a UHF radio. We determined then, at a very early stage of the project, that funding profile and level would not permit the 'make' option. It was adopted then that we would procure these best available commercial radios and space qualify them. The terms 'best' and 'space qualify' for this project, mean delivering a set of radios which meet: the funding constraint, the short delivery schedule, and environmental requirements of shock, vibration and thermal. We projected that, with some effort, we could meet these requirements using the commercial Motorola radios. A second layer of trade-off study was later conducted, to determine/ascertain that following the philosophy of space qualifying best available commercial radios was still the optimum approach. This second trade-off study compared the Motorola commercial radios with military standard radios, using the same factors of considerations. We found that we could still maintain schedule within cost, using the commercial radios. Though military radios would be more mechanically robust, they are also bigger, heavier, and consume more DC power. So the decision remained in procuring the Motorola radios.
The trade-off study for the antenna was not nearly so involved. It was fairly clear at the start of the study that we would need to 'make' our own antennas. We were not able to find any commercial antenna which would meet our mechanical and thermal requirements. Since its electrical requirements are fairly straight forward, it was a matter of fitting in its design, build and test within our budget and schedule constraints.

Now we have come to describing the journey from commercial radio modems to flight qualified units, and the design, build and test procedure of the antennas. We begin with the environmental requirements for the Telecom hardware. Then we will provide further details of the hardware, first the radio modems, followed by the antennas.

During the Martian surface operations, the radios are predicted to see temperatures from -40C to +40C, since they will reside inside a warm electronic box. The antennas may see temperatures from -95C to +20C. The predicted acoustics levels are:

Frequency	PSD (G^2/Hz)
20Hz	0.002 (3.4g)
80Hz	0.04 (30g)
450Hz	0.04 (72g)
2000Hz	0.002 (34g)

Shock tests to satisfy the specification level of 50Hz 50g for the radio modem was done at the Microrover system level acoustic tests.

(add Figure AA from IOM 3363-94-064, the predicted acoustic levels)

As for the radiation environment, the mission is conducted during a minimum solar activity. The total dose levels for the mission is <200rads. With these requirements, we developed the environmental test procedures. This paper will focus mainly on the environmental tests of the radios, since the antennas' tests were done together with the mechanical subsystem.

Perhaps the most challenging consequence of selecting commercial radios is the radiation susceptibility of its components. Parallel with the trade-off studies, we performed a radiation susceptibility analysis test. We found early on, that the CMOS components are susceptible to single event latch up. A series of radiation tests conducted, verified this condition. The results from these tests also led to a solution. Though these radios will latch up when subjected to low level radiation, they recover upon DC power cycling. Thus on the Microrover, its software checks regularly for this latched radio condition; the radio's current will abnormally change during latch up. Should a latch is detected, the radio is power cycled automatically and the latch-up occurrence is recorded and reported. On the Lander, a hardware current detector is added to the power converter board of the radio modems. This circuit will automatically power cycle the radio if it detects a high current level for longer than the normal transmit period of the radio.

With the radiation issue resolved, a batch of radios were procured, as candidates for flight hardware. The only requirement we put on the manufacturer is that these radios should all come from the same commercial production lot. Once they were received at JPL, they were subjected to a thermal and electrical screening test. All thirty radios went through a thermal burn in, powered on in Standby mode:

-55C to +60C, 1atm, 6 cycles, 60C/hour rate
30 minute dwell at +60C, no dwell at -55C
48 hour dwell at +60C

The purpose for this thermal burn in was to screen out commercial workmanship defects. After the thermal burn in, they were electrically tested at -30C. At the end of this screening test, we did note a degradation in electrical performance on four of the thirty radios. The rest of the radios were then ranked, based on their overall electrical performance. Two radios were selected as the flight pair, two as their spares, two as qualification test units, one for SIM vehicle (System Integration Model) and one for SIM spare. These are the eight radios which were repackaged to flight quality.

The repackaging philosophy we selected to follow was, to keep the radios as close to their original forms as possible, replacing and adding only the necessary items. To be specific, we wanted to make sure that the electrical performance of the radios is not altered. But we did want to make certain that these radios will withstand thermal cycles, shock & vibration conditions. After much discussion, we came up with the following plan: replace all plastic connectors and switch with soldered-in wire jumpers; replace fuse with a jumper wire; pot/stake down all variable components; mount the radio boards on JPL built stainless steel frames; add heaters and temperature sensors; replace commercial grade RF connector with more reliable SMA connectors; wrap the assembly with fiber glass - Aluminum tape - fiber glass sandwich cover, replacing the heavier commercial metal casing, for weight reduction.

By not doing too much alterations to these radios, we argue that we did increase their mechanical integrity while maintained their electrical performance. We weighted each proposed alteration from original commercial state, against the risk of actually performing that altering assembly procedure. If the assembly process carries too high of a risk for damaging the radio boards, then the alteration was voted against.

(add photos of repackaged radios, perhaps somehow show the pre-packaging and post-packaging photos, a photo of the wrapped radio)

Immediately after they were repackaged, the radios went through an electrical health test. All eight of them passed this post packaging health check. The radios were then put through a series of thermal and vibration tests. All radios were subjected to the flight acceptance level environmental tests specified above. The two qualification units were subjected to a more severe thermal cycle and higher vibration levels. Following each environmental tests, the radios were checked for their electrical performance. They all passed the environmental tests as verified by their electrical performance.

(how much data do we want to show here?)

In parallel with the radio modems work, was the antenna development effort. This section will focus on the antennas design, build and field tests, since all of the environmental tests were done by the mechanical subsystem as part of the integrated Microrover assembly tests. We will report on the final tuning of the antennas, but first the requirements for the antennas. The goal was to deliver one Rover and one Lander antenna, which are inexpensive to fabricate and test, have mechanically simple deployment scheme, and low mass. The ultimate goal is to simply maintain RF link between Sojourner and the Lander via the antennas. The primary mission has a distance requirement of but approximately 10 meters radius, which means a low gain antenna would suffice.

We decided then on a monopole antenna design, with:

Fc = 459.7 MHz
BW > 25KHz
VSWR < 2:1
Gain 0-1dB
Weight < 100grams

A monopole antenna was the logical choice because at this frequency, it is simple to manufacture, easily implemented/mounted on the mobile Rover, gives the smallest amount of solar panel shading and can be made as light as the raw materials allow.

The antenna is a linearly polarized radiating quarter-wavelength monopole, achieved by removing the outer copper coaxial ground of a semi-rigid cable. The transmission line feeding the monopole is balanced using traditional methods. Breadboard antennas were built and mounted on RF mock-ups of the MPF Lander and Rover. We performed a series of field tests at the JPL antenna range, using these mock-ups to tune the antennas performance. At this frequency, the dimensions and shape of the spacecraft and vehicle play a major role in the antennas performance. All of the antenna tuning was done empirically to determine the optimum physical length. Following these field tests, we went through a couple of design iterations to develop a tuning scheme for these antennas, so that final tuning on the flight hardware can be done easily. Once the flight antennas were built, we performed final electrical tuning on the Rover SIM vehicle and on the Lander flight spacecraft.

(add mechanical drawings of antennas, some combination of drawing numbers: 10159480, 10159488, 10159489, final VSWR plot from antenna on SIM vehicle as an example of how the matched antenna response looks like)

Draft ideas for the 'lessons learned' closing paragraph:

- looking back, going with commercial radios was still the best choice for the funding profile and the short delivery schedule constraints
- we could have put more effort in coming up with a method of testing the "best pair" of radios, rather than the ranking process based on individual radios' performance. we encountered the low temperature higher BER than required.
- BER, i.e., link performance was not set until very late in the game, as flight hardware was going through final electrical tests. we never really sought support from the Telecom systems folks to help with link analysis, until it was very late in the game.
- with a short delivery flight project, interfaces must be determined/negotiated early: the problem with the DCD glitch would have been discovered much earlier had the software interface with the Lander's AIM computer been tested earlier in the project phase.
- future Telecom hardware for similar application will benefit from the advances in wireless LAN, personal communication systems (wireless world in general).
- frequency assignments were handled properly early on, which is important to note for future projects, should they want to use commercial hardware. NASA and the commercial world tend to have exclusive frequency allocations.

We have presented the hardware implementation philosophies, design and repackaging details and environmental test results. As closing remarks, we offer a few "lessons learned" thought and comments on future UHF Telecom subsystems. Right up to launch, we maintained that selecting commercial radios for this project application remained our best option. We met the ultimate goal of delivering a function, not fancy, UHF radio link, within budget. We had twenty-four months turn around to produce flight hardware from commercial radios and deliver antennas we made in house.

We had plenty to learn as the project progressed. With such a short delivery flight project, it is particularly critical to set/determine all subsystem interfaces and requirements early. For one, we did tackle the radiation effects early, but we did not address the BER requirement. Secondly, while we established good digital interfaces/tests with the Microrover software team, we did not/were not able to establish similar relations with the Lander software team.

The consequence of not having a solid ER requirement early, was less motivation to test RF link performance between flight candidate radios. All throughout thermal screening, pre/post packaging, post vibration health checks, the radios were tested with a 'control' radio. all RF link was established between the flight radios and this one 'control' radio. The flight radios' performance were ranked based on such RF link test scenario. What we found during the final thermal acceptance test, when we had the flight radio pairs communicating to each other, the flight spare radios with each other (second pair) and the qualification radios to each other (third pair), was that the third pair showed a better performance over temperature than the second pair of radios. Serendipitously, the flight pair showed the best performance. The lesson is, we should have tried harder to come up with a way to find the best pair of radios. We did give it a brief thought, but were quickly discouraged by the thought of testing each radios, paired up with the other twenty-nine candidate units. The amount of test time it would take, was simply impractical.

The consequence of not establishing good interface tests/agreement with the Lander software team was a bit more severe. In April 1996, seven months prior to launch, when all hardware were in final environmental acceptance tests, we stumbled into a communication 'glitch' at the digital interface to the Lander computer. The UHF communication protocol is set up with the Rover as the 'master' of the communication link. With the Lander serving as the 'slave' of this communication link, it relies on the data carrier detect line to be activated. When this DCD line becomes activated, the Lander expects to see data. If data is not received, it immediately responds to the Rover with a 'no acknowledge.' Some of the very sensitive radios, however, will show false DCD triggering. This cases undesired communication response from the Lander. Once this undesired response of 'no acknowledge' is initiated by the Lander, the communication link is pretty much hung up. The Rover could go into a 'failed communication link' contingency sequence. In commercial, ground, application, this DCD line is used as a tuning test port only. Thus, false DCD triggering does not disrupt the communication link. It took a considerable last minute effort to solve this problem, and to ensure that we will not have a false DCD triggering on these commercial units. We did solve this issue around mid November, less than a month to launch. We could have saved ourselves this heroic/intensive trouble shooting effort, had we established early interface tests with the Lander computer software team.

Conclusion

As parting words, we include a note on the future applications of UHF telecommunication hardware. For line-of-sight, surface-to-surface link, ground to low Martian orbit, single chip transceivers could be the best options. They are commercially available. The trade-off factors would include: low cost, short delivery schedule, possible radiation (single event latch up) sensitivity, adapting flight requirements to available components. These future missions should take advantage of the advances in the cellular phone technology and the wireless LAN development.