Small Satellite Access of the Space Network

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Small satellites have been perceived as having limited access to NASA's Space Network (SN). The potential for satellite access of the space network when the design utilizes a fixed antenna configuration and low-power, coded transmission is analyzed. From the analysis, satellites using this configuration in high-inclination orbits are shown to have a daily data throughput in the 100 to 1000 Mbit range using the multiple access communications service.

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INTRODUCTION

There is considerable interest at this time in developing small satellites for quick-turnaround missions to investigate near-Earth phenomena from space; see, for example [1]. One problem to be solved in mission planning is the means of communications between the control infrastructure in the ground segment and the satellite in the space segment. A nominal small-satellite mission design often includes an omni-directional or similar wide-pattern antenna on the satellite and a dedicated ground station for telemetry, tracking, and command support. These terminals typically provide up to 15 min of coverage during an orbit that is within the visibility of the ground station; however, not all orbits will pass over the ground station so that coverage gaps will exist in the data flow. To overcome this general limitation on data transmission for low-Earth-orbiting satellites, the Space Network (SN), operated by the National Aeronautics and Space Administration, has been designed to transmit data to and from user satellites through the tracking and data relay satellites (TDRS) in geostationary orbit and interfacing to the White Sands Complex (WSC) in New Mexico for the data ground entry point. The advantage of the SN over a fixed ground station is that all low-Earth-satellite orbits will be within the visibility area of at least one TDRS within the SN for a large part of the orbit and the potential exists to establish a communications link if the user satellite can point an antenna in the direction of any one of the relay satellites. Small satellite users have not often considered using the SN because of perceived problems in scheduling communications and the cost in weight and power to use gimbaled, directional antennas for the communications support. This work addresses the potential for SN access using nongimbaled antennas in the design of the small satellite using modest transmission power to achieve the necessary space-to-ground transmissions. The advantage of using the SN is in the reduction of mission costs arising from using the SN infrastructure instead of a dedicated, proprietary ground station using a similar type of communications package. From the simulations and analysis presented, we show that a modest satellite configuration can be used with the space network to achieve the data transmission goals of a number of users and thereby rival the performance achieved with proprietary ground stations. In this study, we concentrate on the return data link (from the user satellite through a TDRS to the ground data entry point). The forward command link (from the ground data entry point through a TDRS to the user satellite) will usually be a lower data rate service and the data volume will also be considerably lower than the requirements of the return link. Therefore, we assume that if the return

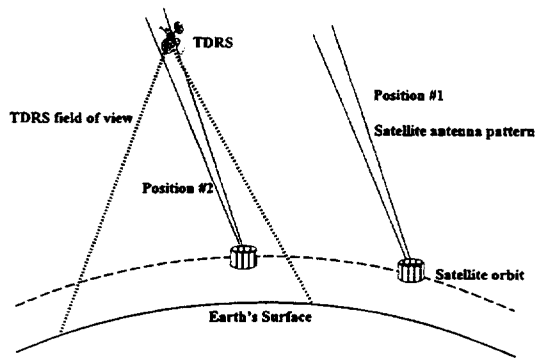

Fig. 1. TDRS-to-satellite access geometry. In position 1, no access between TDRS and user satellite. In position 2, access is possible.

link requirements are satisfied, then the forward link requirements can also be satisfied.

For the conceptual design of a small satellite system, we make the following assumptions.

1) The communications subsystem is able to supply an output power of 10 W.

2) The antenna system can provide a gain of at least 5 dB over internal losses, pointing losses, polarization losses, etc.

3) The satellite is spin stabilized with the long axis of the spacecraft lying along the radial vector connecting the satellite with the center of the Earth.

4) The antenna system is surface mounted on the satellite along a radial vector connecting the satellite with the center of the Earth and pointing towards the local zenith and away from the center of the Earth.

5) Communications contact between the satellite and the SN can be initiated as the satellite sweeps past a TDRS position in its orbit as illustrated in Fig. 1.

6) An SN S-band multiple-access (SMA) service can be used for the communications link. This implies that the TDRS antenna is capable of tracking the satellite using open-loop techniques.

For the purposes of this study, we assume that the SN is composed of three active TDRS located at $-174°$, $-41°$, and $+85°$ longitude and denoted as TDRS-West, TDRS-East, and TDRS-Z, respectively. Each TDRS can support K-band and S-band single-access communications and SMA communications [2]. The choice of the TDRS to be used on a given data service depends on the relative satellite positions, the availability of communications links, and the requested service duration. The data link between the SN and the ground communications networks is run through the WSC facility which interfaces with the user satellite's control center utilizing NASA's communications links. Presently, the SMA service has the greatest probability of availability to the small satellite user so it is used in the data throughput analysis. The SMA service uses code division multiplexing with each user having a return carrier frequency of 2287.5 MHz. This investigation looks at two possible SN access modes: a single TDRS is available to support access and the possibility of using the full constellation of three operational TDRS spacecraft forming the full SN constellation.

In this study, we use the commercially available simulation package Satellite Tool Kit [3] to simulate the orbits of a spin-stabilized satellite and the three TDRS satellites over a 30 day period to determine the access potential. Associated with the access information is the determination of the slant path between the spin-stabilized satellite and each TDRS. This information is used to determine the data rate that can be supported given the transmitted power and antenna gain. We do not attempt to compare the expected data throughput with a general ground station because that would be a function of the ground station antenna size and receiver electronics both of which can be varied over a wide range.

BASELINE ANTENNA DESIGN

In order for the concept of using the SN for communications support to be effective, we assume that sufficient transmission power can be obtained from the communications system in the direction of the SN without steering the antenna. A simple method to accomplish this is to have a fairly nondirectional antenna system, i.e., one with a large half-power beamwidth (HPBW). The tradeoff for a large HPBW is a low gain for the system thereby giving a low effective isotropic radiated power (EIRP). In this study, we are assuming that a helical antenna is available to supply all of the transmission and reception gain. For typical helical antennas, the HPBW and directivity D may be computed by using the relationships [4]

$$\mathrm{HPBW} = \frac{52°}{(C/\lambda)\sqrt{N(S/\lambda)}}$$

$$D = 15\left(\frac{C}{\lambda}\right)^2 \frac{NS}{\lambda}$$

where C is the helix circumference, N is the number of turns, S is the spacing of the turns ($S = C\tan(\alpha)$), and λ is the radiation wavelength. Following [4], C was fixed at 0.92 λ (the λ corresponded to that of the return service frequency through the SN), and the pitch angle α was set to 13° in this analysis. Based on [4], the antenna gain is taken to be the computed antenna directivity value. Table I lists available HPBW and gains for helix antennas that might be used with the SN S-band return frequencies. Based on these results, our assumed minimum EIRP for the study should be achievable with this technology. The HPBW is used to determine an important parameter in the orbital analysis of the next section. We use the HPBW

TABLE I
Theoretical Helical Antenna Performance

Number of Turns	Gain (dB)	HPBW
3	9.1	71°
5	11.3	55°
10	14.3	39°
21	17.5	27°

to constrain the maximum pointing angle between the spin-stabilized satellite and each TDRS. The maximum value of this pointing angle is taken to be one-half of the antenna HPBW in the communications system. That is, we assume that a contact between a satellite and a given TDRS begins or ends at those points along the orbit of the satellite where the boresight pointing angle between the satellite and the TDRS is equal to one-half of the HPBW angle. When the pointing angle is greater than this, we assume that there is insufficient power to close the communications link and no communications will be attempted. Whenever the pointing angle is less than one-half of the HPBW, then it is assumed that there is sufficient link power for the communications link between the satellite and the TDRS and a return link will be possible. In the simulations, this pointing angle between the satellite and the TDRS will be computed at each moment to determine the potential for a return link.

DETERMINING ORBITAL ACCESS

To determine if using the space network can be an effective alternative to the fixed ground station model we first need to determine the access potential for a simple satellite communications system. The computer simulation package Satellite Tool Kit was used to predict the three-dimensional positions of all three TDRS and a spin-stabilized satellite with a zenith-pointing antenna which is taken to be an appropriate analog for small satellite designers. For this study, the mean orbital elements for the TDRS positions were taken from [5] and are listed in Table II. Satellite Tool Kit propagates the orbital elements over the 30 day period for each satellite to account for the perturbations caused by the variations in the gravitational field of the Earth.

TABLE III
Sun-Synchronous Orbital Inclination Angle as Function of Orbital Altitude

Altitude (km)	Inclination Angle (degrees)
600	97.8
700	98.2
800	98.6
900	99.0
1000	99.5
1100	99.9
1200	100.4

A set of simulations was run in which the spin-stabilized satellite was given orbital elements corresponding to an orbital altitude between 600 km and 1200 km. The orbital inclination angle for the set of simulations was varied from 0° through 100°. Two commonly used orbital inclination angles from this set are reported here: 28.5° and sun-synchronous. The other orbital elements for the spin-stabilized satellite, Right Ascension of Ascending Node, Argument of Perigee, and Mean Anomaly, were set to 0° since we were not interested in predicting an exact position of a real satellite but determine general access characteristics. The orbital inclination angle i for a sun-synchronous orbit is a function of the orbital altitude and is given by [6]

$$i = \cos^{-1}\left[\frac{0.9856^\circ/\text{day}}{-(3/2)J_2\sqrt{\frac{\mu}{(R+h)^3}}\left[\frac{R}{(1-e^2)(R+h)}\right]^2}\right].$$

Here, R is the radius of the Earth, h is the mean orbital height, J_2 is the second-order gravitational zonal harmonic coefficient, e is the orbital eccentricity (assumed to be 0), and μ is the product of the universal gravitational constant and the mass of the Earth. Table III gives the sun-synchronous orbital inclination angle as a function of orbital altitude.

Satellite Tool Kit treats antennas as "sensor objects" in the simulation having an associated field of view for determining visibility and access. Each sensor object has a conic field-of-view with a half angle and a positioning direction defined relative to the satellite. For each TDRS, the SMA antenna

TABLE II
Tracking and Data Relay Satellite Orbital Elements

Element	TDRS East	TDRS West	TDRS-Z
eccentricity	0.0003746	0.00003342	0.000555
right ascension of the ascending node	86.2181°	93.3433°	70.5384°
argument of perigee	216.5846°	243.3013°	221.1338°
mean anomaly	324.2369°	186.8302°	184.2067°
mean motion (rev/day)	1.00266752	1.00272053	1.00270378
inclination angle	0.3747°	0.0373°	2.9472°
epoch (1997)	46.4517419	48.52874914	34.71312596

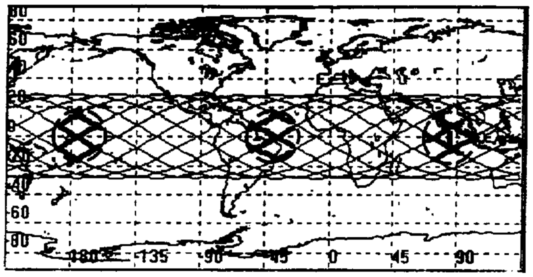

Fig. 2. Simulated 24 h ground track for spinning-satellite contact with SN. Highlighted areas within circles along ground track near TDRS positions at −174°, −41°, +85° longitude show times when contact possible.

was defined to have a field-of-view half-angle of 13° and an initial positioning direction towards the center of the Earth. The spin-stabilized satellite was given a fixed antenna pointing towards the local zenith and the field-of-view half-angle of the antenna was varied according to which antenna HPBW was being simulated. In the simulations, an access of a TDRS by the spin-stabilized satellite occurs when the field-of-view computation shows that both antenna systems are mutually visible as illustrated in Fig. 1. The simulation analysis recorded the start and stop time of each access period between the spin-stabilized satellite and each TDRS, the pointing angles, and the slant range between the satellites.

The following sections discuss the results obtained by this analysis.

ORBITAL ANGULAR COVERAGE

Using the simulations with the orbital characteristics described above, we can investigate when there is a possibility for SN coverage under the constraint that a spin-stabilized satellite has no active positioning mechanism for the antenna. Rather, the satellite relies on its communications antenna sweeping past each of the TDRS locations within the SN to provide the contact opportunity. For the simulation parameters mentioned above, it was found that there was no time interval when more than one TDRS satellite location was simultaneously visible from the spin-stabilized satellite. It was also found that each of the three TDRS locations had similar results when averaged over the 30 day simulation period so only the results for TDRS-West, at −174° longitude, are given here when discussing the results for a single TDRS. Fig. 2 illustrates a 24 h segment of the simulations using a 28.5° orbital inclination angle, a 600 km orbital altitude, and a 20° half-angle for the spin-stabilized satellite's antenna field-of-view. Highlighted positions within the circles centered on each TDRS position show the opportunities along the spin-stabilized satellite's ground track when the satellite can access each TDRS. If the ground tracks were shown for the full 30 day simulation period on a single plot, then the entirety of the circles would be filled by these highlighted regions along the spin-stabilized satellite's ground track.

The orbital inclination angle and the antenna field-of-view of the spin-stabilized satellite control the contact durations and the number of contacts per day between that satellite and each TDRS. For the orbital altitudes considered here, the altitude does not affect the results to the same extent that the other parameters do. If the spin-stabilized satellite had an orbital inclination angle of 0°, then the simulations show that there would be a contact with each TDRS as the satellite swept under the TDRS subsatellite points and each contact would have a duration as determined by the antenna HPBW. As the orbital inclination angle grows, the simulation results show that the total number of contacts per day drops and not every orbit always receives a contact possibility. In the inclined-orbit cases, a maximal-length contact, limited only by the antenna HPBW, occurs for those orbits where either the orbital ascending node or descending node lies near the TDRS subsatellite point. Other orbits have contacts of shorter duration with polar orbits having the fewest contacts and shortest average contact duration. Figs. 3–6 summarize the simulation results for the number of contacts and contact duration as averaged over the 30 day simulation periods. Each figure shows the results over the 600 through 1200 km orbital altitude range considered. Each figure is for a single orbital inclination angle and antenna field-of-view combination. The plots illustrate the average number of daily contacts through both a single TDRS and the three-TDRS constellation, the average contact duration with a single TDRS, and the total average daily contact time through both a single TDRS and the constellation. Fig. 3 illustrates the results for the case of a 28.5° orbital inclination and a 20° half-angle for the antenna field-of-view on the spin-stabilized satellite. Here, we find that the typical orbit will provide five contacts per day, each having an average duration of 8 min yielding a total daily contact time of 40 min. The entire SN constellation would provide approximately 15 contacts per day at 8 min per contact giving a total contact time of 120 min. Fig. 4 illustrates the results for a 45° antenna half-angle at a 28.5° orbital inclination angle, Fig. 5 uses a 20° antenna half-angle and a sun-synchronous orbital inclination angle, and Fig. 6 uses a 45° antenna half-angle and a sun-synchronous orbital inclination angle. The contact information for each individual TDRS is similar to that of a low-Earth-orbit satellite accessing a fixed ground station. For example, using the same simulation software, we find that a satellite in a 900 km altitude orbit communicating with a fixed ground station at 32.5° N would typically have 6.7 contacts per day with an average duration of 14.6 min for a total contact time of 98 min when the orbital inclination angle is 28.5°. When the orbit is sun-synchronous, the same satellite and ground

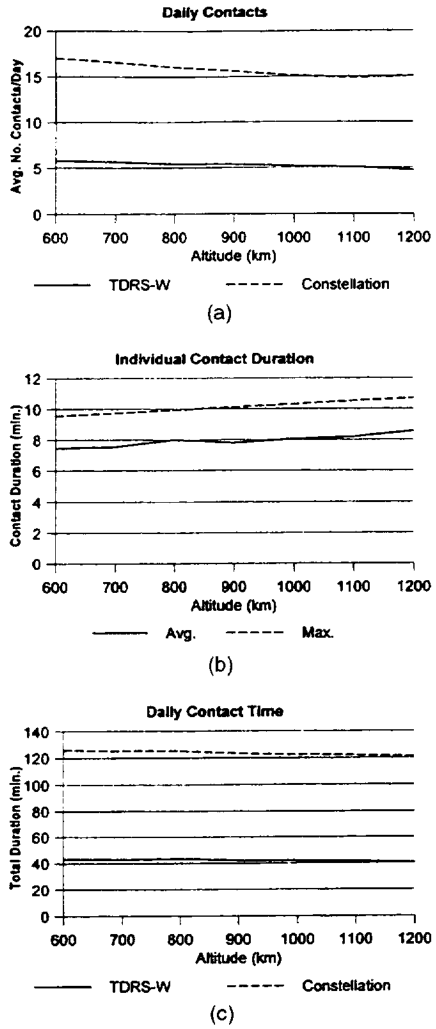

Fig. 3. Simulated number of (a) contacts per day, (b) single-TDRS contact duration, and (c) total daily contact time for 28° orbital inclination and 20° pointing cone half-angle.

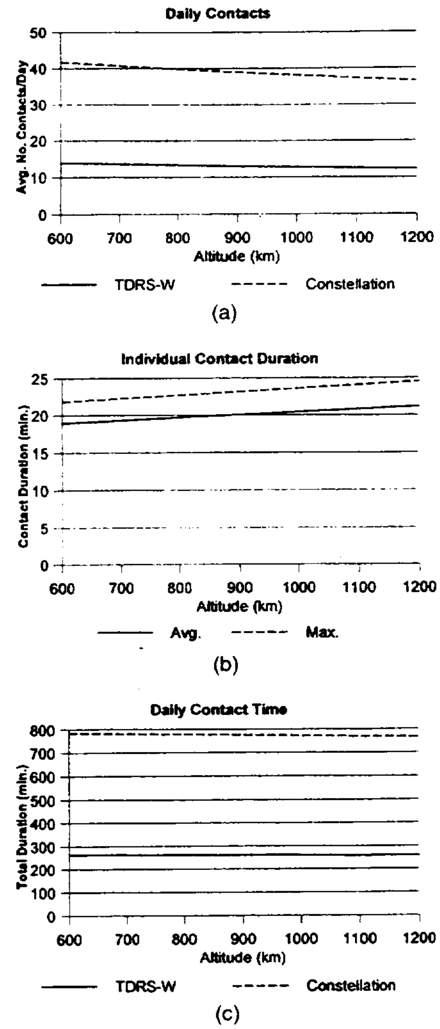

Fig. 4. Simulated number of (a) contacts per day, (b) single-TDRS contact duration, and (c) total daily contact time for 28° orbital inclination and 45° pointing cone half-angle.

station configuration would have 5.5 contacts per day at 13 min per contact for a total contact time of 71.5 min. In this simulation study, we find that the SN constellation acts like a network of three fixed-location ground stations spread around the surface of the Earth. From the simulation studies, we can conclude that small orbital inclination angles or large antenna HPBW angles are needed to have large numbers of contact minutes per orbit and a large number of orbits per day on which a contact occurs. The penalty for having a fixed antenna or narrow HPBW angle is seen in the results illustrated in Figs. 3–6 because some orbits have no contact time. However, this is similar to transmitting data to a single, fixed ground station where the contacts are clustered in two groups occurring twice each day.

The HPBW of the fixed antenna restricts total access since orbits can have times where no SN access is possible due to the angle between the simulated spin-stabilized satellite position and the relay satellites exceeding the HPBW angle. The short contact times and few number of contacts for a narrow antenna field-of-view is least at lower inclination angles and is worst at 90 deg inclination angles. For inclined orbits, the mitigation for the low total contact duration per day is to increase the antenna HPBW. For the 45 deg half-angle case, there are many instances where, on a given orbit, only one of the three TDRS satellites is visible while on the next orbit, a different TDRS is visible. Therefore, for the wide antenna HPBW case, there are relatively few orbits when at least one of the TDRS cannot be scheduled for short periods based on a visibility restriction.

The visibility needs to be balanced with the data rate support available with the different antenna gains. An antenna with a narrow HPBW will have a higher antenna gain than an antenna with a wider HPBW. The former antenna will be able to support a higher data rate with the same data quality. Therefore, the overall data throughput will be a function of both the contact duration and the data rate. In the next section, we look at the throughput that is available based on

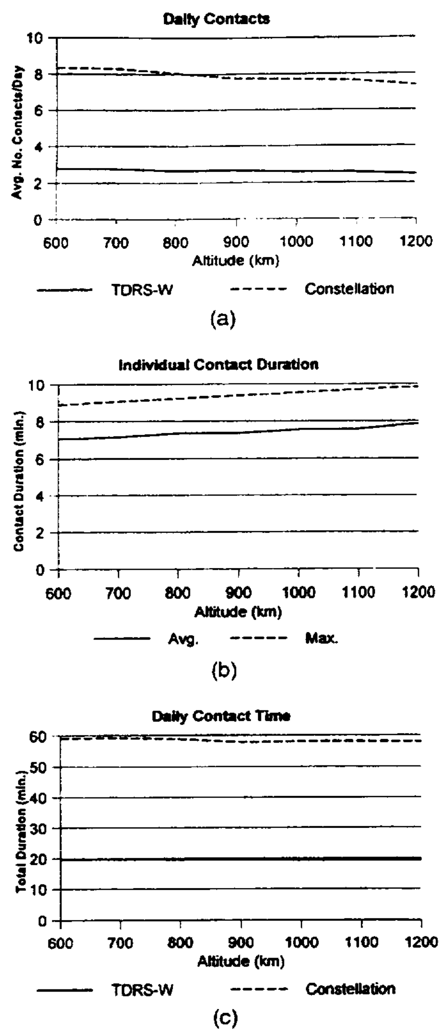

Fig. 5. Simulated number of (a) contacts per day, (b) single-TDRS contact duration, and (c) total daily contact time for sun-synchronous orbital inclination and 20° pointing cone angle.

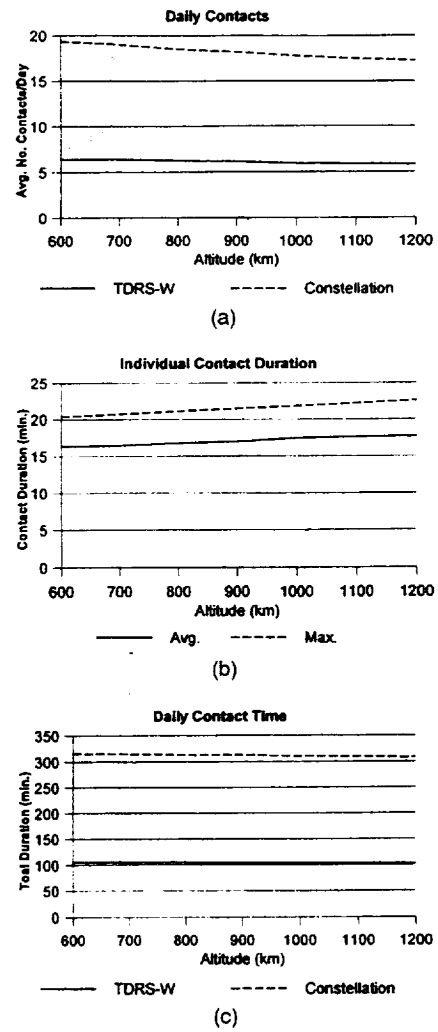

Fig. 6. Simulated number of (a) contacts per day, (b) single-TDRS contact duration, and (c) total daily contact time for sun-synchronous orbital inclination and 45° pointing cone half-angle.

both the access time and the data rate that can be supported.

EXPECTED DATA RATE SUPPORT

Once the slant path is found from the simulations, the expected maximum data rate that can be supported is determined. Based on design information given in [2], the expected data rate R_d for a TDRS SMA service can be computed from

$$R_d(\text{dBbit/s}) = \text{EIRP} - M + K + L_s + L_{pol} + L_{pnt} + L_{nc} + L_{rfi} \quad (1)$$

where M is the link margin, L_s is the space loss, L_{pol} is the antenna polarization loss, L_{pnt} is the antenna pointing loss, L_{nc} is the system noncompliance loss, and L_{rfi} is the RFI margin (all losses and margins are in dB units). The units on the data rate are $10\log(\text{bit/s})$ or dBbit/s. The constant K is a service-specific parameter and equals 221.8 dB for an SN multiple access service with a worst case bit error rate of 10^{-5} when the data are convolutionally coded with a standard rate $\frac{1}{2}$ and constraint length 7 code (this is a standard NASA communications configuration when using the SN). To determine the maximum transmission rate possible, we would assume that the link margin and the polarization, pointing, noncompliance, and RFI losses are 0 dB. The space loss is estimated using [2]

$$Ls(\text{dB}) = -(32.45 + 20\log(R) + 20\log(f)) \quad (2)$$

where R is the slant range in kilometers and f is the multiple access transmission frequency of 2287.5 MHz. The link margin M is taken to be at most 3 dB corresponding to the maximum margin required within the antenna HPBW. Naturally, if the system designer is able to supply a larger margin, then the contact duration can be extended to the limit of the useful margin provided in the design. The extent of the larger contact region can be determined

TABLE IV
SN Available Data Rates as Function of EIRP and Slant Range With 0 dB Link Margin and 0 dB Implementation Loss

Slant Range (km)	Data Rate (bps) EIRP = 15 dBW	EIRP = 19.3 dBW
35000	42476	114325
35200	41995	113030
35500	41288	111127
35700	40826	109866
36000	40149	108062
36500	39056	105122
36700	38632	103979
37000	38008	102300
37500	37001	99590

once the useful margin has been determined on an individual case basis.

These relationships were used to generate a listing of potential data rates as a function of satellite EIRP and slant range with the results given in Table IV. In making the computations, we assumed that the designers of the spin-stabilized satellite have provided a communications system with an amplifier capable of supplying 10 W of output power for communicating with a TDRS. Further, we assume that the satellite designers use a 5-turn helix antenna, as described in Table II, for the communications antenna. This combination of a 10 dBW amplifier output and a 11.3 dB antenna gain would give an expected EIRP of 21.3 dBW on-axis. The 5-turn helix antenna has an expected HPBW of 55° which would allow up to 22.5° of off-axis pointing to stay within a 3 dB margin. Allowing for a maximum 20 deg off-axis pointing to correspond with the simulations, we reduce the antenna's gain by 2 dB to account for this which gives an EIRP of 19.3 dBW. The analysis was also performed with a more realistic design estimate for total system losses (internal component losses, polarization mismatch loss, etc.) amounting to 4 dB and subsequently the EIRP was reduced to 15 dBW. No other losses were assumed at this point without having actual candidate hardware for a spacecraft. The results in Table IV are then a realistic upper limit for the achievable data rates. In analyzing the 45 deg half-angle case, we assume that an EIRP of only 15 dBW will normally be available from the spin-stabilized satellite, although performance is given for the 19.3 dBW case as a comparison if an alternative technology is used. This is because a helical antenna would need to be operated considerably off-axis to support the broad pointing angles.

The maximum slant paths for the various orbital configurations are given in Table V with a typical value being 36000 km. These maximum slant paths correspond to the edges of the service support window and are used to set the data rate for the pass. In

TABLE V
Spin-Stabilized-Satellite-to-TDRS Maximum Slant Paths

Pointing Half-Angle	Inclination Angle	Orbital Altitude 600 km	900 km	1200 km
20°	28.5°	35561 km	35529 km	35077 km
20°	sun-synch	36561 km	35263 km	34976 km
45°	28.5°	36958 km	36720 km	36482 km
45°	sun-synch	36948 km	36718 km	36479 km

actuality, during any satellite service support time, the slant path to a TDRS will vary through the pass and will be minimal at the midpoint of the pass and highest at the end points of the pass (pass start and stop times). The pass maximum path length then sets a worst case slant path length and the lowest data rate assuming that the data transfer rate is kept constant during the pass. As the path becomes shorter, the data rate remaining constant has the effect of reducing the channel bit error rate thereby making the link more reliable in the middle region of the service window.

We can estimate the total daily data volume desired to be transmitted through the space network over the range of small-satellite missions by considering that at the 50th percentile, NASA estimates that the daily data volume generated in these missions is equivalent to a continuous production rate of 10 kbit/s [7]. This corresponds to a total production of 864,000,000 bits per day. The required minimum data rate necessary to transport this desired data volume is a function of the contact duration per day and the supported data rate for the communications system. In general, we see that narrow pointing angles from a narrow HPBW antenna capable of supporting a relatively high data rate and only a few contacts with the SN each day can be traded against a low-gain, wide-HPBW antenna, and therefore a relatively low data rate system which has many contacts per day. For a given maximum number of total contact minutes per day that may be dictated by operational considerations, it may be possible to have a higher data throughput by using a high-gain communications system with a few daily contacts than by using a low-gain antenna with more daily contacts. With the number of contacts per day and the data rate that can be supported determined, we can estimate if any configuration provides support at the desired daily data throughput level. The daily throughput is computed by multiplying the average daily contact duration by the data rate determined from the maximum slant path for the orbital altitude and pointing angle. Sample results are given in Tables VI–IX for single-TDRS contacts and full SN constellation results at 15 dBW and 19.3 dBW EIRP. In each table, the total daily throughput is given as a function of orbital altitude and orbital inclination angle. From these tables, we can see

TABLE VI
Contact Duration and Throughput for TDRS-W as Function of Orbital Altitude, Inclination Angle, and Antenna Half-Angle When EIRP is 15 dBW

	TDRS-W Contact Duration (min.)				Throughput (Mbit/day)			
	Orbital Inclination				Orbital Inclination			
	28.5°		sun-synchronous		28.5°		sun-synchronous	
	Half-angle		Half-angle		Half-angle	Half-angle	Half-angle	Half-angle
altitude (km)	20°	45°	20°	45°	20°	45°	20°	45°
600	43.3	264.2	19.6	105.3	107	603	49	240
900	42.1	260.7	19.6	104.4	104	604	49	242
1200	40.5	258.0	19.4	103.3	103	605	49	241

TABLE VII
Contact Duration and Throughput for Three-TDRS Constellation as Function of Orbital Altitude, Inclination Angle, and Antenna Half-Angle when EIRP is 15 dBW

	TDRS Constellation Contact Duration (min.)				Throughput (Mbit/day)			
	Orbital Inclination				Orbital Inclination			
	28.5°		sun-synchronous		28.5°		sun-synchronous	
	Half-angle		Half-angle		Half-angle	Half-angle	Half-angle	Half-angle
altitude (km)	20°	45°	20°	45°	20°	45°	20°	45°
600	126.1	784.3	59	315.9	312	1789	146	720
900	123.4	774.7	57.9	313.1	306	1796	146	726
1200	121.1	766.1	58	308.7	309	1795	148	723

TABLE VIII
Contact Duration and Throughput for TDRS-W as Function of Orbital Altitude, Inclination Angle, and Antenna Half-Angle when EIRP is 19.3 dBW

	TDRS-W Contact Duration (min.)				Throughput (Mbit/day)			
	Orbital Inclination				Orbital Inclination			
	28.5°		sun-synchronous		28.5°		sun-synchronous	
	Half-angle		Half-angle		Half-angle	Half-angle	Half-angle	Half-angle
altitude (km)	20°	45°	20°	45°	20°	45°	20°	45°
600	43.3	264.2	19.6	105.3	289	1622	131	646
900	42.1	260.7	19.6	104.4	281	1626	133	651
1200	40.5	258.0	19.4	103.3	278	1627	133	650

TABLE IX
Contact Duration and Throughput for Three-TDRS Constellation as Function of Orbital Altitude, Inclination Angle, and Antenna Half-Angle when EIRP is 19.3 dBW

	TDRS Constellation Contact Duration (min.)				Throughput (Mbit/day)			
	Orbital Inclination				Orbital Inclination			
	28.5°		sun-synchronous		28.5°		sun-synchronous	
	Half-angle		Half-angle		Half-angle	Half-angle	Half-angle	Half-angle
altitude (km)	20°	45°	20°	45°	20°	45°	20°	45°
600	126.1	784.3	59	315.9	841	4814	393	1939
900	123.4	774.7	57.9	313.1	823	4833	393	1953
1200	121.1	766.1	58	308.7	831	4832	398	1947

that a single TDRS within the SN cannot give the required coverage time to support users up to the 50th-percentile level when the spin-stabilized satellite has an EIRP of 15 dBW and a SMA service is used. At this lower EIRP, a long contact time through the entire SN constellation from a wide half-angle antenna is required to give the desired data throughput when a SMA service is used as seen in Table VII. If we have the higher EIRP available, then we can achieve the desired throughput by using either a wider half-angle antenna and a single TDRS or a narrow half-angle antenna and the full constellation as seen in Tables VIII and IX. The exact choice will need to be determined in the context of a specific mission model for the satellite.

A fixed ground station can usually achieve this same throughput with lower EIRP or with a higher data rate because of the lower space loss involved in transmitting to a fixed ground station. However, a direct comparison cannot be made without specifying a combined antenna and receiver system so that the link budget can be determined for a candidate system. In this study, we are bounding the parameters necessary to achieve the desired throughput without resorting to a proprietary ground station.

In this analysis, we are constraining ourselves to fixing the data rate to give the desired bit error rate at the edges of the coverage area which also corresponds to the highest space loss on the communications link. This occurs because we fix the slant range in (2) to the maximum range for a given contact. Because the actual space loss will vary over the contact time, we can look to variable-rate coding techniques as being potentially useful to make the data transmissions more efficient. This analysis was also constrained by using the SMA communications service on the SN. This is the lowest performance communications service of the three service types available on the SN. The S-band single access (SSA) communications service has the next-higher performance level in the system. Referring back to (1), the service-specific constant K is 230.7 dB for an SSA service [2] versus 221.8 dB for an SMA service. This difference of 8.9 dB implies that we have the potential to trade higher data rates, shorter access times, and system availability to achieve the optimum mission model by using both the SMA and SSA communications services.

The contact times for an individual TDRS or the entire SN constellation will need to be balanced against operations constraints. While the 45° half-angle antenna may give up to 4.8 Gbit of data throughput per day, it also requires 770 min per day of contact time. This service duration may be operationally unacceptable in scheduling the SN when trying to accommodate higher priority users. Operationally, the narrow-pointing case is expected to be easier to realize in the SN scheduling system than the broader-pointing case. This indicates that a preferred mode for operating the system will be to efficiently use a short contact time with a high-gain antenna rather than depending upon a low-gain antenna with a long contact potential that cannot be realized in the actual network.

CONCLUSIONS

The orbital analysis shown here indicates that accessing the SN for space-to-ground communications from a spin-stabilized satellite with a fixed antenna is not only possible but makes operational sense. The limited antenna pointing provides contact times comparable with those found is contacting fixed ground stations. Using a modest transmission power and all TDRS satellites in the SN, the desired goal of 864 Mbit data throughput per day can be achieved with approximately 120 min of contact per day when using the SN SMA communications service. If the SN SSA service is used, then the desired data throughput can be achieved with shorter contact periods. The lower gain antenna systems on the spin-stabilized satellite will allow for greater numbers of contacts per day but at a lower transmission rate. The required contact duration in this case might be considered to be operationally objectionable. In the cases presented here, no attempt is made to vary the transmission rate through the pass. If this can be done, then even greater throughput is possible because the fixed rate used here is chosen to meet the bit error rate criterion at the limits of the contact duration.

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REFERENCES

[1] Cvetkovic, S. R., and Robertson, G. J. (1993)
Spacecraft design considerations for small satellite remote sensing.
IEEE Transactions on Aerospace and Electronic Systems, **29** (Apr. 1993), 391–403.

[2] National Aeronautics and Space Administration (1995)
Space Network (SN) Users' Guide (revision 7).
Goddard Space Flight Center, Nov. 1995.

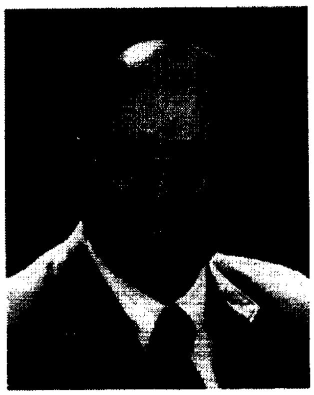
[3] *Satellite Tool Kit* (version 3) (1997)
Analytical Graphics, King of Prussia, 1997.

[4] Stutzman, W. L., and Thiele, G. A. (1981)
Antenna Theory and Design.
New York: Wiley, 1981, p. 267.

[5] NORAD 2-Line Elements.
Available via anonymous ftp in the directory pub/space at archive.afit.af.mil.

[6] Chobotov, V. A. (ed.) (1996)
Orbital Mechanics.
American Institute of Aeronautics and Astronautics, Reston, VA, 1996, p. 218.

[7] Miller, W. (1994)
Private communication.



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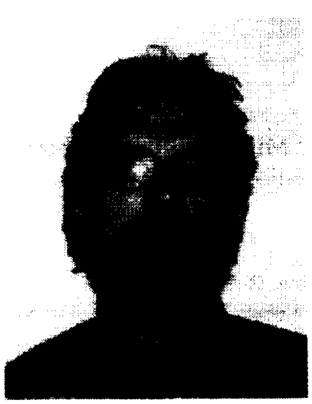

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