INFORMATION INFRASTRUCTURE FOR LONG TERM HABITATION OF SPACE ENVIRONMENTS

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Abstract

Information infrastructure including communications, remote sensing, and global positioning networks are key to the long-term habitation of space environments. GPS, Internet, and Landsat have proven their usefulness in opening every part of the Earth for exploration and habitation. Similar systems must be in place prior to human habitation of other environments. Existing and proposed information infrastructure for the Earth, Mars, and the Moon are explored in this paper.

Introduction

A network consists of a series of nodes that are connected such that any node can communicate with any other node. The significance of a network is that the capabilities of the network often exceed that of the sum of its nodes. Networks rest on a layer of information infrastructure: hardware and software that facilitates communication and the exchange of information. A mature information infrastructure includes capabilities for voice, video and data communications, the ability to determine where you are with respect to the other nodes, and a source of information about your surroundings.

In planning the expansion of human civilization throughout the solar system the development of the supporting information infrastructure is critical. The only product to have been successfully transported from space for a profit is information; the ad hoc information networks that tie satellites and space probes to the Earth has been sufficient so far but fails in the respect that it is not a true network. Communication is constrained to a fixed number of vectors. As the consumers of information become increasingly spread out throughout the solar system this ad hoc network will fail to be sufficient to support human endeavors in space.

Human factors increase the importance of information infrastructure. Humans are fragile, both physically and psychologically. Critical hazard information, such as solar flare data, must be routed through the solar system without a mandatory layover at Earth. As the experience on the Mir space station has shown, humans require contact with friends and family to remain productive. Personal communications channels must always be open, though their availability may be constrained by the priorities of the mission designers.

Finally, the availability of information infrastructure facilitates colonization. The fact that communications and positioning information is available on any point on the planet allows people to live and work anywhere on the planet. Similarly, the availability of information infrastructure in space will allow people to live and work anywhere in the solar system. The settlement of the High Frontier in any large scale will require these capabilities.

Earth-Based Information Infrastructure

Information infrastructure on Earth represents the case of evolved infrastructure. Some of it is space based, such as Landsat and GPS, and some of it is ground based, such as the Internet. On Earth each of the principal pieces of information infrastructure was developed independently. Each was designed separately and represents the best of a breed. In each case there were predecessors that were eliminated in a competitive marketplace.

The Landsat program has continuously acquired multi-spectral images of the Earth for more than 28 years. In a sun-synchronous polar orbit, Landsat satellites observe the entire globe as the Earth rotates beneath them. Landsat images have provided data that have allowed scientists to study the atmosphere, oceans, land, vegetation, glaciers and other aspects of the Earth's environment. The fact that Landsat passes over the same location periodically and its sun-synchronous orbit provides a uniform shadow allows the program to provide images that show change on a global scale. Finally, data from Landsat have allowed for precise resource location.

The Global Positioning System (GPS) consists of 25 satellites in 6 orbital planes 60 degrees apart, inclined about 55 degrees from the equatorial plane. The GPS provides line-of-sight coverage of between five and eight satellites from any point on Earth. This provides X, Y, Z, and time positioning.

The GPS system was originally designed to support military applications. Each satellite has an Earth-facing L-band antenna that sends out several signals. The first is called the C/A-code signal and is used for civilian positioning applications. The second is called the P-code signal and is encrypted and transmitted at a much higher data rate than the C/A-code signal. Both signals consist of pseudo-random noise that is pre-generated and available to both the transmitter and receiver. Both signals are transmitted with a navigation message that consists of satellite ephemeris information. There are three additional signals transmitted by GPS satellites. These signals are used for a nuclear warning system and future expansion.

Using signals from at least four overhead satellites, civilian GPS receivers can accurately position to within approximately 100 meters. This resolution can be enhanced by the use of differential GPS or pseudolite systems that provide additional ground based location signals. Military GPS applications are reputed to be on the order of ten times more accurate.

The Internet is Earth's universal communications network. It provides for the exchange of packet data without any centralized source. It was designed in the Cold War to operate in the event of a nuclear strike. Therefore it can function until all of its nodes are disabled. (or until the last link between any two nodes is disabled) It can dynamically deal with changing network traffic patterns and failing links by re-routing traffic on an as-necessary basis. The end result is a network that can handle any kind of traffic, raw data, video, voice, images, etc. Traffic can optionally be encrypted using public key encryption methods. This prevents unauthorized third parties from accessing sensitive information.

The biggest problem the Internet has right now is guaranteed availability of bandwidth. Applications such as voice and video require certain minimum bandwidth levels in order to function properly. Modifications to standard Internet protocol (IP) traffic that provide tags to guarantee bandwidth availability have been quite successful in private corporate networks. These technologies, however, are not yet universal. The growing use of the Internet as a media delivery network makes their widespread adoption in the next few years likely.

The problem with applying an information infrastructure designed for use on Earth in a different environment is lack of proper optimization. Each piece of the Earth's information infrastructure was optimized, deployed and is supported independently. More importantly, each piece of the Earth's information infrastructure represents an evolved component. Each is the winner of a competition to be commercially viable. In space environments, these design techniques are no longer viable as the number of customers is far smaller and the limitations on cost are far stricter.

An Information Infrastructure for Mars

As part of the AIAA 2000 Undergraduate Space Design competition[1], the design group Little Green Men (LGM) prepared a plan for a Mars-based information infrastructure. This infrastructure consists of a satellite constellation that provides communication, remote sensing, and global positioning through IP architecture. IP architecture provides for a single communications layer on top of which nearly any other kind of data can be routed. IP architecture also enables advanced capabilities such as routing and caching that allow for system transparency. A user at any point in Martian space, or for that matter on Earth, can access data anywhere on the Martian surface.

The LGM constellation consists of three types of satellites. These are the Low Mars Orbiter (LMO), the Areostationary Orbiter (ARO) and the Remote Imaging Orbiter (RIO). There are 9 LMOs, deployed in a Walker 9/3/2 constellation. The Walker constellation allows for line-of-sight access to 3 satellites from any point on the Martian surface. UHF transponders are used both for communications and global positioning. On-the-fly channel bonding is used to combine UHF communications channels to allow for higher bandwidth rates. UHF antennas also allow for the use of omni-directional antennas to reduce pointing requirements. This allows the LMO, which uses the Space Innovations Limited MiniSIL-2L bus, to be spin stabilized to minimize spacecraft cost.

The ARO provides for high bandwidth communication relays and detailed weather sensing. The ARO uses the Hughes HS-601HP satellite bus to provide a 3 axis stabilized platform to achieve the ground pointing requirements for the weather instruments and the Earth pointing requirements of the high bandwidth antennas. The RIO, using the same bus but employing different instrumentation, is placed in a sun synchronous orbit. Ka-band transponders are used for high bandwidth data transmission to and from Earth.

The LGM proposal also allows for ground stations to provide detailed information from the ground. These ground stations are also used to deploy rovers. This scheme provides more detailed information as required by the AIAA Request for Proposal. Pseudolite systems on ground stations allow for detailed three-dimensional real-time positioning in the vicinity of the ground station. This allows for precise future landings in the vicinity of the ground stations. Table 1, 2, and 3 show the orbital elements of all satellites. Figure 1 outlines the frequency breakdown for each communication segment.

Each of the thirteen satellites acts as a node on the Martian Internet, which LGM refers to as Martianet. Each satellite has an intelligent router and a data access controller. The intelligent router dynamically routes communications between satellites and other Martian Internet nodes such as ground stations and eventually astronauts. The routers allows for dynamic bandwidth allocation and the maximization of communication resources.

The fundamental property of IP traffic is that it is packet based. Almost any type of information can be broken up into packets and sent over IP networks. As all data are sets of packets, these packets can be interleaved such that an unlimited number of data streams can be transmitted and received simultaneously. The use of routing tags on the packets allows for dynamic prioritization of traffic. Telemetry data can be transmitted at one priority while critical hazard data can be transmitted at another, preempting the transmission of less important data.

The use of IP in space is experimental. The UoSAT-12 spacecraft is the first spacecraft to have an operational TCP/IP stack. Users, from anywhere on the planet, were able to access the satellite using standard TCP/IP infrastructure. They could use their web browser to retrieve images and send commands to the spacecraft. In addition, they did not need a direct connection to the spacecraft since their requests are routed to the spacecraft through intermediaries as appropriate. This was a huge advance over traditional serial command and data handling systems. The use of standardized hardware means that the latest advances in IP technology can quickly be applied to space applications.

On top of the IP layer there is a data access layer of software. This software is located on the data access controllers on each satellite. The data access layer makes Martianet behave as a single system to the user. A user can pull up a terminal and point a web browser to any Martian Internet node. From that node a user can query a database. If the answer to the query does not exist in the queried node, the query is forwarded to neighboring nodes.

Data is cached as it is accessed. This means that if people are constantly accessing the same data from a remote node, the data are copied to a local node. The data access layer also allows for specialized data access controller facilities on Earth to accommodate millions of potential Earth-based users. In addition, all command and telemetry requests are routed through the data access architecture.

The proposed architecture was to be deployed in the 2015-2020 timeframe for a total system cost on the order of five billion dollars. This figure includes ten years of system operations. It is likely, however, that microelectronic machine (MEMS) and satellite-on-a-chip technology will become widespread in the interval and allow for a very drastic reduction in system cost.

An Information Infrastructure for the Moon

In designing an information infrastructure for the Moon it is important to consider the orbital resources of the Moon. The Moon is relatively close to the Earth. For many applications, it may be possible to communicate directly with Earth-based infrastructure. However, a system similar to that proposed on Mars is still useful as it allows for great reduction in antenna sizes and addresses latency issues. Latency between the lunar surface and low lunar orbit is several orders of magnitude lower than that between the Earth and the Mon.

The existence of Earth-Moon Lagrange points is critical. The Lagrange points, labeled L1 through L5, are points in which the gravitational attractions of the Earth and the Moon on a third body result in a net of zero gravitational force. Bodies placed at these points, or in kidney bean shaped orbits around them, tend to stay there. It should be noted that the points L1/L2 are not stable in the radial direction; satellites placed there must consume propellant to maintain radial stability.

Finally it should be noted that the Earth is in lunar synchronous orbit. This is the property that keeps the same face of the Moon pointing at the Earth at all times. From the reference point of an observer on the Moon the Earth revolves in its orbit at the same rate the lunar surface rotates. Figure 2 shows a diagram of the Earth-Moon Lagrange points.

The Lagrange point L1 is in an ideal position to serve as a relay between the Earth and the Moon. A relay at L1 could serve the same purpose, reducing transmission power requirements, as the ARO satellites proposed for Mars. A Walker constellation could be placed in low lunar orbit and serve as a communications relay. Orbiting 100 miles from the surface of the Moon, such a constellation would greatly reduce power requirements and increase available bandwidth for lunar surface users. For purely communications purposes, a constellation of as little as four satellites could be sufficient. (It may be possible to use Earth's GPS satellites to provide positioning.[2]) Global positioning requires a line of sight to at least three satellites for a real time two-dimensional fix. Even the four satellite version could provide positioning capabilities, albeit not in real-time. Three-dimensional positioning in real time requires at least 11 satellites.

A nine-satellite system is the baseline for the design presented in Figure 3 and Table 1. Also in the baseline design is a polar orbiting lunar imager, similar to the proposed lunar polar orbiter. Proposed instruments would include a visual and infrared mapping spectrometer, a gamma ray spectrometer, a laser altimeter, an infrared radiometer and magnetometers.[3] The final element of the proposed configuration is a L1 halo orbit based relay. This relay would be situated between the Earth and the Moon and reduce power requirements on the low lunar orbiters. A relay at L2 was deemed unnecessary in the baseline design. However, if large-scale development of the lunar dark side takes place, this may be necessary. These satellites are shown in Tables 1-3 with their Mars based counterparts.

Inter-satellite communications would be in the high UHF band. Ground to satellite communication would be in the low UHF band. Earth-Moon communication would be in the K band. Inter-satellite communications are used to relay messages from satellites out of site of the Lagrange point L1. This is identical to the proposed frequency breakdown for the LGM Mars proposal, which is shown in Figure 1.

One obvious disadvantage to the use of omni-directional antennas is potential interference. This may be a significant issue if large radio telescopes were built on the dark side of the Moon. The problem can be addressed by the use of selective signal transmission. In dark side regions reserved for radio astronomy, the omni-directional antennas can be turned off.

Towards a Solar System-Wide Internet

One of the most important design characteristics for a planetary information infrastructure is extensibility. As human habitation of the solar system becomes more widespread, it is critical that the information infrastructures deployed at various locations in the solar system can interoperate. Standards must be proposed early and be peer reviewed. The Interplanetary Internet Study Group (IPISG) serves as an arbiter for these standards. Their proposed baseline for interplanetary Internet applications is to use traditional IPV4 based Internets on each planet and to bridge the Internets on the name server level. Their proposed baseline proposal would have packets sent to www.yahoo.com.Earth.sol and www.yahoo.com.mars.sol routed appropriately.

Un-eclipsed and higher bandwidth communications will also become more important. At solar conjunction, the sun obstructs the communication path between the user and the Earth. Though not a problem for lunar applications, on Mars, the Earth is not available approximately four percent of the year. Davidovich '99 proposed a constellation of three satellites in a polar solar orbit that can provide 100% communications availability throughout the solar system. Even a single satellite in polar orbit can provide 99.9% availability to most points in the solar system. These relay satellites become even more important with the use of laser communications links. Modern fiber-optics technology suggests that bandwidths on the order of gigabits per second may be possible with advanced space-based laser communication schemes. Communications on such a scale may be necessary to support very large-scale settlements such as those proposed in the Jovian Trojan (Jupiter-Sun Lagrange) points. (Perhaps the most resource rich location in the solar system[4]*)*

Conclusions

In recent decades an information revolution has, by some pundits, transformed the world economy from being largely based on the exchange of goods and services to being largely based on the exchange of information. The fantastic growth of the Internet and growth in communications capabilities has facilitated this change. This change was not anticipated when early plans for space settlement and colonization were prepared. As acknowledged by the AIAA 2000 Space Design Competition, human expeditions to Mars must be preceded by the development of information infrastructure at Mars. Similarly, permanent human settlement of the Moon and of the rest of the solar system must be preceded by the development of a comprehensive information infrastructure for those locales.

References

1. AIAA Foundation, *Request for Proposal: Mars Information Infrastructure*, AIAA Foundation Undergraduate Team Space Design Competition, 1999-2000.
2. "Finds 2000 Grants," Internet, Accessible at http://www.finds-space.org/2000.html on 7/1/00.
3. "ARTEMIS," Internet, Accessible at *http://isu.isunet.edu/Programs/SSSP/DPS/iso89/ARTEMIS.html* on 7/2/00.
4. Lewis, J., "Mining the Sky", Perseus Publishing, 1997

5. Davidovich, S. M. and Whittington, J., Concept for Continuous Inter-Planetary Communications, Space Manufacturing 12, Challenges and Opportunities in Space, SSI, 1999
6. "The Global Positioning System," Internet, Accessible at http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html on 6/28/00
7. "Landsat 7 Home Page," Internet, Accessible at http://landsat.gsfc.nasa.gov/ on 6/27/00
8. Aslam, K., Craig, L., Lappe, D., Jaeger, S., Jones, J., Thomas, J., and Weiler, D., "LGM AIAA 2000 Space Design Competition Report," University of Illinois, 2000
9. "Interplanetary Internet Study Group," Internet, Accessible at *http://ipnsig.org* on 6/23/00
10. "OMNI Web Server Main Page," Internet, Accessible at http://ipinspace.gsfc.nasa.gov on 6/23/

Table 1: Orbital Elements for the Delta(9/3/2) Walker Constellation

	LMO1	LMO2	LMO3	LMO4	LMO5	LMO6	LMO7	LMO8	LMO9
Eccentricity	0	0	0	0	0	0	0	0	0
Semi-major axis (Mars, km)	6200	6200	6200	6200	6200	6200	6200	6200	6200
Semi-major axis (Moon, km)	1840	1840	1840	1840	1840	1840	1840	1840	1840
Inclination (deg)	68	68	68	68	68	68	68	68	68
Longitude of ascending node (deg)	0	0	0	120	120	120	240	240	240
Argument of latitude at epoch (deg)	0	240	120	80	320	200	160	40	280

Table 2: Orbital Elements for the Areostationary Orbiters & L1 Relay

	ARO1	ARO2	ARO3	L1 Relay
Eccentricity	0	0	0	N/A
Semi-major axis (km)	20480	20480	20480	58000
Inclination (deg)	0	0	0	N/A
Longitude of ascending node (deg)	-100	20	140	N/A
Argument of latitude at epoch (deg)	0	0	0	N/A

Table 2: Orbital Elements for the Remote Imaging Orbiter & Lunar Polar Orbiter

	RIO	LPO
Eccentricity	0	0
Semi-major axis (km)	3895	2500
Inclination (deg)	91	90
Longitude of ascending node (deg)	0	0
Argument of latitude at epoch (deg)	-30	-30

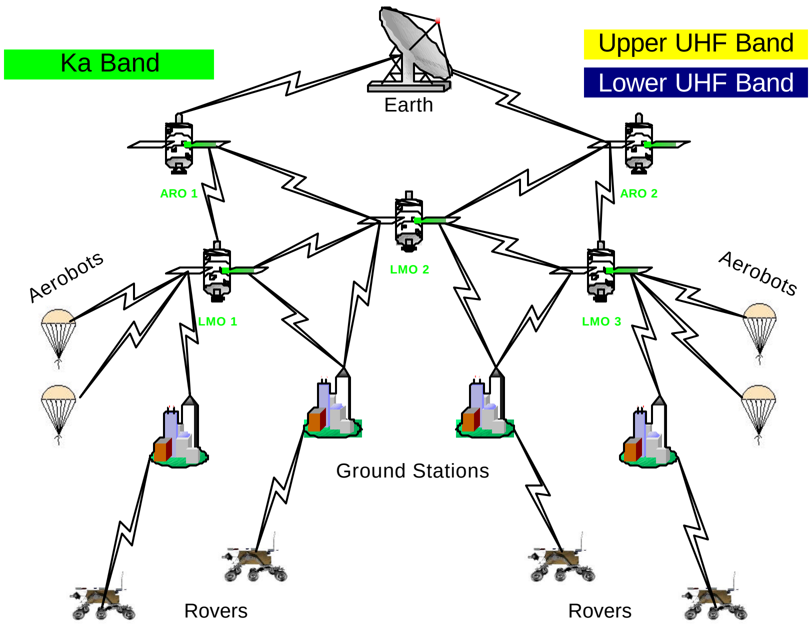

Figure 1: Proposed Frequency Breakdown at Mars

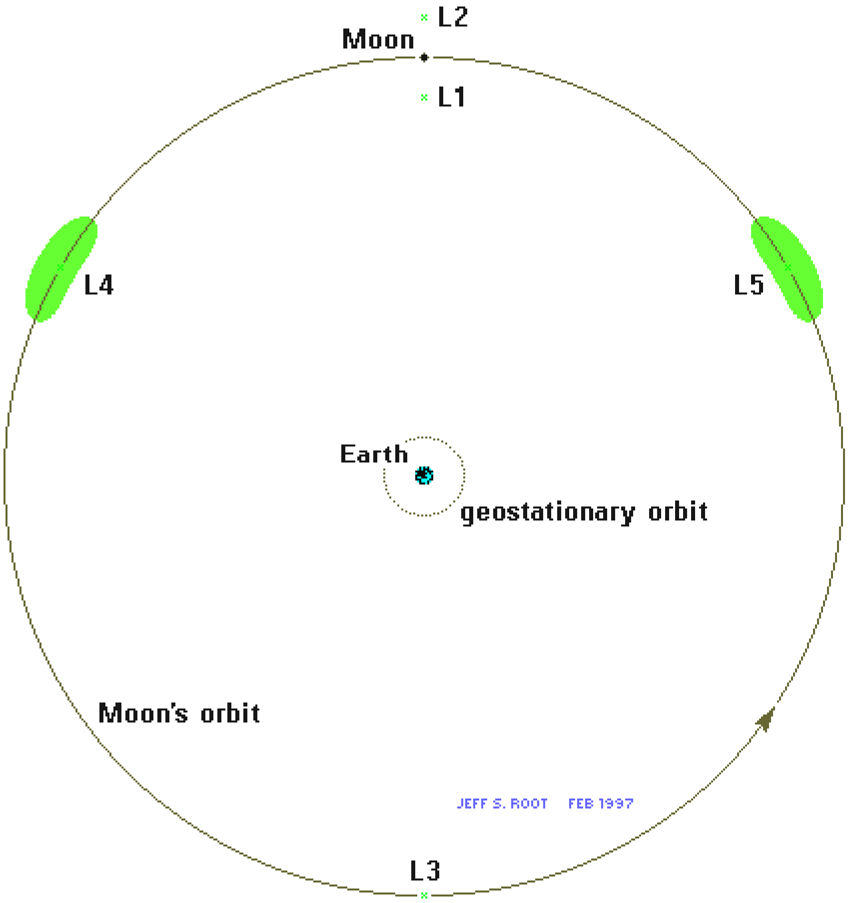

Figure 2: Earth-Moon Lagrange Points