MARS NETWORK: STRATEGIES FOR DEPLOYING ENABLING TELECOMMUNICATIONS CAPABILITIES IN SUPPORT OF MARS EXPLORATION,
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Introduction: The coming decade of Mars exploration will involve a diverse set of robotic science missions, including *in situ* and sample return investigations, and ultimately moving towards sustained robotic presence on the Martian surface. In supporting this mission set, NASA must establish a robust telecommunications architecture that meets the specific science needs of near-term missions while enabling new methods of future exploration. This paper will assess the anticipated telecommunciations needs of future Mars exploration, examine specific options for deploying capabilities, and quantify the performance of these options in terms of key figures of merit.

Anticipated Telecommunications Needs: Various classes of Mars science missions can be characterized by their telecommunications needs and constraints.

Remote Sensing Orbiters: Highly capable deep space links will be required to provide global, high-resolution, multi-spectral mapping of Mars. For example, consider a high-resolution three-color visible imager. Mapping the entire planet at 1m resolution represents an uncompressed data volume of about 5000 Terabits. This enormous data volume, if it were to be returned in a single Martian year, translates to an average continuous data rate of over 100 Mb/s, roughly three orders of magnitude larger than current Mars-Earth links. Aggressive use of data compression along with increased deep space link performance will be required to achieve such science goals.

Large In-Situ Landers/Rovers: In situ surface exploration will demand both increased data return and connectivity. Data volume requirements will be driven by science needs as well as operational considerations. For example, a single three-color stereo panorama, imaged with 1 mrad resolution, represents about 0.5 Gb of data. Increases in rover mobility will naturally drive an increase in desired data return, as the number of "independent" sites visited will scale with rover traverse range. In addition to data volume, communications link availability will be an important consideration, particularly for complex surface operations. Finally, all landed missions will desire telecommunications visibility and support during entry, descent, and landing, to provide full characterization of EDL systems in the event of any anomaly.

Small Scouts/Aerobots/Microprobes: These missions are characterized by their small size (<100 kg) and highly constrained energy budgets. Typically, they cannot afford the mass and energy required for any meaningful data return directly over a deep space link. Rather, these missions require, and are enabled by, energy-efficient relay communications. Concepts range from single-element scouts or aerobots, communicating directly to an orbiting relay satellite, to "sensor webs" consisting of large numbers of extremely small microprobes carrying out focused, collaborative science via inter-element communications links.

Sample Return Missions: In addition to all the considerations which apply to large lander/rover missions, sample return will also require critical real-time telemetry support during launch of a Mars Ascent Vehicle as well as radio tracking for orbit determination and rendezvous with an Orbiting Sample Canister (OSC).

Potential Mars Network Elements: A variety of techniques and communications elements are candidates to meet these needs.

Direct-to-Earth Links: Orbiter data return, either for remote sensing science orbiters or for telecom relay orbiters, is limited by the deep space comm link capability. Use of high-power traveling wave tube amplifiers (>100W) can increase data rates to over 100 kbps at X-band. Use of DSN 70m apertures (not recommended for extended operations) or transition to Ka-band offers further 6 dB performance increases in the near term. Migration to optical communications wavelengths offers a longer-term path to further growth in deep space comm channel capability. A prototype is currently in development for a next-generation multi-functional optical instrument with capability for narrow-angle (high-resolution) science imaging, optical navigation and ranging in addition to optical communication at data rates 100's of kbps from Mars. NASA's longer-term optical comm roadmap forecasts Mars-to-Earth link capabilities in excess of 10 Mbps.

Landed vehicles will be constrained to much smaller mass, power, and volume for any direct-to-Earth links, and hence lower data rates. Mars Pathfinder utilized a link with a 30cm antenna and 15W radiated power, corresponding to a link capability of less than 1 kbps to a DSN 34m antenna at maximum Earth-Mars distance. In addition, surface energy constraints typically limit use of this direct link to a small fraction of a sol. On the other hand, because Earth is above the horizon for most of the sunlit portion of a Mars sol, direct-to-Earth links are useful for low-rate command and telemetry for large rovers/landers during surface operations.

Short-range Surface-to-Surface Communications: Multi-element missions, such as a lander and rover carrying out sample return, will require low-power, low-mass *in situ* comm links. Sensor webs will demand even lower-power, highly integrated comm systems. Wireless RF solutions will highly leverage terrestrial commercial developments, while novel free-space optical approaches utilizing scanning lasers and modulatable retro-reflectors offer extremely low-power solutions.

Low-Altitude Orbiters with UHF Relay Capability: Because of their low slant ranges to surface users, low-altitude orbiters can support extremely energy-efficient, high-rate UHF (400 MHz) links from the surface of Mars, even when utilizing operationally simple omnidirectional links on both the surface and orbital spacecraft. This makes these orbital assets of prime importance for small scouts, aerobots, and microprobes characterized by highly constrained mass and energy budgets and inability to point highly directional communications antennas. Typical UHF link performance for omni-to-omni links scales roughly as $\frac{32\,kbps \times (P_T / 1\,W)}{(R\ / 1000\,km)^2}$, so a typical 10W lander radio can achieve rates of up to 1 Mbps to a low-altitude orbiter when it passes overhead.

Two primary classes of low-altitude orbiters have been considered. Science orbiters are typically deployed in low (~400km) sun-synchronous polar orbits in order to support global, high-resolution remote sensing. Adding a UHF proximity link telecommunications payload to these orbiters is an extremely cost-effective way to add to the Mars orbital telecommunications infrastructure. On the other hand, the polar orbit implies short (5-10 min), infrequent (typically twice per sol) contacts for near-equatorial landers, where most near-term missions will be targeted. The second option is dedicated telecom satellites, deployed into optimal orbits to support planned surface activity. For instance, an equatorial orbiter at an altitude of 800 km can support 12 passes per sol for an equatorial lander, with coverage out to +- 30 deg latitude.

Constellations of 3-6 low-altitude orbiters can provide global coverage, frequent contact every 1-2 hrs, and data return of 1-10 Gb/sol for future Mars exploration, along with intrinsic robustness and resilience to the loss of a single element. In addition, crosslink observations between constellation orbiters can yield accurate atmospheric profiles globally distributed in Mars latitude and longitude.

Mars Areostationary Relay Satellites: An areostationary satellite is the Mars-equivalent of an Earth geostationary satellite. From the areostationary altitude of 17,000 km, a Mars Areostationary Relay Satellite (MARSAT) would have continuous visibility of a landed surface vehicle. Utilizing directional links, data rates of 1 Mbps can be achieved from a modest surface radio (e.g., 20 cm antenna, 5 W radiated power). With a high-capability Earth link, MARSAT can thus enable end-to-end data transfer of up to 1 Mbps from the Martian surface back to Earth, capable of supporting streaming video or other high-bandwidth applications. The primary challenge of a MARSAT mission is the high cost of achieving areostationary orbit. Chemical propulsion requires a large propellant mass which drives the mission to a Delta III-class launch vehicle. Solar Electric Propulsion options are being explored as potential lower-cost alternative for an areostationary orbiter. MARSAT would also provide an interesting science platform for visible or IR imagers in terms of characterizing global-scale atmospheric phenomena.

Elliptical Orbiters: By the time of the workshop, we will also have new results to present for the telecommunications performance of a mini-constellation of two elliptical orbiters. Such a design appears to offer some of the advantages of MARSAT, such as much higher connectivity than low-altitude orbiters, without the high delta-V costs of achieving areostationary orbit.

Integrated Information/Communications Architecture: Design of the communications network supporting Mars will greatly benefit from integrating *in situ* information processing for science and support operations. Greater efficiencies may be expected by performing local processing and subsequent transport of the processed information, rather than simply communicating raw high-bandwidth sensor data. These gains primarily stem from the reduced energy consumption of computation versus communications. Bandwidth is also better utilized. Increased processing tends to produce outputs characterized by smaller volume (in terms of bits needed to represent them) together with greater dynamics and unpredictability. In order to accommodate this increased variability using assets remotely operated on Mars, new and adaptive communications protocols and information handling techniques are required.

Navigation Considerations: While the emphasis of this abstract has been on telecommunications, we will also report on the potential of these assets to provide radio Doppler and range tracking for support of precision approach navigation, surface navigation, and MAV/OSC navigation.

Analysis: Based on different candidate program science strategies, pros and cons of various combinations of these telecommunications options will be characterized quantitatively in the presented paper in terms of key figures of merit, including data return, connectivity, operational simplicity, cost, and risk.

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