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Duplex Direct Data Distribution System

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1. INTRODUCTION

This report presents a set of end-to-end system concepts for implementing a Duplex Direct Data Distribution (D4) system. The D4 system is intended to provide high-data-rate commercial direct communications service between the National Aeronautics and Space Administration (NASA) spacecraft in low earth orbit (LEO) and the respective principal investigators (PIs) associated with these spacecraft. Candidate commercial services were assessed regarding their near-term potential to meet NASA requirements. Candidates included Ka-band and V-band geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellite relay services and direct downlink ("LEO teleport") services. Four realistic, near-future concepts were analyzed based on specific selected candidate services:

- A direct link (uplink plus downlink) between a LEO spacecraft and a miniature autonomous earth station
- A space-based relay based on a future Ka-band NGSO satellite system
- A hybrid link using both direct and relay services to achieve full duplex capability
- A dual-mode concept consisting of a direct and a relay link operating independently.

The concepts were analyzed in terms of contact time between the NASA spacecraft and the communications service and the throughput that could be achieved. Cost estimates were also performed. The throughput and cost estimates were used to compare the concepts.

1.1 Requirements

The concepts for implementing a D4 system are required to meet certain specific NASA requirements. The D4 system will support NASA mission spacecraft in LEO and will have the following characteristics:

R1. The system will utilize one or more commercial satellite communication (SATCOM) services.

R2. The services will be available within 5 years (2005).

R3. The services will operate at Ka-band or higher frequency.

R4. The system's links will be full duplex.

R5. The system will support the use of Transmission Control Protocol (TCP) and Internet Protocol (IP).

R6. The system will support a data rate of up to 622 Mbps in the return direction.

R7. The system will support symmetric and asymmetric traffic on the link.

1.2 Assumptions

A1. Missions: The NASA LEO missions are assumed to be those compiled in a previous Science Applications International Corporation (SAIC) report [IOAT], which consists of NASA missions for the years 2000 to 2010. For the purposes of this study, we ignore the fact that these missions may not be equipped with Ka-band communications capability.

A2. Coverage and Latency: It is assumed that the system will not require global coverage and that some level of tolerance of latency is acceptable. In general, the commercial services with global coverage or global coverage except the poles are considered to provide low latency. Other services provide significantly less coverage and are considered to result in relatively high latency (some significant fraction of an orbital period or more) because of the need to store data onboard in parts of the orbit where coverage is not available.

A3. Deployment: The services will be assumed to be available by 2005 if they are currently at least under development and have a planned first launch at least 1 year prior to 2005. If no deployment information is available, the service will be assumed not to be available by 2005.

A4. Altitude: It is assumed that the satellites belonging to the commercial SATCOM service are above LEO altitude with their antennas pointed downward. It is assumed that other antennas, such as inter-orbit and inter-satellite links (ISLs), will not be available to a user of the service.

A5. Protocols: It is assumed that NASA will use commercial off-the-shelf (COTS) applications and, therefore, that the TCP and IP protocols used by the D4 system should be COTS to the maximum extent possible.

A6. Regulatory: It is assumed that the system must conform to International Telecommunications Union (ITU) regulations concerning mobile terminals. For example, use of a Mobile Satellite Service (MSS) would be in compliance, whereas use of a Fixed Satellite Service (FSS) would not be. However, use of an FSS by a spacecraft for receive only (i.e., the mission spacecraft does not transmit) would be in compliance.

Costing Assumptions

Our approach to cost estimation was to assume that each concept would be implemented as a commercial service that would charge a usage fee that is a function of data rate. We did not carry out a bottom-up cost analysis incorporating engineering, infrastructure, operations, maintenance, and other elements that would be used by the system provider to derive their pricing. The bottom-up approach is beyond the scope of the current study.

For satellite services that do not yet exist, we assumed that they will be priced to compete with similar terrestrial services. This is based on the fact that these services will compete head-to-head with terrestrial services in the same broadband market. For example, the Chief Executive Officer (CEO) of Spaceway stated that Spaceway will be priced to cost less than the equivalent terrestrial service. "We will not only deliver a rich mix of services but also sell bandwidth on demand—speed and capacity as you need it, when you need it—and at a cost that's likely to be 20–30 percent lower than the costs of competing land-based services such as frame relay." [KAUL].

Currently, most terrestrial wide area networks (WANs) are implemented as virtual private networks employing technologies such as frame relay and asynchronous transfer mode (ATM), and this is what we used for our cost model. These services are available with pricing based on either a usage rate or a flat rate. The basic approach for the cost model was to start with a baseline flat rate per month and then, for the usage-based model, divide by the number of minutes per month to get a cost per minute.

A market survey of frame relay and ATM prices conducted in 1999 is described in [WILL]. This source summarizes the results by stating the prices of high data rate services as multiples of the basic T1 price. We adopted this approach and used the following relative cost formulas:

- Cost of DS-3 (45 Mbps) = 5 times the cost of T1 (1.544 Mbps)
- Cost of OC-3 (155 Mbps) = 1.5 times the cost of DS-3
- Cost of OC-12 (622 Mbps) = 2 times the cost of OC-3.

Finally, a cost for the baseline T1 is assumed. A survey of T1 price quotes on the Internet shows a wide range of values, from less than $500 per month up to $2,000 per month, or $0.012 to $0.046 per minute.

The above assumptions result in the values for terrestrial rates shown in Table 1-1.

Table 1-1. Terrestrial Rates

Data Rate	Cost per Minute
T1 (1.544 Mbps)	$0.012 – $0.046
DS-3 (45 Mbps)	$0.06 – $0.24
OC-3 (155 Mbps)	$0.09 – $0.36
OC-12 (622 Mbps)	$0.18 – $0.72

The NASA Direct Data Distribution (D3) Ka-band downlink system was developed for high data rate downlink service. Because there exist commercial services that are currently quoting prices for this type of service at X-band, we used these as a basis for estimating the cost of a service using the D3 equipment.

2. SYSTEM CONCEPTS

The Statement of Work called for the development of a set of system concepts driven by the selection of a set of commercial SATCOM services. For each selected commercial service and corresponding concept, there would be three modes of communication: (1) between a LEO mission platform and the service to the service's ground stations, (2) between a LEO mission platform and the service to the PI through a terrestrial network, and (3) between the LEO mission platform and the PI directly. However, we found that there were two fundamental types of commercial service: (1) the direct, or line-of-sight service, and (2) the SATCOM relay service. These are distinguished primarily at the link and physical layers. We chose to pursue the analysis using space-ground links as the fundamental element.

The result of this approach is that the problem is decomposed somewhat differently than envisioned by the Statement of Work. Instead of selecting a set of concepts each having the three modes described above, we defined the concepts in terms of single and multiple mode categories. Within the single mode category, there were three space-ground link architectures: direct, relay, and a hybrid of the two. Multiple mode concepts then can be generated as combinations of the single mode types. Among the multiple mode possibilities, we examined a dual mode concept. The classification then looks as follows:

- Single mode:
  - Direct (line of sight)
    - Simplex
      - Uplink (to the mission spacecraft)
      - Downlink (from the mission spacecraft)
    - Full duplex
      - Symmetric
      - Asymmetric
  - Relay
    - Simplex
      - Forward (to the mission spacecraft)
      - Return (from the mission spacecraft)
    - Full duplex
      - Symmetric (equal data rate in both directions)
      - Asymmetric (different data rate in each direction)
  - Hybrid
    - Full duplex (e.g., simplex direct + simplex relay)
      - Symmetric
      - Asymmetric
- Dual Mode:
  - Direct + relay, for example
- Three-Mode:
  - Direct + relay + relay, for example.

The end-to-end system can be decomposed into a terrestrial network component and a space-to-ground component. The terrestrial network component can be implemented using standard

TCP/IP networks and can be decoupled from the space-to-ground component. The decoupling or partitioning may be accomplished at the IP layer using gateways with Border Gateway Protocol operating between the terrestrial and space network gateways, as described in [IOAT]. Additional partitions may be required at the TCP layer, depending on whether or not TCP needs to be optimized for higher performance. The architecture at the higher layers, that is, at the IP and TCP layers, is driven in part by characteristics at the lower layers. For example, the bandwidth-delay limitation of TCP (see Section 3) and the means of improving it will depend in part on the propagation delay at the physical layer.

2.1 Direct Link Concept

The direct link architecture is defined as a line-of-sight wireless link between the mission spacecraft and an earth station. The link may be simplex, as in the case of the D3 experiment, or full duplex, as in the case of a duplex extension of D3, called D4. We studied the full duplex case, which is illustrated in Figure 2-1. The direct concept assumes the use of the D3 Ka-band dual beam 622 Mbps phased-array spacecraft antenna and transmitter and its associated receive earth station to achieve a direct downlink. In addition, it assumes a co-boresited or integrated spacecraft receiver and earth station transmitter for a direct uplink. The direct link may be symmetric (traffic capacity is the same in both directions) or asymmetric (traffic capacity is different in each direction). The asymmetric case is illustrated in the figure.

2.1.1 Candidate Services

There are several companies providing turn-key ground-station service, as shown in Table 2-1. These companies currently provide service at S-band and X-band, but Universal Space Network (USN) and Allied Signal DataLynx have indicated a willingness to add Ka-band capability if requested. The intentions of Swedish Space Corporation are not known. With the addition of Ka-band capability, USN and DataLynx meet all of the requirements of Section 1.

2.1.2 Concept of Operation

This concept considers an end-to-end operational scenario that meets the objective of directly serving PIs with LEO mission data. From the user perspective, the concept allows a PI or other authorized individual located anywhere within the global Internet to access the PI's mission spacecraft whenever it is in contact with an earth station. Using COTS applications in a Windows, UNIX, or other COTS environment, the PI will be able to send commands to the experiment and receive limited outputs from the spacecraft in real time. However, due to the special requirements of TCP, to fully utilize the available bandwidth of the D3 hardware, high volume data from the spacecraft must be stored at an intermediate server before being made available to the global Internet. This is referred to as a store-and-forward architecture.

Possible applications are video teleconferencing to the International Space Station (ISS) and high bandwidth streaming video from the ISS, as well as downloads of large imagery files from earth resources spacecraft.

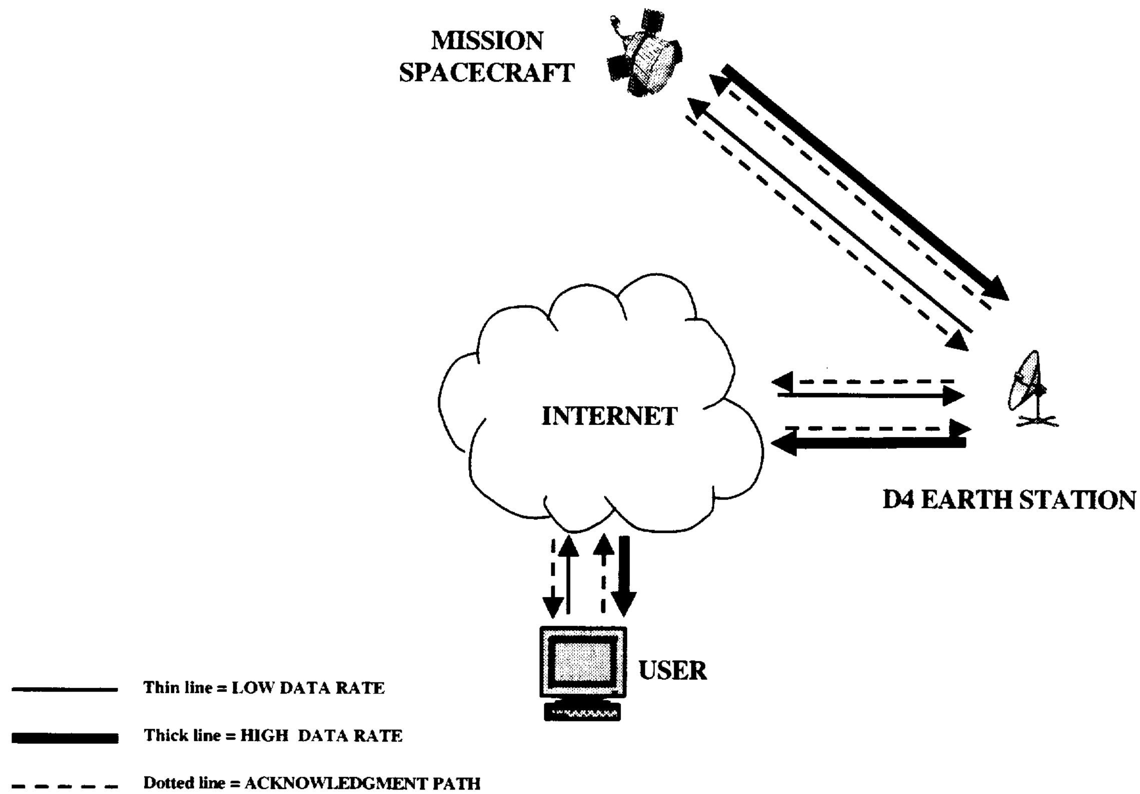

Figure 2-1. Direct Link Architecture

Table 2-1. Candidate Earth Station Services

Direct Downlink Candidates	Status	First Launch	Available by 2005	Ka-Band or Higher	MEO Orbit or Higher	Regulatory Compliance	Reference
Universal Space Network	Proposed	N/A	X	X	N/A	X	Note A
Allied Signal DataLynx	Proposed	N/A	X	X	N/A	X	Note A
Swedish Space Corp.	Unknown	N/A			N/A	X	Note A

Note A: Corporate web site is primary reference.

Our analysis, based on the characteristics of the NASA-developed Ka-band space-ground communication system components, suggests that the spacecraft and earth station can maintain contact for a period of several minutes or more per intercept per earth station. Sequential intercepts by other earth stations serve to increase the total contact time for a single orbit. The concept is to deploy multiple low-cost autonomous earth stations in locations that optimize the contact time within a given geographic area, such as CONUS. The earth stations should have contiguous coverage patterns. As the spacecraft moves between earth stations, a virtual link is maintained as in a terrestrial cellular telephone system. Thus, as far as the user is concerned, the connection is continuous within the coverage area. This allows for the use of a connection-oriented protocol such as TCP. This is feasible as long as a mechanism such as Mobile IP (MIP) is used and, in addition, the gaps in coverage are small enough to ensure that TCP does not time out, as explained in the next paragraph and in Section 3.

IP, TCP, and Application Layer Architectures

Because the spacecraft, acting as an IP host, is physically moving within the network, the routers within the network must be updated as to the location of the spacecraft. This function is provided by MIP, as discussed in Section 3. Using MIP requires that the portion of the network connecting the spacecraft to the ground is partitioned from the rest of the terrestrial network, as shown in Figure 2-2, because the rest of the network does not use MIP. Partitioning is accomplished by means of an IP layer gateway.

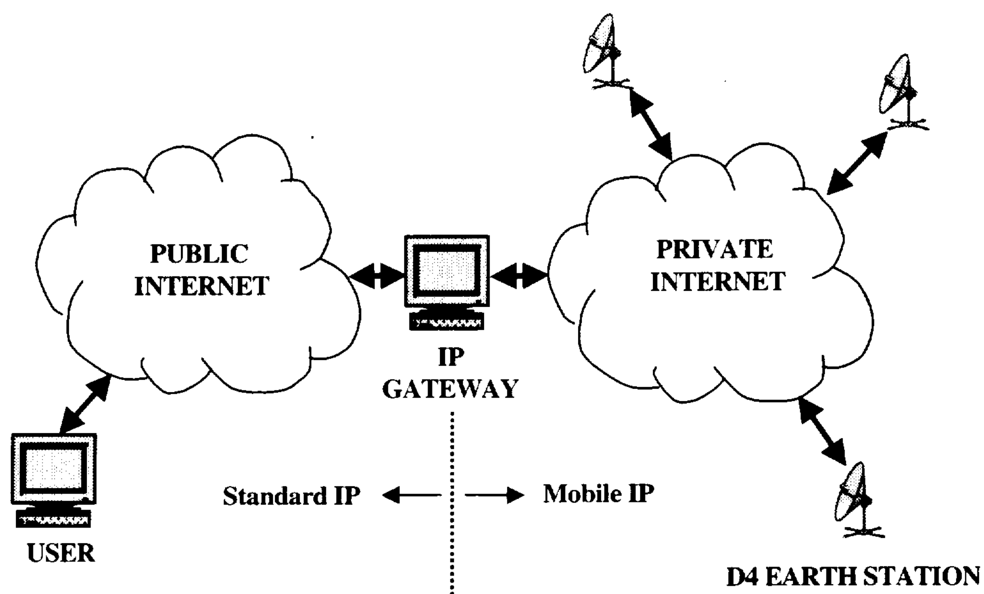

Figure 2-2. IP Layer Gateway

To establish and maintain a virtual link using TCP, there is a requirement for acknowledgment packets to be received or the protocol will consider the connection to be broken. The TCP connection can be maintained across a hand-over between earth stations as long as the gap between data and corresponding acknowledgment packets is less than the TCP timeout constant. Thus, gaps in coverage must be less than this to maintain the connection.

Another feature peculiar to TCP is that, to fully utilize the high bandwidth of the link, TCP must be optimized by tuning some of its parameters to values different from the default TCP settings resident in a typical Windows or UNIX desktop. Because TCP is an end-to-end protocol, both ends of the connection must have the same settings for maximum performance. This necessitates a partition by means of a gateway at the TCP layer for high data rate connections, as shown in Figure 2-3. Outside of the partition, it must be assumed that random users will have the default TCP settings, which will limit the data rate available to them. Their TCP connection must terminate at the gateway. Inside the partition, the spacecraft will use an optimized instance of TCP, and its connection will also terminate at the gateway. So there is no end-to-end connection between the user and the spacecraft for the high data rate connection. This means that files transferred from the spacecraft over the high data rate connection must be stored, however briefly, at the TCP gateway. Hence the need for a store-and-forward architecture. Note that the

TCP gateway is functionally distinct from the IP gateway and may reside at both a different logical and physical location within the network.

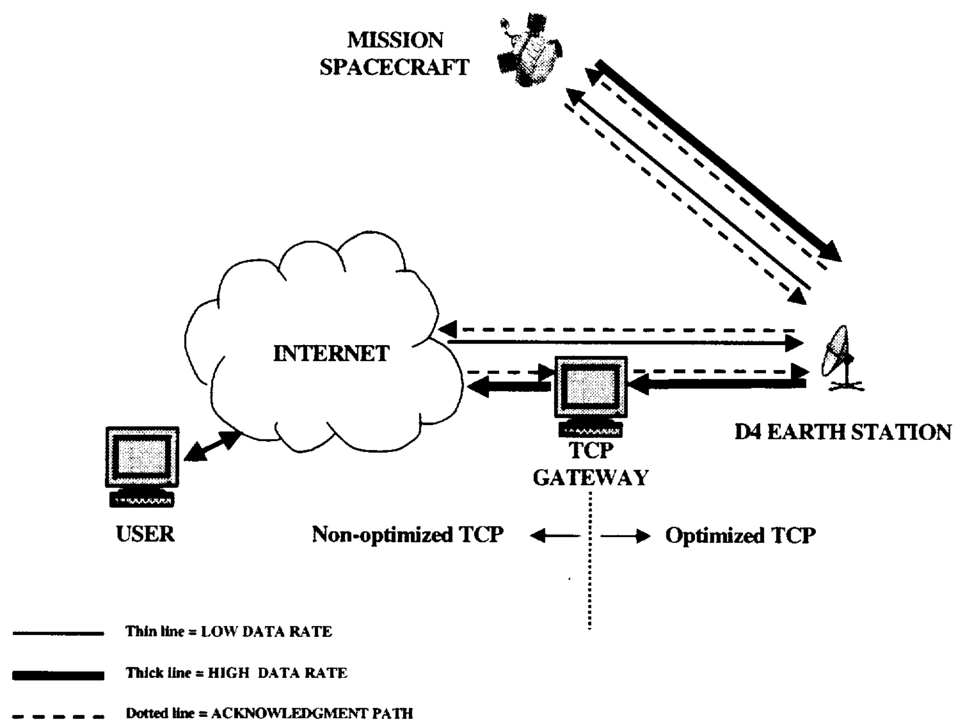

Figure 2-3. TCP Layer Gateway

On the other hand, for lower data rate communications, such as a web browser interface to the command and control functions of the spacecraft, or for "quick-look" downloads of compressed imagery, the gateway should not be needed because an optimized instance of TCP should not be needed. Therefore, the store and forward architecture need not apply to a command channel. This is illustrated in Figure 2-3 by the thin line bypassing the gateway.

Multiple Access

Occasionally, multiple spacecraft will be in the coverage area of a single ground site and must be accessed simultaneously. Because multiple spacecraft generally are in different directions of the sky and the antennas are high-gain antennas, each spacecraft must have a high gain beam dedicated to it. For mechanically scanned parabolic dishes, this implies multiple physically distinct terminals. Using phased arrays, such as on the D3 device, multiple beams per antenna are an option. For multiple independent earth stations operating simultaneously at the same site, spectrum or time sharing methods would have to be used to prevent interference.

The design of the multiple access protocol and other aspects of the link protocol, such as link establishment and handover protocols, were not investigated in this study.

2.1.3 Throughput Estimate

Site Selection

Based on the operational concept of a LEO ground network supporting globally dispersed PIs, two typical LEO missions were selected for detailed analysis: the ISS and a nominal polar orbiter in a 98.2° inclination sun-synchronous orbit. Simulations were run for these orbits to determine the line of sight contact time with representative earth station locations. A four-site network in CONUS serving the ISS orbit and a two-site network serving polar missions were chosen.

Each of the CONUS sites was an existing government facility where a suitable terrestrial communications infrastructure was assumed to exist. The CONUS sites are Ellsworth Air Force Base (AFB), Fort Lewis, Hill AFB, and KI Sawyer AFB. Kennedy Space Center was also included in the analysis, to compare the results at a lower latitude site. Because the number of contacts with the orbiter increases as the location of the earth station approaches the orbit's inclination angle (highest latitude), site selection emphasized higher latitudes. An optimization of the latitude to maximize contact time was not performed because this was done in earlier work by NASA Glenn Research Center (GRC). The CONUS sites were also chosen for contiguous coverage.

The polar sites are Poker Flats, Alaska, and Spitzbergen, Svalbard, where X- and S-band service to polar missions is already provided. Wallops Island was included in the analysis for comparison to a lower latitude site.

The concept can be extended to other geographic deployment patterns than the ones discussed here. For example, for non-polar missions, it may be desirable to have a global distribution of earth stations to more evenly distribute the contact events and minimize storage onboard the spacecraft.

Contact Time Analysis

Satellite Tool Kit (STK), Version 4.1, developed by Analytical Graphics, Inc., was used for the calculations and the geographical depictions of the results. Each location was analyzed for contact times over a 10-day period, from which daily and per-pass averages were determined. The average daily throughput per site was calculated as the product of the average contact time and the data rate. Throughput was calculated only for the return side of the link. Depending on the degree of overlap between sites, the throughput for multiple sites considered as a single system may be roughly approximated as the sum of the throughputs for each site.

The spacecraft was assumed to have a phased-array antenna with a conical beam scan capability. The spacecraft downlink antenna was assumed to be able to scan from a maximum angle away from the antenna boresite (the antenna scan half-angle) to the same angle on the opposite side of the boresite. The antenna boresite is assumed to be always pointed at spacecraft nadir. Antenna scan half-angles of 42°, 50°, 60°, and 70° were simulated for the ISS orbit case. The earth station antenna is assumed to be able to scan from a minimum elevation angle above the horizon necessary for a clear line of sight to the same angle above the opposite horizon. Elevation angles of 5° and 10° were simulated. In the ISS case, the maximum antenna scan half-angle needed by the spacecraft to maximize contact with an earth station with a 5° elevation angle was 70°. For the polar orbit case, the maximum spacecraft antenna scan half-angle needed was found to be

64°. Thus, to determine a spacecraft scan angle requirement to maximize contact times with the earth station, orbit, receive locations, and minimum earth station, elevation angles must be considered.

The period of observation was chosen to be 10 days to minimize any aberrations in results due to differing diurnal orbit characteristics. The average daily contact time for an earth station was defined by dividing the total contact time results by 10.

The graphic outputs of the simulations are shown in Figures 2-4 to 2-9. Summary results of the analysis are presented in Tables 2-2 and 2-3.

2.1.4 Cost Estimate

A rough order of magnitude cost was estimated based on current commercial rates for similar services. USN is a provider of X-band direct downlink service at rates up to 300 Mbps. DataLynx from Allied Signal is another LEO teleport service. It operates an X-band station in Alaska and is allied to other partners worldwide, such as Swedish Space Corporation, which operates stations at far northern latitudes. Data rates are comparable to USN. These companies currently quote rough-order-of-magnitude prices in the range from $5 to $15 per minute, with a one-time engineering charge of approximately $150,000. The per-minute and one-time charges will probably decrease as more customers use the services and as usage grows.

For a future Ka-band system operating at 622 Mbps, we assumed that the cost will be in the same range even at the higher data rate due to the use of smaller, lower cost earth stations, combined with decreasing prices over time and a steep discounting curve with respect to bandwidth.

2.1.5 Spectrum Considerations

Selection of suitable Ka-band frequencies for the direct link concept should be studied with respect to susceptibility to interference and equipment compatibility with Tracking and Data Relay Satellite System (TDRSS)-H, I, and J RF equipment and commercial radio frequency (RF) equipment. Federal Communications Commission or National Telecommunications and Information Administration (FCC/NTIA) and ITU filings for the selected Ka-band frequencies should then follow.

Figure 2-10 summarizes the Ka-band frequency allocation to different services and orbits, according to the ITU. The NASA Ka-band direct links may qualify for the 500-MHz MSS/ NGSO band (uplink: 28.6 to 29.1 GHz and downlink: 18.8 to 19.3 GHz) that is shared with the Teledesic system.

The NASA Ka-band direct link may also qualify for the earth exploration satellite services (EESS) band, shown in Figure 2-10. As far as priority is concerned, EESS is secondary to other services shown in the figure. A suitable selection may be a 100-MHz band from 28.5 to 28.6 GHz for uplink and a 200-MHz band from 18.6 to 18.8 GHz for downlink.

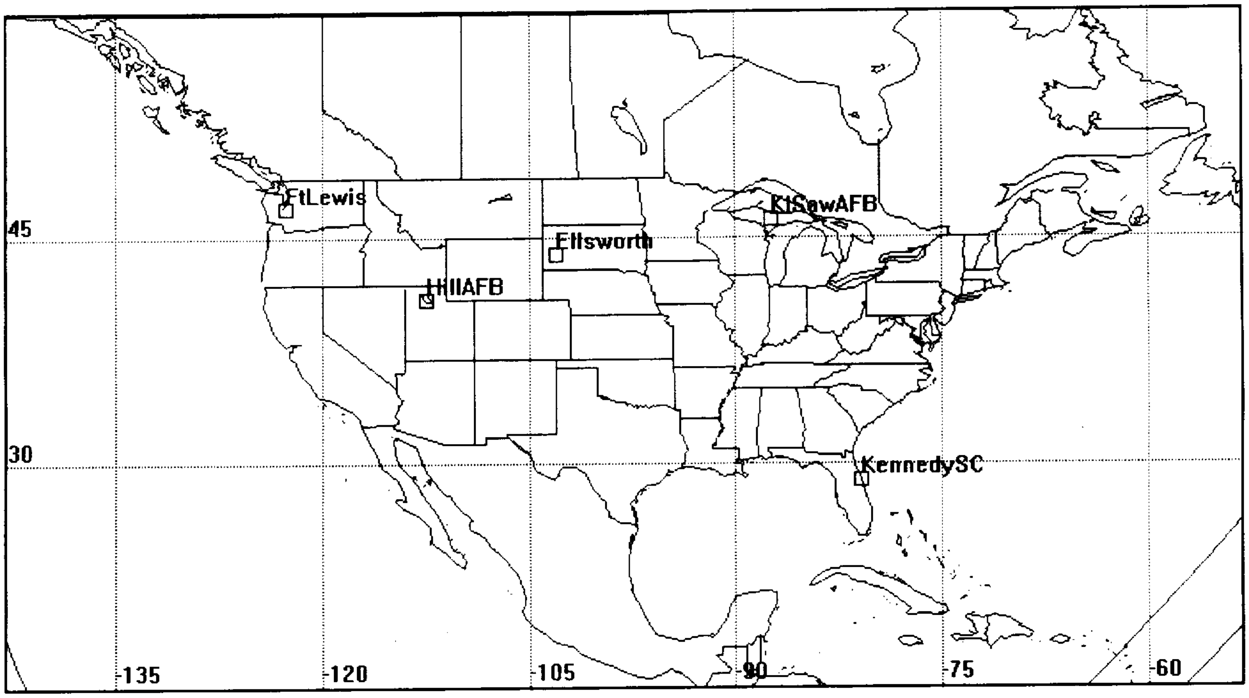

Figure 2-4. Five Stations Used in ISS Orbit Simulation

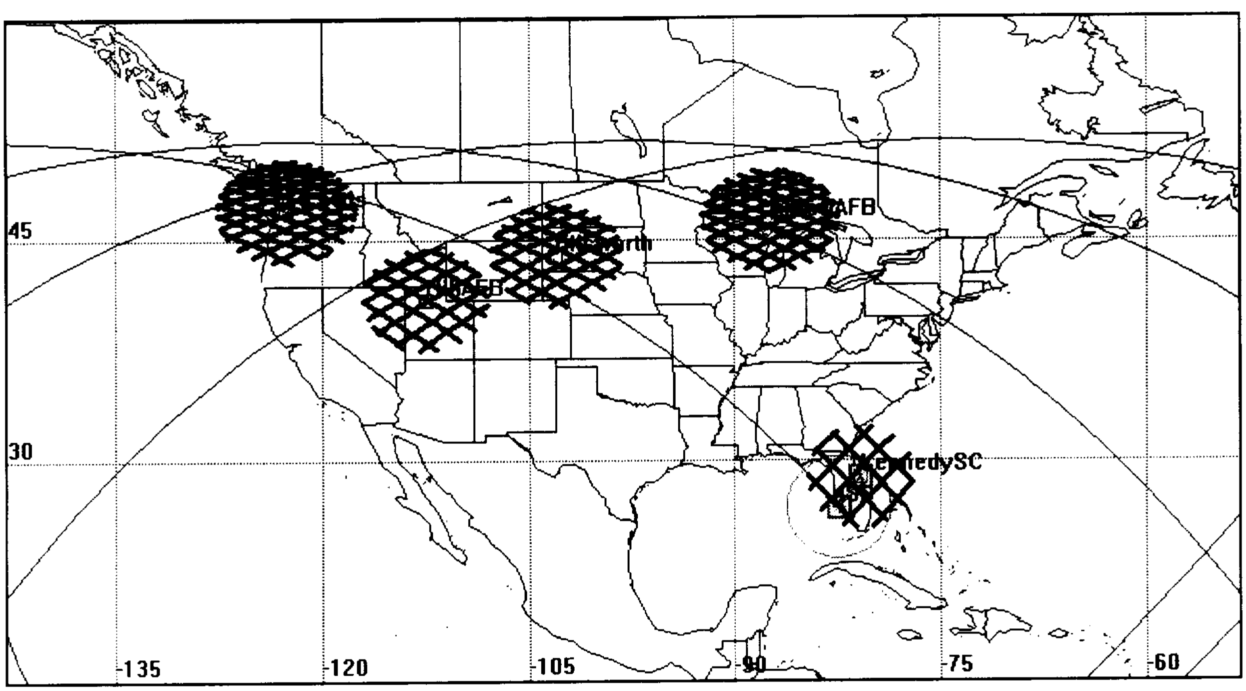

Figure 2-5. ISS Orbit Contacts, 42° Scan Angle

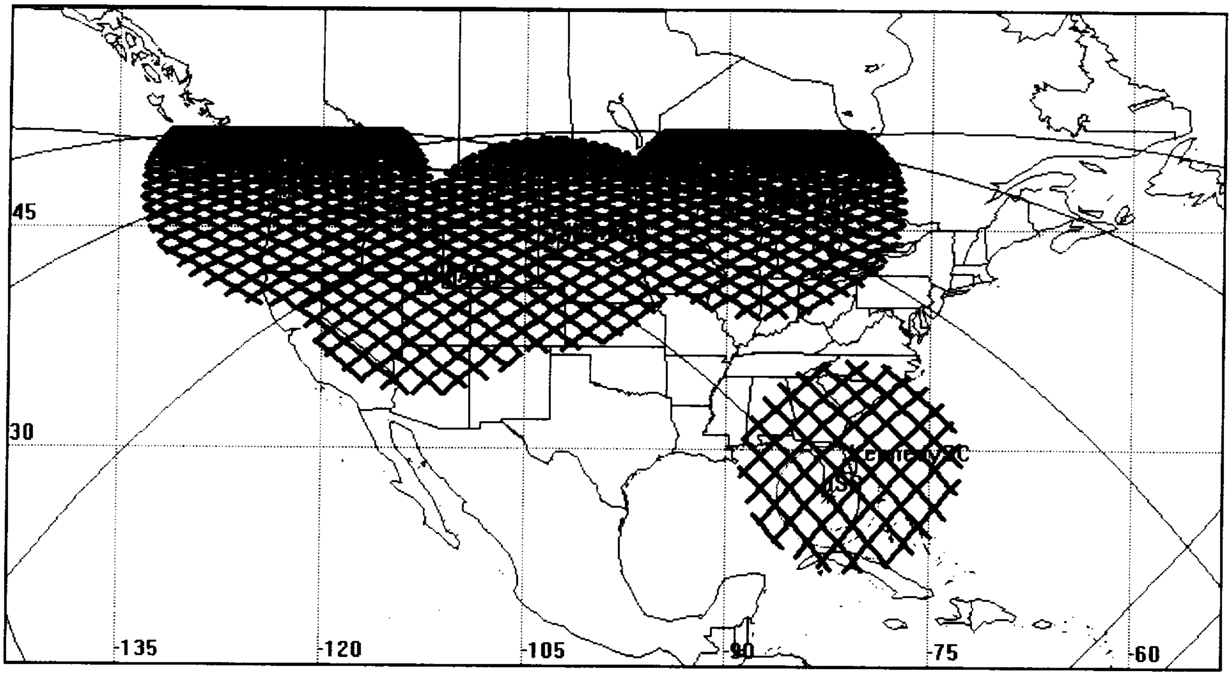

Figure 2-6. ISS Orbit Contacts, 60° Scan Angle

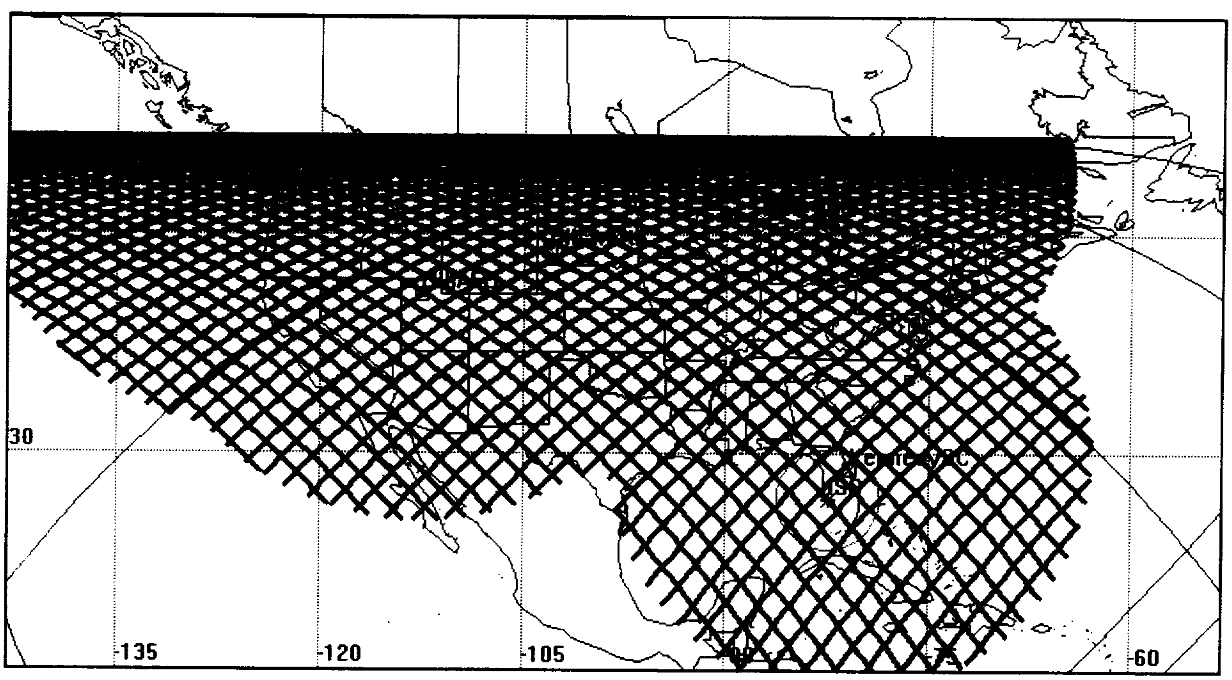

Figure 2-7. ISS Orbit Contacts, 70° Scan Angle

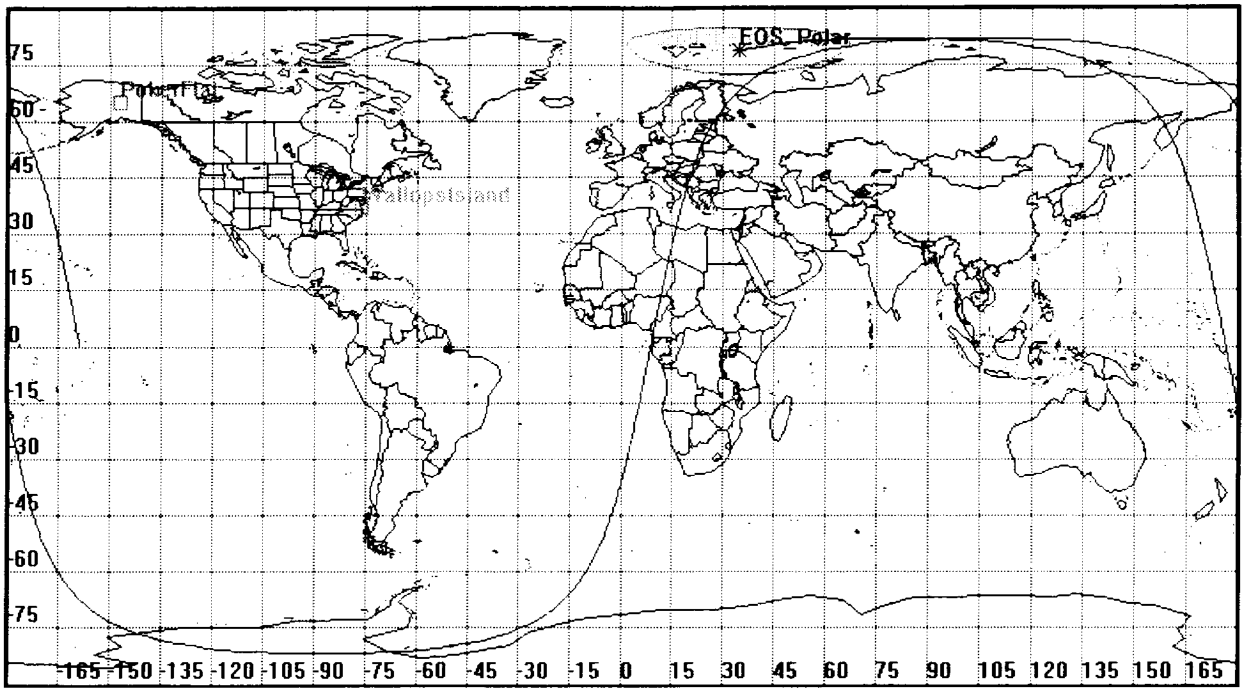

Figure 2-8. Three Stations Used in Polar Orbit Simulation

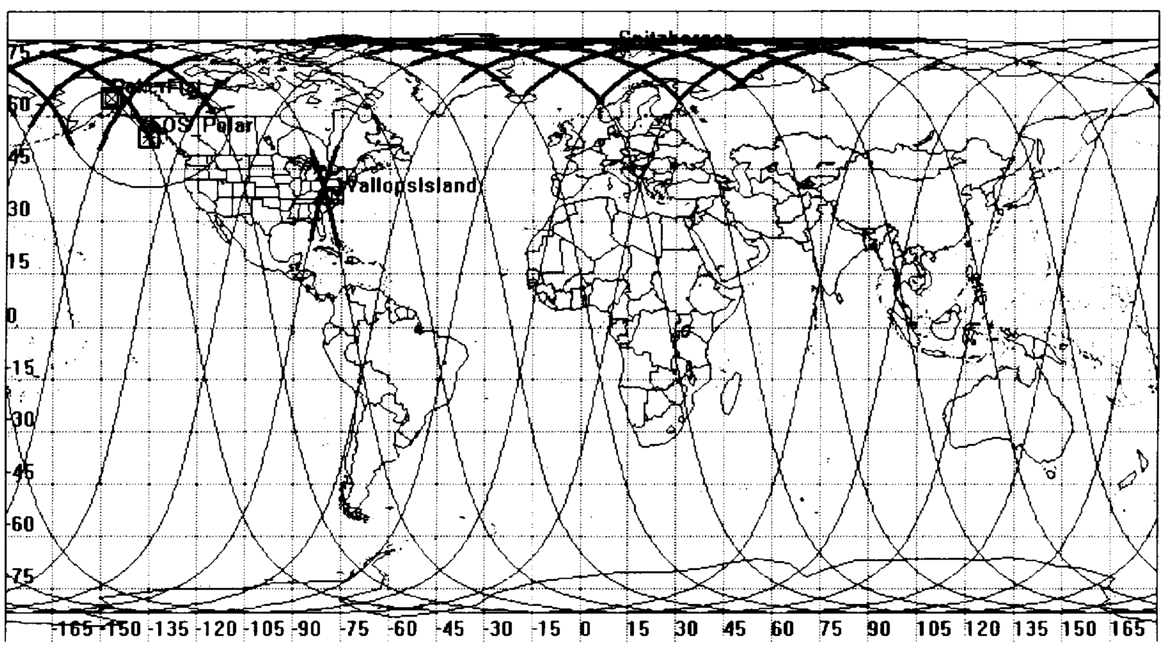

Figure 2-9. Polar Orbit Contacts

Table 2-2. Summary of Contact Times for the ISS Orbit with Five Earth Stations

51.6° Inclination – 404 Km Altitude (Circular)				
Spacecraft Antenna Scan Half-Angle(°)	Earth Station Location	Earth Station Elevation Angle (°)	Mean Duration (seconds)	10-Day Total (seconds)
42	Ellsworth AFB	5 or 10	84.0	1,344
	Fort Lewis	5 or 10	86.2	1,896
	Hill AFB	5 or 10	85.4	1,196
	KI Sawyer AFB	5 or 10	88.8	1,776
	Kennedy SC	5 or 10	86.3	776
50	Ellsworth AFB	5 or 10	115	2,643
	Fort Lewis	5 or 10	109	3,817
	Hill AFB	5 or 10	116	2,212
	KI Sawyer AFB	5 or 10	112	3,366
	Kennedy SC	5 or 10	110	1,430
60	Ellsworth AFB	5 or 10	176	7,024
	Fort Lewis	5 or 10	201	9,031
	Hill AFB	5 or 10	177	5,472
	KI Sawyer AFB	5 or 10	193	9,059
	Kennedy SC	5 or 10	181	3,446
70	Ellsworth AFB	5	445	28,021
	Ellsworth AFB	10	343	19,867
	Fort Lewis	5	446	27,228
	Fort Lewis	10	355	19,520
	Hill AFB	5	432	27,930
	Hill AFB	10	307	18,712
	KI Sawyer AFB	5	452	27,546
	KI Sawyer AFB	10	358	19,665
	Kennedy SC	5	391	17,205
	Kennedy SC	10	306	10,393

Table 2-3. Summary of Estimated Contact Times for a Polar Orbit with Three Earth Stations

98.2° Inclination – 705 Km Altitude (Circular)				
Spacecraft Antenna Scan (°)	**Station Location**	**Elevation Angle (°)**	**Mean Duration (Seconds)**	**10-Day Total (Seconds)**
42	Poker Flats	5 or 10	159	3,659
	Spitzbergen	5 or 10	177	10,463
	Wallops Island	5 or 10	179	1,785
50	Poker Flats	5 or 10	215	7,084
	Spitzbergen	5 or 10	247	16,814
	Wallops Island	5 or 10	219	3,295
60	Poker Flats	5 or 10	360	22,288
	Spitzbergen	5 or 10	417	38,349
	Wallops Island	5 or 10	385	10,011
64	Poker Flats	5	568	52,295
	Poker Flats	10	429	36,433
	Spitzbergen	5	590	77,270
	Spitzbergen	10	492	53,080
	Wallops Island	5	536	22,518
	Wallops Island	10	440	14,970

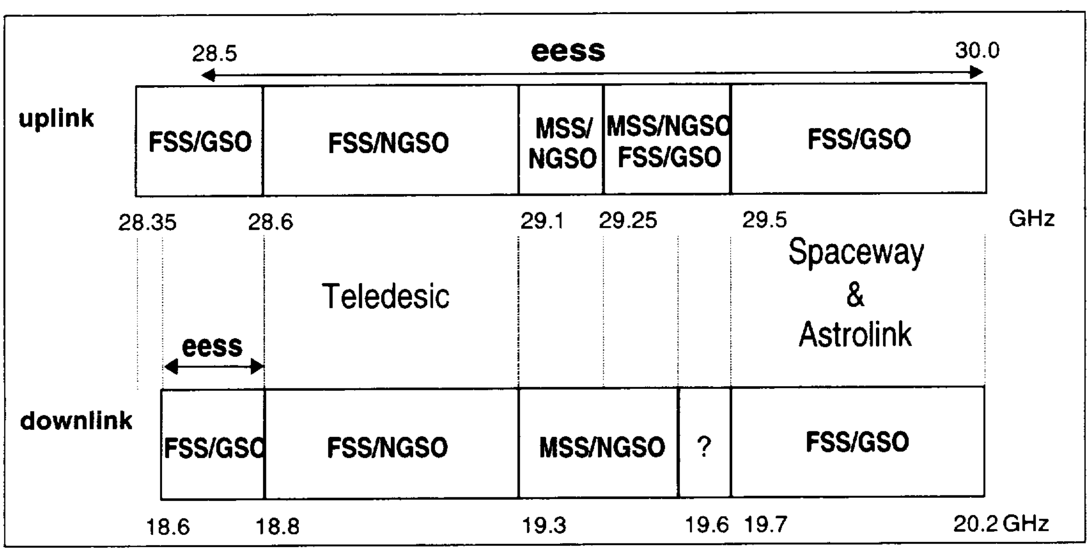

Figure 2-10. ITU Allocations in the Ka-Band

From general interference considerations, sharing with the FSS/NGSO (e.g., Teledesic), as opposed to sharing with the FSS/GSO (e.g., Spaceway), will result in more interference, and the coordination will be more difficult.

NASA should also consider using the same Ka-band frequencies that the TDRSS-H, I, and J satellites will operate on (the ISL return link: 25.25 to 27.50 GHz and ISL forward link: 22.55

to 23.55 GHz) if it is acceptable to FCC/NTIA and ITU. It will be simpler to share with GSO satellites and to perform coordination within NASA.

Teledesic is not likely to be deployed within the next several years. Accordingly, the FSS/NGSO Ka-band should be treated as the primary candidate. Note also that if Teledesic or Teledesic-like systems were deployed, one could still implement the concept by placing earth stations in unpopulated areas where Teledesic does not have any customers other than the backhaul links associated with the earth stations; therefore, coordination would be straightforward.

2.1.6 Technology Considerations

The Ka-band transmitter and receiver developed for the D3 project would have to be augmented with an uplink transmitter and receiver to provide full duplex operation to operate using the TCP protocol. The minimum uplink data rate required would have to be at least sufficient to carry the acknowledgments generated by the 622 Mbps downlink. In Section 3.3, this issue is analyzed, and the results of a simplified simulation are discussed.

The uplink system would operate at 29 GHz, assuming that 19 GHz is the downlink frequency. This would include a receive phased array on the spacecraft and a transmitter and tracking dish on the ground. A 1-meter or less sized dish appears to be feasible for the asymmetric case. Using these assumptions, point designs were done for the uplink for the asymmetric and symmetric cases. These are shown in Table 2-4.

The purpose of the concept discussed in this section is to extend the performance of the D3 system, including increased contact time per earth station. One way of accomplishing an increase in contact time capability by means of an increase in scan angle would be to mount four phased array antennas side by side at 90° with respect to each other. Unfortunately, this would also require an increase in transmitter power to accommodate the greater slant range, all other parameters being equal. For comparison, the current state of the art for solid state power amplifiers is approximately 6 watts [UHM].

Table 2-4. Point Design Link Budgets for D4 Uplink (705 km Altitude)

Parameter	Symmetric Case	Asymmetric Case
Frequency (GHz)	29	29
Data Rate (Mbps)	622	0.256
Data Rate (dB)	87.9	54.1
Eb/No	8.2	8.2
Gs	20	20
Ts (500°K)	27	27
Gt (1 meter)	48.1	48.1
Losses (rain+gas) (dB)	16	16
Boltzmann's constant (dB)	–228.6	-228.6
Free space loss	189.1	189.1
Terminal Power (dBW)	31.5	-2.3
Terminal Power (W)	1412	0.59

2.2 Space Relay Concept

The space relay link architecture is defined as a system that uses a satellite relay service to link the mission spacecraft to an earth station, as illustrated in Figure 2-11. It shows a full duplex forward TCP connection and a full duplex return TCP connection over the same physical channel. The asymmetric case is shown, in which the forward connection, for command and control, has a low data rate, and the return connection, for science data, has a high data rate. Because TCP connections are illustrated, the respective acknowledgment streams are also represented.

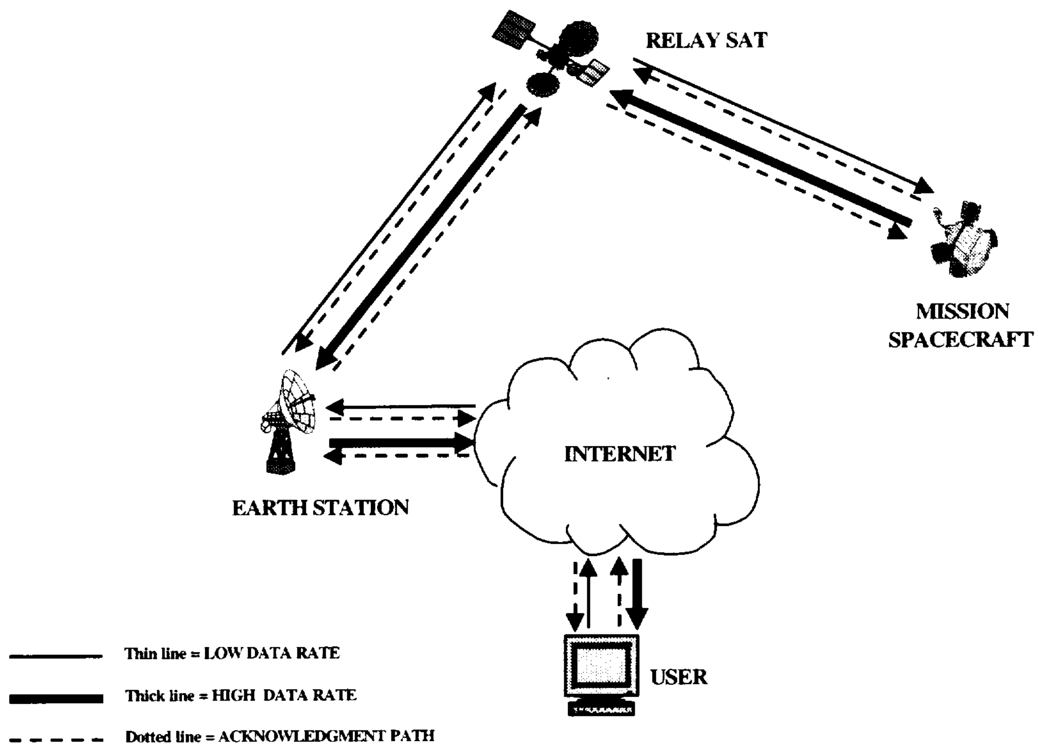

Figure 2-11. Space Relay Architecture

2.2.1 Candidate Services

Commercial SATCOM services that operate in full-duplex mode fall into two general categories of ITU-defined services: MSS and FSS. These categories are further defined by their orbits: either GSO or NGSO. Examples of these categories with some nominal characteristics are shown in Table 2-5.

Existing and proposed SATCOM services relevant to this application were identified and listed in Table 2-6. The evaluation criteria are based on the requirements and assumptions in Section 1. The table shows the compliance of each candidate with respect to the evaluation criteria. The first two columns, *status* and *first launch*, are not criteria but were used to derive likelihood of deployment by 2005 in accordance with assumption A3 in Section 1.

Table 2-5. Space Relay and ITU Services

Architecture	Space Relay			
ITU Designation	MSS GSO	MSS NGSO	FSS GSO	FSS NGSO
Example	Spacehab/Inmarsat	New ICO	Hughes Spaceway	TRW GESN
Coverage	Global except for poles	Global visibility	Regional spot beams	Global visibility; spotbeams
Frequency	L-band	L-band	Ka-band	Ka-, V-bands
Forward Data Rate	64 kbps	Unknown	10's to 100's of Mbps	10's to 100's of Mbps
Return Data Rate	64 kbps	~100 kbps	10's of Mbps	10's to 100's of Mbps
Orbit	GEO	MEO	GEO	MEO and GEO
Latency	Real time	Real time	Hours or days	Real time
Service Start Date	2003	2003	2002	After 2010

Selection Results

None of the candidates among the SATCOM services meets all of the criteria. Most Ka-band and V-band systems are either in the FSS category, and therefore ruled out on regulatory grounds, or are at this time merely "paper satellites," proposals with little likelihood of deployment [FOL1]. Assuming that one or more criteria could be relaxed, potential candidates in each category are discussed below.

MSS GSO

SAIC found in the Integrated Operations Architecture (IOA) study [IOAT] that Inmarsat was a realistic candidate for supporting NASA missions, even though it operates at L-band. Inmarsat is currently and for the near future one of the few near-global MSSs. It has definite application to NASA missions for low data rate communications such as Telemetry, Tracking, and Command (TT&C). It could be used by a PI to send commands to a spacecraft, but because it has such a low data rate, it has limited application for large file transfers from the mission platform. Because of the near-global nature of the service, it can be used for latency-sensitive applications, unlike almost all of the other SATCOM services discussed in this report. Another advantage is that Spacehab is developing a space-qualified terminal to operate with Inmarsat and is planning to provide this service commercially [SHAB].

MSS NGSO

In the MSS NGSO category, New ICO appears to be the only near-term candidate. It does not operate at Ka-band, nor will it have megabit-per-second capacity. In the longer term, there is StarLynx, a medium earth orbit (MEO) system. StarLynx is a V-band system. It is considered to be a "paper satellite," and skepticism regarding the V-band systems is even greater than for the Ka-band satellites. See, for example, [FOL1]. If we ignore the probability of the system being deployed, it appears to best meet the requirements of all the candidates. Because little is known about its design, it is hard to assess the feasibility of interfacing with a LEO spacecraft. On the other hand, because the deployment is so far in the future, there is time for NASA to influence the design.

Table 2-6. Candidate SATCOM Services

Candidates	Status	First Launch	Available by 2005	Ka-Band or Higher	MEO Orbit or Higher	Regulatory Compliance	Reference
MSS GSO							
Spacehab/Inmarsat	Under dev.	2003	X		X	X	[SHAB]
Inmarsat I-4	Under dev.		X		X	X	[ESAS]
Inmarsat Horizon	Proposed			X	X	X	[LLST]
Boeing Connexion Ku	Under dev.	N/A	X		X	X	[CONX]
Boeing Connexion Ka	Proposed	2005		X	X	X	
Hughes StarLynx	Proposed	2005		X	X	X	[FAA1]
MSS NGSO							
New ICO	Under dev.	2001	X		X	X	[LLST
Globalstar	Deployed	deployed	X			X	[LLST]
Hughes StarLynx	Proposed	2005		X	X	X	[FAA1]
FSS GSO							
SES Astra	Deployed	deployed	X	X	X		[AWST]
Hughes Spaceway	under dev.	2002	X	X	X		[SPAC]
LM Astrolink	under dev.	2003	X	X	X		[LLST]
EuroSkyWay	under dev.	2002	X	X	X		[LLST]
Wild Blue (iSky)	under dev.	2001	X	X	X		[LLST]
Telesat ANIK F2	under dev.	2002	X	X	X		[TSAT]
Loral Cyberstar	proposed		X	X	X		[LLST]
Matra Marconi WEST	proposed			X	X		[AWST]
CAI Satcom	proposed			X	X		[TRW1]
Hughes Expressway	proposed	2005		X	X		[FAA1] [TRW1]
Hughes SpaceCast	proposed			X	X		[TRW1]
Loral CyberPath	proposed			X	X		[TRW1}
Spectrum Astro Aster	proposed			X	X		[TRW1]
PanAmSat V-Stream	proposed			X	X		[TRW1]
LM Q/V Band	proposed			X	X		[TRW1]
GE StarPlus	proposed			X	X		[TRW1]
FSS NGSO							
Alcatel SkyBridge	under dev.	2002	X				[FAA1]
Boeing NGSO FSS	proposed	2005			X		[FAA1]
HughesLINK	proposed	2005			X		[FAA1]
HughesNET	proposed	2005					[FAA1]
Teledesic Ku Suppl.	proposed	2005			X		[FAA1]
Virtual GEO Sat	proposed	2005			X		[FAA1]
Teledesic	proposed	2005		X	X		[LLST]
@Contact	proposed	2006		X	X		[FAA1]
LM-MEO (Ka)	proposed	2005		X	X		[FAA1]
Skybridge II	proposed	2005		X			[FAA1]
Spaceway NGSO	proposed	2005		X	X		[FAA1]
Teledesic VBS	proposed	2006		X			[FAA1] [TRW1]
OSC OrbLink	proposed	2005		X	X		[FAA1] [TRW1]
Denali Pentriad	proposed	2005		X	X		[FAA1] [TRW1]
GE StarPlus	proposed			X	X		[TRW1]
Globalstar GS-40	proposed			X			[FAA1] [TRW1]
LM MEO (V)	proposed	2005		X	X		[FAA1] [TRW1]
TRW GESN	proposed	2005		X	X		[FAA1] [TRW1]

FSS GSO

The FSS candidates were ruled out based on the regulatory problem of a mobile terminal interfacing to a fixed service. This problem is beyond the control of NASA, so the criterion cannot be "relaxed."

Even if the regulatory problem could be solved, there are major technical problems when interfacing to the new generation of onboard processed, dynamically assigned, spot-beam satellites. As a case in point, SAIC investigated the Spaceway system to a level of detail sufficient to determine that it cannot be made to interoperate with a moving spacecraft. The Spaceway beams are too narrow, so the contact time is too short to allow appreciable data transfer and perhaps too short to establish the link. The network operating system is designed to have constant contact with earth stations, which are assumed to be located at fixed positions.

There are other Ka-band satellites that are bent-pipe systems and have broader beams than Spaceway. An example is the ANIK F2 satellite. Unlike the case of Spaceway, interfacing with these systems may be technically feasible.

FSS NGSO

Broadband NGSO systems have the potential to provide global coverage. Unfortunately, the regulatory problem rules out the FSS NGSOs, including Teledesic. In addition, there is skepticism as to the likelihood of their deployment.

The Federal Aviation Administration (FAA) model [FAA1] posits two scenarios for the proposed NGSO systems in the 2000–2010 time frame: an optimistic one and a pessimistic one. The optimistic one is for two broadband NGSO systems to be deployed, and the pessimistic one is for only one to be deployed. This rather negative picture implies that most of the proposals are in reality "paper satellites" that will never be deployed. The NGSO system that is probably closest to deployment is Skybridge, which is a Ku-band system. Based on the literature surveyed for this report, we rate the probability of operational deployment of the systems in the "proposed" category as very low.

There are significant business risks faced by these systems. [NOLL] lists the risks as:

- The satellites spend 70 percent of their time over the earth's oceans and thus are not usable for much of their life.
- The many years needed to design, manufacture, and launch the satellites mean that the technology is nearly obsolete by the time it is finally placed in orbit.
- The radio bands used for the communication are line-of-sight and do not work indoors, in the shadows of buildings, or under trees.
- The enormous initial investment for the large number of satellites means that the initial service may be very costly.

According to [CROS], only four broadband Ka-band systems have a high probability of going into service in the United States in the next 3 to 5 years. They are Hughes Spaceway, Loral Cyberstar, Lockheed Martin Astrolink, and Teledesic. In our opinion, Teledesic will not be deployed in that time frame because the chief investor and builder, Craig McCaw, will wait to see how New ICO performs before proceeding with Teledesic. Also, Teledesic does not currently appear to be under development. The recent selection of a new prime contractor indicates that the design must start again from the beginning.

Inter-Satellite Service Approach

It should be mentioned that many of the above services will have ISLs, which operate under the ITU classification of Inter-Satellite Service. Theoretically, a NASA spacecraft could interface to a commercial ISL without regulatory conflict. However, the design of the ISL hardware would have to be changed to accommodate the different tracking requirements of a LEO spacecraft. Other internal system design details would have to change as well. This implies that NASA would have to be a partner with the commercial provider early in the design stage of the commercial system. It is unlikely that this could be done for systems that will be deployed by 2005.

If the design of the ISLs of one of the commercial MEO systems could be modified to accommodate NASA requirements, presumably the main spot beam tracking subsystem could be modified as well. For example, the MEO satellite could be commanded to track a NASA platform over the ocean, where service is not otherwise provided and where interference with other users is minimal.

2.2.2 Concept of Operation

Given that the FSS systems must be ruled out on regulatory grounds and the near-term MSS systems do not operate at Ka-band, the most viable candidate for this architecture appears to be Hughes StarLynx. StarLynx is an MSS that has a GSO and an NGSO (MEO) component. Therefore, a notional MEO constellation based on StarLynx was assumed. For example, the MEO orbit is assumed to be 10,000 km at an inclination of 55°.

The architecture allows the NASA LEO spacecraft to communicate directly with the MEO relay spacecraft. NASA data would be relayed to the MEO satellite when LEO-to-MEO connectivity could be established. The relayed data may be directly received by a PI's earth station, or the data may be received at a gateway facility. In the latter case, either the Internet or other terrestrial means will be necessary to connect the user to the gateway.

2.2.3 Throughput Estimate

Lacking technical details of the StarLynx design, some simplifying assumptions were made to estimate throughput. It is assumed that the MEO constellation will provide continuous coverage to mobile terminals and that the mobile terminals can roam anywhere in the service area. We further assumed that NASA would be able to influence the design such that the service area covers the entire area visible to the satellite spot beams. Then for LEO missions below a certain orbital inclination, global coverage would be available. Assuming that contact with the service is available for a nominal 80 percent of the day, the contact time would be 69,120 seconds per day.

StarLynx is stated to provide a 2 Mbps data rate using a 1-foot diameter terminal antenna and 8 Mbps using a 2-foot diameter terminal antenna [TRW1]. Using the 8 Mbps value, the throughput per day is 553 gigabits.

2.2.4 Cost Estimate

The pricing for services such as StarLynx will likely be set to compete with terrestrial broadband service. The cost estimate, therefore, can be estimated based on terrestrial service. We assume present-day prices. From our cost assumptions (Section 1), the cost of T1 ranges from $500 to $2,000 per month, or $0.012 to $0.046 per minute. We assume that the cost of 8 Mbps service is two times the cost of T1 service, or $0.024 to $0.092 per minute.

2.2.5 Spectrum Considerations

Currently, the relay communication services provided by NASA are categorized by the ITU as Space Research Service (SRS), Space Operation Service (SOS), and Inter-Satellite Service. For example, the TDRSS H, I, and J satellites will provide Ka-band service under the Inter-Satellite Services category. On the other hand, commercial satellite communication services available now or in the foreseeable future are FSS, Broadcast Satellite Service (BSS), and Radio-Determination Satellite Service (RDSS). All candidate commercial satellite services are either MSS or FSS. The Ka-band FSS allocations are different from the Ka-band Inter-Satellite Service allocations, as shown in Figure 2-10 in Section 2.1.5.

Thus, technically, by using commercial satellite services to meet relay communication requirements by LEO spacecraft, NASA would be in non-compliance with the ITU. Such non-compliance usage may be acceptable if NASA could show that the usage would not cause harmful interference to other systems. In the past, similar non-compliance usage has occurred [VUON]:

- To promote the Direct Broadcast Satellite (DBS) service, the FCC in 1987 allowed partial usage of the BSS Ku-band for FSS [FCC].
- The FCC allowed Qualcomm to use a FSS Ku-band transponder of a Gstar satellite for its OmniTracs service, which is MSS, on a non-interference basis (i.e., if harmful interference is detected, the service must be stopped) [NICH].
- Intelsat and COMSAT (not the ITU) allowed the Navy to use CSCI/Intelsat's FSS C-band global transponders on a non-interference and experimental basis for the Challenge Athena project, which is MSS [HEAR].
- Hughes Communication Inc. (HCI) (not the ITU) has also allowed the Defense Airborne Reconnaissance Office (DARO) to use CSCI/HCI's FSS Ku-band transponder on a non-interference and experimental basis for relay communication testing of its unmanned aerial vehicles (UAVs), which are MSS [SMIT].

2.2.6 Technology Considerations

To use the Inmarsat MSS GSO service, no new technology would be needed, assuming Spacehab, Inc., is successful in developing this service. As reported in [IOAT], Spacehab is developing the space-qualified terminal for use with Inmarsat.

To use StarLynx, a full-duplex spacecraft terminal would have to be developed at V-band. It may be noted that Hughes plans to develop a tracking phased array antenna for the mobile user terminals for this service.

To use an ISL interface to one of the NGSO systems, the spacecraft terminal would have to be either an RF terminal, most likely at V-band (extremely high frequency [EHF]), or an optical terminal. One advantage of the ISL approach is that the same technology could be used on the NASA spacecraft as on the commercial satellite.

If it is desired to use a Ka-band service, a full-duplex spacecraft terminal would have to be developed. An example of a Ka-band link budget was calculated for a LEO mission communicating with a GSO service. Table 2-7 summarizes a link power budget computed to support a data rate of 6 Mbps with an Eb/No of 8.2 dB from the NASA LEO satellite to a geosynchronous orbit (GEO) relay satellite. An Eb/No of 8.2 dB should be sufficient to achieve near-error-free operation with the proper selection of modulation and forward error correction, such as an inner convolutional code with an outer Reed-Solomon code. Assuming a 1.5° GEO beamwidth, a required a LEO equivalent isotropic radiated power (EIRP) of 52.6 dBW is computed. Assuming the 0.5° beam, a required LEO EIRP of only 43.6 dBW is obtained. As a point of reference, the NASA GRC Ka-band phased array is rated at 39 dBW at 19 GHz [WALD]. Thus, a somewhat higher power space qualified phased array would be necessary to support 6 Mbps. The GRC space-based phased array can support 622 Mbps space-to-earth even accounting for atmospheric and rain losses, but in the example considered here, the LEO-to-GEO free space loss is so great (212.3 dB) that 6 Mbps is not achievable. Another phased array being developed by NASA (along with commercial partners) is specified to operate in the TDRSS bands (22.25–27.5 GHz) and generate an EIRP ≥ 33 dBW [PELL].

2.3 Hybrid Concept

The hybrid category is defined as a system that uses different link types for the forward and return paths. In the commercial SATCOM world, hybrid architectures most often refer to a split link consisting of a forward path utilizing a relay satellite and a return path utilizing a landline. A good example that demonstrates the feasibility of the approach is Hughes DirecPC (first generation). This is a broadband Internet access service and is illustrated in Figure 2-12.

Table 2-7. Link Power Budget Summary – NASA LEO to GEO Relay

Parameter	1.5°	0.5°
NASA LEO EIRP	52.6 dBW	43.6 dBW
FSLup	212.3 dB	212.3 dB
Pointing Loss	0.5 dB	0.5 dB
Polarization Mismatch	0.2 dB	0.2 dB
Demod Loss	2.0 dB	2.0 dB
GEO Rx Gain (1.5°)	41 dBi	50 dBi
Data Rate	6 Mbps	6 Mbps
Eb/No	8.2 dB	8.2 dB

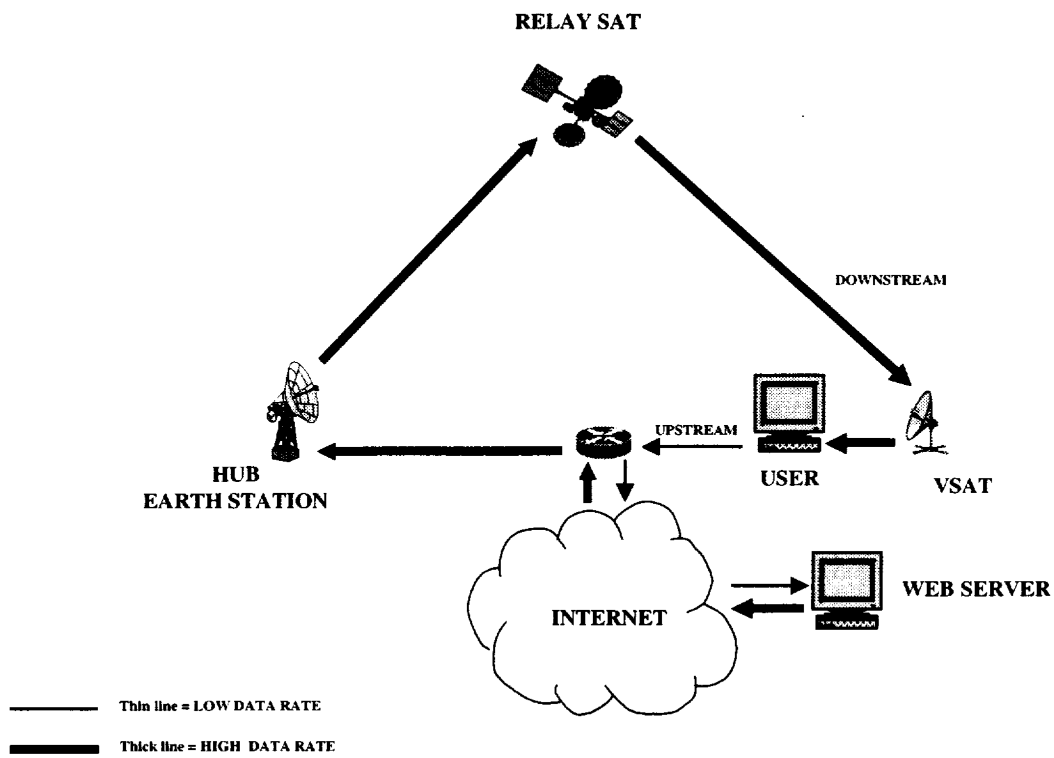

Figure 2-12. Hughes DirecPC Hybrid SATCOM Architecture

2.3.1 Concept of Operations

In our case, use of a landline is not applicable. Instead we considered the case of using a direct downlink architecture for the return link and a space relay architecture for the forward link. This concept is illustrated in Figure 2-13. The direct downlink utilizes the D3 hardware. The forward data travels to the spacecraft via the space relay link, and TCP acknowledgments travel back to the ground via the direct downlink. The return data travels from the spacecraft to the ground via the direct downlink, and the TCP acknowledgments for this data travel back to the spacecraft via the relay service. The rationale for this architecture is that, because the TCP acknowledgments for the 622 Mbps downlink can be carried on a relatively narrowband channel, using a SATCOM relay service to carry these packets is a viable alternative to using a direct uplink. For example, because many spacecraft will carry S-band transceivers compatible with TDRSS, the TCP acknowledgment packet stream for the direct downlink could be carried back to the spacecraft through a TDRSS S-band channel. Another example would be to accomplish the same thing using the Spacehab Inmarsat transceiver.

There are many variations within this architecture. The two links may be simplex or duplex. They may have differing or equal bandwidths (asymmetric and symmetric cases, respectively). The relay link may carry only acknowledgments, or it may carry additional user application channels such as command and control.

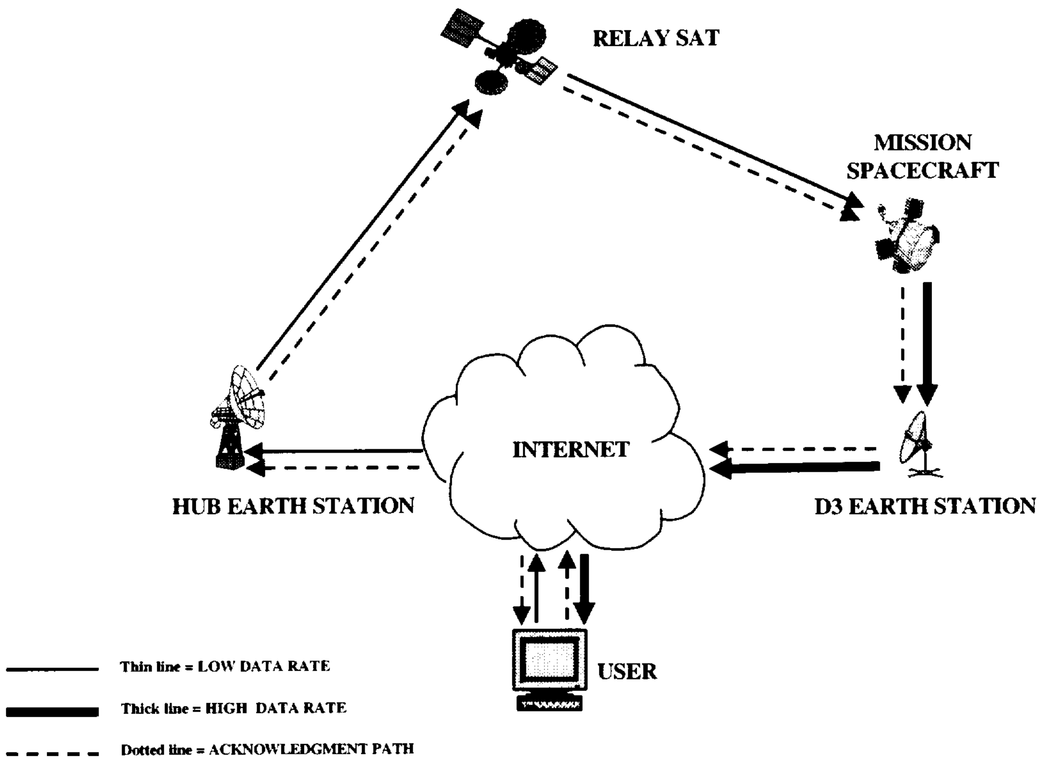

Figure 2-13. Hybrid Architecture

At least two variations appear to make sense for the application:

- Simplex forward, simplex return
- Duplex forward, simplex return.

Examples are given in Table 2-8 along with the salient features of each.

Table 2-8. Hybrid Architecture Examples and Features

Architecture	Hybrid			
Subcategory	Simplex forward, simplex return		Duplex forward, simplex return	
Forward Data Path (FDP)	Relay		Relay	
Acknowledgment (ACK) Path for FDP	Direct		Relay	
Return Data Path (RDP)	Direct		Direct	
ACK Path for RDP	Relay		Relay	
Relay Path Implementation Example	BSS: DirecPC	FSS: 1-Way VSAT	MSS: Inmarsat	ISS: TDRSS S-band
Direct Path Implementation	D3	D3	D3	D3
Relay Frequency Band	Ku	Ku	L	S
FDP Data Rate (Mbps)	6	35	0.064	0.256
Coverage (Best Case)	Continental	Continental	Global except poles	Global except poles
Propagation Delay	GEO	GEO	GEO	GEO
Data Latency	High	High	High	High

Because this architecture only requires a simplex link over the relay path, BSS and FSS may be considered in addition to MSS. For example, a direct broadcast video satellite can be used to create the forward path of the link, as shown in the second column of the table.

Note that the case of simplex forward/simplex return is compatible with ITU regulations for FSS and BSS. This is because the user (the NASA mission platform) does not transmit to the service; it only receives from the service. There are thus no interference issues. However, some FSSs may require a full duplex link to the service because the network operating system may need to communicate with the user terminal on a nearly continuous basis.

The second column in the table shows a BSS used to provide a forward path for commands and also for TCP acknowledgments to the spacecraft.

The third column in the table shows a one-way very small aperture terminal (VSAT) service as another way to create the same forward path.

The fourth column in the table shows a near-global, mobile service, Inmarsat, used to create the forward path. It is a full duplex service, so packets may travel over the direct path or the relay path in the return direction. Unfortunately, it is a narrow-band service, so it limits the number of acknowledgment packets available to the TCP connection for the return path. An alternative approach would be to use the Inmarsat full duplex link for TCP/IP interactive communications with the spacecraft and a protocol other than TCP on the direct link. This is discussed in the next section as a combination architecture.

The last column in the table shows TDRSS as the relay service, another way of achieving the same thing. Using this service has the advantage of being able to use an existing narrowband transceiver on the spacecraft.

2.3.2 Throughput Estimate

As in the previous concepts, throughput refers to the throughput in the return direction. That is, we considered only the asymmetric case for the throughput estimate. The throughput for this concept is theoretically the same as for the direct architecture because it would use the D3 hardware for the return side of the system. However, the throughput could be limited to less than the capacity of the D3 if the relay service data rate is not sufficient to carry the TCP acknowledgment packets. This might be the case with Inmarsat, for example.

2.3.3 Cost Estimate

For the cost estimate, we assumed that the cost for the return link would be the same as for the direct architecture. The cost for the forward (relay) link falls in a broad range, depending on which service is assumed. We assumed the cost for the forward link would be $1.29 to $13 per minute, using the SOMO catalog prices for TDRSS MA service [SOMO].

2.4 Combination Concept

There are many possible combinations of the basic direct and relay architectures. However, we considered only one, which might be called a dual-mode system in analogy to cellular telephone handsets that can access two different wireless systems.

NASA has expressed an interest in a system concept that would give a PI three optional methods of communicating with the PI's spacecraft through:

1. A direct link earth station at the PI's site
2. The Internet to a remotely located direct link earth station
3. The Internet through a space relay satellite.

From these three scenarios, we see that there are two basic link architectures involved: a direct link and a space relay link. Because the PI can establish a connection in any of the three scenarios, both link types must operate independently. Scenarios 1 and 2 are direct architectures, and scenario 3 is a space relay architecture. But because the links operate independently, it is not a hybrid architecture in our sense of the term.

A direct link at the PI's site (scenario 1) has the advantage of not requiring a high-bandwidth WAN connection. It also has the advantage that the local area network (LAN) maximum transmission unit (MTU) and the TCP maximum segment size can be configured to a large size to minimize the number of acknowledgments and thereby minimize the uplink data rate component of the full duplex link, as explained in Section 3.3.

Scenario 2 is equivalent to the Direct Concept discussed in Section 2.1. There it was shown that TCP requires a partition between the private network that the spacecraft uses to connect to the earth and the public terrestrial Internet. This is to optimize TCP inside the partition to accommodate the high data rate of the link. (The optimization includes the use of an unusually large maximum segment size and MTU, as in scenario 1.) Thus, scenario 2 requires a store-and-forward architecture for the 622 Mbps connection. There is a gateway server where files must be stored before the PI can access them. Thus, scenario 1 allows real-time, direct 622 Mbps connection to the spacecraft by the PI, whereas scenario 2 does not. However, scenario 2 does not preclude a low data rate real-time connection in parallel with the high data rate store-and-forward path. It is possible to make the store-and-forward aspect invisible to the user in this manner. As far as the user can tell, there is real-time interactive contact with the spacecraft. However, some form of agent software would carry out the task of actual high-speed file transfers from the spacecraft.

This approach lends itself to another, simpler, implementation, that is, to dispense with TCP for the direct downlink because end-to-end TCP cannot be used anyway. Instead User Datagram Protocol (UDP) could be used. Then a direct uplink would not be required because acknowledgments would not be required. TCP/IP would be used on the space relay link (scenario 3) for PI-spacecraft interaction. Because this interactive application requires only a low data rate, a low data rate service such as Inmarsat or the TDRSS MA S-band service could be used. This concept is shown in Figure 2-14.

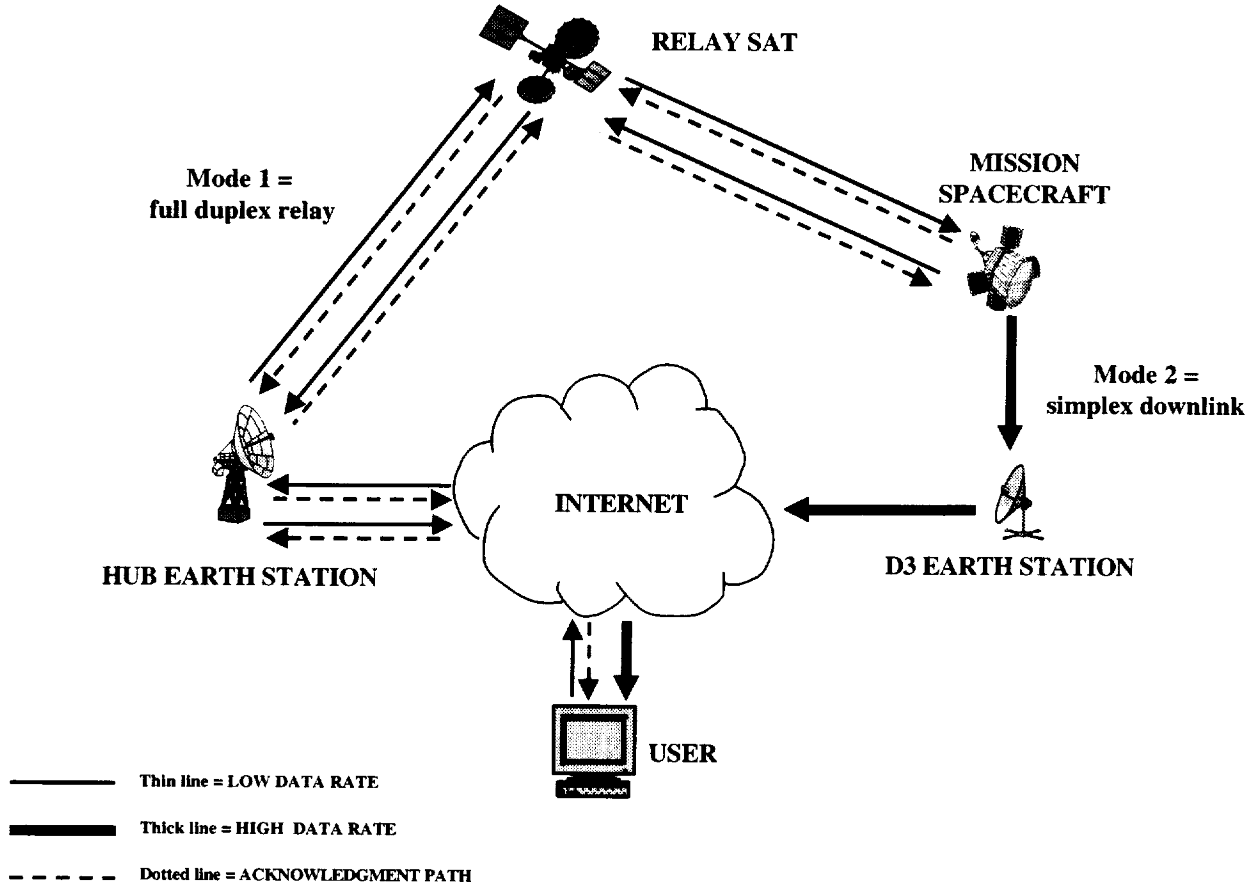

Figure 2-14. Dual Mode Concept

3. PROTOCOL CONSIDERATIONS

In this section, we present some issues that arise with respect to TCP/IP and its planned deployment in 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 mission payloads, which at this time are assumed to be operating at LEO. This a priori selection is presented in Section 2. Given the standard layering model used in designing and developing communications systems of today (and the Internet, in particular), we rely on a decoupling of link layer technology from the IP logical network. The IP network is 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.[1]

From these previously selected scenarios, we present the potential issues that arise when standard TCP/IP is used for end-to-end communication between a user (e.g., PI) residing in the terrestrial portion of the Internet and the target spacecraft payload. We also discuss another IP technology known as multicast, which can dramatically reduce bandwidth usage between an earth station and the satellite payload in cases of one-to-many communication.

Pursuant to the request of NASA, an underlying goal in the following is to present issues as they relate to communication with standard TCP/IP protocols used on the Internet. We define standard TCP/IP as that version of the protocol that is bundled in operating systems such as Win98, Solaris, and Linux. In cases where standard TCP/IP is considered problematic, we present options that can address these concerns. We also follow the NASA request of focusing 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.

3.1 TCP Considerations

On the Internet today, nearly 95 percent of all traffic carried by IP and traversing an Internet service provider (ISP) is TCP based. The other 5 percent is a mix of UDP and Internet Control Message Protocol (ICMP)—the former predominantly used for Domain Name Service (DNS) and name resolution, and the latter used to provide feedback (typically, echo requests) for network operators.

3.1.1 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 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 minutes. Such a condition causes the source to view the destination as being unreachable, and thus state for that connection

[1] Note that this is a slight departure from the Open Systems Interconnect (OSI) model, which separates the session and presentation layer from the application. Hence, with the Internet model, we end up with five layers, while the OSI model uses seven layers.

is removed. Hence, if a file transfer connection were broken, then the information accumulated at that point will have been lost, requiring that a new file transfer session be initiated.

This 2-minute gap problem is directly related to the types of scenarios presented in Section 2. If a given scenario does not provide global coverage over both land and sea, then it is subject to the condition described above. In all of the detailed concepts we analyzed, this problem will exist.

3.1.2 SCPS

The Satellite Communications Protocol Standards (SCPS) is an ongoing effort that has set aggressive goals. It can be characterized as an all inclusive design to address a variety of perceived weaknesses of TCP/IP in support of satellite 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 (i.e., commands).

An examination of the transport protocol of SCPS, referred to as SCPS-TP, shows that the designers use a Selective Negative Acknowledgment (S-NACK) to trigger the retransmission of data. This is in contrast to the standard TCP option of Selective Acknowledgment (SACK). Tests have shown that S-NACK can produce throughputs of approximately 30 percent faster than SACK. However, if one were to take into consideration the need to have SCPS-TP interact with standard TCP, then it can be argued that a substantial amount of buffer space will be needed to compensate for the disparate measures of throughput. Figure 3-1 is an example of an SCPS-TP connection between the mission payload and a gateway, and another connection between the gateway and a user located somewhere in the Internet. Thus, if there is a sustained rate of traffic from the payload to the gateway that is being forwarded at 30 percent or higher speeds (shown as the SCPS-TP connection), then the gateway has to be configured with enough buffer space to compensate for the slower speed of the standard TCP connection or data will be dropped.

One means of addressing this problem is to insert an additional flow control message into SCPS-TP so that it will only transmit as fast as the standard STP connection can support. The irony in such an action is that the purported increase in throughput by an SCPS-TP connection is negated when standard TCP is used to complete the end-to-end communication between the user and the mission payload.

3.1.3 Vendor Support

Unfortunately, the 2-minute gap problem is one that is not really addressed by the vendor community because so few terrestrial systems encounter it. Some vendors are working on "smart" web browsers and servers that can retain state for an extended period of time to compensate for broken connections due to acknowledgment timeouts. However, this is an example in which the solution is bound to one type of application. In addition, it is really a proprietary solution that may or may not be compatible with other vendors.

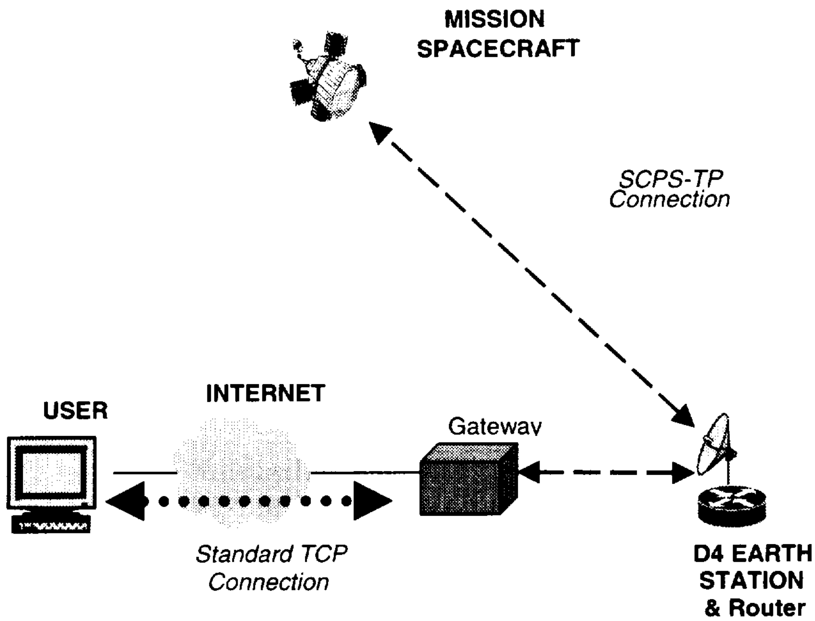

Figure 3-1. Interfacing SCPS to Standard Internet

One potential solution to the 2-minute gap problem is rather "low-tech" in nature and involves manual distribution of 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 a LEO satellite is reachable by the user. From previous discussions with NASA, it was determined that a worst-case scenario may involve connectivity periods of just 90 seconds. Although this can be considered plenty of time for quick downloads of information, the ability to synchronize time over various distances can be problematic (e.g., how accurate is your wristwatch to the time displayed on your computer?).

To address the 2-minute 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 IP Considerations

3.2.1 Mobile Host Problem

Placing an IP address in a mission payload makes it become an IP node. Given that the payload is an end point (i.e., it does not act as a relay for other nodes) with applications loaded on it, the type of node is that of an IP host, as opposed to a router. The initial design of the Internet and the accompanying suite of protocols assumed a scenario in which hosts would be pretty much static and non-moving. More specifically, the designers did not envision hosts moving from one routing location to another while an end-to-end connection (e.g., a file transfer) took place. Hence, if a host moves from one routing location to another, all TCP connections will be broken. This is compounded with the need to track the movement of the host so that subsequent datagrams can be forwarded to it.

The purpose of MIP 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 subnetworks by the IP community. Routers are used to connect subnetworks, which can be the same or of different design (e.g., ATM, Ethernet, or SATCOM).

Given that IP is a logical network that overlays physical networks, it is also possible to have two or more IP networks overlay the same physical network. This is a common practice with IP-over-Ethernet in that two sets of hosts are attached to the same Ethernet LAN. One set is assigned from the pool of 10.0.x.x IP addresses, while another set may be assigned from the pool of 198.116.x.x IP addresses. Even though the hosts from both sets are sending datagrams to the same physical network, they need a router to forward the traffic from one IP routing location (e.g., 10.0.x.x) to another location (e.g., 198.116.x.x).

Included in the above model is the association of identity and location within an IP address. IP routers distribute information about where groups of address prefixes are located in the virtual Internet. In addition, the entire IP address (e.g., 198.116.63.2) identifies the host and, more importantly, is used in identifying an end-to-end TCP connection.

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. MIP sidesteps this problem by using encapsulation. Figure 3-2 shows an abstract example of a correspondent host (CH) sending traffic to the home network of the MH. The data traffic is then encapsulated and sent to the current location of the MH. Return traffic is then sent from the MH to the CH. This flow of traffic is called triangle routing.

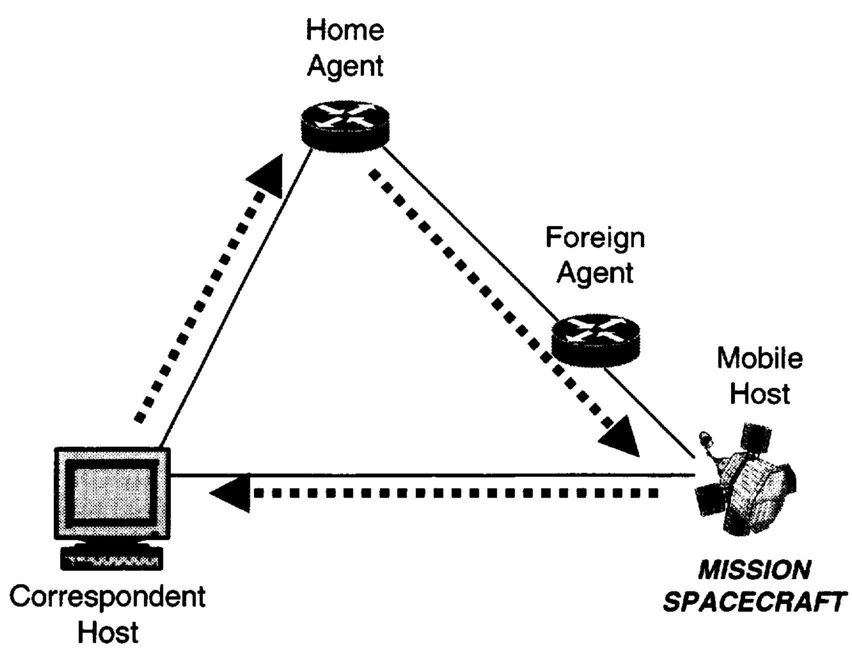

Figure 3-2. Example of a Correspondent Host Sending Traffic to the Home Network of the Mobile Host

The use of encapsulation allows the system to retain existing end-to-end connections as the MH moves to different locations. What is not shown in the figure is the discovery and registration process of the nodes (routers and hosts) used to update the current location of the MH. It is important that the speed by which a node moves to different locations does not eclipse the speed by which discovery and registration occur. Although there have been various simulation efforts concerning MIP, there has not been a definitive study as it relates to how fast an MH can travel. This is partly because the dynamics of where different nodes reside on the Internet together with various configuration parameters are hard to pin down. In addition, when an MH moves, there is the possibility that some IP traffic will be lost because it has been sent to the old location. This means that it will have to be retransmitted, and TCP will re-enter its slow start algorithm.

In an attempt to produce an abstract rough order of magnitude, we attempt to characterize the maximum speed of an MH as the following:

$$Max\ Speed < (0.33\ seconds) + RTT(MH \leftrightarrow FA) + RTT(FA \leftrightarrow HA) + 2*RTT(CH \leftrightarrow MH)$$

where,

RTT	=	Round Trip Time between two IP nodes (host or router)
FA	=	Foreign Agent
HA	=	Home Agent
MH	=	Mobile Host
CH	=	Correspondent Host.

We decide on the above values based on the following. Discovery messages are sent on a periodic basis based on one-third of the lifetime field. The minimal value of this field is 1 second; thus the shortest period of time in which a node can receive an advertisement message is 0.33 seconds.

From this discovery, the MH sends a registration message to the FA, which in turn triggers a registration from the FA to the HA. We include the time it takes for two RTTs between the CH and the MH so that a possible retransmission message can be sent with additional traffic from either the CH or the MH. Again, we need to stress that the above is just a rough approximation that provides a minimum bound for establishing MIP-based connectivity. The important conclusion from the above is that, with minutes of contact time between a ground station and the payload, MIP can be configured to support the discovery and tracking of LEO satellites acting as MHs.

3.2.2 Vendor Support

A number of major vendors such as Cisco, Nokia, and Nortel are actively involved in the design and development of MIP. However, their full participation in terms of a number of COTS products being currently available is small or non-existent. This is an economic issue but can probably be traced to a lack of public demand. One interesting item to note is Sprint's plan to become an MIP provider.

3.3 Full-Duplex Channel Requirements

TCP/IP requires a full-duplex channel. For a basic application such as file transfer, all the data travels in one direction, and the other direction serves to carry only acknowledgments. In this discussion we will assume this case. There is a simplified theoretical formula for calculating the data rate due to acknowledgments:

$$R = M \div 40$$

where,

R = Ratio of data bytes sent to acknowledgment bytes received
M = Maximum transmission unit (MTU) in bytes
40 = Size of an acknowledgment in bytes.

The MTU represents the maximum number of bytes that a *physical* network such as Ethernet can send as a unit or packet. The default MTU is 576 bytes. The typical MTU is 1,500 bytes, which is the size of an Ethernet packet. Note that at the Ethernet layer, the discussion is in terms of MTU, and at the TCP layer, the equivalent parameter is the maximum segment size. Optimum efficiency of packetization occurs when a single TCP segment fits exactly within a single physical network packet.

Theoretically, for TCP the MTU can be set to ([2**16]–40) = 65,496. Using this formula, we get 65,496/40 or 1,637.4:1. Hence, for every 64K byte packet sent, 40 bytes are needed in return. This is actually the worst case scenario because, as more packets are sent, acknowledgments can be sent less frequently. In the next pass, an acknowledgment can be sent for the next two packets that were sent—that is, the sliding window takes effect.

However, the above formula only applies for the MTU of an end-to-end path. When communicating from an arbitrary location on the Internet, the *actual* MTU used in the above equation is the smallest MTU that exists along the path between a user and the payload. One can expect that this will be 1,500, with a worst case of 576. For M=1,500, the result is R = 38:1.

This discussion is significant for the case where a direct downlink occurs at the same physical location where the end-user PI is located. In this case, the PI and the earth station can be on the same physical network, where the MTU can be set at a known maximum value to optimize the value of R. This would allow a lower uplink data rate to be used and a lower terminal EIRP. When the earth station is not at the same location as the end-user, the end-user has no control over the MTU, and the worst case must be assumed. A higher uplink data rate would then be required. Alternatively, the network could be partitioned, as discussed in Section 2.1, and the MTU could be controlled within the partition.

To confirm actual TCP behavior, SAIC ran a series of OPNET simulations of a simple TCP connection operating at 622 Mbps and assuming a bit error rate (at the TCP layer) of 10E-12 to determine what data rate would be required for the acknowledgment traffic. The assumptions used in the simulations are shown in Table 3-1.

Table 3-1. OPNET Simulation Assumptions

OPNET Scenario Settings	
Client-Server Separation	2,340 km (fixed)
User Channel Bit Error Rate	10E-12 (gaussian distributed noise)
Physical Channel Data Rate	622 Mbps
Packet Generation Statistics	Deterministic, Constant Rate
TCP Parameter Settings	
Maximum Segment Size (bytes)	Various: 8K-40 to 64K-40
Receive Butter (bytes)	Various: n x 64K
Receive Buffer Usage Threshold (of RCV BUFF)	0.0 (OPNET default)
Delayed ACK Mechanism	Segment/Clock Based (OPNET default)
Maximum ACK Delay (sec)	0.200 (OPNET default)
Fast Retransmit	Enabled (OPNET default)
Fast Recovery	Enabled (OPNET default)
Window Scaling	Enabled
Selective ACK (SACK)	Disabled (OPNET default)
Nagle's SWA Avoidance	Disabled (OPNET default)
Karn's Algorithm	Enabled (OPNET default)
Retransmission Threshold (sec)	Attempts Based (OPNET default)
Initial Retransmission Timeout (RTO) (sec)	1.0 (OPNET default)
Minimum RTO (sec)	0.5 (OPNET default)
Maximum RTO (sec)	64 (OPNET default)
RTT Gain	0.125 (OPNET default)
Deviation Gain	0.25 (OPNET default)
RTT Deviation Coefficient	4.0 (OPNET default)
Timer Granularity (sec)	0.5 (OPNET default)
Persistence Timeout (sec)	1.0 (OPNET default)
Output	Time to transfer 100 Mbyte file minus time to transfer 10 Mbyte file

The output of the simulation is the time to transmit a 100 MB file minus the time to transmit a 10 MB file. This gives the time to transmit a 90 MB file without the transient condition at the start of file transfer due to the slow start congestion algorithm. This allows one to calculate the average data rate during the steady state portion of the transmission. The results are shown in Table 3-2. The best time observed is 1.21 seconds. This corresponds to a data rate of 595 Mbps. The lowest data rate for the acknowledgment channel that allows for a 1.21 second transfer time is 256 Kbps. This particular simulation was run with a setting for the TCP maximum segment size of 65,496 octets, the maximum allowed, and a receive buffer (window) size of at least 32 times 65,536 octets (2.097152 MB), that is, a scale factor of 32 under the window scaling option. This means the receive buffer allocation must be set to at least 2,097,152 bytes in the TCP configuration file.

This simulation indicates that the ratio of the data packet data rate to the acknowledgment packet data rate can be as high as 2,324 under optimum conditions.

Table 3-2. OPNET Simulation Results

Max Segment Size	Receive Buffer Size (65536)	Return Channel Bandwidth (bits/sec)										
		2E+06	1E+06	512000	256000	128000	64000	32000	16000	8000	4000	2000
65496	x256	1.21	1.21	1.21	1.21	1.46	2.93	5.86	11.80	25.07	50.76	118.91
	x128	1.21	1.21	1.21	1.21	1.63	3.28	6.53	13.18	28.27	55.48	133.47
	x64	1.21	1.21	1.21	1.21	1.72	3.49	6.91	14.00	30.67	61.80	143.39
	x32	1.21	1.21	1.21	1.21	1.77	3.58	7.07	14.52	29.04	61.20	152.33
	x8	2.96	2.99	3.05	3.15	3.41	3.92	7.63	16.14	34.32	68.64	162.24
32728	x256	1.22	1.22	1.22	1.46	2.93	5.87	11.72	23.48	49.59	101.85	231.23
	x128	1.22	1.22	1.22	1.62	3.25	6.53	13.05	26.14	55.19	114.73	247.23
	x64	1.22	1.22	1.22	1.71	3.43	6.90	13.80	27.62	59.07	121.29	272.51
	x32	1.22	1.22	1.22	1.74	3.49	7.06	14.12	28.24	60.54	117.49	285.63
	x8	2.75	2.77	2.83	2.95	3.64	7.37	14.94	30.70	61.40	122.80	304.45
16344	x256	1.22	1.22	1.46	2.93	5.86	11.71	23.44	47.48	99.09	203.77	460.83
	x128	1.22	1.22	1.62	3.25	6.51	13.01	26.03	52.78	109.57	226.17	481.47
	x64	1.22	1.22	1.70	3.41	6.85	13.66	27.41	55.91	115.97	235.53	479.71
	x32	1.22	1.22	1.73	3.46	6.96	13.84	27.85	55.36	117.08	242.57	541.47
	x8	2.62	2.65	2.72	3.54	7.12	14.15	29.04	56.60	116.16	278.40	584.12
8152	x256	1.22	1.46	2.94	5.87	11.74	23.49	47.32	94.84	198.09	404.17	916.19
	x128	1.22	1.62	3.26	6.52	13.04	26.07	52.62	105.24	219.77	446.25	1012.83
	x64	1.22	1.70	3.42	6.84	13.68	27.41	55.41	111.12	232.29	466.89	1038.75
	x32	1.22	1.73	3.46	6.92	13.84	27.68	55.36	113.58	234.45	473.93	1056.83
	x8											

Forward channel 622Mbits/sec
One way delay 0.0078sec (each way)
Data Size 90MBytes

Note that for a file size of 90 MB and a bit error rate of 10E-12, the probability of a single error is very low. For larger files, the probability of an error increases. When an error occurs, an entire segment must be retransmitted. Because the segments are so large, this would result in a degradation of the average throughput. Thus, the very high ratio of 2,324 is obtained at the expense of degraded throughput for large files.

3.4 Link Layer

The Operating Missions as Nodes on the Internet (OMNI) project at 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. 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.

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. A spacecraft was selected that could support high-level data link control (HDLC) framing in hardware: the UoSAT-12. This framing was chosen for the link-level protocol on the space to ground link because of its near universal use in terrestrial networking. This allowed 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 simple mail transfer protocol (SMTP), were scheduled to be demonstrated in the latter part of year 2000.

The OMNI project results discuss the success and feasibility of exploiting the capabilities of the HDLC and provide examples of the HDLC/frame-relay/IP packet formats as successfully used in the experiment. The feasibility of using IP protocols aboard small LEO spacecraft appears to be very low risk [RASH].

4. RESULTS AND CONCLUSIONS

4.1 Comparison of Concepts

In this section, we summarize the results of our analysis by comparing the throughput and cost estimates that were derived for each concept. The throughput comparison is shown in Tables 4-1 and 4-2, and the cost comparison is shown in Table 4-3.

Table 4-1. Throughput Comparison, ISS Orbit

	TDRSS SA, Ku Band	D4 Single Beam	D4 Dual Beam	Hybrid	Dual Mode	Commercial X-Band Downlink Service	Commercial X-Band Downlink Service	Commercial MSS NGSO StarLynx
Antenna beam scan (°)		50	42	50	50	50	70*	
Return link data rate (Mbps)	50	622	1,244	622	622	300	300	8
Data transfer time relative to OC12	12	1	0.5	1	1	2	2	78
Average contact time per day (sec)	43,200	337	178	337	337	337	2,755	69,120
Throughput per day (Gbits)	2,160	210	221	210	210	101	827	553

*Spacecraft antenna scan angle needed to match earth station with a 5° elevation angle
Note: Earth station located at KI Sawyer AFB

Table 4-2. Throughput Comparison, Polar Orbit

	TDRSS SA, Ku Band	D4 Single Beam	D4 Dual Beam	Hybrid	Dual Mode	Commercial X-Band Downlink Service	Commercial X-Band Downlink Service
Antenna beam scan (°)		50	42	50	50	50	64*
Return link data rate (Mbps)	150	622	1,244	622	622	300	300
Data transfer time relative to OC12	4	1	0.5	1	1	2	2
Average contact time per day (sec)	3,600 nominal	1,681	1,046	1,681	1,681	1,681	7,727
Throughput per day (Gbits)	540	1,046	1,301	1,046	1,046	504	2,318

*Spacecraft antenna scan angle needed to match earth station with a 5° elevation angle
Note: Earth station located at Spitzbergen

Table 4-3. Cost Comparison

	Commercial Terrestrial OC12	Commercial MSS GSO Inmarsat	Commercial MSS NGSO StarLynx	Commercial X-Band Downlink Service*	TDRSS SA, Ku-Band	TDRSS MA, S-Band	D4 Single Beam	D4 Dual Beam
Data rate (Mbps)	622	0.064	8	300	150	0.1	622	1,244
Cost per minute	\$0.18–\$0.72	\$1–\$7	\$0.024–\$0.096	\$5–\$15	\$18–\$200	\$1.29–\$13	\$5–\$15**	\$7–\$22
Cost per Gbit	\$0.005–\$0.019	\$260–\$1,820	\$0.05–\$0.20	\$0.28–\$0.83	\$2–\$22	\$215–\$2,167	\$0.13–\$0.40	\$0.09–\$0.29

*Add \$150,000 set-up charge per mission
**Cost estimated based on commercial X-band service

4.2 Conclusions

For a layered communications architecture model, the distinguishing characteristics of the end-to-end system concepts reside primarily at the physical layer and link layer. We therefore studied a set of alternative link layer architectures. These consisted of two basic architectures, direct and relay, and combinations of these. The combinations may be constructed to achieve the different scenarios described in the Statement of Work. These two basic architectures were analyzed separately in terms of three fundamental metrics: contact time, throughput, and cost. The other architectures can be characterized in terms of the metrics of two basic ones.

4.2.1 Direct Architecture

The asymmetric full duplex direct link architecture using TCP/IP is feasible using the D3 millimeter wave downlink system developed by NASA GRC augmented by an uplink system with a very modest data rate requirement. The need for a duplex link is driven by the requirement for using TCP.

The throughput of the D4 system can be increased roughly in linear proportion by deploying earth stations at multiple sites. There is no apparent technical obstacle to maintaining a virtual link connection as a spacecraft passes between contiguous earth station coverage regions. Gaps between the regions may also be tolerated as long as the gap in time does not exceed the TCP timeout parameter.

The optimum D4 earth station locations are a function of mission specifics. They depend on the mission's specific output requirement, the degree of latency that can be tolerated, and the orbital inclination, among other things. For a given mission, the optimum location is close to the highest latitude of the spacecraft ground track.

Distributions of stations within the continental United States for serving a mission, such as the ISS, were studied, and a relatively small number of stations, such as four, can provide almost full continental coverage. We did not attempt to find the best locations for global coverage.

For the ISS case, Table 4-1 shows that a network of approximately 10 D4 earth stations could achieve the same daily throughput as TDRSS under the assumptions shown. The cost table, Table 4-3, shows that this could be accomplished at a significantly lower per-minute cost and per-bit cost. Note, however, that the cost picture is complicated by the one-time set-up charge of $150,000 per mission that is a feature of current commercial LEO services. This cost would presumably decline as the number of missions using the service increases.

Comparing the D4 system with the existing X-band technology, the D4 system obviously has higher throughput when compared with an equivalent X-band system having the same antenna scan angles. However, the existing X-band terminals, including NASA's Earth Observing System (EOS) polar ground stations, have scan angles of 5° elevation above the horizon. When operating with a spacecraft antenna that can match the earth station scan, a much higher throughput can be achieved. This result is represented in column 8 of Table 4-1.

For the polar case, Table 4-2 shows that the throughput improves by a factor of 5 due to the higher frequency of contacts. The comparison with TDRSS, therefore, is more favorable. The comparison with the X-band earth stations again depends on the scan angle that is assumed.

The D4 system would be especially efficient in serving polar missions because one or two earth stations near the pole can obtain a high amount of contact time, as well as a high frequency of contacts. The utility of polar sites is further multiplied by the fact that most high data rate LEO missions are polar orbiters.

As the results show, the throughput per earth station can be substantially improved by extending the angle that the ground and spacecraft antennas can scan. Because contact time is a non-linear function of scan angle, a relatively modest increase in scan angle can provide a large increase in contact time. However, this benefit must be traded against the need for increased spacecraft EIRP to compensate for the increased slant range.

4.2.2 Relay Architecture

A D4 direct link system could be supplemented by a space relay link system. We assessed commercial satellite communications technologies and concluded that there are no services that meet the minimum criteria for a Ka-band, broadband MSS for NASA LEO/MEO mission platforms within the next 5 years. In the longer term, many MEO systems have been proposed that would improve the coverage to global or near-global coverage. However, most of these systems will be FSS. There is also uncertainty about the likelihood of deploying these systems.

One proposed system, Hughes StarLynx, meets all of the criteria except that it will not be available by 2005. It is an MSS, operates at V-band, and has both GEO and MEO constellations. The 8 Mbps data rate is relatively low, using the 2-foot diameter VSAT terminals to be designed for the typical user. The low data rate is compensated for by the essentially global coverage. It seems likely that higher data rates would be available should the service ever be deployed. However, we consider the likelihood of deployment to be low.

In estimating costs, it was found that the broadband satellite services will be priced competitively with terrestrial services so that, for a given data rate, the cost per bit should be roughly comparable. However, as in terrestrial services, there will be a steep discounting curve as a function of data rate.

4.2.3 Hybrid and Combination Architectures

Two other architectures were described: the hybrid and combination architectures. The hybrid architecture consists of a direct downlink using the D3 system and a space relay service for transporting the TCP acknowledgments back to the spacecraft. This architecture makes sense for spacecraft carrying a TDRSS S-band transceiver, for example. The acknowledgments could be carried by the S-band link.

Among the possible combined architectures, one stands out as effective and practical. This is a "dual-mode" combination of a simplex high data rate direct downlink, using UDP instead of TCP, combined with a low data rate, full duplex TCP/IP link using a SATCOM service such as Inmarsat or TDRSS MA. The high data rate link would be used for returning latency-tolerant instrument data from the spacecraft. The low data rate link would be used for real-time interactive commands between the PI and the spacecraft.

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LIST OF ABBREVIATIONS

ACK	Acknowledgment
AFB	Air Force Base
ATM	Asynchronous transfer mode
BSS	Broadcast Satellite Service
CEO	Chief Executive Officer
CH	Correspondent host
CONUS	Continental United States
COTS	Commercial off-the-shelf
D3	Direct Data Distribution
D4	Duplex Direct Data Distribution
DARO	Defense Airborne Reconnaissance Office
DBS	Direct Broadcast Satellite
DNS	Domain Name Service
EESS	Earth exploration satellite service
EHF	Extremely high frequency
EIRP	Equivalent Isotropic Radiated Power
EOS	Earth Observing System
FA	Foreign Agent
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDP	Forward Data Path
FSS	Fixed Satellite Service
GEO	Geosynchronous orbit
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
GSO	Geostationary orbit
HA	Home Agent
HCI	Hughes Communication Inc.
HDLC	High-level data link control
ICMP	Internet Control Message Protocol
IOA	Integrated Operations Architecture
IP	Internet Protocol
ISL	Inter-satellite link
ISP	Internet service provider
ISS	International Space Station
ITU	International Telecommunications Union

LAN	Local area network
LEO	Low earth orbit
MEO	Medium earth orbit
MH	Mobile Host
MIP	Mobile IP
MSS	Mobile Satellite Service
MTU	Maximum transmission unit
NASA	National Aeronautics and Space Administration
NGSO	Non-geostationary orbit
NTIA	National Telecommunications and Information Administration
OMNI	Operating Missions as Nodes on the Internet
OSI	Open Systems Interconnect
PI	Principal investigator
RDP	Return Data Path
RDSS	Radio-determination satellite service
RF	Radio frequency
RTO	Retransmission timeout
RTT	Round trip time
SACK	Selective acknowledgment
SAIC	Science Applications International Corporation
SATCOM	Satellite communication
SCPS	Satellite Communications Protocol Standards
SCPS-TP	SCPS Transport Protocol
SMTP	Simple mail transfer protocol
S-NACK	Selective negative acknowledgment
SOS	Space Operations Service
SRS	Space Research Service
STK	Satellite Tool Kit
TCP	Transmission Control Protocol
TDRSS	Tracking and Data Relay Satellite System
TT&C	Telemetry, Tracking, and Command
UAV	Unmanned aerial vehicle
UDP	User Datagram Protocol
USN	Universal Space Network
VSAT	Very small aperture terminal
WAN	Wide area network

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13. ABSTRACT ***(Maximum 200 words)***

The NASA Glenn Research Center (GRC) is developing and demonstrating communications and network technologies that are helping to enable the near-Earth space Internet. GRC envisions several service categories. The first of these categories is direct data distribution or D3 (pronounced "D-cubed"). Commercially provided D3 will make it possible to download a data set from a spacecraft, like the International Space Station, as easily as one can extract a file from a remote server today, using a file transfer protocol. In a second category, NASA spacecraft will make use of commercial satellite communication (SATCOM) systems. Some of those services will come from purchasing time on unused transponders that cover landmasses. While it is likely there will be gaps in service coverage, Internet services should be available using these systems. This report addresses alternative methods of implementing a full duplex enhancement of the GRC developed experimental Ka-Band Direct Data Distribution (D3) space-to-ground communication link. The resulting duplex version is called the Duplex Direct Data Distribution (D4) system. The D4 system is intended to provide high-data-rate commercial direct or internet-based communications service between the NASA spacecraft in low earth orbit (LEO) and the respective principal investigators associated with these spacecraft. Candidate commercial services were assessed regarding their near-term potential to meet NASA requirements. Candidates included Ka-band and V-band geostationary orbit and nongeostationary orbit satellite relay services and direct downlink ("LEO teleport") services. End-to-end systems concepts were examined and characterized in terms of alternative link layer architectures. Alternatives included a Direct Link, a Relay Link, a Hybrid Link, and a Dual Mode Link. The direct link assessment examined sample ground terminal placements and antenna angle issues. The SATCOM-based alternatives examined existing or proposed commercial SATCOM services that could be available in the 2005 time frame. The alternatives were evaluated and compared in terms of average daily system throughput and cost per bit. Throughput was estimated based on hypothetical scenarios supporting the International Space Station and polar orbiting missions. The feasibility of using standard TCP and a modified TCP was evaluated and risks were identified. An estimate of the TCP acknowledgment data rate required to support a return channel rate of 622 Mbps was developed using OPNET.

14. SUBJECT TERMS
Direct data distribution; Duplex direct data distribution; Space communications; Space-to-ground communications; Broadband communications; Ka Band; Phased array; Commercialization; Commercial communications services; Miniature autonomous ground terminal; SATCOM; Space protocols; TCP; Mobile IP; In-space Internet

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