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Internet Technologies for Space-Based Communications: State of the Art and Challenges

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INTERNET TECHNOLOGIES FOR SPACE-BASED COMMUNICATIONS: STATE OF THE ART AND CHALLENGES[1]

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ABSTRACT

The Internet is rapidly changing the ways we communicate information around the globe today. The desire to provide Internet-based services to anyone, anywhere, anytime has brought satellite communications to the forefront to become an integral part of the Internet. In spite of the distances involved, satellite links are proving to be capable of providing Internet services based on Internet protocol (TCP/IP) stack. This development has led to the question particularly at NASA; can satellites and other space platforms become an Internet-node in space? This will allow the direct transfer of information directly from space to the users on Earth and even be able to control the spacecraft and its instruments. NASA even wants to extend the near earth space Internet to deep space applications where scientists and the public here on Earth may view space exploration in real time via the Internet. NASA's future solar system exploration will involve intensive in situ investigations of planets, moons, asteroids, and comets. While past missions typically involved a single fly-by or orbiting science spacecraft, future missions will begin to use fleets of small, highly intelligent robotic vehicles to carry out collaborative investigations. The resulting multi-spacecraft topologies will effectively create a wide area network spanning the solar system. However, this will require significant development in Internet technologies for space use.

This paper provides the status of the Internet for near earth applications and the potential extension of the Internet for use in deep space planetary exploration. The paper will discuss the overall challenges of implementing the space Internet and how the space Internet will integrate into the complex terrestrial systems those forms the Internet of today in a hybrid set of networks. Internet. We envision extending to the deep space environment such Internet concepts as a well-designed layered architecture. This effort will require an ability to develop and infuse new physical layer

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technology to increase network bandwidth at very low-bit error rates. In addition, we identify network technologies such as routers and switches needed to maintain standard application layer interfaces, while providing low-cost, efficient, modular networking solutions. We will describe the overall architectural approach to extending the concept of the Internet to space and highlight the important technological challenges and initiatives that will make it a reality.

INTRODUCTION

The rapid development in the terrestrial Internet technologies in last few years have the potential to change the current paradigm of how the information is exchanged between space and ground. The development of space Internet (or internetworking) has the potential to provide the seamless flow of information from the earth observing satellites, platforms, International Space Station and Shuttle to scientists and the public here on earth and allow the control of instruments by the scientists. This will enhance the ability to predict weather as well open new possibilities for research. An interactive, high data rate Internet type connection through space relay communications networks would enable authorized users anywhere to control space-based experiments in near real time and obtain experimental results immediately. A space based communications network architecture consisting of satellite constellations connecting orbiting space science platforms to ground users can be developed to provide this service. While past missions typically involved a single fly-by or orbiting science spacecraft, future missions will begin to utilize fleets of small, highly intelligent robotic vehicles to carry out collaborative investigations. The resulting multi-spacecraft topologies will effectively create a wide area network spanning the solar system. It will require an ability to develop and infuse new networking and communication technology breakthroughs to increase network bandwidth, while maintaining standardized application layer interfaces, and providing low-cost, efficient, modular network communication solutions. In addition, the continuing technological advances in satellite communications and computer networking have resulted in commercial systems that now can potentially provide capabilities for communications with space-based science platforms.[1] This reduces the need for expensive government owned communications infrastructures to support space science missions while simultaneously making available better service to the end users.

As NASA approaches the next millennium, the agency enters a new era of planetary exploration. The first era consisted of fly-by missions to most of the solar system's planets, culminating in the Voyager mission, with its Grand Tour of Jupiter, Saturn, Uranus, and Neptune. These fly by missions gave us or first brief snapshots of these remote worlds. The second era of planetary exploration has been based on remote sensing orbiters, such as the Magellan mission to Venus and the Mars Global Surveyor. These orbiters can provide much greater data volume, higher science resolution and, due to their extended stay, a better understanding of the temporal dynamics of the planets. The third era, which we are now entering, takes us into the realm of detailed *in situ* exploration. This era will involve landers, rovers, aerobots, and even sub-surface or submarine vehicles that will directly probe the planets, moons, comets, and asteroids throughout the solar system.

In this new era of exploration, we will move from single-spacecraft missions, with simple point-to-point communications, to more complex network topologies, with dedicated relay satellites, constellations of spacecraft flying in formation, and multiple robotic vehicles working collaboratively. A fundamental goal of this era of exploration will be to establish a virtual presence throughout the solar system. Clearly, the fidelity of this virtual presence will largely be determined by the capabilities of the communications network across which information will flow. This era of exploration calls for the creation of an "Interplanetary Internet".

ARCHITECTURAL CONCEPTS

Future requirements of NASA enterprises to provide information directly to users over heterogeneous communication networks can be met by the development of open-standard, seamlessly inter-operable network architectures based on Internet protocols. The NASA Earth Science, Human Exploration and Development of Space (HEDS), and Space Science enterprises have expressed a strong desire to expand their information gathering and dissemination capabilities in communication networks in the near future by the application of Internet technology. Furthermore, real-time interactive communications between humans, machines, and instruments in space is desirable to expand our reach in space.

The approach to this research requires that NASA identifies and integrates innovative inter-networking technologies that adhere to an open standard, seamlessly interoperable communication architecture based on the Open Systems Interconnections (OSI) seven-layer model. All the layers are not needed for the space-based Internet communications' applications. In Fig. 1, the various layers and their simplified functions are presented. This will allow the interfacing of NASA Science spacecraft or spacecraft constellations via a NASA or commercial satellite network to the emerging terrestrial Internet. It will look at systems designed for use on a constellation of spacecraft orbiting in formation, and communicating to other spacecraft in low Earth orbit and to ground users.

Through a modular concept, varieties of communication concepts proposed by NASA missions are evaluated and system level technologies (hardware and software) are identified and developed at lower TRLs. However, the starting point for this research proposal is to establish high data rate communications via ATM, LAN, and Ethernet technologies from an orbiting spacecraft in low Earth orbit to ground users through a geosynchronous transfer satellite.

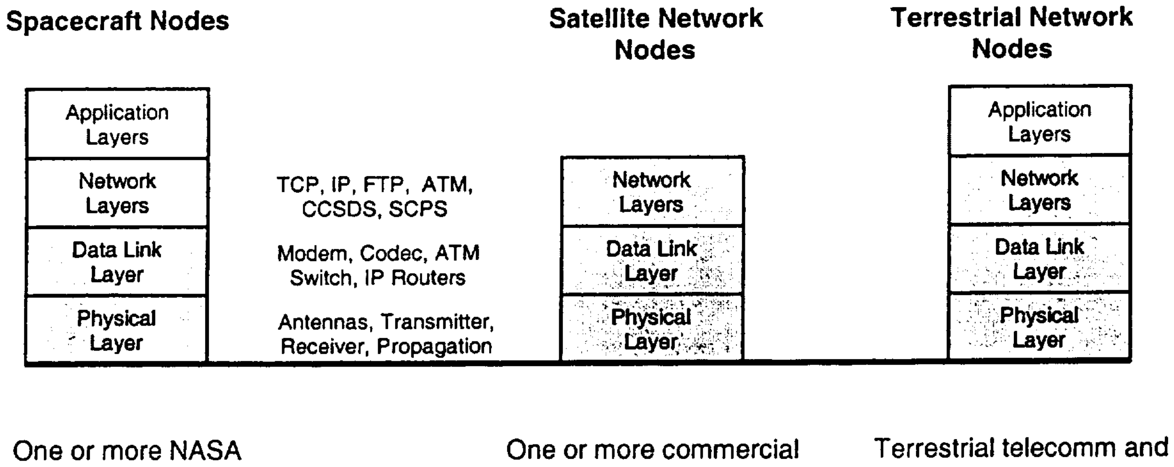

Figure 1 - Reference Model for the Space Internet

Physical Layer Architecture for Near-Earth Space Internet

A study of the potential application of six current or proposed commercial satellite networks to provide data relay services for low earth orbit (LEO) spacecraft and other space missions was carried out.[2] It showed that a large range of maximum daily data throughput (from 1.5 Mbits to 288 Gbits), could be obtained, depending on the particular satellite network and the space science platform's orbital characteristics. The corresponding average service time per orbit, maximum null time, and user terminal requirements also varied considerably. Hence, fulfilling a particular space science mission need for Internet connectivity to ground users would require consideration of a number of possible commercial satellite solutions, including a combination of two or more satellite networks.

Figure 2 is a depiction of potential connectivity between a user/experimenter on the ground and an orbiting space science platform. Depending on its orbital characteristics, the science platform has the potential to connect to commercial communications satellites in low, medium or geostationary earth orbits (LEO, MEO, or GEO, respectively). LEO or MEO satellites can relay through GEO satellites to ground stations or can connect directly to gateway earth stations. LEO, MEO and GEO constellations may include intersatellite links allowing access to specific earth station locations. Experimenters can access the space science platforms through the gateways using standard terrestrial Internet connections or more directly using their own dedicated earth station.

The complexity of such architectures ranges from a relatively simple connection of an experimenter to a space science platform through a single GEO spacecraft. The complex connection includes a combination of LEO or MEO constellations with intersatellite linking, relays through GEO satellites, and terrestrial Internet connection to a commercial gateway. The simplest architectures will present the fewest implementation problems, but architectures that are more complex may be required to meet space science mission goals for coverage, connectivity time, and data throughput.

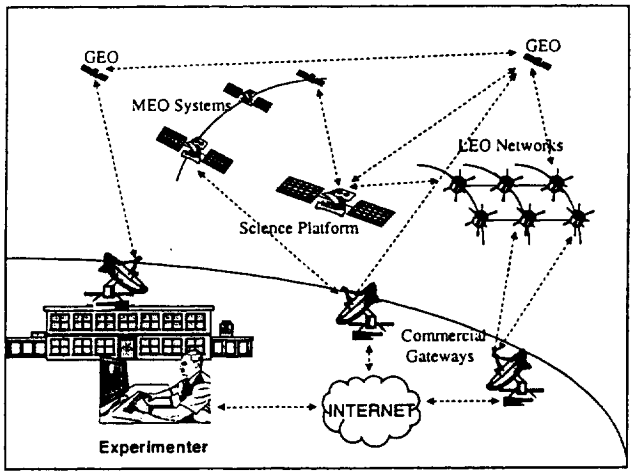

Figure 2 - In-Space Science Platform Internet Connections to a Ground Based Experimenter[3]

CURRENT STATE OF THE ART

To date, a low data rate Internet experiment using a commercial router has been performed on Shuttle. In the technology, interoperability and standards areas, number of advances have been made and are outlined in recently held workshop on satellite networks[4] which are critical to the development of space Internet.

Assessment of network architectures, identification of required new or improved technologies, and investigation of data communications protocols are also being performed through testbed and satellite experiments and laboratory simulations.

In the transport protocols area, the main focus is on TCP (Transmission Control Protocol), since the reliability and congestion control portions of this protocol are linked to the delay and bit-error rate of the network. The effects of TCP over a ground-to-GEO satellite-to-ground link is summarized by Allman et.al.[5] However, when the delay is not fixed, for instance, in a ground-to-GEO satellite-to-LEO satellite link, the varying delay may have an effect on the performance of TCP. If the round-trip-time (RTT) changes too rapidly, TCP may assume a piece of data has been lost, when in fact the acknowledgment for the data is on its way back. RTT is defined as the time for data to be sent from the source computer to the destination computer plus the time for the acknowledgment of the received data to be returned to the source computer. Such actions would greatly decrease the efficiency of transmission and reduce network performance. Protocol adaptations that can accommodate the delay variations expected in a complex space-based network and improve overall network performance are under development.[6]

TECHNOLOGICAL CHALLENGES AND INITIATIVES FOR NEAR-EARTH INTERNET

Development, implementation and operation of an Internet-like network in a rapidly changing space environment presents major technical challenges in the area of spacecraft mobility, protocols, information security, network reliability and miniaturized and agile hardware elements. Depending upon the complexity of the network architecture, significant variations in the total path length between the space science platform and the ground-based experimenter will occur. The relative motion between the orbiting space science platform and the network of commercial communications satellites (LEO, MEO, GEO or combination) relative to the ground stations can result in potentially complex path length profiles. In addition, hand-offs between communicating spacecraft occur as the commercial satellites come into and move out of view of the space science platform. The frequency of hand-offs could range from several per orbit to several per minute depending on the commercial communications network and network architecture being used.

The path length variations result in a corresponding variation of RF propagation parameters that, in turn, affect the signal quality, bit-error rate, and protocol performance. The two key RF propagation parameters are the signal delay and the signal strength. The variation of signal delay primarily affects the performance of Internet protocols as discussed in the following section. The variation in signal strength, where longer path lengths result in reduced signal strength at both space and ground receivers, creates a corresponding variation in the bit-error rate of the transmitted data. Hence, the longer path lengths induce more errors, requiring more frequent retransmission of data packets and reducing the efficiency of the transmission. Overall network performance will vary in a complex fashion, and understanding these variations and designing the network architecture to accommodate them is important in meeting the goals of the space science mission.

Advanced hardware technology required for an in-space Internet networks include space-based tracking antennas, routers and miniaturized network modules. Multi-element phased array antennas which can electronically steer to acquire and track moving spacecraft, and rapidly re-acquire new spacecraft during hand-offs must be made as small, lightweight and affordable as possible. Network routers, performing functions similar to high-speed routers that currently provide the switching functions for the Internet, must be developed for use in space in order to achieve a true Internet type network in space. The routers must be small, lightweight, low power and radiation tolerant to enable an efficient and cost effective space network. A program to develop routers for space applications that are compatible with the commercial Internet has been initiated. A conceptual block diagram of the network module is shown in Figure 3, such modules may or may not include routing functions. The modules allow the interface to spacecraft computer, bus, and the communication module. The network module is reconfigurable and allows the spacecraft to become the node on the Internet by its ability to package data in IP packets or ATM packets.[7]

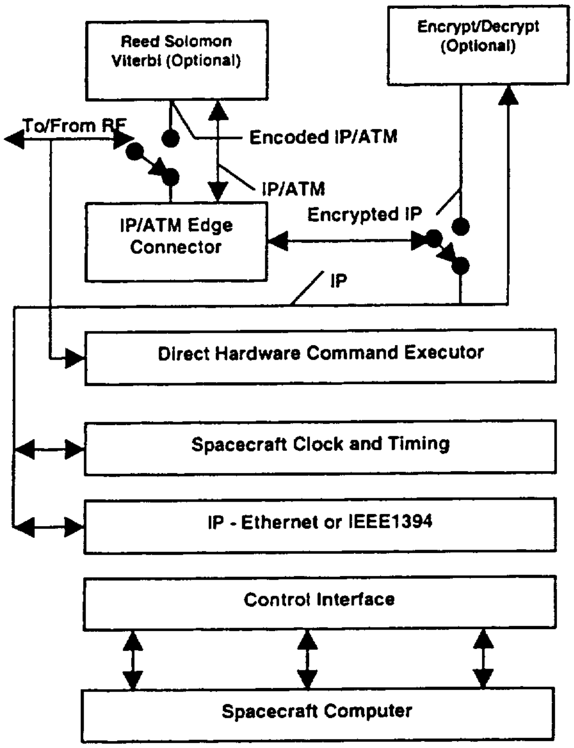

Figure 3 - Network Module Concept

Another challenge involves Internet routing protocols. Due to the movement of satellites, relative to each other, there are times when a line-of-sight connection cannot be maintained between the two objects. Consider the simple case of a LEO communicating through a GEO to the ground. In this scenario, when line-of-sight communication is lost to the GEO, the satellite either must establish a connection to another GEO satellite, on the other side of the earth, or wait until it passes around the earth to reacquire the previously lost GEO. In this case, changes in the routing of packets may need to be made, in order to allow the LEO to start transferring data over this new link. If the scenario is changed to communications between two LEO satellites, the routing must be changed more often to keep relatively constant communication between the objects. This may include the two LEO satellites communicating over the same GEO satellite or grow to a LEO-to-GEO-to-ground station-to-terrestrial Internet-to-ground station-to-GEO-to-LEO connection. In this case there is a potential of multiple routing changes taking place in a single orbit, with periods of outages or data lost due to packet corruption, re-ordering, duplication, etc., during hand-offs, which decrease the performance of the transport protocol and degrade the performance of the network.

INTERPLANETARY INTERNET: ARCHITECTURE AND TECHNOLOGIES

Much as the terrestrial Internet has changed the way in which we move and share information here on Earth, we envision an Interplanetary Internet that fundamentally changes the way we move information across the solar system.[8] Looking to the success of the Internet as a guide, we highlight the following characteristics of the Interplanetary Internet:

- **Breakthrough communications bandwidth increases on interplanetary links:** Achieving meaningful virtual presence will demand significant increases in data return from solar system targets. The extreme range of deep space missions leads to severe communications bandwidth limitations. For example, the 30 Mb/sol average data return from the Mars Pathfinder mission corresponds to a continuous time-averaged data rate of only

300 bps between Mars and Earth. Achieving for deep space the kind of bandwidths we take for granted in the terrestrial applications will require orders-of-magnitude increase in communications capability. In the near term, moving from our current X-band (8-GHz) deep space frequency to a higher Ka-band (32 GHz) frequency promises to provide roughly a four-fold increase in deep space performance.[8] New coding techniques and planned DSN technology upgrades will provide additional incremental improvements. New high-power spacecraft transmitters and large, inflatable spacecraft antennas provide a path to much higher spacecraft EIRP and, in turn, higher data rates. In the longer term, optical communications has the potential to further increase deep space telecommunications performance.[9]

- **Seamless end-to-end information flow across the solar system:** The Internet has changed how we think about data. Rather than worrying about handling individual bits, we focus on packets and files, and can easily direct these data anywhere in the world. In much the same we, the Interplanetary Internet will support seamless data transfer from nodes throughout the solar system. A rover will initiate a file transfer to a PI on Earth, and that PI will generate commands that can be routed from his/her desktop to the spacecraft as easily as we send e-mail today.

- **Layered architecture for evolvability and interoperability:** Perhaps the greatest success of the Internet, as it celebrates its 30th anniversary, is the fact that its creators were able to establish a clean, layered architecture that has been able to accommodate three decades worth of explosive technology growth in physical layer communications capability while maintaining stable higher-level transport and application layer interfaces. It is crucial that the Interplanetary Internet likewise establish at the outset well-designed layered interfaces to allow this same level of evolvability and interoperability.

IP-Like Communications Protocols Tailored To Operate Over Long Round Trip Light Times:

The long round-trip light times experienced on deep space links, ranging up to 40 min for a Mars mission and up to more than 8 hrs for a Pluto mission, preclude the direct use of standard Internet Protocols. The "chatty" nature of these protocols breaks down under these long RTLT conditions. NASA is developing a suite of communications protocols that deliver the kind of reliable file transfer that we take for granted over the Internet, but that are tuned to the characteristics of deep space links. For example, the CCSDS File Delivery Protocol will provide a deep –space equivalent of the Internet's FTP application layer functionality, ensuring reliable file delivery even through intermittent, multi-hop deep space links.[10]

Efficient, Miniature Short-Range Communications Systems:

Just as we can buy a PCM/CIA card that slips into our laptops and provides a plug-and-play interface to the Internet, we will need to develop standardized short-range radio systems for communications between robotic rovers, landers, and relay orbiters. Low mass, volume, and power will be key figures of merit for these systems. The Micro Communications and Avionics System (MCAS) being developed under NASA's Cross Enterprise Technology Development targets a highly integrated short-range radio incorporating a mixed signal ASICs and

MEMS-based oscillators and filters to achieve aggressive mass, power, and volume goals.[11]

Integrated Communications and Navigation Services:

Similar to the way in which wireless communications is being bundled with GPS to provide full comm/nav solutions on Earth, we will want to bundle navigation functionality into short-range relay radio systems. For example, the Autonomous Formation Flyer radio system being developed for New Millennium ST3 will provide precision intersatellite navigation, determining the range between ST3 constellation elements to an accuracy of 1 cm.[12]

Mars Network: First Stop on the Interplanetary Internet

Mars provides the first planet at which many of these concepts will be put into practice. The coming decade calls for an unprecedented level of exploration of Mars, with an international set of missions involving sophisticated landers and rovers for returning Mars samples. as well as globally distributed microlanders, penetrators, and aerobots to carry out detailed in situ investigations of the chemical, geological, and biological history of our neighboring planet. The number of missions and breadth of activity on the surface motivate the need for a dedicated infrastructure at Mars to provide enhancing and enabling telecommunications and navigation capabilities. Current capabilities will simply not support the complexity of anticipated mission concepts nor the richness of expected data sets. For example, the Mars Pathfinder mission provided mean data return of only 30 Mb/sol, more than an order of magnitude less that the data volume represented by a single full-resolution panorama imaged by the Pathfinder PANCAM instrument. The limitation of just a few hours of contact time per sol, due to the high energy-per-bit demands of the direct-to-Earth link utilized by the Pathfinder lander, constrained the ability of scientists and mission planners to quickly close decision loops with the Sojourner rover. And current earth-based navigation limited the targeting of the landing site to an accuracy of about 100 km.

Over the past year, NASA has developed plans for establishing such an infrastructure in the form of an evolving constellation of satellites in orbit about Mars.[13] The Mars Network as currently envisioned would incorporate two classes of orbiting spacecraft to provide this infrastructure, as shown graphically in Figure 4.

One element of the Mars Network would be provided by a six-satellite constellation of very low-cost, low-altitude microsatellites. Launched as piggyback payloads aboard commercial Ariane-V launches, these low-mass (220 kg) microsats would be placed into geosynchronous transfer orbit, from which they would first inject into a trans-lunar parking orbit and then, at the appropriate time, inject into an interplanetary cruise trajectory to Mars. Upon arrival at Mars, the microsat would inject into a highly elliptical orbit and then aerobrake down to a circular orbit with an altitude of 800 km. The ultimate six-satellite constellation, deployed over a series of Mars launch opportunities, would deploy two satellites in near-equatorial retrograde orbits along with four satellites in inclined, 111-deg retrograde orbits. The resulting constellation provides full global coverage, with enhanced performance near the equatorial region The microsats would carry an X-band or Ka-band deep space link, with performance constrained by the 80-cm size limitation of the microsat high gain antenna. Communications links between the microsats and users on the surface would be provided by a proximity link UHF payload. These same links would provide Doppler and range navigation observables. Once complete, the constellation would provide nearly 10 Gb/sol of data return from Mars, sensitive relay links enabling low-mass, low-power surface communications systems, frequent contact with 20-30 passes per sol, and high-accuracy positioning, allowing 10m position accuracy for surface rovers.

The second element of the Mars Network is built upon a higher-performance spacecraft that would be capable of supporting near-continuous video from the surface of Mars along with other high-bandwidth data throughput. The Mars Areostationary Relay Satellite (MARSAT) would fly in a 17,000-km circular orbit, with a period of 1 sol, providing a continuous view of one hemisphere of the planet. From this high altitude, omnidirectional UHF links to the surface are not practical; rather, MARSAT would utilize a directional X-band link via a 1.3m high-gain antenna for the proximity link between the surface and MARSAT. A surface user with a small X-band communications terminal (e.g., a 20 cm antenna with just 2 W of transmitted power) would be able to establish a 1 Mb/s link to MARSAT. A second Ka-band high-gain antenna (1.5 m) on MARSAT, with a high-power, 100 W traveling wave tube amplifier, would then enable a 1 Mb/s data rate on the deep space link to a single 34m DSN ground antenna.

With the combination of a low-cost microsatellite constellation along with higher-performance MARSATs, the Mars Network has the potential to dramatically increase data return from Mars. As shown in Figure 5, the initial deployment of the microsatellite constellation provides more than an two orders-of-magnitude increase in data volume return relative to Mars Pathfinder. The addition of MARSAT provides another order-of-magnitude growth. With deployment of three MARSATs, and the aggressive infusion of new RF technologies such as Ka-band inflatable antennas, the capability for data return from Mars can grow to 300 Gb/sol, four orders of magnitude above Pathfinder. This remarkable growth in data return will fundamentally change the way we experience Mars, enabling new science mission concepts and providing new ways to involve the public in the coming decade of Mars exploration.

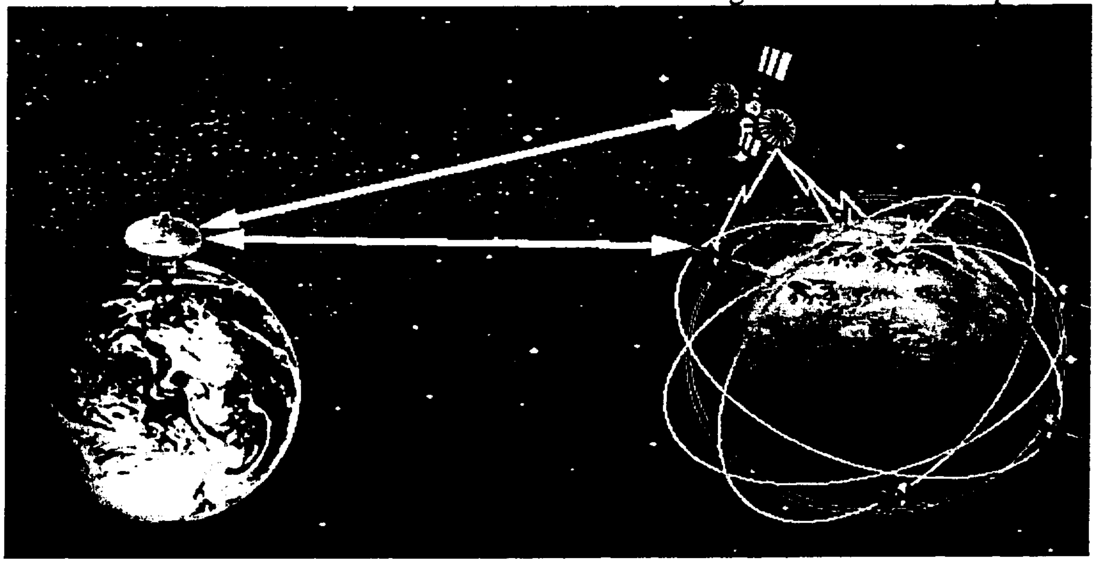

Figure 4 - Conceptual View of a Mars Network for Providing Enhanced and Enabling Telecommunications and Navigation Capability for Future Robotic and Human Mission to Mars

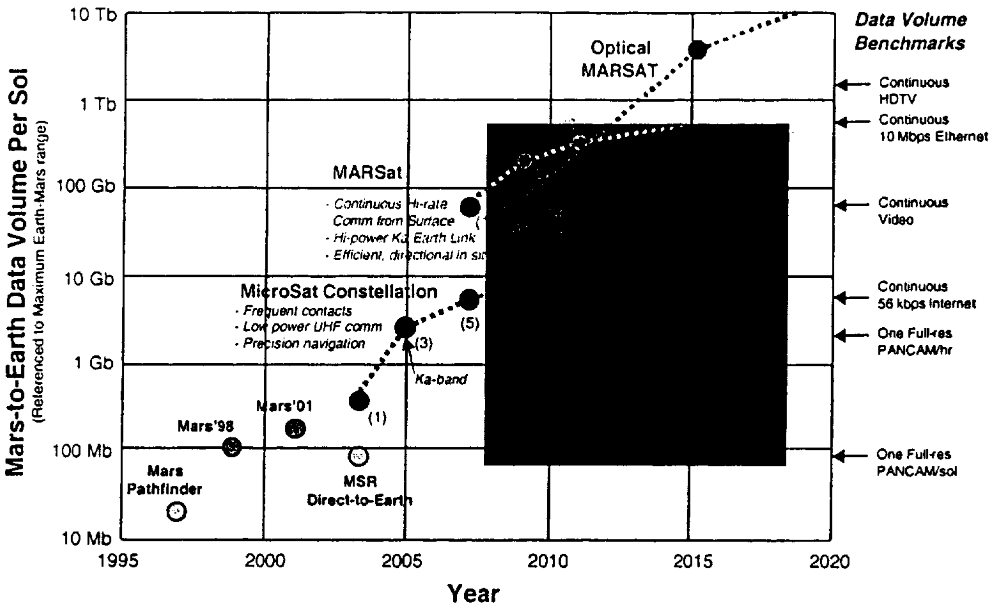

Figure 5 - Increase in Interplanetary Mars-Earth Data Return as the Mars Network is Deployed[14]

SUMMARY

Internetworking of spacecraft and platforms via relay satellite networks to ground based networks based on open-architecture standards will greatly improve the timely availability of space data to the users. Furthermore, it is likely that such an infrastructure will allow new ways to perform earth science. NASA is performing research on critical protocols and technologies to enable efficient performance of such networks. NASA is developing and assessing communication and networking technologies that will allow development of Internet in space for earth science missions in secure and timely manner.

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