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Broadband communication support for earth observation from the International Space Station

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Abstract

In order to support the communications needs of Earth-observing instruments on the International Space Station (ISS), alternative communications architectures to provide broadband support need to be considered. In this paper, we evaluate the direct-to-ground option in terms of coverage. We show that a direct-to-ground option is a feasible solution to enhance the limited communication capabilities provided from the current ISS infrastructure. In order to ensure efficient end-to-end communication support and deal with the complications of the space environment, COTS (Commercial, Off The Shelf) equipment with recently demonstrated protocol modifications need to be adopted. We also demonstrate that selecting the most appropriate location for placement of the ground stations is an important design issue that can ensure optimal coverage and maximize throughput. As both the need for broadband services from the ISS and from other upcoming space-missions increases, this option will play a role in enhancing the currently limited space-relay architecture until a next generation relay system is deployed.

Keywords: Space communications; Transport protocols; Coverage analysis; Earth observation

1. Introduction

Increased interest in observing the Earth from space has resulted in the need for the ability to collect and download tremendous amounts of data from Earth-observation platforms in orbit. One of the most comprehensive Earth-observing platforms in space is the International Space Station (ISS). It is a unique opportunity for the scientific and business community to conduct experiments and collect scientific information on a serviceable platform. In order for the potential of this facility to be fully utilized, however, there is a pressing need to provide a more flexible communications

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capability that can support in certain cases high data-rate downloads and high availability of access to the scientists that are conducting experiments. Clearly, the current infrastructure and network topology that are in place cannot support the growing needs of the scientific community and can sometimes be a limiting factor on doing interesting and profitable research onboard the ISS.

The work we describe here represents a study of alternative solutions for supporting broadband communications from Earth-observing instruments onboard the ISS, including the possible use of commercial technology and commercial assets and infrastructure (both in space and on the ground). Three possible communications solutions include NASA's existing Tracking and Data Relay Satellite System (TDRSS), commercial satellite constellations, and direct downlink to ground.

1.1. Motivation/significance

In order to enable cost-effective global access to experimental data from Earth-observing platforms such as the ISS, there will be a need to provide high quality, broadband communications connectivity. At the same time, advances in communications technology could allow investigators on Earth to enjoy a virtual presence onboard the ISS. However, there are limitations on the current ISS communication system and TDRSS that will not satisfy these broad communications needs in the long term.

For example, the current Ethernet onboard the ISS that provides the network backbone for services on the ISS was designed a number of years ago, and does not have the speed necessary to support the new high-demand services. In addition, TDRSS was designed in the 1970's with the initial purpose of relaying Tracking, Telemetry, and Control (TT&C) between NASA satellites and the ground. Its services have worked well, but it is becoming increasingly saturated with increased numbers of missions using its services and increased bandwidth requirements for individual missions.

For these reasons, NASA is investigating alternative long-term solutions for supporting communications from ISS payloads, including the use of commercial technology and commercial assets and infrastructure in space and on the ground. Gradual commercialization of space communications operations could enable [1]:

- reduction in cost for NASA's and the European Space Agency's (ESA) broadband communication needs,
- better, faster and easier dissemination of space-mission and experimental data if some of the available bandwidth and global coverage of future commercial constellations can be utilized,
- deployment of next generation commercial satellite constellations (since space agencies might become major customers),
- faster development in the satellite industry and the participation of other commercial entities in experiments and development programs in space, such as future space habitats and planetary missions.

There are a number of research and technology issues that need to be addressed before these services become possible. Among the most important are issues related to:

- supporting mobile IP,
- supporting security (e.g., IPSec issues),
- tracking, coverage and antenna technology,
- handover issues,
- traffic profiles of services that need to be supported,
- multiple access techniques and network management that allow on-demand access to space data.

1.2. Approach

In support of NASA's initiative in evaluating alternative solutions for ISS communications, we have started an effort to investigate the use of possible next-generation commercial satellite constellations for supporting broadband communications for the ISS. As a first step we have developed a simulation model for this scenario, consisting of the ISS, models of several commercial satellite constellations, the existing NASA network and the ground network of candidate commercial constellations. This research work addressed the following topics:

- Identification of potential commercial systems as candidates for investigation, starting from simple Geosynchronous Earth Orbit (GEO) Ku/Ka-band systems that currently exist and moving to the next generation, more broadband, Ka-band or V-band Medium Earth Orbit (MEO)/Low Earth Orbit (LEO) systems.
- Development of a detailed simulation model that includes the network architecture and topology of the hybrid network, and in particular:
  – ISS (treated as an extremely low LEO satellite) and the ground network,
  – commercial systems' constellation orbit model, ground network topology, information on routing options through the constellation, Inter-Satellite Links (ISLs) if any,
  – detailed simulation studies to quantify the performance of candidate satellite systems for specific services, protocols and traffic scenarios, and to recommend potential design modifications to ensure telescience QoS requirements are met.

In this paper we list three possible ways we can improve on the current state of the art and thus provide a transition to a system that can deliver higher communication rates to more users and enable transparent access to space. We then proceed to analyze one such option, the direct-to-ground delivery of data from the ISS, in greater detail, as this solution could provide a way to enhance the communications capability in the short term and augment the existing NASA-supported infrastructure. We comment on the economics and cost of doing this as well, since on top of any performance advantages this transition can only happen if it also makes sense from the business point of view.

2. Communication options

2.1. Option 1: Using existing TDRSS

This option is the current communication infrastructure for the ISS, whereby an antenna on the ISS points upward to communicate with one of the Tracking and Data Relay Satellite System (TDRSS) satellites, which relays the data to the NASA ground terminals.

TDRSS consists of 7 satellites in geostationary orbit around the globe that relay data from LEO and MEO satellites to ground facilities at the White Sands Complex in New Mexico and Guam. The satellites have the capability to forward and return data in the S and Ku-bands at speeds of up to 300 Mbps in the Ku-band [2].

These systems were developed in the 1970's and have been heavily used over the past two decades. A new generation of TDRS satellites (called TDRS-H, TDRS-I, and TDRS-J) has recently started to augment the older system and provide additional capacity for users. These new generation TDRS satellites have the additional capability to relay data in Ka-band at up to 300 Mbps without modifications to the ground stations, and up to 800 Mbps with ground station modifications. A new tunable, wideband, high-frequency service offered by the 15-foot antennas provides for the capability of these high data rates. This Ka-band frequency also establishes interoperability with the international community such as the Europeans and Japanese [3].

Together, the TDRS satellites provide 100% coverage for all satellites in LEO orbit, and a very reasonable transmit rate. TDRSS is currently the only system designed to relay communications for fast-moving LEO spacecraft. This makes TDRSS an excellent option to provide communications for the ISS in the long-term future.

Although this system has excellent coverage, its system capacity is being used to its maximum. In addition, there are currently limitations on the main ISS Access Communication System that provides the link to the TDRSS:

- the current design of the ISS high-rate Ku-band antenna uses NASA proprietary components, making any future communication system expensive and difficult to implement quickly,
- limitations in the current NASA ground network connectivity mean that high-rate global

data dissemination could face significant limitations,
- many commercial users will need commercially supported broadband communications.

For all these reasons it makes sense to consider a new uniform architecture that is based on commercial standards to support future commercial services.

2.2. Option 2: ISS to a commercial satellite constellation acting as relay (in GEO or non-GEO orbit)

This option essentially means using a commercial fleet of satellites in lieu of using TDRSS. There are many Ka-band satellite communication systems, scheduled to be deployed within the next few years, that provide services such as voice, data, video broadcasting, and many others. This is likely a long-term solution, as there are currently no commercial systems operating at these frequencies that can communicate with moving assets in space. However, if potential interest develops, satellite companies could add a payload to future system expansions that could do that and offer a service to NASA or other paying customers to relay the data to the satellite operator's gateway and connect to NASA via terrestrial links [4].

The intended customers of these commercially provided services, however, are generally businesses and in some cases, home consumers, not a NASA spacecraft moving in a LEO orbit. Thus, usage of these systems as a relay may not be optimum for the needs of the ISS. These systems will likely use multiple spot beam antennas pointed towards populated areas of the earth, received by either fixed antennas or slow-moving users. Its ability to maintain communications with the ISS traveling at over 17,000 mph (27,000 kph) at an altitude of about 230 miles (400 km) passing through its hundreds of spot beams may be limited. Coverage is not likely to be nearly as good as that provided by TDRSS, and commercial prices charged by these service providers may be expensive.

2.3. Option 3: ISS direct to Ka-band ground terminals

Instead of relaying data through commercial assets in space, the ISS could send the data directly to the ground terminals of satellite companies planning to deploy Ka-band satellite systems. The ground networks could be used as access points for downloading ISS data from the ISS Direct-to-Ground (DTG). However, these commercial satellites, as discussed earlier, are generally placed in geostationary orbit for simplicity and to allow customers to downlink from the satellites without having to track the satellites. This means, though, that the ground stations will be comprised of ground terminals that are not capable of tracking, and instead are fixed to point towards specific stationary satellites.

Fixed terminals will not be able to track a fast-moving satellite such as the ISS. Due to the possible limited tracking capability, the coverage these terminals provide to a rapidly moving LEO spacecraft might not be sufficient, and there might be a need to either add tracking capability to these terminals or augment the coverage by adding additional terminals distributed globally. The latter is not a likely option, considering it would not be an effective cost trade-off.

Because it is uncertain when these commercial systems will actually be realized, new fixed Ka-band terminals could be added to existing NASA ground facilities that are already distributed world-wide. These terminals would have tracking capability, and only incur the incremental cost of additional staff and equipment since they would be located at existing facilities. In addition, the communications infrastructure is already in place at these NASA ground facilities.

Fig. 1 shows all three possible communication options. Note that the TDRSS option is represented in this figure, though not explicitly mentioned, since TDRSS can be treated as one of the GEO satellites. Also, in this figure, note that the direct-to-ground bandwidth rate is labeled as 48 Mbps, which is the maximum communication capability based on the ISS current communications infrastructure.

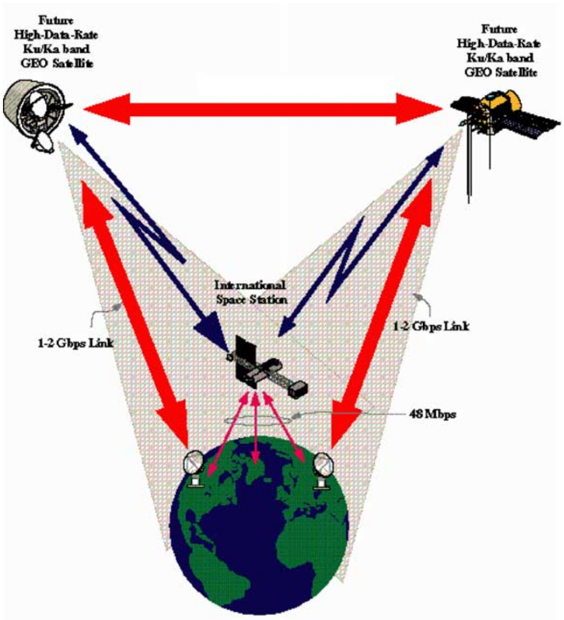

Fig. 1. ISS communication options.

3. Communication protocols issues

In order to get the best application performance with the consideration of cost, we need to design the whole communication protocol stack carefully. Although protocol issues in ground-based networks are well understood, additional challenges with communicating in the space environment require consideration of more constraints as well as compatibility with ground networks. In this section, we discuss some issues related to protocol support. These also relate to TCP/IP and its planned deployment in future NASA satellite mission payloads. The approach taken in this analysis relies on the initial selection of link layer scenarios that represent different types of communication between Earth terminals and the ISS science payloads discussed earlier. We assume the standard layering model used in designing and developing communications systems of today (and the Internet, in particular), that rely on a decoupling of link layer technology from the IP network, which is then also decoupled from the end-to-end transport layer, capable of ordered delivery and retransmissions due to packet loss. Finally, the Internet layering model decouples the application from the underlying transport layer.

We try to focus on end-to-end communication between users and the payload (versus store-and-forward designs), as well as NASA's desire to rely as much as possible on Internet-related COTS products, which primarily rely on TCP as the underlying transport protocol, with sufficient modifications to optimize issues related to the space environment.

3.1. Link topology

The topology of all the nodes in the network supporting the ISS and the physical layer protocol set the hard limit of our protocol design. Such limits include ground customer coverage, propagation delay, frequency and bandwidth choice, power consumption, and bit error rate. Table 1 shows a summary of possible systems for relaying data in space and their properties as compared to communicating directly to ground.

In terms of the actual IP stack architecture, NASA is investigating the use of IP protocols in space, away from systems that require several gateways and custom layers. Legacy systems used Consultative Committee for Space Data Systems (CCSDS) standards [5] and gateways to interface between those layers and the ground IP infrastructure. The goal is to move into a direction where IP

Table 1
Possible space communication architectures

Relay system	Delay	Bandwidth constraint	ISS power Consumption	Antenna tracking
TDRSS (GEO)	Long	S, Ku, Ka	Small	Easy
Commercial GEO	Long	Various	Small	Difficult
Commercial LEO or MEO	Short w/large variance	Various	Small	Difficult
Direct to ground	Short w/large variance	Ku, Ka	High	Easy

can be the underlying protocol across the full communication link, with data directly on top.

3.2. TCP considerations

3.2.1. Two-minute timeout

In general, after a TCP connection is made, state information (that uniquely identifies the end-to-end connection) is retained until either the source or the destination terminates the connection. Given this model, a TCP connection can exist indefinitely at both the source and destination hosts. One condition that can terminate the connection in an untimely manner is when the source has sent a packet and it has not received an acknowledgment within 2 min. Such a condition causes the source to view the destination as being unreachable, and thus state for that connection is removed. Hence, if a file transfer connection is broken, then the information accumulated at that point will have been lost, requiring that a new file transfer session be initiated.

This 2-min gap problem is directly related to the types of scenarios presented here. If a given scenario does not provide global coverage over both land and sea, then it is subject to the condition described above. Since it is unlikely that COTS equipment manufacturers will be addressing this unique problem, this has to be done at the system design for a particular solution. One way to do that is by manual distribution of the scheduled availability of mission payloads by ground stations. The measure of success, in this case, can be attributed to the total period of uninterrupted time that the ISS is reachable by the user. To address the 2-min gap problem, it is likely that some combination of a gateway and customized solution (at least between the mission payload and the gateway) will need to be developed.

3.2.2. SCPS

The Space Communications Protocol Standards (SCPS) [6] is an ongoing standardization effort trying to address a variety of perceived weaknesses of TCP/IP in support of space communications. In trying to accomplish its goals of high throughput with minimal disruption in traffic flow and user access, SCPS has defined a suite of protocols ranging from the application to the transport and down to the network layer. All of these SCPS protocols are derivatives of the standard TCP/IP suite and yet cannot peer directly with TCP/IP without a gateway to translate the protocol primitives. So if this option is selected the appropriate modifications need to be performed at the gateway points.

3.3. IP considerations

3.3.1. Mobile host problem

The purpose of Mobile IP is to retain end-to-end connections as the mobile host (MH) moves from one logical IP routing location to another. Typically, these locations correlate to separate physical networks, which are termed sub-networks by the IP community. Routers are used to connect sub-networks, which can be the same or of different design.

When a host moves from one IP routing location to another, it must change its IP address. The tight association between locality and identity means that such a change will also break any existing end-to-end TCP connection made with that host. Mobile IP sidesteps this problem by using encapsulation, that allows the system to retain existing end-to-end connections as the MH moves to different locations. It is important that the speed at which a node moves to different locations not eclipse the speed at which discovery and registration occur (Fig. 2).

Mobile IP can be used in satellite communications to enable a host to maintain its identity as satellite contact moves from one ground station to another. The ISS can be modeled as a single host with different modules, or as a space LAN segment with different hosts. For the former, we are trying to simulate it with basic functions in Mobile IP. However, the mobility of the ISS in space is different from that of a mobile ground host, and results in several advantages:

1. *Fewer mobile hosts and foreign agents*

Compared to the hundreds of thousands of mobile hosts on the ground, there are only about 10 ISS modules. Thus, the state information of each host can be saved in advance without much worry about scalability. Also, fewer foreign agents can also mean that some semi-permanent connections can be setup in advance.

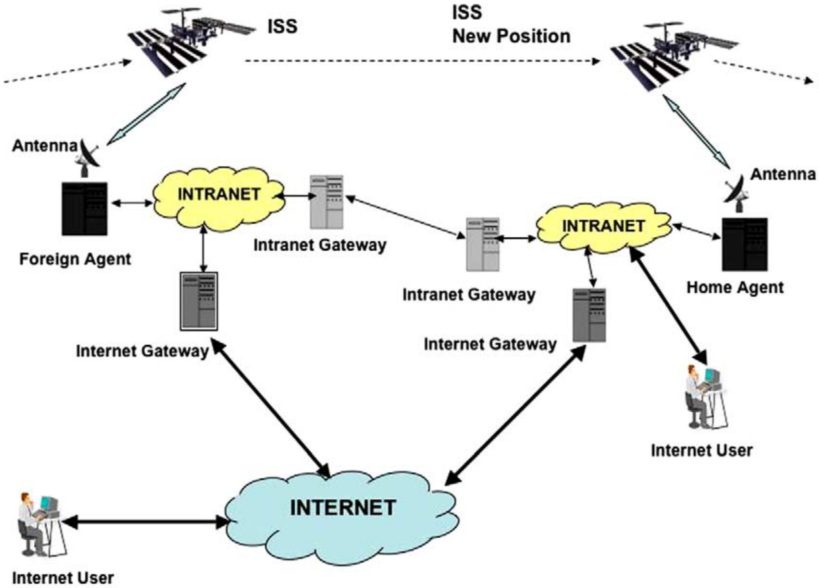

Fig. 2. ISS direct to ground protocol architecture.

2. *Predictability*
Unlike the random movement of ground mobile hosts, the ISS is moving within a predictable orbit, and access time to each ground terminal is highly predictable. Thus, greater intelligence can be added to the location management.
3. *Centralized management*
ISS communications will have to be managed in a central way by NASA. However, for supporting commercialized service, access needs to be controlled in the network center. We can further optimize mobility support by considering these particular properties. If we want to model ISS as a mobile LAN, the main focus will be on the mobile router, which serves as the interface between the space LAN and the ground networks.

The first Mobile Router demonstration in space is coming up in the near future. This involves a CISCO Mobile Access Router (MAR3251) demonstration on one of the UK-DMC Satellites that was launched in September 2003 [7].

3.4. Link layer issues

The Operating Missions as Nodes on the Internet (OMNI) project at NASA Goddard Space Flight Center (GSFC) is designed to demonstrate the use of standard IP for space communication systems. Recent experiments have been performed with the UoSAT-12 spacecraft and the CANDOS experiment in the last shuttle mission. The work is focused on defining the communication architecture for future NASA missions. The use of standardized communications technology for spacecraft both simplifies design and permits the exploitation of commercial telecommunication advances [8].

The rationale for the use of IP is that it provides a basic standardized mechanism for end-to-end communications among applications across a network. The UoSAT-12 payload supports high-level data link control (HDLC) framing in hardware, allowing for simple, straightforward interfacing with existing routers. Interoperability was ensured by encapsulating the IP over frame-relay/HDLC. Thus, only software changes were required to adapt the satellite to use IP. Store-and-forward commanding and data delivery, using the simple mail transfer protocol (SMTP), were demonstrated in 2000. The OMNI project results discuss the success and feasibility of exploiting the capabilities of HDLC and provide examples of the HDLC/frame-relay/IP packet formats as successfully used in the experiment. The CANDOS payload (February 2003) demonstrated UDP, Mobile IP and other protocol performance from the Space Shuttle, connecting via the TDRS relay satellite [9,10].

An end-to-end communication architecture for future space-missions, using the Internet Protocol (IP) as the "glue" that connects everything together, is clearly feasible. IP provides a basic standardized mechanism for end-to-end communication between applications across this network topology.

4. Effects on coverage for ISS direct to ground

We will examine the type of coverage available for using existing NASA facilities augmented with Ka-band terminals for ISS communications in the near future, and discuss this option versus using TDRSS and a commercial relay constellation. Coverage is the amount of time that a satellite is able to "see" a facility above the horizon (with certain constraints) during its orbit around the Earth, and is important because the greater amount of coverage available, the more data can be transmitted between the two. We will see how the location of the stations (latitude, longitude), as well as their minimum elevation angle, and the ISS antenna's scan angle (also called cone angle) affect the coverage.

The antenna onboard the ISS communicating with the ground will be assumed to be a phased-array antenna, which is a group of antennas in which the direction of the radiation pattern can be moved not by gimballing the antenna, but by varying the relative phases of the respective signals feeding the antennas. Since the antenna's radiation pattern can move in any direction up to a certain angle from the center line, we will model the antenna as a cone with varying half-cone, or "cone" angles, as shown in Fig. 3. An antenna with full field of view is able to move from one side of the local horizon to another and thus has a cone angle of 90°. We define cone angle as the angle from the center line H to the edge, and minimum elevation angle as the angle between the horizon and the outer edge of the antenna's view, as shown in Fig. 3. Fig. 4 shows the definition of spacecraft inclination.

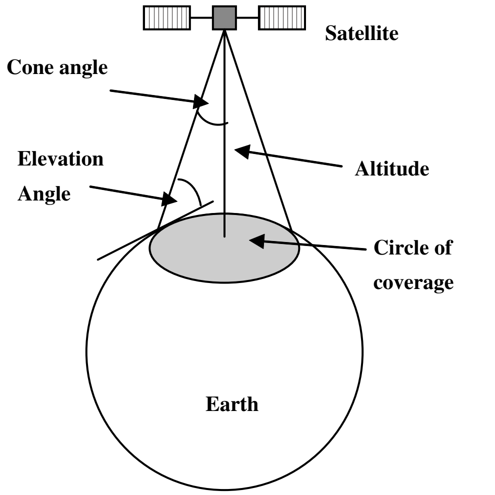

Fig. 3. Definition of cone angle and elevation angle.

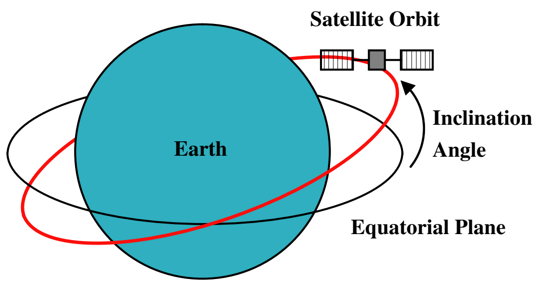

Fig. 4. Definition of a satellite's inclination.

A simulation of the ISS communicating to ground stations was developed using the Satellite Tool Kit [11], which included the ISS (400 km circular orbit, with 51.5° inclination), the downlink antenna on the ISS, and selected NASA ground stations around the world. The scenarios were created with a run time of 10 days in order to minimize aberrations in results. As shown in Fig. 4 the inclination of a satellite is the angle between the orbit plane and the inertial equatorial plane of the earth. The minimum elevation angle of an antenna on the ground is the angle between the horizon and the lowest direction that the antenna can point and still have contact with the satellite, considering obstacles on the ground such as buildings or terrain.

The latitude and longitude of the stations are first varied, with the stations having 0° minimum

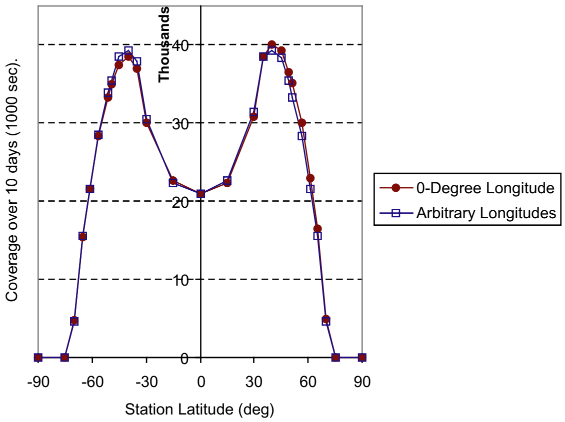

Fig. 5. Coverage for varying station [lat, long].

elevation angles and the ISS onboard antenna having full field of view. Fig. 5 shows the distribution of the coverage, which peaks at locations near the inclination angle of the satellite. In this case, the station that has the most coverage is the one placed at ±40° latitude. The coverage drops off dramatically for stations placed above the inclination angle, and becomes zero for stations placed at ±75 latitude and higher.

In addition, the coverage achieved by a station is dependent only on its latitude position and not its longitude. As shown in Fig. 5, there is high correlation between stations placed at zero longitude versus random longitude.

To examine the effects of elevation angle for this scenario, the minimum elevation angle was varied, with the ISS main antenna having a cone angle of 90°. The results in Fig. 6 show that the coverage is almost uniformly reduced at each station as the elevation angle is increased. Also, the location of the peak coverage increases slightly as the minimum elevation is increased because the field of view of the station is reduced; the station must be placed closer to the satellite's inclination in order to provide a more local north contact under the satellite.

For a particular station, the coverage is approximately a logarithmic relationship with respect to the minimum elevation angle. In addition, the coverage is more sensitive to elevation angle (i.e., more affected by it) when the elevation angle is

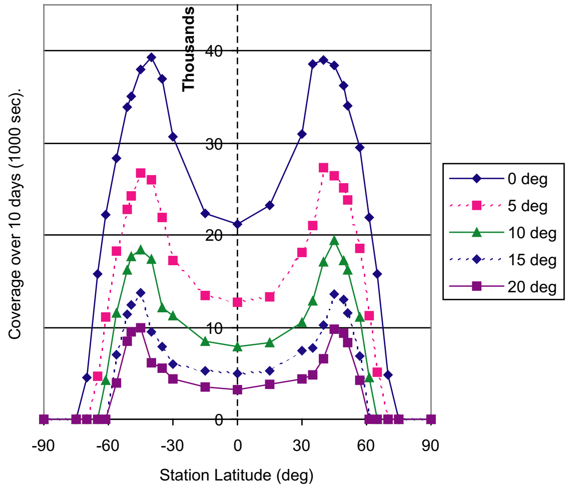

Fig. 6. Coverage for varying elevation angle.

low rather than high. When the elevation angle is below 60°, small changes in the elevation angle greatly affect the coverage.

For fixed elevation angles, the best possible coverage can be achieved with an ISS antenna cone angle of about 75°, as shown in Fig. 7. This is essentially the maximum field of view of the earth at this particular altitude given the curvature of the earth. In addition, coverage drops off significantly when the cone angle is decreased slightly below

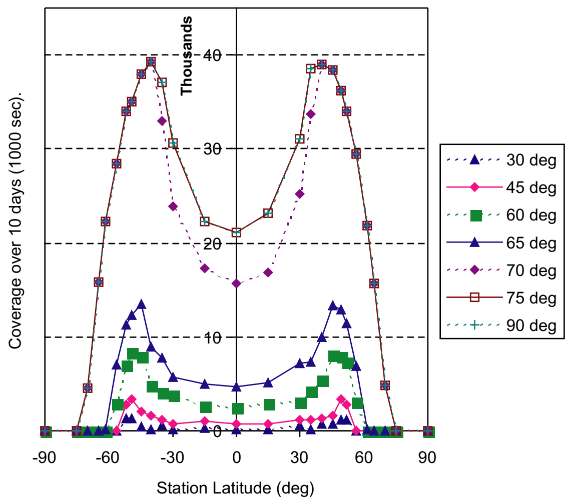

Fig. 7. Coverage for varying ISS antenna cone angles.

70°, and quickly approaches zero as the cone angle approaches zero. Also, there is greater sensitivity when the ISS cone angle is large as compared to when it is small. This indicates that there is a significant gain in coverage per degree change in cone angle when the cone angle is near 70°. In addition, the coverage reaches its maximum and becomes flat sharply near 70°, but maintains a smooth function all the way up to 90°. Close inspection reveals that for cone angles between 67° and 0°, the curves do not approach the origin, but rather reach zero at a particular point as the cone angle decreases, and stay flat.

We next examine the variation of coverage with respect to both the ground stations' minimum elevation angle and the ISS antenna cone angle. One station was chosen for this analysis, while its minimum elevation angle and the ISS antenna cone angle were varied. As seen from Fig. 8 there are areas where the coverage is constant for certain elevation angles and ISS cone angles. In general, for a particular minimum station elevation angle, e, the coverage is unaffected by the ISS cone angle, α, until the cone angle is considerably smaller than $90°-e$. This is due to the geometry of the ISS antenna and the station as the ISS approaches the station and makes a contact within each other's field of view. In addition, for a particular cone angle, the coverage is unaffected by the elevation angle, until the elevation angle is nearly greater than $90°-\alpha$. So, there is a boundary between changing and non-changing coverage for various minimum elevation angles and cone angles. Thus, knowing this, we can freely adjust the ISS cone angle and ground station minimum elevation angles for configurations where one does not affect the other.

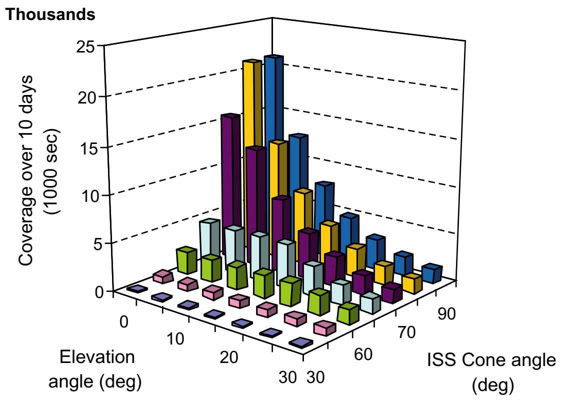

Fig. 8. Coverage for varying elevation angle and cone angle.

5. Coverage study: results and comparison

5.1. Coverage

The initial design of an ISS direct-to-ground communication system involves various issues of coverage, including: (1) antenna power, (2) total coverage availability, (3) duration of each link, and (4) speed of each link.

To determine a first-order coverage capability of the direct-to-ground architecture, we focus on an Earth-observing application involving an imaging instrument on the ISS. An onboard remote-sensing device will take images of the surface of the Earth or collect other data on or under the Earth surface and format it into images. The images are temporarily stored onboard the ISS, and downloaded to the ground at the next available ISS contact with a ground station. The application has a minimum requirement of being able to download at least 120 images per day, with each image size about 12 Gbits. These images, which require a total throughput of 1440 Gbits in every 24-h period, must be available for commercial customers in the US.

We first determine the ground stations needed to satisfy this throughput requirement, knowing that stations placed near the satellite's inclination provide the best coverage. Stations were chosen closest to the ISS's inclination, with minimal overlapping of their coverage cones. Fig. 9 shows the six US ground stations providing the best coverage with 10° minimum elevation angle and ISS antenna cone angle of 60°.

The stations are ranked in order of best to worst coverage in Table 2. The table also shows the cumulative coverage achieved first for the best station, Sioux Falls, and for adding each subsequent station to the group of stations that can communicate with the ISS. Note that when the ISS has two or more ground stations in sight, this period of

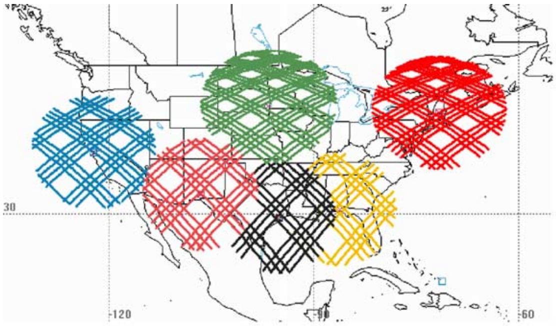

Fig. 9. Ground track of ISS with access to six US stations.

Table 2
Coverage for US ground stations

	Individual access (s)	Cumulative access (s)	
		10 days	1 day
Sioux Falls	6416	6416	642
Boston	5968	12,310	1231
Berkeley	4302	16,476	1648
White Sands	3723	19,973	1997
Eglin Air Force Base	3633	23,984	2398
NASA Johnson Space Center	3585	25,630	2563

time is counted only once for the multiple stations. Due to this overlapping of stations, the cumulative access times are slightly less than the sum of the individual access durations.

From this data we can determine the best stations to use by calculating the throughput for using the best station, and adding each subsequent station until the desired throughput is achieved. Table 3 shows the amount of throughput achieved with each incremental station in Gigabits per day for transmit speeds of 180, 361, and 622 Mbps. If each downloaded image size is 12 Gbits, the table also shows the number of files that can be downloaded in a 24-h period. Thus, using a direct-to-ground architecture does provide enough coverage for a typical store-and-forward application.

5.2. Commercial constellation relay option

In comparison with an example commercial relay system such as Astrolink, the direct-to-ground option offers about the same amount of coverage at similar costs. The Astrolink system (as defined in its original FCC application filing for a Ka-band satellite system) consisted of nine geostationary satellites in five orbital positions distributed mainly over largely populated areas of the globe, as shown in Fig. 10. The labels on the map denote the longitudes of the planned orbital positions of the geostationary satellites. Note that Astrolink, as well as other commercial system antennas only point towards populated areas where they expect to have business, whereas TDRSS covers the whole Earth, including the oceans. The Astrolink satellites would have been capable of download speeds of up to 20–110 Mbps through multiple spot beams operating in the Ka-band [12]. Since most of the proposed Ka-band systems never matured to implementation for business reasons, this option was not pursued further.

Table 3
Throughput for US ground stations

	Data throughput (Gb) for specified transmit rates (Gbps)			Cumulative no. of image downloads for image size 12 Gbits		
	180 Mbps	361 Mbps	622 Mbps	180 Mbps	361 Mbps	622 Mbps
Sioux Falls	115	232	399	9	19	33
Boston	222	444	766	18	37	63
Berkeley	297	595	1025	24	49	85
White Sands	360	721	1242	29	60	103
Eglin AFB	432	866	1492	35	72	124
JSC	461	925	1594	38	77	132

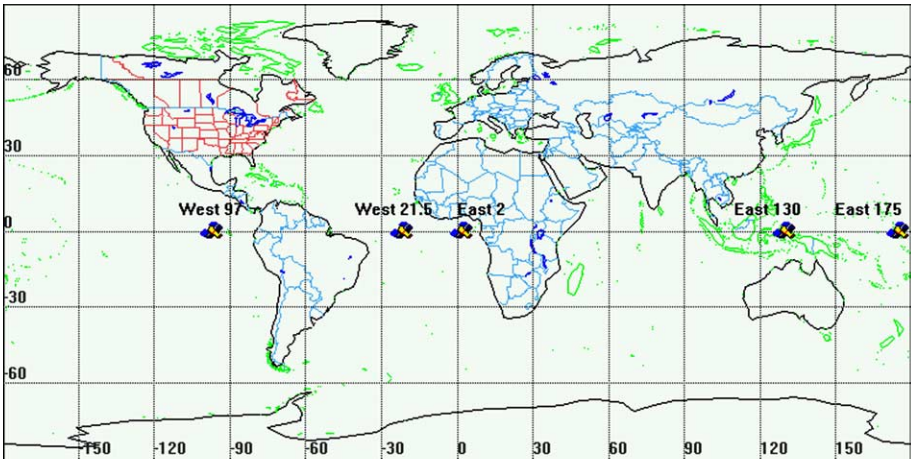

Fig. 10. Astrolink constellation at the five orbital positions.

Table 4
Comparison of strengths of three architectures

	Direct to ground	Commercial relay	TDRSS (Ku)
Advantages	Flexible, scalable, prices competitive, good for store-and-forward applications	Very little system setup required	100% Coverage, good for real-time or on-demand applications
Disadvantages	Not good for real-time applications, requires additional building of facilities	Prices and entire system uncertain, systems not tailored to needs of ISS customers	Possible slow ISS onboard communications system, capacity for commercial applications may be limited later

6. Summary and future work

Overall, as shown in Table 4, the direct-to-ground architecture is suitable for store-and-forward applications that do not require large amounts of coverage. TDRSS is the best option to use for real-time applications, such as video conferencing, due to its continuous coverage. While the direct-to-ground option offers flexibility, using a commercial relay system may allow easier setup and less initial cost investment [4].

We plan to expand the model to develop the framework for handover/connectivity support analysis and plan to continue developing the simulation platform to:

- perform end-to-end optimization and suggest solutions to support particular protocols or QoS requirements for specific services over the space-to-ground link,
- investigate traffic characteristics of particular services and find ways to optimize dynamic resource/capacity sharing that would maximize revenue,
- analyze the business case study and explore ways to maximize revenue by (1) estimating the bandwidth cost of this commercial service, and (2) investigating dynamic pricing solutions for different customers,
- analyze other types of spacecraft as well as other classes of commercial relay satellites,
- finally, as NASA looks into a complete new relay satellite design including broadband IP support and Inter-satellite link between the relay satellites, it will be interesting to evaluate the new possibilities that such a system will provide in the future.

In conclusion, we have shown that a direct-to-ground option is a feasible solution to enhance the limited communication capabilities provided from the current ISS infrastructure. In order to ensure end-to-end TCP/IP support and deal with the complications of the space environment, COTS equipment with recently demonstrated protocol modifications need to be adopted. Selecting the most appropriate location of the placement of the ground stations is an important design issue that can ensure optimal coverage and maximize throughput. As both the need for broadband services from the ISS and from other upcoming space-missions increases, this option will play a role in enhancing the currently limited space-relay architecture until a next generation relay system is deployed.

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