IMPROVED SMALL SATELLITE ACCESS OF THE SPACE NETWORK

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SECTION 1 - EXECUTIVE SUMMARY

This report contains the results of a study performed under the sponsorship of the National Aeronautics and Space Administration (NASA) made as a grant to the Center for Space Telemetering and Telecommunication Systems at New Mexico State University. The purpose of this phase of the grant is to increase user access to the Space Network (SN) run by NASA for supplying space-to-ground communications for satellites and associated control centers. The identified need is to bring more users into the community of those accessing the SN, especially those in the small satellite class of users.

The initial phase of the study concerned the potential for modifications to the standard transponder used in the SN. The results of that investigation are summarized in Section 4. The basic conclusion was that significant could not be made beyond those already planned by suppliers of the devices.

As the hardware modifications were being investigated, a second option was developed, namely to consider changes to the operational mode for the small satellites. This operational concept was to use a single, fixed-pointing antenna in a spin-stabilized satellite and let the antenna pattern sweep past the Tracking and Data Relay Satellites (TDRS) in the SN. The question to be answered by this phase of the study was twofold: could enough contact time per day be made available using this simple operating mode and could the data rate be high enough to allow for sufficient data throughput to satisfy the user community using existing components. Section 2 outlines the methodology and simulation results to answer these questions. Section 3 contains a summary of an operational simulation of a simple satellite payload using these contact scenarios. The simulation is not all-inclusive but shows how a payload simulation could be configured to utilize variable contact times.

The answer to both of the questions desired to be answered is affirmative. By carefully choosing the correct system transmission power and antenna pattern, the system will allow support to the 50th percentile of expected systems. It is recommended that based on this initial study, further work be done to quantify the exact parameters for transmission through the space network and to optimize usage of the contact time to maximize throughput.

SECTION 2 - FIXED ANTENNA ACCESS POTENTIAL FOR SMALL SATELLITES

2.1 OPERATIONAL CONCEPT

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 drawback in the mission planning is the ease of communications between the earth control infrastructure and the small satellite. The nominal mission design includes a dedicated ground station for telemetry, tracking, and command support. These terminals typically provide approximately 10 minutes of coverage during an orbit; however, not all orbits will pass over the ground terminal. For larger missions, the Space Network (SN) has been used to transmit data to and from orbit using the Tracking and Data Relay Satellites (TDRS) in space and interfacing to the White Sands Ground Terminal (WSGT) complex in New Mexico as the ground entry point. The advantage to the SN is that most orbits will have at least one opportunity for contact with a TDRS in the overall system constellation. 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 gimballed, directional antennas for the communications support. Mission design tradeoffs include the required power to transmit to a relay satellite at geostationary orbit versus a ground station at the earth's surface. An additional tradeoff is the amount of on-board storage required for once-per-orbit data dumps versus storage for data dumps once or twice per day. This report addresses the potential for Space Network access using non-gimballed antennas and modest transmission power.

For the small satellite system, we make the following assumptions:
a) the communications subsystem is able to supply a minimum of 10 W of output power,
b) the antenna system can provide a minimum gain of 5 dB
c) the antenna system is surface mounted along a radial vector connecting the satellite with the center of the earth and pointing away from the center of the earth
d) the small satellite is spin stabilized with a nadir orientation, that is, the long axis of the spacecraft is along the above radial vector
e) satellite contact between the small satellite and the TDRS can be initiated as the small satellite sweeps past the TDRS position in its orbit
f) a SN S-Band Single-Access (SSA) service or Multiple Access (MA) service can be used for the communications link; this implies that the TDRS antenna is capable of open-loop tracking at a minimum.

This configuration is illustrated in Figure 1 where the nominal two TDRS positions are illustrated along with a potential small satellite orbit (drawing is not to scale). The nominal operational mode for the SN is for a satellite in orbit to receive data via a link to and from the TDRS. The data link between the TDRS and the ground is run through the WSGT facility which is connected with the ground portion of the communications network. The choice of which TDRS the small satellite uses depends upon its relative orbital position with respect to the earth and each TDRS. The SN is unable to support satellites in the zone of exclusion over the Indian ocean; however, at other times, the contact can be scheduled for when the TDRS is within the small satellite's field of view. This

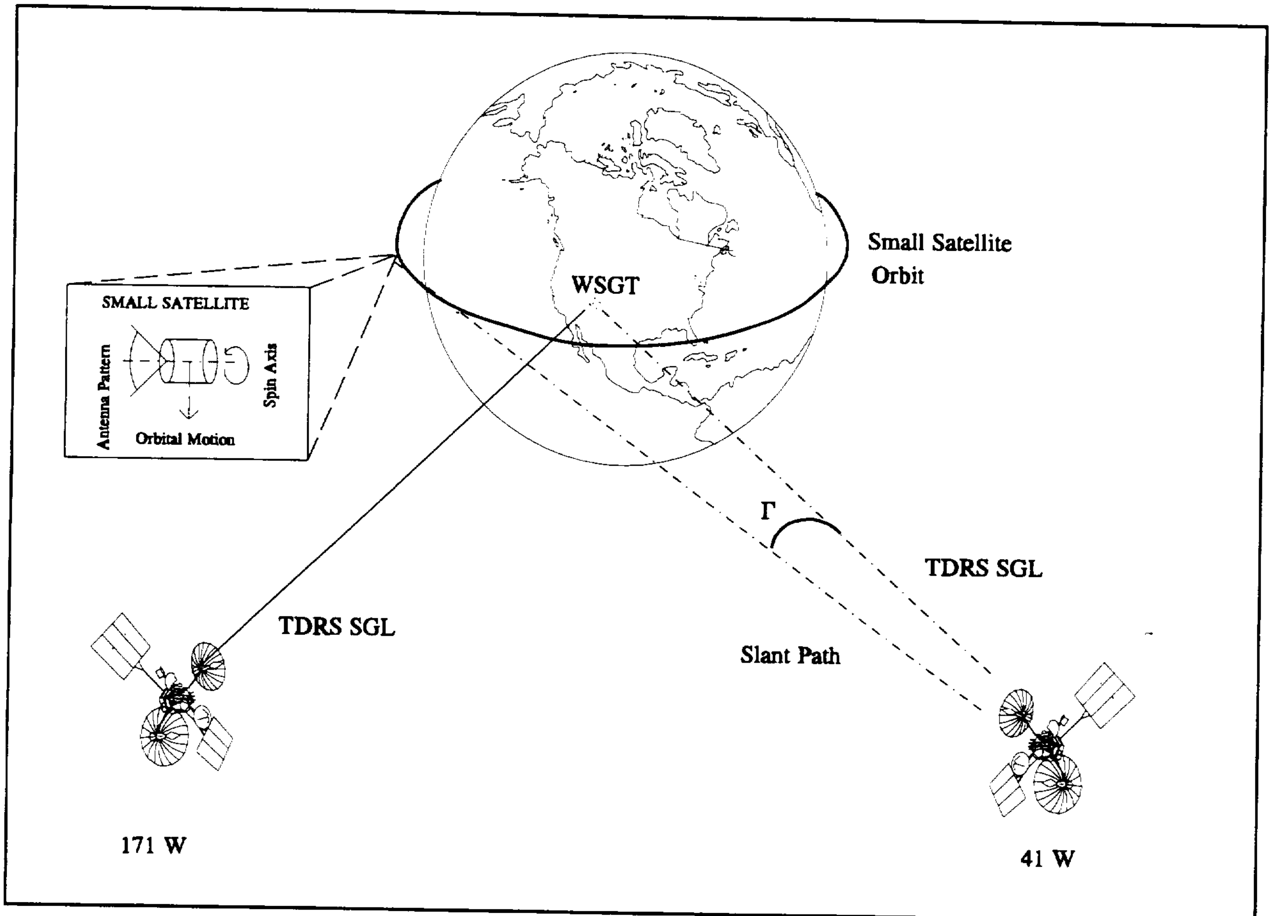


Figure 1 - Geometry for a satellite accessing the TDRS satellites in the Space Network.

investigation looks at two possible TDRSS access modes: a single TDRS is available to support access and the possibility of using the full constellation of two operational TDRSS spacecraft. Although there are several operational TDRS presently on orbit, for the purposes of this investigation, only the minimal two-satellite constellation at 41° W and 171 ° W longitude is assumed.

For both modes being considered, the return service communication frequencies assumed are as follows [2]:

a) SSA: 2200 to 2300 MHz,
b) MA: 2287.5 MHz

For simulation purposes, we will assume a middle frequency for the SSA service at 2250 MHz

2.2 FIXED GROUND STATION ACCESS

In providing low-earth orbiting satellites with telemetry, tracking, and command support, the design often plans for support through a dedicated ground station network at a fixed location. Typically, there are two or three access times per day separated by several orbits when the contact can be initiated and meaningful data transmission can occur. Table 1 illustrates typical contact times for various orbital inclinations with a satellite orbital period of 90 minutes. The contact times were derived using an orbital simulation in the program Orbital Workbench. The assumed ground station was set to be 107° W longitude, 32° N latitude, 1 km elevation, and the minimum elevation pointing angle of 10° above the local horizon. Similar results are obtained with different ground station locations. A single fixed ground station can be expected to give two to four meaningful contacts per day with up to 5 minutes per contact for this orbital altitude.

Table 1. Sample Fixed Ground Station Access

Orbital Inclination (degrees)	minimum contact minutes	maximum contact minutes	Number of contacts per day
< 25	0	0	0
25	2.5	2	2
30	5	2.5	4
40	2.5	4.5	5
50	5	5	2
60	1.5	4.5	3
70	0.5	5	3
80	4	4.5	2
90	3	4.5	2
100	4	5	2
110	3	3.5	2

2.3 BASELINE ANTENNA DESIGN

In order for this concept to work, we are assuming that sufficient power can be obtained from an antenna without steering. The only way that this can be done is to have a fairly non-directional antenna system, i.e., one with a large Half-Power Beam Width (HPBW). The tradeoff with a large HPBW is a low gain for the system thereby giving a low EIRP. In this study, we are assuming that a helix or microwave patch antenna is available to supply all of the transmission and reception gain. For typical helical antennas, the HPBW and directivity, D, may be computed from [3] using the relationships

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

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

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 [3], C was fixed at 0.92λ with λ that of the return service and the pitch angle, α, was set to 13° in this analysis. Based on [3], the gain is taken to be directivity value. Table 2 lists available HPBW and gains for typical helix antennas at the Space Network S-Band return frequencies.

Based on the results listed in Table 2, our assumed minimum EIRP for the study should be achievable with this technology.

Table 2. Helix Antenna Performance

Number of Turns	Gain (dB)	HPBW (degrees)
5	11.3	54.8
10	14.3	38.8
21	17.5	26.8

The HPBW given in Table 2 is related to the antenna pointing used in the later sections. The antenna pointing threshold angle will be taken to be one-half of the HPBW in degrees.

2.4 ORBITAL ANALYSIS

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. For the purposes of this study, Keplerian mechanics [4], [5] are used to predict the three-dimensional positions of a single TDRS and a test satellite. For the thirty-day study run with eccentric orbits, second-order corrections for the earth's shape are included [5]. For this study, the orbital elements for the TDRS positions were taken from [6] and are listed in Table 3. The satellite orbital elements were generated to give uniform coverage through one day and are given in Table 4. The two TDRS mean orbital elements were given at different epochs. The elements were brought into a common epoch by using the program Orbital Workbench with full perturbation models to propagate the elements to a common epoch. From that point on, the test satellite and the both TDRSS spacecraft were the same common epoch. In computing the orbital access we make the assumption that the orbital elements do not undergo any significant changes over the simulation period other than those caused by the non-spherical earth. In the following paragraphs, we outline the methodology by which the simulation of the coverage was computed.

Table 3. Tracking and Data Relay Satellite Orbital Elements

element	East TDRS	West TDRS
eccentricity, e	0.000144	0.0000844
right ascension of the ascending node, Ω (degrees)	189.2052	95.5081
argument of perigee, ω (degrees)	145.5958	268.6361
mean anomaly at epoch, M (degrees)	114.2497	69.4703
mean motion (rev/day)	1.0026905	1.0027593
inclination angle (degrees)	0.044	0.0703
epoch (year 1994)	17.038495	16.36754216

Table 4. Small Satellite Orbital Elements	
element	**value**
eccentricity, e	0.001
right ascension of the ascending node, Ω	100 degrees
argument of perigee, ω	0 degrees
mean anomaly at epoch, M	100 degrees
mean motion (revs/day)	14, 15, 16
inclination angle	0 through 110 degrees
epoch (year 1994)	17.03849500

For any satellite without orbital changes, the mean anomaly, M, is computed using the uniform equation of motion in terms of the orbital period P and the mean anomaly at the initial epoch by

$$M = \frac{2\pi}{P}(\Delta t) + M_o$$

For satellites following an elliptical path, the eccentric anomaly, E, is computed from the mean anomaly, M, and the orbital eccentricity, e, by solving Kepler's equation

$$M = E - e\,\sin(E)$$

This solution is usually performed by numerical techniques. In our case, the solution was determined using the numerical equation solver function built into MATHCAD or by a subroutine performing Newton's method for finding the roots of an equation in the BASIC program. Once the eccentric anomaly is computed, the true anomaly, θ, is computed from

$$\theta = \tan^{-1}\left[\frac{\sqrt{1-e^2}\,\sin(E)}{\cos(E) - e}\right]$$

From knowing the satellite's mean motion in revolutions per day, we know its period, P, in seconds. We can then compute the orbital semimajor axis, a, by using Kepler's third law in the form of

$$a = \left[\left(\frac{P}{2\pi}\right)^2 \mu\right]^{1/3}$$

where μ is the gravitational parameter for the earth with value $\mu = 3.986 \times 10^5$ km^3/s^2. The true anomaly, θ, is used with the semimajor axis, a, and the orbital eccentricity, e, to compute the radial distance from the center of the earth to each spacecraft in the simulation using the relationship for the radial distance, r,

$$r = \frac{a(1 - e^2)}{1 + e\cos(\theta)}$$

The spacecraft orbit is perturbed by the atmosphere, the gravitational attraction of the sun and moon, and the non-spherical earth. For the single-day analysis in MATHCAD, no perturbations were included while in the BASIC program for the thirty-day simulation runs, we included the perturbation due to the non-spherical earth. Other perturbations were ignored. The first perturbation effect is the regression in the Right Ascension of the Ascending Node (RAAN or Ω) while the second effect is the rotation of the line of apsides (the line joining the apogee and perigee point). The regression rate for the change in the RAAN is computed from

$$\frac{d\Omega}{dt} = \frac{-3nJ_2R_o^2\cos(i)}{2a^2(1-e^2)^2}$$

where R_o is the radius of the earth (6378 km), n is the mean motion of the satellite, and J_2 is the zonal constant of 0.00108263 for the earth. The constants a, i, and e are the orbital elements for the semi-major axis, orbital inclination angle, and orbital eccentricity, respectively. The mean motion, n, used in this equation is computed from

$$n = \sqrt{\frac{\mu}{a^3}}$$

The rotation of the line of apsides causes the argument of perigee, ω, to shift. The rotation rate in the line of apsides is computed from

$$\frac{d\omega}{dt} = \frac{3nJ_2R_o^2(4 - 5\sin^2 i)}{4a^2(1-e^2)^2}$$

where the symbols are as defined previously.

Once the rates are computed, the orbital elements RAAN and ω are adjusted each time step in the simulation to account for the perturbation since the last time step.

The Cartesian coordinate unit vectors describing the current orbital position can then be computed as a function of the orbital elements and the quantity $u = \omega + \theta$. The unit vectors are given by

$$\begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \begin{pmatrix} cos(\Omega)cos(u) - sin(\Omega)cos(i)sin(u) \\ sin(\Omega)cos(u) + cos(\Omega)cos(i)sin(u) \\ sin(i)sin(u) \end{pmatrix}$$

The true position in Cartesian coordinates is then the radial distance, r, times the unit vector for the satellite. If **T** and **S** are the unit vectors pointing to a TDRSS satellite and the small satellite, respectively, then the central angle, γ, as seen from the center of the earth between the unit vectors can then be computed via

$$\gamma = cos^{-1}(\vec{T} \cdot \vec{S})$$

If the respective satellite unit vectors are scaled by their radial difference to form a position vector to each satellite, these position vectors can be differenced and the magnitude computed to find the slant path, d, between the TDRS and the small satellite. If R_T is the radial distance to a TDRSS satellite from the center of the earth, and d is the slant path between the test satellite and the TDRSS satellite, then the local elevation angle, El, that the TDRSS satellite makes at the small satellite is computed from

$$El = cos^{-1}\left(\frac{R_T}{d} sin(\gamma) \right)$$

The angle of interest is not the elevation angle but the complement to this angle which gives the desired pointing angle $\mathbf{\Phi}$. Once the elevation angle, El, is found, then we compute the pointing angle from

$$\Phi = 90° - El.$$

This pointing angle is then used to determine whether an access through either the East or West TDRS is possible at a given moment. These orbital positions and pointing angels are then updated each time step and a determination is made if the TDRS is visible to the small satellite as a function of the threshold angle.

2.5 COMPUTATIONAL METHODOLOGY

These computations were initially entered into the MATHCAD analysis package to form a document containing the analysis, the expected contact minutes per orbit, and the associated worst-case slant path. When it was time to investigate non-circular obits over a 30-day period with orbital perturbations included, the MATHCAD document was converted to a computer program in Visual BASIC for the simulation. The Visual BASIC program was checked against the MATHCAD results to insure consistency over a 24-hour period.

For analyzing circular orbits, the orbital periods for the small satellite were varied from 14 through 16 revolutions per day over one full day at a resolution of 100 points per orbit. The orbital inclination angle for the small satellite was varied from 0° through 110°. Three threshold angles for the pointing angle were considered: 20°, 40°, and 60° to account for narrow, medium, and wide beam antennas and to include the pointing that the TDRSS satellites are capable of in single access mode. These values do not exactly correspond to HPBW measurements for specific antenna configurations. They were chosen to allow adequate gain margins for full EIRP at AOS/LOS for the satellite. During the computation, if the pointing angle was within the threshold, then the TDRSS satellite was visible from the small satellite. The results recorded the following data

a) access time per day (minimum, maximum, and average) to both TDRSS satellites individually,
b) access time per day when both satellites were visible to the small satellite,
c) access time per day of the whole TDRSS systems (time when either or both TDRSS satellites was visible to the small satellite), and
d) access time to each TDRS satellite and the constellation on a per-orbit basis.

For the non-circular orbits, the Visual BASIC program produced the same outputs as the MATHCAD document. The orbital inclinations were kept to two values: 98° corresponding to a sun-synchronous satellite and 63° corresponding to one without nodal regression. These two orbital inclinations were considered to be the most useful for planning purposes rather than a continuum of possible inclination angles as was done in the circular orbit case.

A sample MATHCAD document and a copy of the Visual BASIC program are included later in sections 2.9 and 2.10, respectively. The following subsections discuss the results obtained by this analysis.

2.6 RESULTS FOR CIRCULAR ORBITS

2.6.1 Orbital Analysis

Using the position vectors derived above, we can investigate when there is a possibility for Space Network access under the constraint that the small satellite has no active positioning mechanism for antenna pointing and relies on the communications antenna sweeping past the TDRSS satellites. Given that standard microstrip patch antennas can have half-power beamwidths (HPBW) of 90° while helical antennas can have HPBW up 50°, we investigate three cases of the pointing angle between the TDRSS satellites and the small satellite expected to be typical: the cases of the pointing being within 20°, 40°, and 60°. The case of the 20-degree pointing will simulate a 5-turn helical antenna and allow sufficient gain margin for maintaining the full, desired EIRP at the contact margins. This is considered to be a most likely candidate for an actual communications system antenna.

For each simulation case, we find the minimum, maximum, and average number of minutes per orbit that the satellite is within this angle. This was done for small satellites having mean motions of 14, 15, and 16 orbits per day which corresponds to orbital periods of 102.9, 96, and 90 minutes, respectively and at orbital inclination angles of 0° through 110°. The computations were made between both the East TDRS and the West TDRS satellite locations and the test satellite. It was found that with this set of parameters, there was no time when both TDRSS satellite locations were simultaneously visible from the test satellite location. It was also found that both TDRSS locations had similar results when averaged over one day. Figures 2, 3, and 4 present this information in the form of a plot of the number of orbits per day whose contact time through a single TDR satellite (TDRS East) exceeds the given ordinate value in minutes for satellite mean motions of 14, 15, and 16 revolutions per day, respectively. Figures 5, 6, and 7 show this same information through TDRS West. As can be seen in both sets of graphs, the number of contact minutes is highly dependent upon orbital inclination angle. Generally, small inclination angles are needed to have large numbers of contact minutes per orbit.

To better see the contact distribution through a single day, the orbital contact times through TDRS East, assuming a 20-degree maximum pointing angle, are given for 14, 15, and 16 revolutions-per-day orbits in Figures 8, 9, and 10. The penalty for not having a steerable antenna is seen in these figures because some orbits have no contact time, even if the small satellite is not within the TDRSS zone of exclusion. In general, high-inclination orbits having contact through a TDRS act in a manner similar to that found when the satellite accesses a single fixed ground station. The advantage that the SN has over a single, fixed ground station is that multiple TDR satellites act in a manner similar to having multiple, geographically-diverse ground stations. For the 40-degree and 60-degree pointing cases, there are many instances where on a given orbit only one of the two TDRSS satellites is visible on a given orbit while on the next orbit, the other is visible. Therefore, there are relatively few orbits when at least one of the two TDRSS cannot be scheduled from a visibility restriction.

The total access time per day is then taken through a full constellation. Figures 11, 12, and 13 show

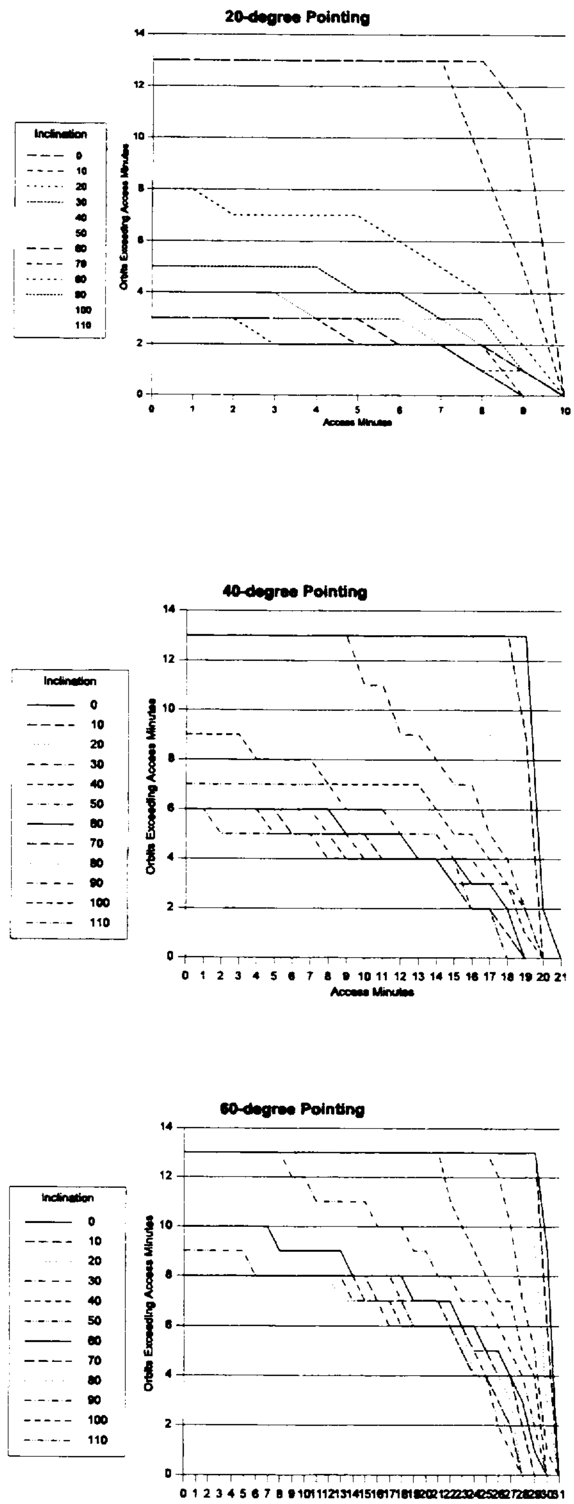


Figure 2 - TDRS East Results for 20, 40, and 60 Degree Pointing at 14 revs/day

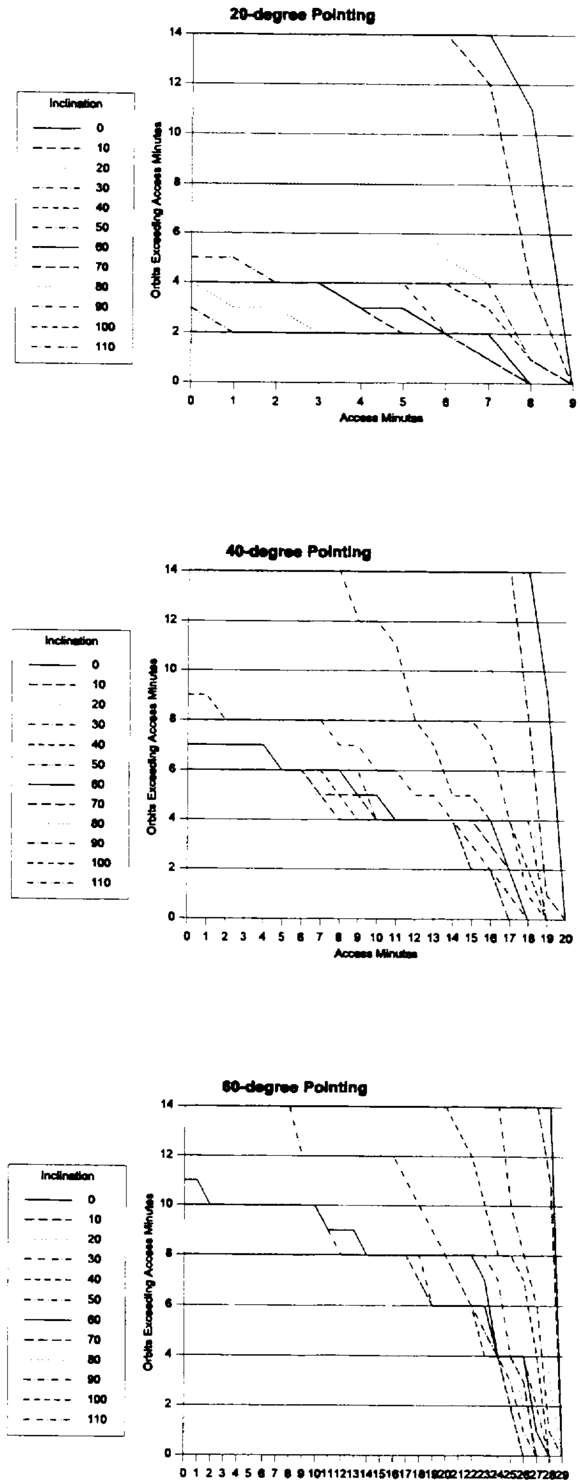


Figure 3 - TDRS East Results for 20, 40, and 60 Degree Pointing at 15 revs/day

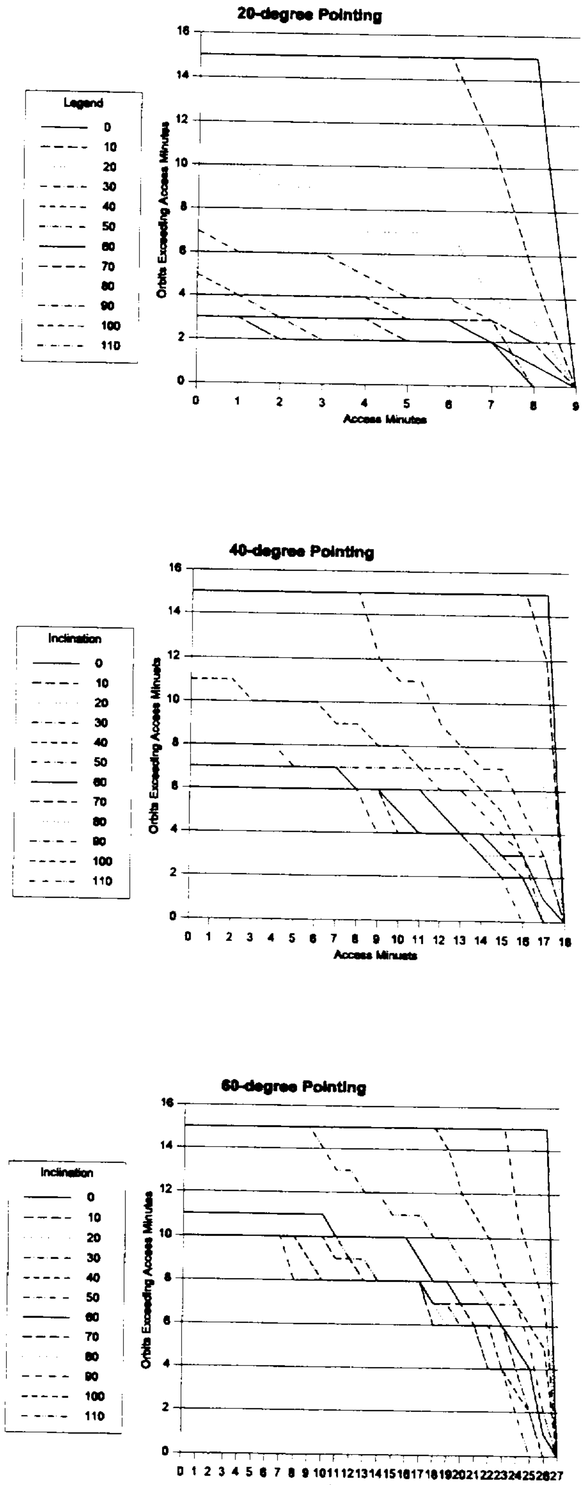


Figure 4 - TDRS East Results for 20, 40, and 60 Degree Pointing at 16 revs/day

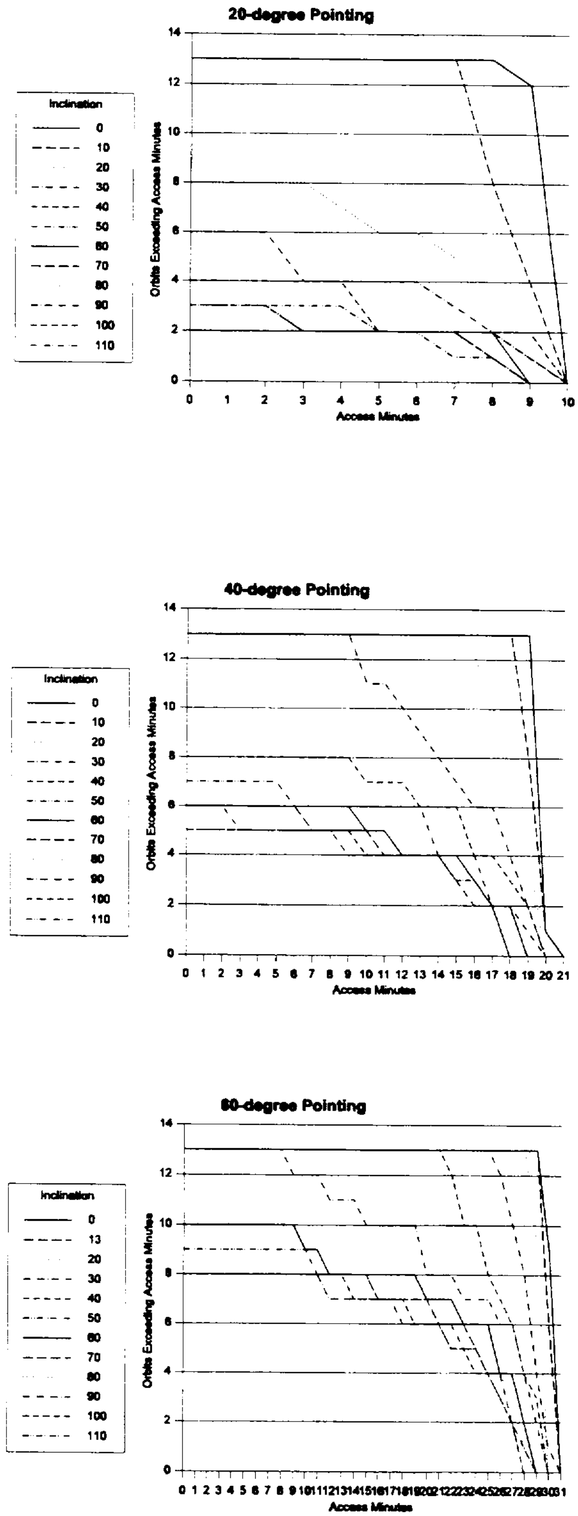


Figure 5 - TDRS West Results for 20, 40, and 60 Degree Pointing at 14 revs/day

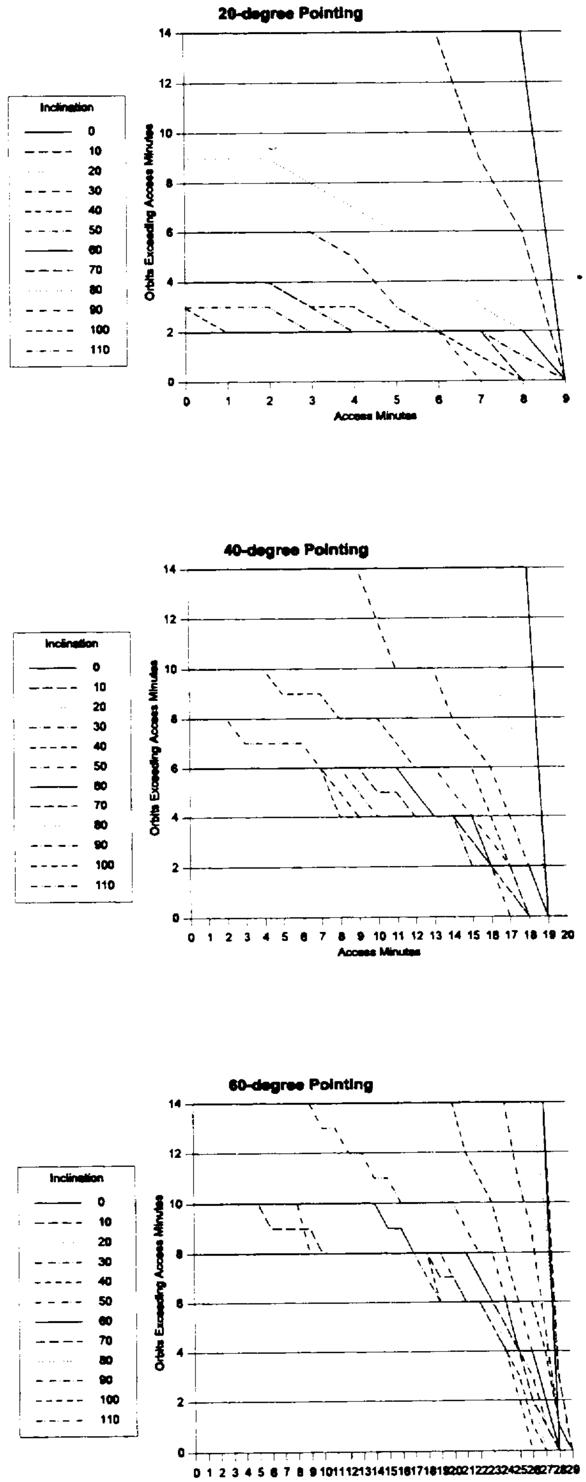


Figure 6 - TDRS West Results for 20, 40, and 60 Degree Pointing at 15 revs/day

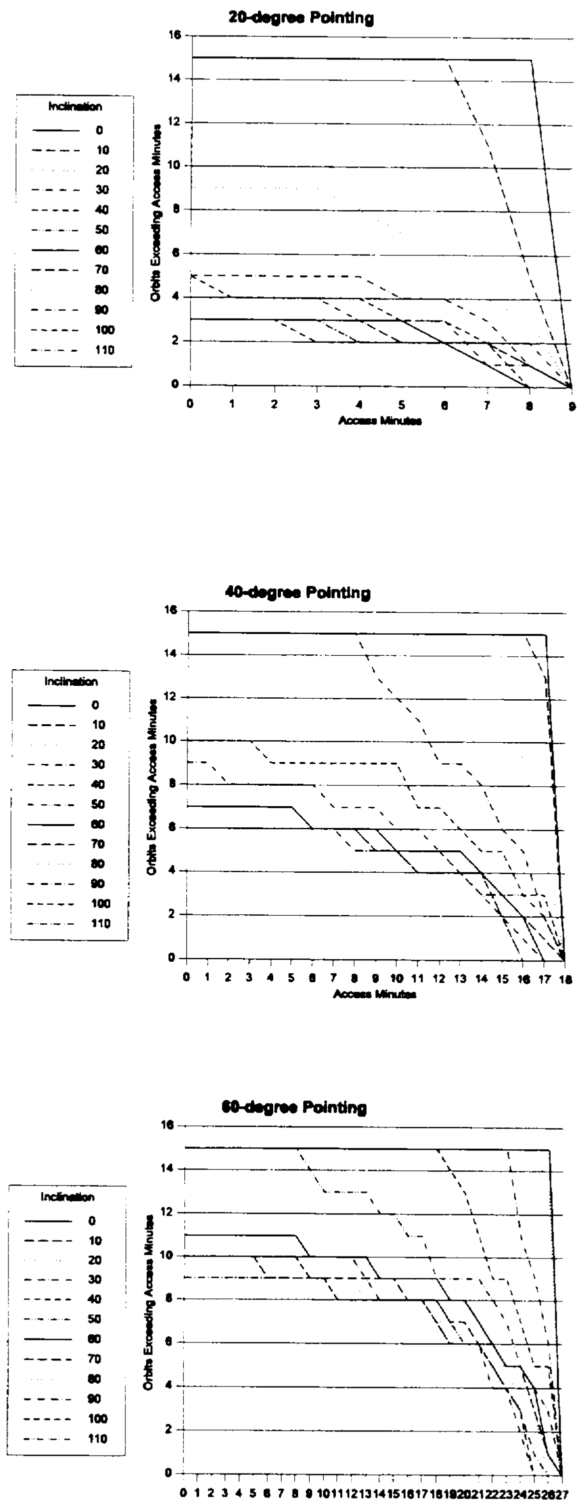


Figure 7 - TDRS West Results for 20, 40, and 60 Degree Pointing at 16 revs/day

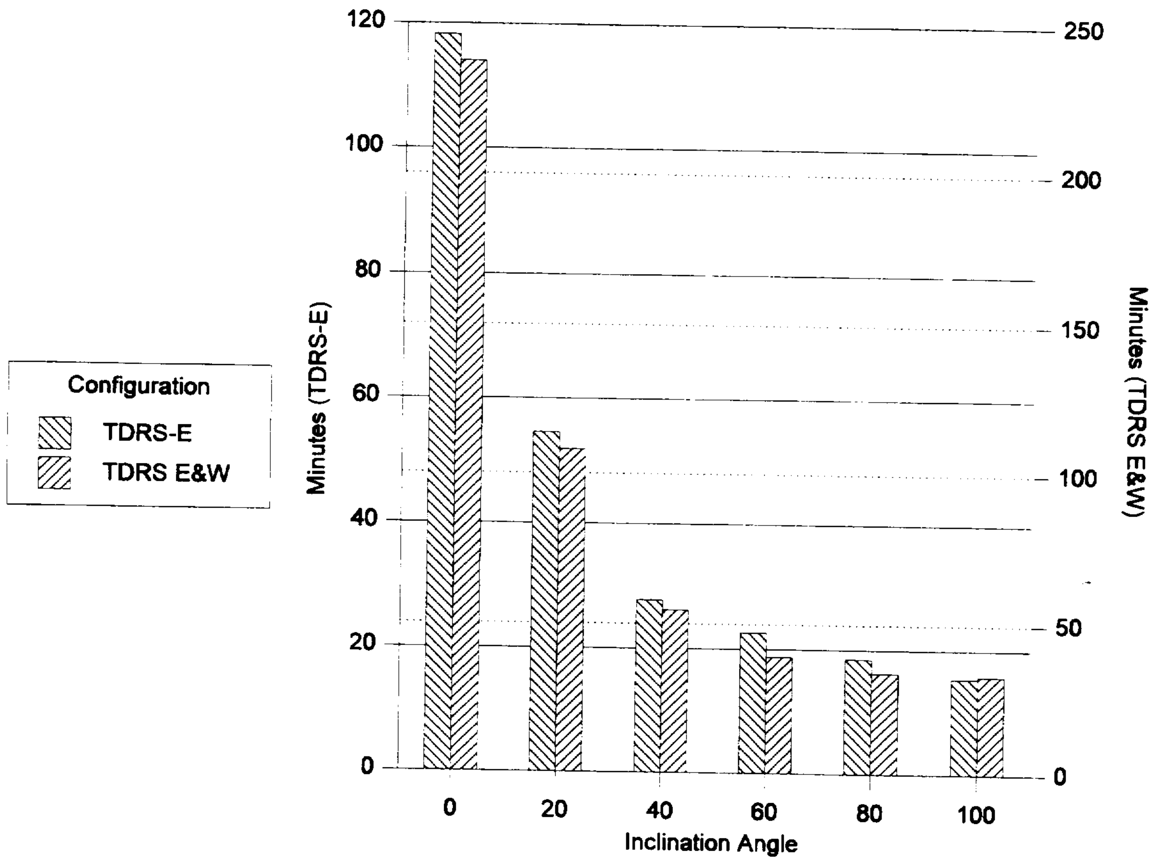


Figure 8 - TDRS East and Constellation Total Daily Access Time for 14 Rev/day with 20-degree pointing.

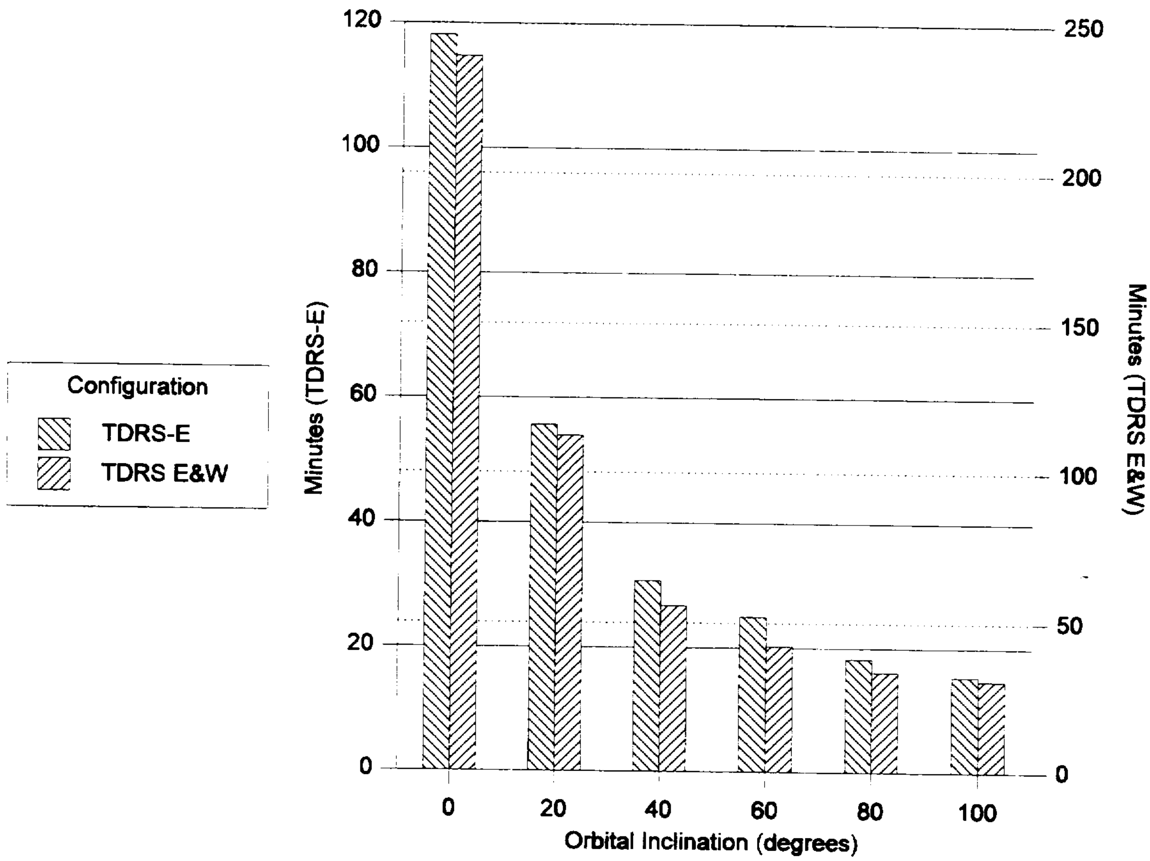


Figure 9 - TDRS East and Constellation Total Daily Access Time for 15 Rev/day with 20-degree pointing.

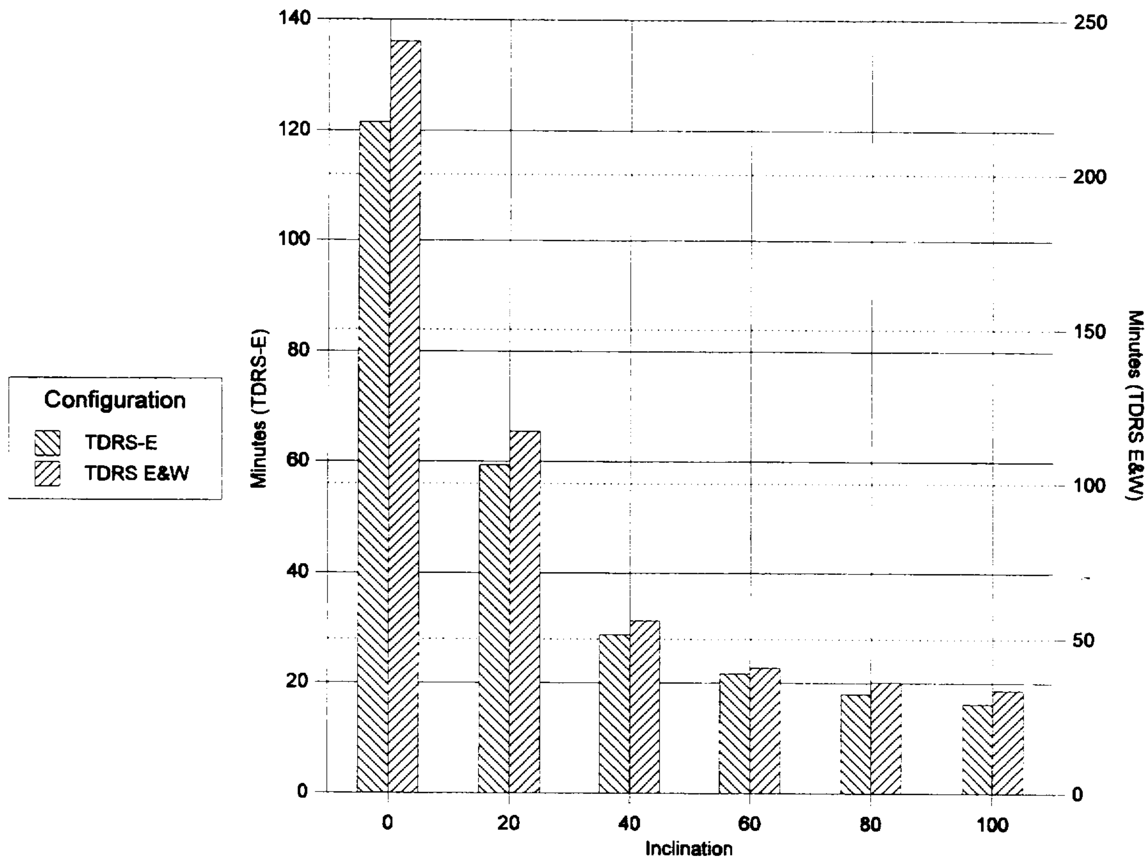


Figure 10 - TDRS East and Constellation Total Daily Access for 16 Rev/day for 20-degree pointing.

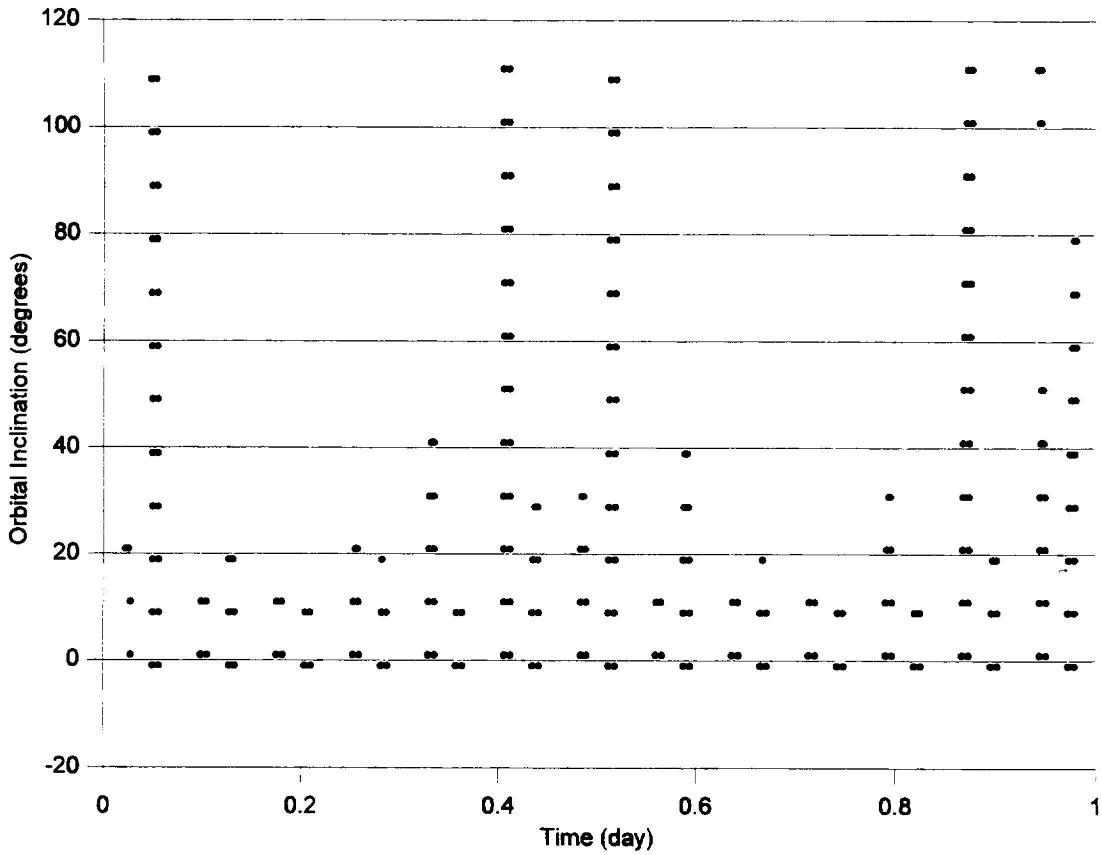


Figure 11 - Orbital Access Instances at 14 Rev/day with 20-degree pointing.

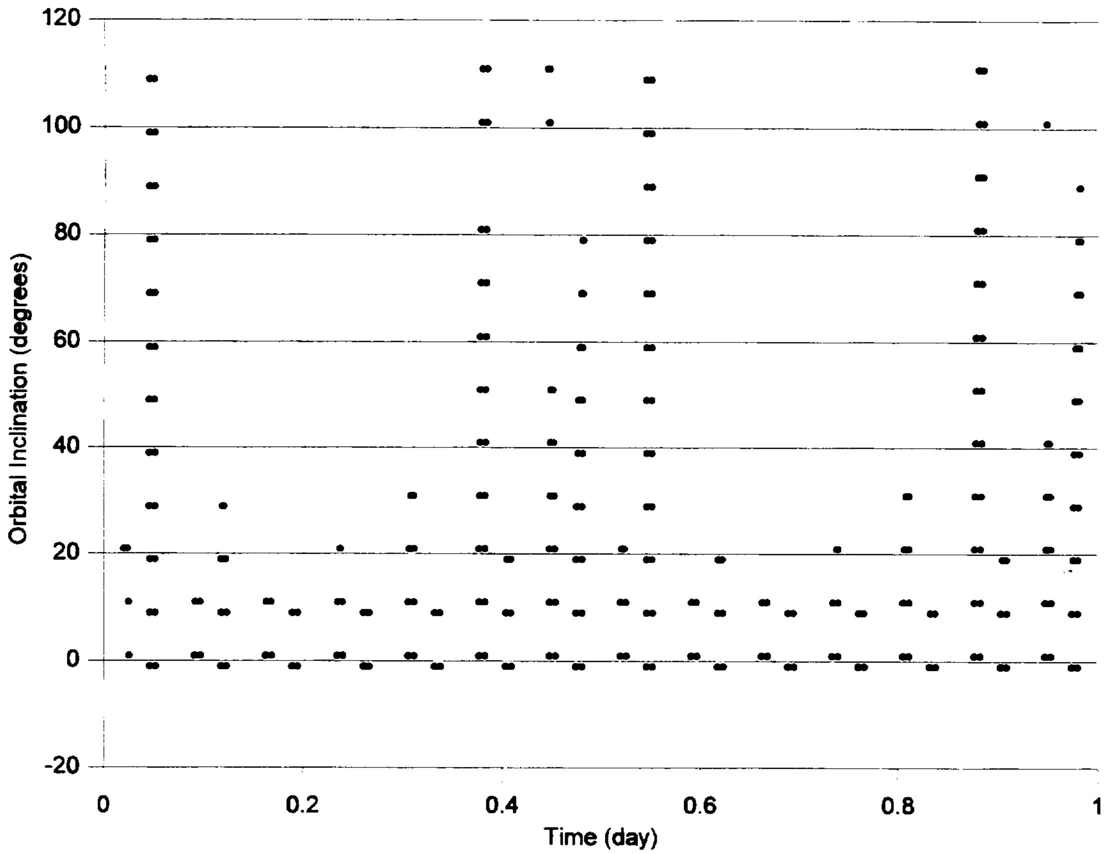


Figure 12 - Orbital Access Instance at 15 Rev/day with 20-degree pointing.

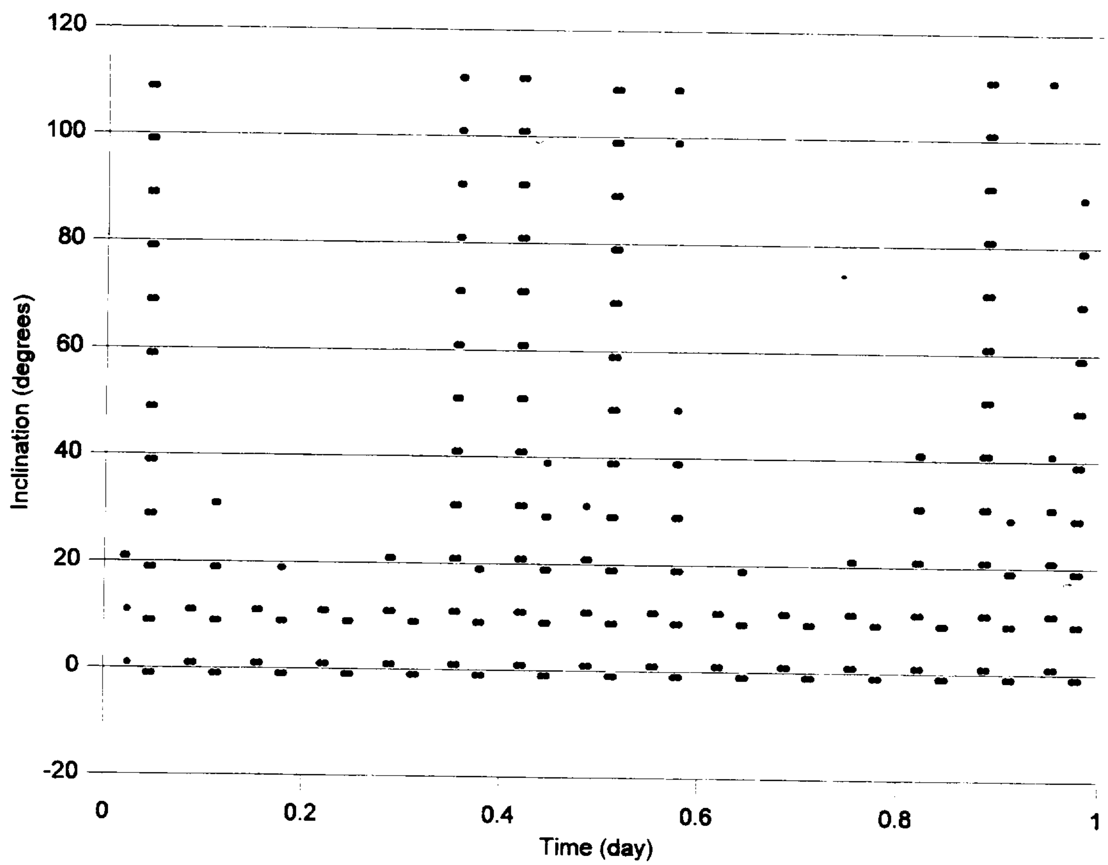


Figure 13 - Orbital Access Instances at 16 Rev/day with 20-degree pointing.

the contact minutes per day on all orbits having contact times through a single TDRS and through the TDRS constellation. These cases are a "worst case" in that a 20-degree pointing restriction was used to generate the graph. A 40-degree or 60-degree pointing restriction would greatly increase the available time. This is shown in Table 5, 6, and 7 where the daily access times in minutes as a function of orbital inclination angle and period, and satellite-to-TDRSS pointing angle are given.

Table 5. 20-degree Pointing Total Daily Access Time in Minutes

	14 rev/day		15 rev/day		16 rev/day	
Inclination (degrees)	**TDRS East**	**SN Constellation**	**TDRS East**	**SN Constellation**	**TDRS East**	**SN Constellation**
0	118.0	237.6	118.1	239.0	121.5	243.0
10	108.0	213.9	109.4	217.9	108.9	217.8
20	54.5	108.0	55.7	112.3	59.4	117.0
30	36.0	71.0	33.6	69.1	38.7	72.0
40	27.8	54.5	30.7	55.7	28.8	55.8
50	23.7	43.2	26.9	45.1	23.4	44.1
60	22.6	39.1	25.0	42.2	21.6	40.5
70	20.6	37.0	23.0	38.0	18.9	38.7
80	18.5	33.9	18.2	33.6	18.0	36.0
90	15.4	30.9	15.4	30.7	16.2	33.3
100	15.4	32.9	15.4	30.7	16.2	33.3
110	15.4	33.0	14.4	34.6	18.0	38.7

Table 6. 40-degree Pointing Total Daily Access Time in Minutes						
	14 rev/day		15 rev/day		16 rev/day	
Inclination (degrees)	**TDRS East**	**SN Constellation**	**TDRS East**	**SN Constellation**	**TDRS East**	**SN Constellation**
0	256.1	511.2	264.0	51.4	259.2	517.5
10	249.9	499.9	250.6	505.9	235.8	510.3
20	231.4	467.0	236.2	474.2	238.5	477.0
30	15.4	391.9	199.7	400.3	200.7	401.4
40	128.6	256.1	127.7	262.1	137.7	270.9
50	108.0	210.9	112.3	216.0	108.0	216.0
60	90.5	180.0	91.2	182.4	95.4	186.3
70	84.3	169.7	82.6	168.0	82.8	165.6
80	76.1	151.2	78.7	160.3	81.0	159.3
90	74.1	147.1	77.8	156.5	78.3	155.7
100	78.2	153.3	77.8	156.5	80.1	159.3
110	82.3	161.5	80.6	161.3	79.2	15.3

Table 7. 60-degree Pointing Total Daily Access Time in Minutes						
	14 rev/day		15 rev/day		16 rev/day	
Inclination (degrees)	TDRS East	SN Constellation	TDRS East	SN Constellation	TDRS East	SN Constellation
0	397.0	794.1	403.2	793.0	404.1	808.2
10	393.9	787.9	400.3	793.0	402.3	801.9
20	386.7	770.4	389.8	778.6	389.7	780.3
30	370.3	740.6	373.4	747.8	376.2	752.4
40	343.5	686.1	349.4	697.0	349.2	698.4
50	293.1	587.3	296.6	596.2	305.1	606.6
60	228.3	455.7	227.5	460.8	235.8	468.0
70	199.5	397.0	194.9	404.2	210.6	418.5
80	188.2	377.5	189.1	376.3	198.0	392.4
90	184.1	369.3	184.3	368.6	192.6	380.7
100	186.2	371.3	181.4	366.7	198.0	393.3
110	195.4	397.0	206.4	409.9	201.6	405.0

2.6.2 Expected Data Rate Support

Once the slant path is computed, the expected maximum data rate that can be supported can be determined. The TDRSS Link Budget Design Table [7] was used to generate a listing of potential data rates as a function of satellite EIRP and slant range with the results given in Table 8. This design table is configured for the various SN service modes at both K-Band and S-Band with only the SSA and MA services being considered here. The maximum slant paths for the various orbital configurations are given in Table 9. These maximum slant paths correspond to the edges of the service support window and will be used to set the data rate for the pass. In actuality, during any satellite service support time, the slant path to a TDRS will vary through the pass and will be minimal at the mid-point 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 and the lowest data rate. As the path becomes shorter, the data rate remaining constant has the effect of reducing the channel

Table 8. SN Available Data Rates as a Function of EIRP and Slant Range for SSA and MA Services with 0 dB link Margin and Implementation Loss				
	SSA		MA	
Slant Range (km)	**Data Rate (kbps) at EIRP = 15 dBW**	**Data Rate (kbps) at EIRP = 19.3 dBW**	**Data Rate (kbps) at EIRP = 15 dBW**	**Data Rate (kbps) at EIRP = 19.3 dBW**
20000	549.0	1478.0	41.2	114.6
20500	522.0	1406.0	39.2	109.2
21000	498.0	1340.0	37.4	104.0
21500	475.0	1278.0	35.6	99.2
22000	454.0	1220.0	34.0	94.8
22500	434.0	1168.0	32.5	90.6
23000	415.0	1118.0	31.0	86.6
23500	397.4	1070.0	29.8	83.0
24000	381.0	1026.0	28.6	79.6
24500	366.0	984.0	27.4	76.4
25000	351.0	946.0	26.4	73.4
25500	337.4	908.0	25.3	70.6
26000	325.0	874.0	24.4	67.8
26500	312.6	842.0	23.5	65.3
27000	301.0	810.0	22.6	62.9
27500	290.0	782.0	21.8	60.6
28000	280.0	754.0	21.0	58.5
28500	270.0	728.0	20.3	56.4
29000	261.0	702.0	19.6	54.5
29500	252.0	679.0	18.9	52.7
30000	244.0	656.0	18.3	51.0

Table 8. SN Available Data Rates as a Function of EIRP and Slant Range for SSA and MA Services with 0 dB link Margin and Implementation Loss				
	SSA		MA	
Slant Range (km)	Data Rate (kbps) at EIRP = 15 dBW	Data Rate (kbps) at EIRP = 19.3 dBW	Data Rate (kbps) at EIRP = 15 dBW	Data Rate (kbps) at EIRP = 19.3 dBW
30500	236.0	635.0	17.7	49.3
31000	228.6	615.0	17.1	47.7
31500	221.0	595.0	16.6	46.2
32000	214.6	577.0	16.1	44.8
32500	208.0	559.4	15.6	43.4
33000	201.4	542.0	15.1	42.1
33500	195.4	526.0	14.7	40.9
34000	190.0	510.0	14.2	39.7
34500	184.6	496.0	13.8	38.5
35000	179.0	482.0	13.4	37.4
35500	174.0	469.0	13.0	36.4
36000	169.4	456.0	12.7	35.4
36500	164.6	443.0	12.3	34.4
37000	160.4	432.0	12.0	33.5
37500	156.0	420.0	11.7	32.6
38000	152.0	409.4	11.4	31.7
38500	148.0	398.6	11.1	30.9
39000	144.2	388.0	10.8	30.1
39500	140.8	378.6	10.5	29.4
40000	137.2	369.0	10.3	28.6

Table 9. Small Satellite Maximum Slant Paths			
	Orbital Mean Motion		
Pointing Angle	**14 revs/day**	**15 revs/day**	**16 revs/day**
20°	35266 km	35582 km	35862 km
40°	36340 km	36615 km	36862 km
60°	38062 km	38265 km	38449 km

bit error rate thereby making the link more reliable in the middle region of the service window. To determine the expected maximum data rate through the Space Network, the standard link budget design table results are used with the worst-case slant paths derived for the orbital viewing angles. This analysis had the following configurations:

a) SSA service: frequency of 2250 MHz, Data Group 2 (DG2) transmission mode, balanced QPSK modulation, and a minimum channel error rate of 10^{-5},
b) MA service: frequency of 2287.5 MHz, Data Group 1 (DG1) mode 1 transmission mode, balanced QPSK modulation, and a minimum channel error rate of 10^{-5}.

In making the computations, we assumed that the SN transponder could supply 10 W of power and that a 5-turn helix antenna, as described in Table 2, was used. This combination would give an expected EIRP of 21.3 dBW on-axis. Allowing for a 20-degree off-axis pointing, we reduce the gain by 2 dB giving an EIRP of 19.3 dBW. No other losses were assumed at this point without having actual candidate hardware for a spacecraft. The results in Table 8 are then a realistic upper limit for the achievable data rates. Also included in Table 8 is the expected data rate if total system losses (internal, pointing, polarization, etc.) amounted to over 4 dB and the EIRP were reduced to 15 dBW. For analyzing the 40-degree and 60-degree pointing cases, we will assume that an EIRP of only 15 dBW is available from the satellite. The helical antenna would need to be operated considerable off-axis in this case or some low-gain antenna system, for example a microwave patch-based antenna, would need to be used and a total gain of 5 dB is assumed.

From the link budget design table, the data rates listed in Table 10 are those expected to be needed to be supported using a SSA return service based on the orbital slant paths derived. Similar results can be obtained for a MA return service by using the Table 8 data rates.

We can estimate the total daily data volume desired to be transmitted through the space network by considering that at the 50th percentile, an average daily data volume is equivalent to an average, continuous production rate of 10 kbps [8]. This corresponds to a total production of 864,000,000 bits per day. The required minimum data rate necessary is a function of the contact duration per day and the supported data rate for the communications system.

Table 10. Maximum Data Rates for SSA Return Service		
Slant Path (km)	**Data Rate (kbps) for EIRP = 15 dBW**	**Data Rate (kbps) for EIRP = 19.3 dBW**
35500	174.0	469.0
36000	169.4	456.0
36500	164.6	443.0
37000	160.4	432.0
38000	152.0	409.4
38500	148.0	398.6

With the number of contacts per day determined and the data rate that can be supported, we are now in a position to determine if any configuration can come close to supporting the desired daily data throughput. Sample results are given in Tables 11, 12, and 13 for 20-degree, 40-degree, and 60-degree pointing thresholds, respectively. In each table, the total daily throughput through a single TDRS and through the SN is given as a function of orbit and satellite EIRP. In all of the calculations, the orbital inclination was taken to be 100° which approximates a sun-synchronous orbit. Other orbital inclinations can be obtained in a similar manner using the previous tables.

Table 11. Daily Throughput for 20-degree Pointing with Orbital Inclination Angle of 100°					
Period (rev/day)	**Contact Minutes**		**EIRP =15 dBW Data Rate (kbps)**	**Throughput (Mbits/day)**	
	TDRS East	**Constellation**		**TDRS East**	**Constellation**
14	15.4	32.9	174.0	160.8	343.5
15	15.4	30.7	169.4	156.5	312.0
16	16.2	33.3	169.4	164.7	338.5
			EIRP =19.3 dBW		
14	15.4	32.9	469.0	433.4	925.8
15	15.4	30.7	456.0	421.3	840.0
16	16.2	33.3	456.0	443.2	911.1

Table 12. Daily Throughput for 40-degree Pointing with Orbital Inclination Angle of 100°					
Period (rev/day)	Contact Minutes		EIRP =15 dBW Data Rate (kbps)	Throughput (Mbits/day)	
	TDRS East	Constellation		TDRS East	Constellation
14	78.2	153.3	164.6	772.3	1514.0
15	77.8	156.5	160.4	748.7	1506.2
16	80.1	159.3	160.4	770.9	1533.1

Table 13. Daily Throughput for 60-degree Pointing with Orbital Inclination Angle of 100°					
Period (rev/day)	Contact Minutes		EIRP =15 dBW Data Rate (kbps)	Throughput (Mbits/day)	
	TDRS East	Constellation		TDRS East	Constellation
14	186.2	371.3	152.0	1698.1	3386.3
15	181.4	366.7	148.0	1610.8	3256.3
16	198.0	393.3	148.0	1758.2	3492.5

From these tables, we can see that a single TDRS within the Space Network cannot usually give the required coverage time to support users up to the 50^{th}-percentile level. Usually, the full SN constellation is required for this type of support. However, from an operational point of view, having the required contact time necessary to achieve this level of support, especially in the 40-degree and 60-degree, may not be possible. Consider the case of 15 orbits per day where using an EIRP of 19.3 dBW and a 20-degree pointing restriction yields 56% of the data throughput of the 40-degree pointing case but at one-fifth of the contact time. Operationally, the narrow-pointing case is expected to be easier to realize in the SN scheduling system than broader-pointing case. This is seeming to indicate 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 an actual network.

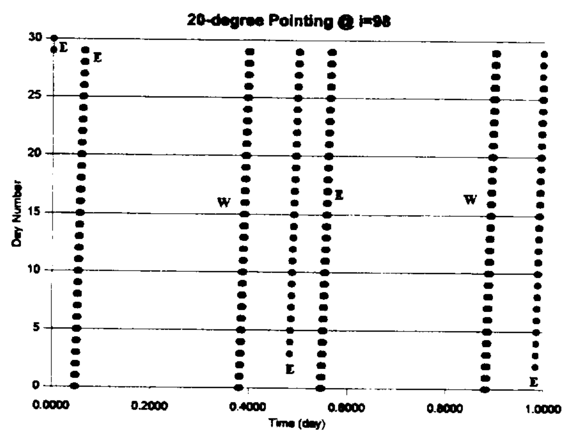
The conclusion that we obtain concerning these orbital cases is that even this modest configuration can be useful in meeting the desired throughput for small satellites.

2.7 RESULTS FOR ECCENTRIC ORBITS

The initial results were derived for circular orbits, however, many satellites will have non-circular orbits as part of the mission design. For this reason, a family of simulations was performed to obtain a sense of how the non-circular orbit cases would behave. In these simulations, the satellite was assumed to again be a helical antenna with a maximum pointing threshold of 20° as was done in the circular orbit case. Because there are several degrees of freedom in non-circular orbit determination, a minimal orbital altitude was fixed at 300 km to allow some basis for comparison. With this altitude fixed, orbital periods of 15, 14, 13, 11, 9, 7, 6, and 5 revolutions per day with inclination angles of 63° and 98° were simulated over 30-day intervals to investigate the performance of non-circular orbits. Figures 14 through 21 illustrate the access times over the 30-day period. In each figure, the notation "W" or "E" indicates whether the access was either through the west or the east TDR satellite, respectively. For each access, a single dot is placed on the graph to indicate the start and stop of the service access time assuming that the satellite needs to be within 20° of the indicated TDRS. On some orbits, the start and stop dots are on top of each other indicating a short contact while on other orbits, the dots can have a separation indicating quite a long pass, on the order of one-half an hour. Tables 14 through 21 summarize the access times for both a single TDRSS and a two-spacecraft constellation at the simulated orbital periods and inclination angles. In reviewing the results, it was noticed that the orbital access distances clustered into two general classes for each access opportunity. The clustering is given in Table 22. Using the data rate results for SSA and MA service types given in Table 8, data rates can be chosen to match the expected slant range in Table 22.

From an examination of Tables 14 through 21 and Figures 14 through 21, we can see that the eccentric orbits tend to have a few access opportunities per day at the high orbital rates and a limited access for low orbital rates. For the lowest orbital rates considered, there were many days within the simulation month where no or only very short access opportunities existed. The average was still quite high in those orbits because other days had on or two very long access orbits so that the monthly average was still respectable. Not shown in the tables is the access for the 40-degree and 60-degree pointing cases because the 20-degree pointing was assumed to be the most likely antenna configuration. With the broader antenna patterns, a factor of 3 to 10 increase in access time, as was found in the circular orbit case, is possible depending upon the configuration.

As a comparison, the same orbits were simulated using Orbital Workbench to determine the access to a fixed ground station at 107° W longitude and 32° latitude. Tables 23 through 30 show the access in the fixed ground station configuration for these same orbits. These simulations were conducted at a timing resolution of 30 seconds. The simulation assumed that the minimum satellite elevation angle visible from the ground station was 5°. If an actual ground station requires a higher minimum elevation angle, then these access times will need to be shortened and the magnitude of the decrease will depend upon the exact minimum elevation angle permitted. The fixed ground station tended to provide larger orbital access in the cases simulated. However, if the antenna beam pattern from the small satellite can be broadened from the restrictive 20-degree case used in the simulation, then the two modes become quite competitive. The main differences seen between these



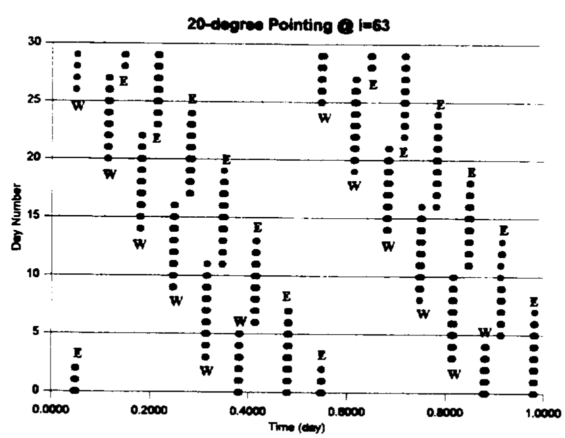
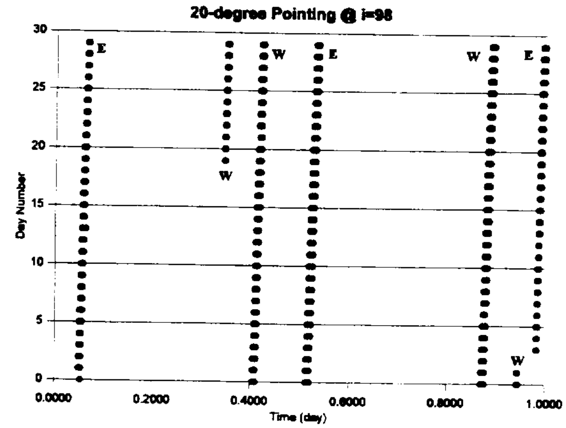


Figure 14 - Eccentric Orbit with Mean Motion of 15 revs/day



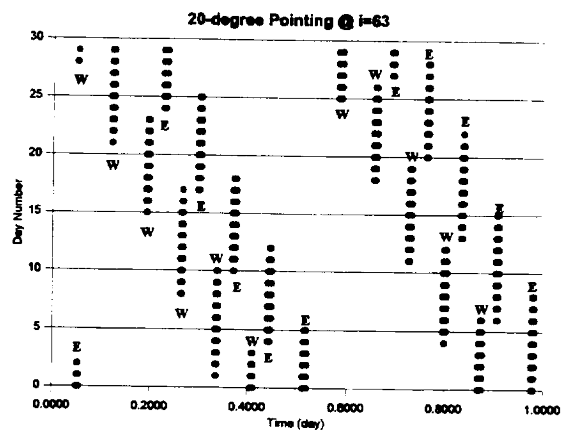
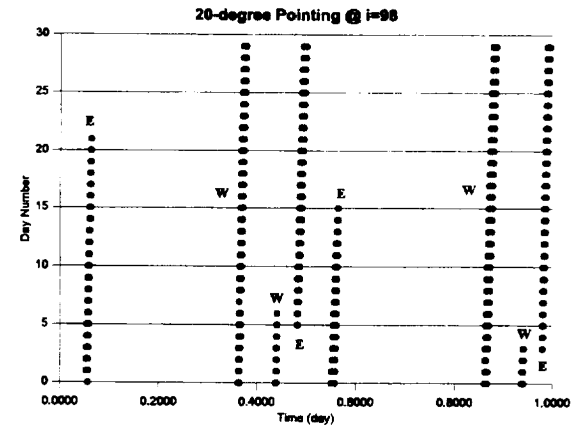


Figure 15 - Eccentric Orbit with Mean Motion of 14 revs/day



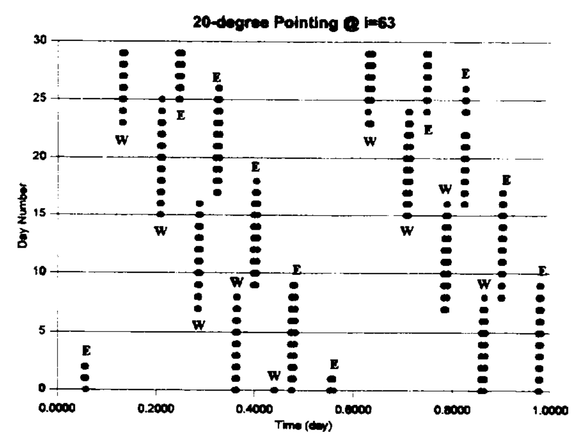


Figure 16 - Eccentric Orbit with Mean Motion of 13 revs/day

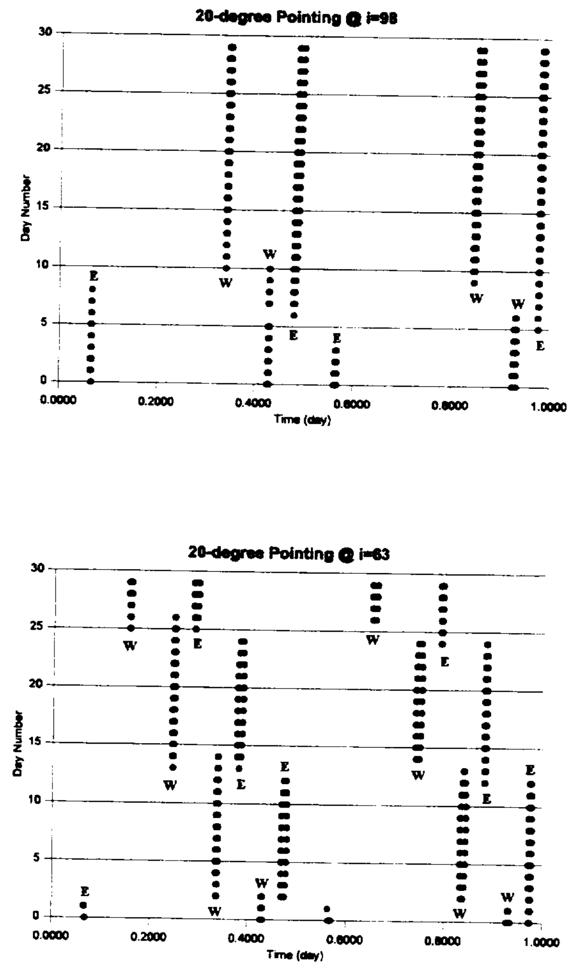
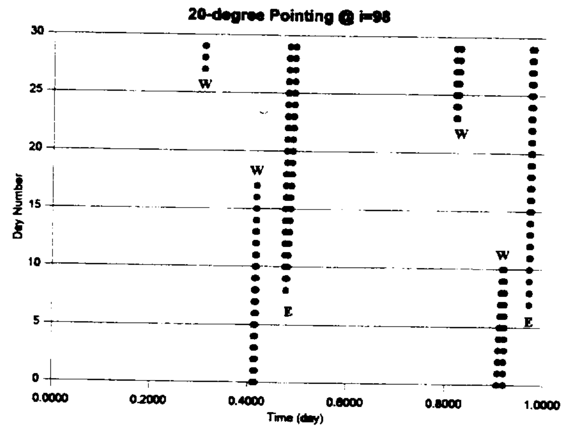


Figure 17 - Eccentric Orbit with Mean Motion of 11 revs/day



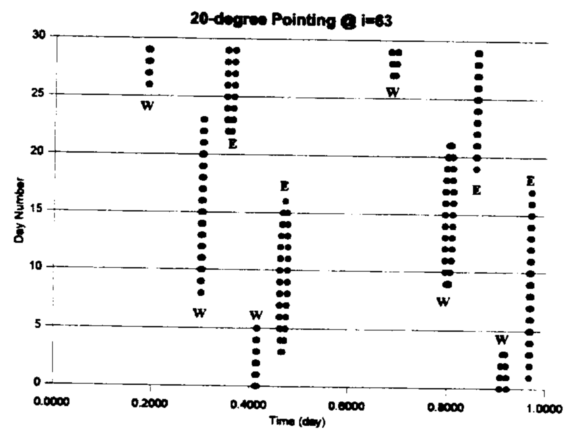


Figure 18 - Eccentric Orbit with Mean Motion of 9 revs/day

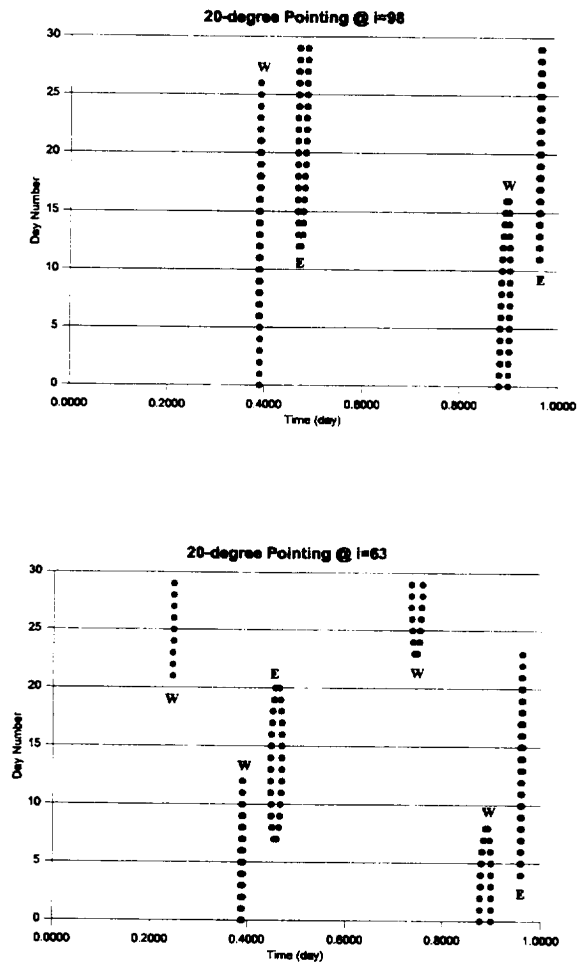


Figure 19 - Eccentric Orbit with Mean Motion of 7 revs/day

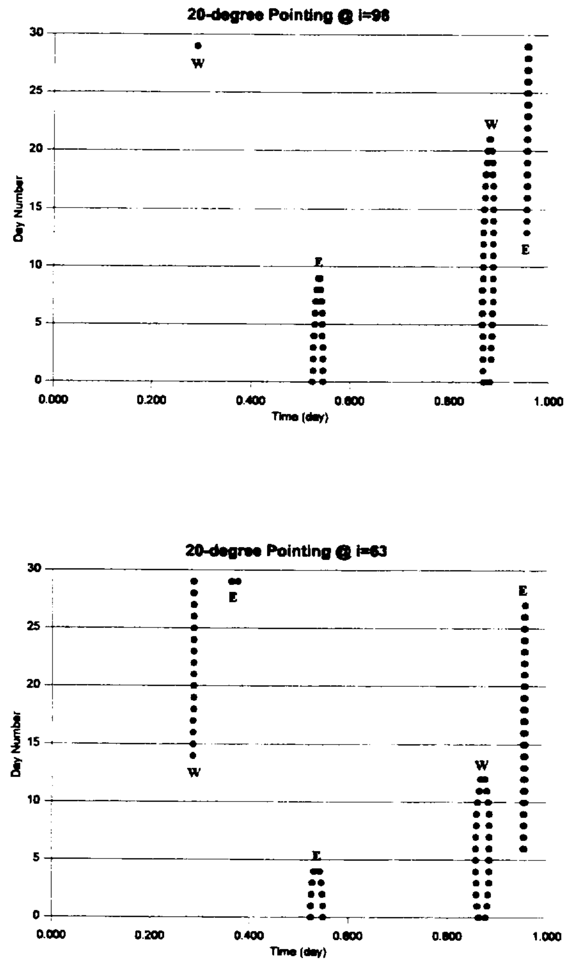


Figure 20 - Eccentric Orbit with Mean Motion of 6 revs/day

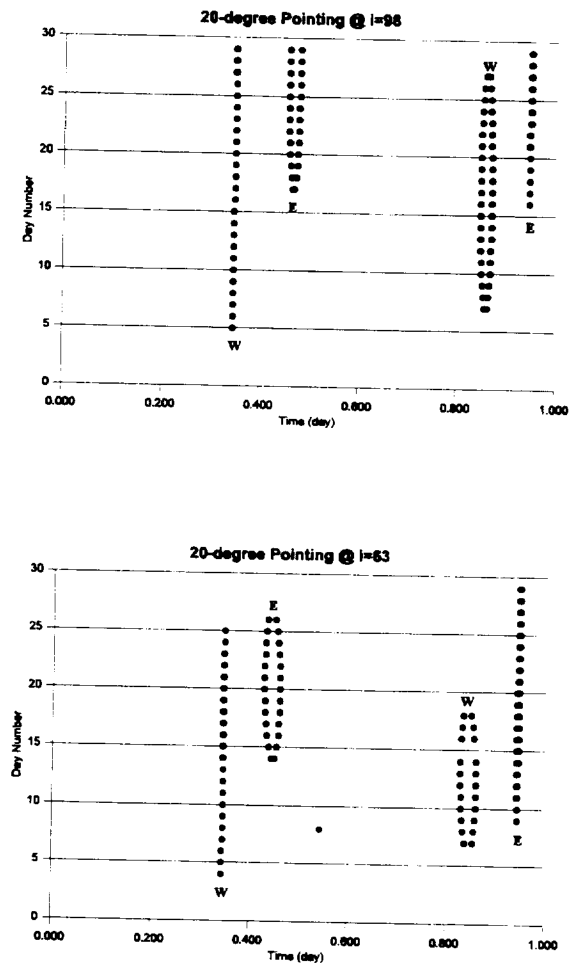


Figure 21 - Eccentric Orbit with Mean Motion of 5 revs/day

Table 14. 30-day Space Network Access in Minutes at 15 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	24.00	39.36	14.40	29.76
1	24.96	41.28	14.40	29.76
2	22.08	37.44	14.40	29.76
3	16.32	38.40	15.36	30.72
4	15.36	39.36	16.32	31.68
5	17.28	36.40	16.32	31.68
6	22.08	39.36	17.28	33.60
7	22.08	38.40	17.28	33.60
8	16.32	33.60	18.24	33.60
9	17.28	42.24	19.20	34.56
10	16.32	38.40	20.16	35.52
11	22.08	38.40	20.16	35.52
12	24.00	40.32	19.20	33.60
13	18.24	33.60	18.24	33.60
14	16.32	22.40	19.20	34.56
15	15.36	38.40	19.20	34.56
16	18.24	38.40	21.12	36.48
17	23.04	40.32	20.16	34.56
18	23.04	39.36	20.16	34.56
19	17.28	31.68	20.16	35.52
20	17.28	38.40	20.16	35.52
21	16.32	38.40	20.16	35.52
22	17.28	34.56	20.16	35.52

Table 14. 30-day Space Network Access in Minutes at 15 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
23	22.08	39.36	19.20	34.56
24	21.12	37.44	20.16	35.52
25	16.32	35.52	20.16	36.48
26	17.28	42.24	22.08	38.40
27	16.32	37.44	20.16	36.48
28	22.08	37.44	20.16	36.48
29	24.00	40.32	19.20	35.20
monthly avg.	19.39	37.61	18.75	34.24

Table 15. 30-day Space Network Access in Minutes at 14 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	20.57	37.03	15.43	32.92
1	21.60	39.09	15.43	30.86
2	20.57	40.11	15.43	29.83
3	16.46	36.00	15.43	30.86
4	20.57	39.08	15.43	29.83
5	19.54	41.44	17.49	32.92
6	16.46	34.97	17.49	32.92
7	19.54	36.00	16.46	30.86
8	19.54	39.08	17.49	32.92
9	17.49	37.03	18.51	33.94
10	19.54	38.05	18.51	33.94
11	20.57	41.14	18.51	33.94
12	18.51	39.08	18.51	34.97
13	18.51	34.97	17.49	32.92
14	20.57	36.00	18.51	33.94
15	17.49	37.03	18.51	33.94
16	17.49	38.06	18.51	32.91
17	20.57	37.03	19.54	34.97
18	20.57	40.11	17.49	33.95
19	15.43	36.00	17.49	32.92
20	18.51	34.97	19.54	36.00
21	20.57	37.03	18.51	34.97
22	17.49	37.03	19.54	36.00

Table 15. 30-day Space Network Access in Minutes at 14 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
23	16.46	36.00	18.51	36.00
24	19.54	36.00	17.49	36.00
25	20.57	41.14	18.51	37.02
26	15.43	34.97	17.49	34.98
27	19.54	36.00	18.51	36.00
28	20.57	38.06	18.51	37.02
29	17.49	37.03	16.46	33.95
monthly avg.	18.93	37.51	17.69	33.81

Table 16. 30-day Space Network Access in Minutes at 13 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	19.94	36.56	14.40	33.23
1	25.48	42.10	14.40	31.02
2	17.72	36.55	13.29	31.01
3	17.72	36.55	13.29	29.91
4	18.83	38.77	13.29	27.67
5	19.94	37.66	16.62	32.13
6	18.83	35.45	14.40	27.67
7	17.72	39.87	18.83	33.23
8	18.83	35.45	18.83	33.23
9	21.05	37.67	19.94	35.45
10	14.40	33.23	18.83	33.23
11	17.72	36.55	16.62	31.02
12	18.83	38.77	18.83	33.23
13	19.94	37.66	17.72	34.34
14	18.83	35.45	18.83	35.45
15	18.83	35.45	16.62	33.24
16	17.72	35.44	15.51	31.02
17	19.94	36.56	15.51	32.13
18	15.51	34.34	14.40	32.12
19	17.72	35.44	15.51	32.13
20	18.83	38.77	15.51	32.13
21	18.83	37.66	14.40	31.02
22	19.94	36.56	13.29	31.01

Table 16. 30-day Space Network Access in Minutes at 13 revs/day				
Day Number	**inclination = 63°**		**inclination = 98°**	
	TDRS East	**Constellation**	**TDRS East**	**Constellation**
23	17.72	37.66	14.40	32.12
24	17.72	37.66	14.40	29.91
25	19.94	36.56	15.51	33.23
26	17.72	36.55	14.40	32.12
27	17.72	35.44	15.51	32.13
28	18.83	37.66	15.51	32.13
29	17.72	36.55	16.62	34.34
monthly avg.	18.65	37.00	15.84	32.09

Table 17. 30-day Space Network Access in Minutes at 11 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	14.40	28.80	11.78	27.49
1	6.55	13.10	9.16	22.25
2	13.09	22.25	10.47	22.25
3	18.33	34.04	6.55	18.33
4	20.95	39.28	2.62	13.09
5	20.95	41.90	2.62	11.78
6	22.25	44.50	2.62	7.86
7	23.56	45.81	6.55	9.17
8	22.25	45.81	6.55	9.17
9	22.25	44.50	9.16	11.78
10	19.64	40.59	10.47	17.02
11	15.71	32.73	11.78	19.63
12	11.78	26.18	13.09	22.25
13	3.93	9.17	14.40	24.87
14	13.09	24.87	14.40	26.18
15	18.33	34.04	15.71	30.11
16	20.95	40.59	15.71	28.80
17	20.95	41.90	17.02	31.42
18	22.25	44.50	17.02	31.42
19	23.56	45.81	18.33	35.35
20	22.25	45.81	17.02	32.73
21	22.25	44.50	19.64	36.66
22	19.64	40.59	18.33	35.35

Table 17. 30-day Space Network Access in Minutes at 11 revs/day				
Day Number	**inclination = 63°**		**inclination = 98°**	
	TDRS East	**Constellation**	**TDRS East**	**Constellation**
23	15.71	32.73	18.33	35.35
24	11.78	24.87	19.64	37.97
25	5.24	9.17	18.33	37.97
26	13.09	24.87	19.64	37.97
27	18.33	34.04	18.33	37.97
28	20.95	29.00	20.95	39.28
29	20.95	41.90	19.64	39.28
monthly avg.	17.50	34.26	13.53	26.01

Table 18. 30-day Space Network Access in Minutes at 9 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	0.00	25.60	0.00	25.60
1	0.00	22.40	0.00	22.40
2	1.60	20.80	0.00	20.80
3	8.00	19.20	0.00	22.40
4	16.00	19.20	0.00	20.80
5	20.80	22.40	0.00	19.20
6	25.60	25.60	0.00	17.60
7	27.20	27.20	0.00	16.00
8	28.80	30.40	1.60	16.00
9	28.80	40.00	6.40	19.20
10	28.80	48.00	9.60	17.60
11	27.20	51.20	12.80	16.00
12	27.20	52.80	14.40	17.60
13	24.00	51.20	16.00	19.20
14	20.80	49.60	17.60	19.20
15	16.00	44.80	20.80	22.40
16	3.20	32.00	19.20	20.80
17	0.00	27.20	20.80	20.80
18	0.00	24.00	22.40	22.40
19	0.00	22.40	22.40	22.40
20	1.60	19.20	22.40	22.40
21	4.80	14.40	22.40	22.40
22	16.00	19.20	22.40	22.40

Table 18. 30-day Space Network Access in Minutes at 9 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
23	20.80	22.40	22.40	25.60
24	25.60	25.60	25.60	32.00
25	27.20	27.20	24.00	32.00
26	28.80	30.40	25.60	35.20
27	28.80	41.60	24.00	36.80
28	28.80	48.00	22.40	35.20
29	27.20	51.20	24.00	40.00
monthly avg.	17.12	31.80	13.97	23.41

Table 19. 30-day Space Network Access in Minutes at 7 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	0.00	37.03	0.00	32.91
1	0.00	37.03	0.00	32.91
2	0.00	39.09	0.00	30.86
3	0.00	37.03	0.00	32.91
4	2.06	39.09	0.00	32.91
5	2.06	37.03	0.00	32.91
6	2.06	30.86	0.00	28.80
7	12.34	34.97	0.00	30.86
8	24.69	34.98	0.00	28.80
9	28.80	32.91	0.00	28.80
10	30.86	32.92	0.00	26.74
11	34.97	34.97	2.06	28.80
12	37.03	37.03	8.20	32.92
13	39.09	39.09	14.40	34.94
14	39.09	39.09	16.46	34.97
15	37.03	37.03	20.57	37.03
16	37.03	37.03	22.63	34.97
17	34.97	34.97	24.69	28.80
18	28.80	28.80	24.69	28.80
19	22.63	22.63	26.74	30.85
20	14.40	14.40	26.74	30.85
21	2.06	4.12	28.80	32.91
22	0.00	2.06	28.80	30.86

Table 19. 30-day Space Network Access in Minutes at 7 revs/day				
Day Number	**inclination = 63°**		**inclination = 98°**	
	TDRS East	**Constellation**	**TDRS East**	**Constellation**
23	0.00	10.29	30.86	32.92
24	0.00	22.63	30.86	30.86
25	0.00	26.74	30.86	30.86
26	0.00	30.86	30.86	30.86
27	0.00	34.97	28.80	28.80
28	0.00	37.03	28.80	28.80
29	0.00	37.03	28.80	28.80
monthly avg.	14.33	30.86	15.16	31.27

Table 20. 30-day Space Network Access in Minutes at 6 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	36.00	55.20	31.20	48.00
1	36.00	64.80	28.80	50.40
2	31.20	64.80	28.80	52.80
3	26.40	62.40	28.80	52.80
4	16.80	55.20	24.00	50.40
5	0.00	38.40	21.60	50.40
6	2.40	40.80	21.60	50.40
7	2.40	40.80	16.80	48.00
8	2.40	38.40	12.00	43.20
9	2.40	38.40	4.80	33.60
10	4.80	36.00	0.00	28.80
11	4.80	23.60	0.00	28.80
12	4.80	16.80	0.00	28.80
13	4.80	4.80	0.00	28.80
14	4.80	4.80	0.00	26.40
15	4.80	7.20	2.40	28.80
16	4.80	7.20	2.40	26.40
17	4.80	7.20	2.40	26.40
18	4.80	9.60	2.40	21.60
19	4.80	9.60	2.40	19.20
20	2.40	7.20	2.40	14.40
21	2.40	7.20	2.40	4.80
22	2.40	7.20	2.40	2.40

Table 20. 30-day Space Network Access in Minutes at 6 revs/day				
Day Number	**inclination = 63°**		**inclination = 98°**	
	TDRS East	**Constellation**	**TDRS East**	**Constellation**
23	2.40	7.20	4.80	4.80
24	2.40	7.20	4.80	4.80
25	2.40	7.20	4.80	4.80
26	0.00	4.80	4.80	4.80
27	0.00	4.80	4.80	4.80
28	0.00	2.40	4.80	4.80
29	19.20	21.60	4.80	4.80
monthly avg.	7.92	23.49	9.04	26.40

Table 21. 30-day Space Network Access in Minutes at 5 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
0	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
4	0.00	2.88	0.00	0.00
5	0.00	2.88	0.00	0.00
6	0.00	2.88	0.00	0.00
7	0.00	28.80	0.00	11.52
8	0.00	37.44	0.00	17.28
9	0.00	43.20	0.00	23.04
10	0.00	48.96	0.00	28.80
11	2.88	51.84	0.00	28.80
12	2.88	54.72	0.00	31.68
13	2.88	54.72	0.00	34.56
14	14.40	63.36	0.00	34.56
15	28.80	72.00	0.00	34.56
16	40.32	80.64	0.00	37.44
17	43.20	77.76	5.76	43.20
18	48.96	74.88	14.40	51.84
19	48.96	51.84	20.16	57.60
20	51.84	54.72	23.04	60.48
21	48.96	51.84	28.80	63.36
22	48.96	51.84	31.68	66.24

Table 21. 30-day Space Network Access in Minutes at 5 revs/day				
Day Number	inclination = 63°		inclination = 98°	
	TDRS East	Constellation	TDRS East	Constellation
23	43.20	46.08	31.68	63.36
24	40.32	40.32	31.68	60.48
25	34.56	34.56	34.56	60.48
26	25.92	25.92	34.56	57.60
27	2.88	2.88	34.56	46.08
28	2.88	2.88	34.56	37.44
29	2.88	2.88	34.56	37.44
monthly avg.	17.86	35.42	12.00	41.55

Table 22. Eccentric Orbit Access Distances		
Orbital Period (rev/day)	**Cluster 1 (1000 km)**	**Cluster 2 (1000 km)**
15	35.8	35.4
14	35.5	34.6
13	35.6	34.1
11	35.7	32.3
9	35.6	29.9
7	35.6	26.4
6	35.7	23.9
5	35.7	20.8

simulations and those listed in Table 1 come from the difference in orbital period (Table 1 used 16 revolutions per day) and, with the higher orbital altitude, the orbital geometry providing for higher orbital altitudes yielding slower passes through the ground station visibility region.

As was mentioned above, an interesting phenomenon was observed with the eccentric orbits, namely, that there tended to be two access classes for the orbits: one with a relatively lower inter-satellite distance than the other. In the access plots of Figures 14 through 20, the distance for each access occurring at the same time each day was approximately the same. As in the circular orbit case, this slant range is the range at the start of the access window and represents the maximum distance during the pass. The lower inter-satellite distance often occurred at the perigee point in the orbit thereby making for contacts with long duration and the possibility of higher data transfer rates. This suggests that whenever possible by mission design rules, the orbital parameters should be chosen such that orbital data transfers occur when the satellite is near its perigee point and that this perigee point should be phased to occur near the earth's equator so that the satellite is pointing towards a TDRS.

Table 23. 30-day Fixed Ground Terminal Access in Minutes at 15 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	37.50	29.50
1	37.50	30.00
2	40.00	30.50
3	40.00	31.50
4	40.00	31.50
5	41.00	32.00
6	40.00	32.00
7	38.50	32.50
8	38.50	32.50
9	38.50	33.50
10	38.50	33.50
11	39.00	34.50
12	39.00	34.50
13	39.00	35.00
14	38.50	35.50
15	38.00	36.50
16	38.50	36.00
17	38.00	37.00
18	38.50	37.00
19	38.00	37.50
20	38.00	37.00
21	36.50	38.00
22	37.00	37.50
23	36.00	38.00

Table 23. 30-day Fixed Ground Terminal Access in Minutes at 15 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	35.50	38.00
25	35.50	37.50
26	35.00	38.50
27	33.50	37.50
28	32.50	36.50
29	31.50	37.50
monthly avg.	37.60	35.00

Table 24. 30-day Fixed Ground Terminal Access in Minutes at 14 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	56.00	50.50
1	57.50	52.00
2	57.50	52.50
3	57.50	53.50
4	58.50	54.50
5	57.50	55.50
6	57.50	56.00
7	57.00	56.50
8	58.50	56.00
9	58.00	57.50
10	57.50	58.00
11	75.00	60.00
12	56.50	61.00
13	57.50	62.50
14	58.50	64.00
15	58.50	64.50
16	58.50	65.00
17	59.00	67.50
18	60.00	69.00
19	59.00	70.50
20	59.50	71.00
21	59.00	72.50
22	58.50	73.00
23	59.50	74.00

Table 24. 30-day Fixed Ground Terminal Access in Minutes at 14 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	59.00	74.00
25	60.00	75.50
26	61.00	75.00
27	62.00	76.50
28	62.00	76.50
29	62.00	77.50
monthly avg.	59.30	64.40

Table 25. 30-day Fixed Ground Terminal Access in Minutes at 13 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	82.50	75.50
1	84.50	77.00
2	88.50	78.50
3	87.50	79.50
4	88.00	81.00
5	90.50	82.00
6	90.00	84.50
7	83.50	84.50
8	84.00	86.00
9	83.50	87.00
10	87.50	88.00
11	89.00	89.50
12	87.50	90.00
13	87.00	90.50
14	91.00	91.50
15	87.00	92.00
16	81.50	93.50
17	82.00	93.50
18	82.50	94.50
19	87.00	95.00
20	86.50	98.00
21	85.00	100.00
22	85.50	101.50
23	85.00	102.50

Table 25. 30-day Fixed Ground Terminal Access in Minutes at 13 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	79.50	104.00
25	81.00	105.00
26	82.00	107.00
27	82.00	107.00
28	85.50	108.00
29	86.50	109.00
monthly avg.	85.40	92.50

Table 26. 30-day Fixed Ground Terminal Access in Minutes at 11 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	145.50	118.50
1	147.00	120.50
2	149.00	122.00
3	150.50	124.00
4	151.50	125.50
5	154.00	127.00
6	157.50	129.00
7	157.50	130.00
8	159.00	131.00
9	158.50	133.00
10	155.50	141.00
11	149.00	145.00
12	144.00	150.50
13	147.50	151.50
14	148.50	154.50
15	150.50	159.50
16	151.00	165.00
17	151.50	168.50
18	155.00	172.00
19	158.00	174.50
20	159.00	177.00
21	157.50	180.00
22	155.50	182.00
23	151.50	184.00

Table 26. 30-day Fixed Ground Terminal Access in Minutes at 11 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	147.50	185.50
25	143.00	188.50
26	145.00	190.50
27	147.50	192.00
28	148.50	193.00
29	149.00	195.00
monthly avg.	151.50	157.00

Table 27. 30-day Fixed Ground Terminal Access in Minutes at 9 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	208.50	173.50
1	211.00	175.00
2	213.00	176.00
3	215.50	176.50
4	216.00	178.50
5	220.50	183.00
6	223.50	196.00
7	226.00	203.50
8	227.00	208.50
9	227.50	212.50
10	227.50	217.50
11	228.00	220.50
12	225.50	224.00
13	223.50	226.00
14	215.50	228.50
15	200.50	236.00
16	204.00	239.50
17	206.00	243.50
18	208.00	247.00
19	210.00	249.50
20	211.50	252.00
21	213.00	254.00
22	215.00	257.50
23	217.00	259.00

Table 27. 30-day Fixed Ground Terminal Access in Minutes at 9 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	219.00	261.00
25	222.00	263.50
26	225.00	265.50
27	226.00	266.50
28	227.50	268.50
29	227.00	270.50
monthly avg.	218.00	227.80

Table 28. 30-day Fixed Ground Terminal Access in Minutes at 7 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	289.00	234.00
1	290.50	240.50
2	292.00	239.00
3	293.50	240.50
4	298.00	240.50
5	300.00	241.50
6	301.00	241.00
7	301.50	241.50
8	302.00	259.50
9	301.50	275.50
10	300.00	285.50
11	298.00	293.00
12	294.50	298.50
13	292.50	304.50
14	286.50	308.50
15	280.00	312.50
16	265.50	317.50
17	255.50	324.50
18	258.00	328.50
19	261.00	333.50
20	263.00	337.00
21	266.00	340.50
22	268.50	344.00
23	271.00	347.50

Table 28. 30-day Fixed Ground Terminal Access in Minutes at 7 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	274.00	350.00
25	277.00	352.50
26	279.50	356.00
27	281.00	358.50
28	284.00	359.50
29	286.50	363.50
monthly avg.	283.70	302.50

Table 29. 30-day Fixed Ground Terminal Access Minutes at 6 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	335.50	262.00
1	338.00	264.00
2	340.50	264.50
3	342.00	264.50
4	343.50	265.00
5	343.50	265.00
6	343.50	263.00
7	343.50	263.50
8	341.50	264.00
9	340.00	263.50
10	337.50	263.50
11	333.00	264.00
12	328.00	291.00
13	320.50	311.00
14	312.00	324.00
15	294.50	333.50
16	286.00	342.50
17	288.50	349.00
18	290.00	355.50
19	291.50	362.00
20	293.00	366.00
21	294.50	371.00
22	298.50	375.00
23	302.00	380.00

Table 29. 30-day Fixed Ground Terminal Access Minutes at 6 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	304.00	382.50
25	306.50	385.50
26	309.00	389.50
27	311.50	393.00
28	312.50	395.00
29	314.00	398.50
monthly avg.	317.90	322.40

Table 30. 30-day Fixed Ground Terminal Access in Minutes at 5 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
0	348.00	310.00
1	351.50	309.50
2	352.00	310.00
3	352.50	310.00
4	354.00	309.00
5	355.00	308.50
6	355.00	309.00
7	355.50	308.50
8	355.50	308.00
9	354.50	308.00
10	351.00	308.00
11	342.50	307.50
12	327.50	307.00
13	333.50	306.50
14	338.00	306.00
15	343.50	306.00
16	202.00	305.00
17	351.00	305.00
18	354.50	332.50
19	356.50	358.50
20	359.50	376.50
21	361.50	389.00
22	363.50	402.00
23	365.50	410.00

Table 30. 30-day Fixed Ground Terminal Access in Minutes at 5 revs/day		
Day Number	**inclination = 63°**	**inclination = 98°**
24	367.00	419.00
25	367.50	427.00
26	368.50	433.00
27	370.00	439.00
28	370.00	444.00
29	371.00	449.50
monthly avg.	349.90	347.40

2.8 REFERENCES

The references cited in this study are as follows.

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2.9 MATHCAD EXAMPLE

The following pages list a MATHCAD document for computing the orbital analysis presented here. The document was developed under MATHCAD version 4.0. The document performs the analysis over a 24-hour period. All results are printed within the document itself. To change any satellite orbital parameters, the user needs to edit the corresponding orbital elements on the first page of the document.

Define Kepler's Equation for the Eccentric Anomaly, EA, in terms of the Mean Anomaly, MA and the orbital eccentricity, ecc:

$$E(MA, ecc, EA) := \mathrm{root}(MA - EA + ecc\cdot\sin(EA), EA)$$

Define the True Anomaly, in terms of the Eccentric Anomaly and the eccentricity

$$\theta(EA, ecc) := \mathrm{angle}\left(\cos(EA) - ecc, \sqrt{1 - ecc^2}\cdot\sin(EA)\right)$$

Define the pointing vector in terms of the RAAN, inclination, and longitude

$$V(\Omega,u,i) := \begin{pmatrix} \cos(\Omega)\cdot\cos(u) - \sin(\Omega)\cdot\cos(i)\cdot\sin(u) \\ \sin(\Omega)\cdot\cos(u) + \cos(\Omega)\cdot\cos(i)\cdot\sin(u) \\ \sin(i)\cdot\sin(u) \end{pmatrix}$$

Define the orbital elements for the first TDRS satellie

$\omega T1 := 145.5958\cdot deg$ $\quad RAANT1 := 189.2052\cdot deg$ $\quad iT1 := 0.0440\cdot deg$

$eccT1 := 0.0001440$ $\quad M0T1 := 114.2497\cdot deg$ $\quad PT1 := \dfrac{1}{1.00269052}$

Define the orbital elements for the second TDRS satellie

$\omega T2 := 262.53868\cdot deg$ $\quad RAANT2 := 87.13790\cdot deg$ $\quad iT2 := 0.0861141\cdot deg$

$eccT2 := 0.0001122134$ $\quad M0T2 := 326.11477\cdot deg$ $\quad PT2 := \dfrac{1}{1.00275934}$

Define the orbital elements for the satellite

$\omega S := 0\cdot deg$ $\quad RAANS := 100\cdot deg$ $\quad iS := 0\cdot deg$

$eccS := 0.001$ $\quad M0S := 100\cdot deg$

$MMS := 16$ $\quad PS := \dfrac{1}{MMS}$

Define the number of points to be examined

Number of Orbits per Day:

Number of Points per Orbit: $ppo := 100$ $\quad opd := MMS$

Index to total points $\quad klst := ppo\cdot opd$ $\quad k := 0, 1 .. (klst - 1)$ $\quad klst = 1600$

Time increment: $\quad \Delta t := (klst)^{-1}$ $\quad \Delta t = 6.25\cdot 10^{-4}$ day

Define the Mean Anomaly vector for each satellite

$MT1_k := \dfrac{2\cdot\pi}{PT1}\cdot(k\cdot\Delta t) + M0T1$ $\quad MT2_k := \dfrac{2\cdot\pi}{PT2}\cdot(k\cdot\Delta t) + M0T2$ $\quad MS_k := \dfrac{2\cdot\pi}{PS}\cdot(k\cdot\Delta t) + M0S$

$MT1_1 = 114.475\cdot deg$ $\quad MT2_1 = 326.34\cdot deg$ $\quad MS_1 = 103.6\cdot deg$

Compute the Eccentric Anomaly for each satellite

$EAT1_k := MT1_k$ $\quad EAT2_k := MT2_k$ $\quad EAS_k := MS_k$ $\quad$ initial guess for the EA

$EAT1_k := E\left(MT1_k, eccT1, EAT1_k\right)$ $\quad EAS_k := E\left(MS_k, eccS, EAS_k\right)$ $\quad$ solve for EA

$EAT1_1 = 114.483\cdot deg$ $\quad EAS_1 = 103.656\cdot deg$

$EAT2_k := E\left(MT2_k, eccT2, EAT2_k\right)$

$EAT2_1 = 326.337\cdot deg$

Compute the True Anomaly for each satellite

$TAT1_k := \theta(EAT1_k, eccT1)$ $\quad$ $TAT2_k := \theta(EAT2_k, eccT2)$ $\quad$ $TAS_k := \theta(EAS_k, eccS)$

$TAT1_1 = 114.490323 \cdot deg$ $\quad$ $TAT2_1 = 326.333263 \cdot deg$ $\quad$ $TAS_1 = 103.711346 \cdot deg$

Compute the longitude of each satellite

$uT1_k := \omega T1 + TAT1_k$ $\quad$ $uT2_k := \omega T2 - TAT2_k$ $\quad$ $uS_k := \omega S + TAS_k$

$uT1_1 = 260.086 \cdot deg$ $\quad$ $uT2_1 = 588.872 \cdot deg$ $\quad$ $uS_1 = 103.711 \cdot deg$

Compute the dot product of the pointing vectors

$DP1_k := V(RAANT1, uT1_k, iT1) \cdot V(RAANS, uS_k, iS)$ $\quad$ $DP1_1 = -0.413$

$DP2_k := V(RAANT2, uT2_k, iT2) \cdot V(RAANS, uS_k, iS)$ $\quad$ $DP2_1 = -0.379$

Compute the angle between the vectors

$\Phi 1_k := acos(DP1_k)$ $\quad$ $\Phi 1_1 = 114.42 \cdot deg$

$\Phi 2_k := acos(DP2_k)$ $\quad$ $\Phi 2_1 = 112.298 \cdot deg$

Define the gravitational parameter $\quad$ $\mu := 3.986008 \cdot 10^5$ km^3/s^2

Define the conversion between days and seconds: $\quad$ $spd := 24 \cdot 60 \cdot 60$

Compute the radial distance for each satellite

First the semi-major axes are found:

$$aT1 := \left[\left(\frac{PT1 \cdot spd}{2 \cdot \pi}\right)^2 \cdot \mu\right]^{\frac{1}{3}} \qquad aS := \left[\left(\frac{PS \cdot spd}{2 \cdot \pi}\right)^2 \cdot \mu\right]^{\frac{1}{3}}$$

$$aT2 := \left[\left(\frac{PT2 \cdot spd}{2 \cdot \pi}\right)^2 \cdot \mu\right]^{\frac{1}{3}}$$

$aS = 6652.6$ kilometers

$aT1 = 42165.5$ kilometers

$aT2 = 42163.6$ kilometers

Second the radial distances are computed

$$radT1_k := \frac{aT1 \cdot (1 - eccT1^2)}{1 + eccT1 \cdot \cos(TAT1_k)} \qquad radT2_k := \frac{aT2 \cdot (1 - eccT2^2)}{1 - eccT2 \cdot \cos(TAT2_k)}$$

$radT1_1 = 42168$ $\quad$ $radT2_1 = 42159.6$

$$radS_k := \frac{aS \cdot (1 - eccS^2)}{1 + eccS \cdot \cos(TAS_k)}$$

$radS_1 = 6654.1$

Compute the slant path difference

$DP1_k := \left| radT1_k \cdot V(RAANT1, uT1_k, iT1) - radS_k \cdot V(RAANS, uS_k, iS) \right|$ $\quad$ $DP1_1 = 45325.772$

$DP2_k := \left| radT2_k \cdot V(RAANT2, uT2_k, iT2) - radS_k \cdot V(RAANS, uS_k, iS) \right|$ $\quad$ $DP2_1 = 45106.551$

Compute the complement to the elevation angle

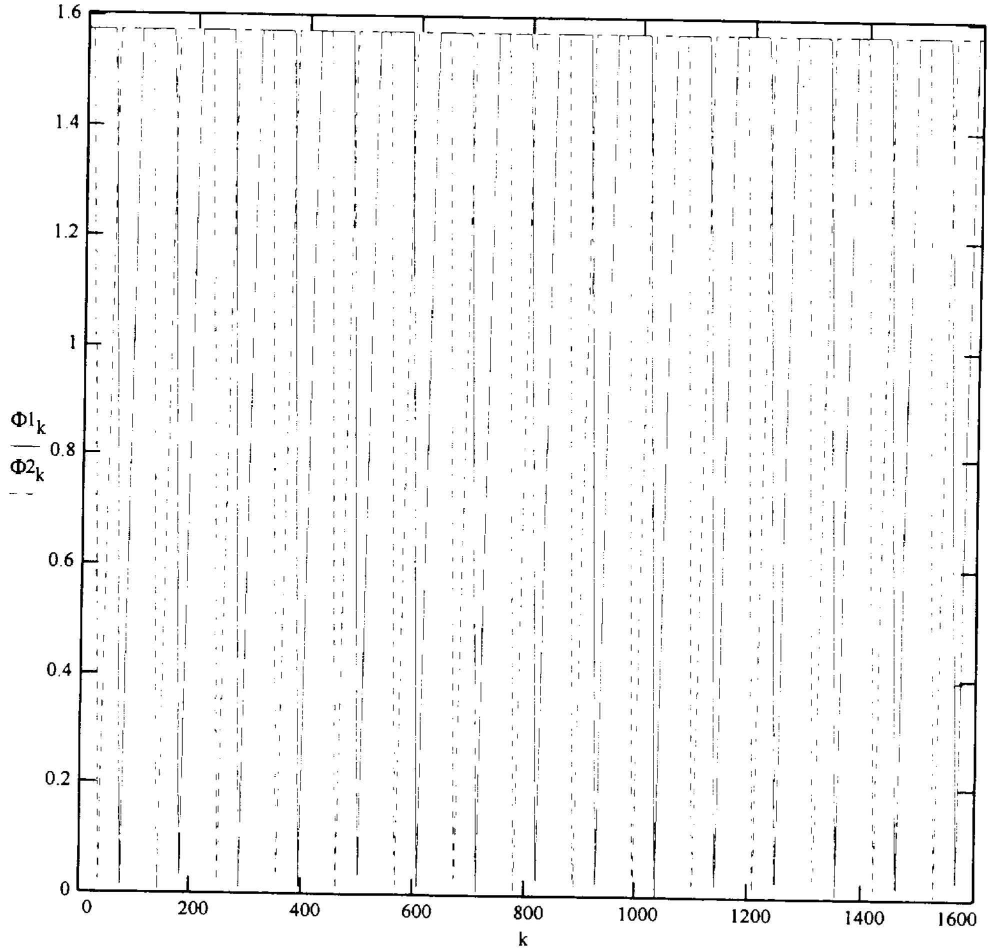
$$\Phi 1_k := if\left(\Phi 1_k < 81.3 \cdot deg, 90 \cdot deg - acos\left(\frac{radT1_k}{DP1_k} \cdot \sin(\Phi 1_k)\right), \frac{\pi}{2}\right)$$

$\Phi 1_1 = 90 \cdot deg$

$$\Phi 2_k := if\left(\Phi 2_k < 81.3 \cdot deg, 90 \cdot deg - acos\left(\frac{radT2_k}{DP2_k} \cdot \sin(\Phi 2_k)\right), \frac{\pi}{2}\right)$$

$\Phi 2_1 = 90 \cdot deg$

Satellite Inclination angle: $iS = 0 \cdot deg$



Define the test angle functions $f(x,lim) := if(|x|>lim,0,1)$

$g(x,y,lim) := if((|x|<lim)+(|y|<lim),1,0)$

$h(x,y,lim) := if((|x|<lim)\cdot(|y|<lim),1,0)$

Define orbit number: $m := 0,1..(opd-1)$

Compute when the satellite is within the desired angular distance of the first TDRS

Initialize the counter variables

$hits\_20_m := 0$ $hits\_40_m := 0$ $hits\_60_m := 0$

Find access time for 20-degree pointing angle

$$hits\_20_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} := hits\_20_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} + f\left(\Phi1_k, 20\cdot deg\right)$$

minutes

max hits: $max(hits\_20) = 11$ access time: $max(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 9.9$

min hits: $min(hits\_20) = 4$ access time: $min(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 3.6$

average hits: $mean(hits\_20) = 9.44$ access time: $mean(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 8.5$

Find the slant path difference at the threshold angle

$rmax_k := 0$

Compute slant path at the threshold angle

$rmax_k := if(|\Phi 1_k| \le 20 \cdot deg, DP1_k, rmax_k)$

Maximum slant path is $max(rmax) = 35844$ kilometers

Find access time for 40-degree pointing angle

$hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + f(\Phi 1_k, 40 \cdot deg)$

minutes

max hits: $max(hits\_40) = 21$ access time: $max(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 18.9$

min hits: $min(hits\_40) = 13$ access time: $min(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 11.7$

average hits: $mean(hits\_40) = 18.94$ access time: $mean(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 17$

Compute slant path at the threshold angle

$rmax_k := if(|\Phi 1_k| \le 40 \cdot deg, DP1_k, rmax_k)$

Maximum slant path is $max(rmax) = 36833.8$ kilometers

Find access time for 60-degree pointing angle

$hits\_60_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_60_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + f(\Phi 1_k, 60 \cdot deg)$

minutes

max hits: $max(hits\_60) = 31$ access time: $max(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 27.9$

min hits: $min(hits\_60) = 24$ access time: $min(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 21.6$

average hits: $mean(hits\_60) = 28.94$ access time: $mean(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 26$

Compute slant path at the threshold angle

$rmax_k := if(|\Phi 1_k| \le 60 \cdot deg, DP1_k, rmax_k)$

Maximum slant path is $max(rmax) = 38443.1$ kilometers

Convert hits to time:

$hits\_20_m := hits\_20_m \cdot \Delta t \cdot 24 \cdot 60$

$hits\_40_m := hits\_40_m \cdot \Delta t \cdot 24 \cdot 60$

$hits\_60_m := hits\_60_m \cdot \Delta t \cdot 24 \cdot 60$

$\sum_m if(hits\_20_m > 5, hits\_20_m, 0) = 132.3$ minutes

$\sum_m if(hits\_40_m > 5, hits\_40_m, 0) = 272.7$ minutes

$\sum_m if(hits\_60_m > 5, hits\_60_m, 0) = 416.7$ minutes

TDRS #1 Inclination: $iS = 0 \cdot deg$ Mean Motion: $MMS = 16$ rev/day

hits_20 =

	0
0	9
1	9
2	9
3	9
4	3.6
5	5.4
6	9
7	9
8	9
9	9
10	9.9
11	9
12	9
13	9
14	9
15	9

hits_40 =

	0
0	18
1	18
2	18
3	14.4
4	11.7
5	11.7
6	16.2
7	18.9
8	18
9	18
10	18.9
11	18
12	18
13	18.9
14	18
15	18

hits_60 =

	0
0	27.9
1	27
2	25.2
3	21.6
4	21.6
5	21.6
6	21.6
7	27
8	27.9
9	27.9
10	27.9
11	27.9
12	27.9
13	27.9
14	27.9
15	27.9

Compute when the satellite is within the desired angular distance of the second TDRS

Initialize the counter variables

$hits\_20_m := 0$ $hits\_40_m := 0$ $hits\_60_m := 0$

Find access time for 20-degree pointing angle

$$hits\_20_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_20_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + f\left(\Phi 2_k, 20 \cdot deg\right)$$

Compute the slant path difference

minutes

max hits: $max(hits\_20) = 10$ access time: $max(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 9$

min hits: $min(hits\_20) = 3$ access time: $min(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 2.7$

average hits: $mean(hits\_20) = 9.38$ access time: $mean(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 8.4$

Find the slant path difference at the threshold angle

$rmax_k := 0$

Compute slant path at the threshold angle

$rmax_k := if\left(\left|\Phi 2_k\right| \le 20 \cdot deg, DP2_k, rmax_k\right)$

Maximum slant path is $max(rmax) = 35844.6$ kilometers

Find access time for 40-degree pointing angle

$$hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + f\left(\Phi 2_k, 40 \cdot deg\right)$$

minutes

max hits: $max(hits\_40) = 21$ access time: $max(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 18.9$

min hits: $min(hits\_40) = 13$ access time: $min(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 11.7$

average hits: $mean(hits\_40) = 19$ access time: $mean(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 17.1$

Compute slant path at the threshold angle

$rmax_k := if(|\Phi2_k| \le 40 \cdot deg, DP2_k, rmax_k)$

Maximum slant path is $max(rmax) = 36857.4$ kilometers

Find access time for 60-degree pointing angle

$hits\_60_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_60_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + f(\Phi2_k, 60 \cdot deg)$

minutes

max hits: $max(hits\_60) = 31$ access time: $max(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 27.9$

min hits: $min(hits\_60) = 24$ access time: $min(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 21.6$

average hits: $mean(hits\_60) = 28.94$ access time: $mean(hits\_60) \cdot \Delta t \cdot 24 \cdot 60 = 26$

Compute slant path at the threshold angle

$rmax_k := if(|\Phi2_k| \le 60 \cdot deg, DP2_k, rmax_k)$

Maximum slant path is $max(rmax) = 38433.7$ kilometers

Compute when the satellite is in the field of view of both TDRS spacecraft as a function of the threshold angle

Initialize the counter variables

$hits\_20_m := 0$ $hits\_40_m := 0$ $hits\_60_m := 0$

Find access time for 20-degree pointing angle

$hits\_20_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_20_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + h(\Phi1_k, \Phi2_k, 20 \cdot deg)$

minutes

max hits: $max(hits\_20) = 0$ access time: $max(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 0$

min hits: $min(hits\_20) = 0$ access time: $min(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 0$

average hits: $mean(hits\_20) = 0$ access time: $mean(hits\_20) \cdot \Delta t \cdot 24 \cdot 60 = 0$

Find access time for 40-degree pointing angle

$hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} := hits\_40_{floor\left(k \cdot \frac{\Delta t}{PS}\right)} + h(\Phi1_k, \Phi2_k, 40 \cdot deg)$

minutes

max hits: $max(hits\_40) = 0$ access time: $max(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 0$

min hits: $min(hits\_40) = 0$ access time: $min(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 0$

average hits: $mean(hits\_40) = 0$ access time: $mean(hits\_40) \cdot \Delta t \cdot 24 \cdot 60 = 0$

Find access time for 60-degree pointing angle

$$hits\_60_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} := hits\_60_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} + h\left(\Phi 1_k, \Phi 2_k, 60\cdot deg\right)$$

minutes

max hits: $max(hits\_60) = 0$ access time: $max(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 0$

min hits: $min(hits\_60) = 0$ access time: $min(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 0$

average hits: $mean(hits\_60) = 0$ access time: $mean(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 0$

Compute when the satellite is in the field of view of either TDRS spacecraft as a function of the threshold angle

Initialize the counter variables

$hits\_20_m := 0$ $hits\_40_m := 0$ $hits\_60_m := 0$

Find access time for 20-degree pointing angle

$$hits\_20_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} := hits\_20_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} + g\left(\Phi 1_k, \Phi 2_k, 20\cdot deg\right)$$

minutes

max hits: $max(hits\_20) = 20$ access time: $max(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 18$

min hits: $min(hits\_20) = 14$ access time: $min(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 12.6$

average hits: $mean(hits\_20) = 18.81$ access time: $mean(hits\_20)\cdot\Delta t\cdot 24\cdot 60 = 16.9$

Find access time for 40-degree pointing angle

$$hits\_40_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} := hits\_40_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} + g\left(\Phi 1_k, \Phi 2_k, 40\cdot deg\right)$$

minutes

max hits: $max(hits\_40) = 42$ access time: $max(hits\_40)\cdot\Delta t\cdot 24\cdot 60 = 37.8$

min hits: $min(hits\_40) = 33$ access time: $min(hits\_40)\cdot\Delta t\cdot 24\cdot 60 = 29.7$

average hits: $mean(hits\_40) = 37.94$ access time: $mean(hits\_40)\cdot\Delta t\cdot 24\cdot 60 = 34.1$

Find access time for 60-degree pointing angle

$$hits\_60_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} := hits\_60_{floor\left(k\cdot\frac{\Delta t}{PS}\right)} + g\left(\Phi 1_k, \Phi 2_k, 60\cdot deg\right)$$

minutes

max hits: $max(hits\_60) = 62$ access time: $max(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 55.8$

min hits: $min(hits\_60) = 54$ access time: $min(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 48.6$

average hits: $mean(hits\_60) = 57.88$ access time: $mean(hits\_60)\cdot\Delta t\cdot 24\cdot 60 = 52.1$

TDRS Constellation Inclination: $iS = 0\cdot deg$ Mean Motion: $MMS = 16$ rev/day

Convert hits to time:

$hits\_20_m := hits\_20_m\cdot\Delta t\cdot 24\cdot 60$

$hits\_40_m := hits\_40_m\cdot\Delta t\cdot 24\cdot 60$

$hits\_60_m := hits\_60_m\cdot\Delta t\cdot 24\cdot 60$

$$\sum_m \mathrm{if}\left(hits\_20_m > 5, hits\_20_m, 0\right) = 270.9$$ minutes

$$\sum_m \mathrm{if}\left(hits\_40_m > 5, hits\_40_m, 0\right) = 546.3$$ minutes

$$\sum_m \mathrm{if}\left(hits\_60_m > 5, hits\_60_m, 0\right) = 833.4$$ minutes

hits_20 =

	0
0	18
1	18
2	18
3	18
4	12.6
5	14.4
6	18
7	18
8	18
9	18
10	12.6
11	15.3
12	18
13	18
14	18
15	18

hits_40 =

	0
0	36
1	36.9
2	36
3	32.4
4	30.6
5	29.7
6	34.2
7	37.8
8	36
9	31.5
10	30.6
11	30.6
12	34.2
13	36.9
14	36
15	36.9

hits_60 =

	0
0	55.8
1	54.9
2	53.1
3	49.5
4	49.5
5	49.5
6	48.6
7	54.9
8	52.2
9	49.5
10	49.5
11	49.5
12	49.5
13	55.8
14	55.8
15	55.8

Determining the orbital contact start time in days for TDRS #1

Case #1: 20-degree pointing

$start_m := 0 \qquad j := 1, 2 .. (klst - 1) \qquad stop_m := 0$

$$start_{floor\left(j \cdot \frac{\Delta t}{PS}\right)} := \mathrm{if}\left[\left(\Phi 1_{j-1} > 20 \cdot deg\right) \cdot \left(\Phi 1_j \le 20 \cdot deg\right), j, start_{floor\left(j \cdot \frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j \cdot \frac{\Delta t}{PS}\right)} := \mathrm{if}\left[\left(\Phi 1_{j-1} \le 20 \cdot deg\right) \cdot \left(\Phi 1_j > 20 \cdot deg\right), j, stop_{floor\left(j \cdot \frac{\Delta t}{PS}\right)}\right]$$

start·Δt =

	0
0	0.043125
1	0.11
2	0.176875
3	0.243125
4	0.31
5	0
6	0.376875
7	0.443125
8	0.51
9	0.576875
10	0.643125
11	0.71
12	0.776875
13	0.84375
14	0.91
15	0.976875

stop·Δt =

	0
0	0.049375
1	0.11625
2	0.183125
3	0.249375
4	0
5	0.31625
6	0.383125
7	0.449375
8	0.51625
9	0.583125
10	0.65
11	0.71625
12	0.783125
13	0.85
14	0.91625
15	0.983125

Case #2: 40-degree pointing

$start_m := 0 \qquad stop_m := 0$

$$start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 1_{j-1} > 40\cdot deg\right)\cdot\left(\Phi 1_j \le 40\cdot deg\right), j, start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 1_{j-1} \le 40\cdot deg\right)\cdot\left(\Phi 1_j > 40\cdot deg\right), j, stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

start·Δt =

	0
0	0.04
1	0.106875
2	0.17375
3	0.24
4	0.306875
5	0.37375
6	0
7	0.44
8	0.506875
9	0.57375
10	0.64
11	0.706875
12	0.77375
13	0.84
14	0.906875
15	0.97375

stop·Δt =

	0
0	0.0525
1	0.119375
8	0.18625
9	0
4	0.2525
5	0.319375
6	0.38625
7	0.453125
8	0.519375
9	0.58625
10	0.653125
11	0.719375
12	0.78625
13	0.853125
14	0.919375
15	0.98625

Case #2: 60-degree pointing

$start_m := 0 \qquad stop_m := 0$

$$start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 1_{j-1} > 60\cdot deg\right)\cdot\left(\Phi 1_j \le 60\cdot deg\right), j, start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 1_{j-1} \le 60\cdot deg\right)\cdot\left(\Phi 1_j > 60\cdot deg\right), j, stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

start·Δt =

	0
0	0.036875
1	0.10375
2	0.17
3	0.236875
4	0.30375
5	0.37
6	0.436875
7	0
8	0.50375
9	0.57
10	0.636875
11	0.70375
12	0.77
13	0.836875
14	0.90375
15	0.97

stop·Δt =

	0
0	0.05625
1	0.1225
2	0
3	0.189375
4	0.25625
5	0.3225
6	0.389375
7	0.45625
8	0.523125
9	0.589375
10	0.65625
11	0.723125
12	0.789375
13	0.85625
14	0.923125
15	0.989375

Determining the orbital contact start time in days for TDRS #2

Case #1: 20-degree pointing

$start_m := 0 \qquad stop_m := 0$

$$start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 2_{j-1} > 20\cdot deg\right)\cdot\left(\Phi 2_j \le 20\cdot deg\right), j, start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[\left(\Phi 2_{j-1} \le 20\cdot deg\right)\cdot\left(\Phi 2_j > 20\cdot deg\right), j, stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

start·Δt =

	0
0	0.01875
1	0.085625
2	0.151875
3	0.21875
4	0.285625
5	0.351875
6	0.41875
7	0.485625
8	0.551875
9	0.61875
10	0.685625
11	0
12	0.751875
13	0.81875
14	0.885625
15	0.951875

stop·Δt =

	0
0	0.025
1	0.091875
2	0.158125
3	0.225
4	0.291875
5	0.358125
6	0.425
7	0.491875
8	0.558125
9	0
10	0.625
11	0.691875
12	0.758125
13	0.825
14	0.891875
15	0.958125

Case #2: 40-degree pointing

$start_m := 0 \qquad stop_m := 0$

$$start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[(\Phi 2_{j-1} > 40\cdot deg)\cdot(\Phi 2_j \le 40\cdot deg), j, start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[(\Phi 2_{j-1} \le 40\cdot deg)\cdot(\Phi 2_j > 40\cdot deg), j, stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$start\cdot\Delta t =$

	0
0	0.015625
1	0.081875
2	0.14875
3	0.215625
4	0.281875
5	0.34875
6	0.415625
7	0.481875
8	0.54875
9	0.615625
10	0.6825
11	0.74875
12	0
13	0.815625
14	0.8825
15	0.94875

$stop\cdot\Delta t =$

	0
0	0.028125
1	0.095
2	0.16125
3	0.228125
4	0.295
5	0.36125
6	0.428125
7	0.495
8	0.56125
9	0
10	0.628125
11	0.695
12	0.76125
13	0.828125
14	0.895
15	0.961875

Case #2: 60-degree pointing

$start_m := 0 \qquad stop_m := 0$

$$start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[(\Phi 2_{j-1} > 60\cdot deg)\cdot(\Phi 2_j \le 60\cdot deg), j, start_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$$stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)} := if\left[(\Phi 2_{j-1} \le 60\cdot deg)\cdot(\Phi 2_j > 60\cdot deg), j, stop_{floor\left(j\cdot\frac{\Delta t}{PS}\right)}\right]$$

$start\cdot\Delta t =$

	0
0	0.011875
1	0.07875
2	0.145625
3	0.211875
4	0.27875
5	0.345625
6	0.4125
7	0.47875
8	0.545625
9	0.6125
10	0.67875
11	0.745625
12	0
13	0.8125
14	0.87875
15	0.945625

$stop\cdot\Delta t =$

	0
0	0.03125
1	0.098125
2	0.165
3	0.23125
4	0.298125
5	0.365
6	0.43125
7	0.498125
8	0
9	0.565
10	0.63125
11	0.698125
12	0.765
13	0.831875
14	0.898125
15	0.965

2.10 VISUAL BASIC ANALYSIS PROGRAM

To facilitate the 30-day analysis used for studying the eccentric orbits, the MATHCAD document given in section 2.9 was converted to a Visual BASIC program. The is programming format was chosen to allow easy use through Microsoft Windows.

To run the program, the user can either associate the program with an icon and then run from Windows or it can be started by using the RUN option under FILE in Windows Program Manager. The first screen to be shown once the program is started is a space graphic. Clicking on the Continue button with the mouse will start the simulation. Five option buttons will then be presented to the user. The Configuration button brings up a screen with check boxes for the satellites to be used in the simulation and a prompt for the user to supply an output file specification. The file name should be in the form "output.dat". Two files will be created from this specification: "output.dat" with the full simulation of access times for 20, 40, and 60-degree pointing and "output.res" with a daily summary of the access information. Clicking on the Continue button will return the user to the Option screen.

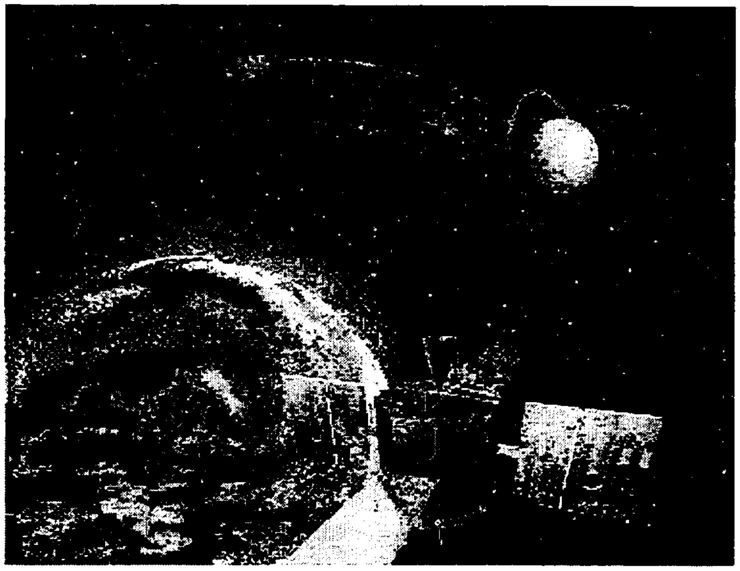
Next, the user should choose the Elements button on the option screen by clicking on that button. This will present the user with a screen to enter the orbital elements for each satellite chosen on the Configuration screen. Clicking on the Continue button will then bring up either the next satellite's element entry form or, after the last satellite, returns the user to the Options screen.

Next, the user should click on the Duration button on the Options screen to bring up the entry form for the simulation duration. Entering the duration and clicking on Done will return the user to the Options screen.

Clicking on the Execute button of the Options screen will cause the simulation to begin.

The output files "output.dat" and "output.res" are ASCII files that can be easily edited with any word processor to extract the desired information.

```
Global Inclin As Double      ' Temp. Inclination Angle
Global RAAN As Double        ' Temp. RAAN Value
Global Eccen As Double       ' Temp. Eccentricity Value
Global Arg As Double         ' Temp. Argument of Perigee Value
Global MAnom As Double       ' Temp. Mean Anomaly Value
Global MMot As Double        ' Temp. Mean Motion Value
Global iSat As Double        ' Test Satellite Inclination Angle
Global RAANSat As Double     ' Test Satellite RAAN
Global eSat As Double        ' Test Satellite Eccentricity
Global ArgSat As Double      ' Test Satellite Argument of Perigee
Global MAnomSat As Double ' Test Satellite Mean Anomaly
Global MMotSat As Double     ' Test Satellite Mean Motion
Global iTE As Double         ' TDRS East Inclination Angle
Global RAANTE As Double      ' TDRS East RAAN
Global eTE As Double         ' TDRS East Eccentricity
Global ArgTE As Double       ' TDRS East Argument of Perigee
Global MAnomTE As Double     ' TDRS East Mean Anomaly
Global MMotTE As Double      ' TDRS East Mean Motion
Global iTW As Double         ' TDRS West Inclination Angle
Global RAANTW As Double      ' TDRS West RAAN
Global eTW As Double         ' TDRS West Eccentricity
Global ArgTW As Double       ' TDRS West Argument of Perigee
Global MAnomTW As Double     ' TDRS West Mean Anomaly
Global MMotTW As Double      ' TDRS West Mean Motion
Global Pi As Double
Global TS, TE, TW  As Integer    ' Control Flags for Satellites
Global Sat$                   ' Identifier String
Global Days As Integer       ' Length of Simulation
Global out$ ' Output File Specification
Global res$ ' secondary file specification
```



Press to Start

Continue

```
Sub Command1_Click ()
   Form4.Hide
   Unload Form1
   Form3.Show 1
End Sub
```

C-2.

Configuration	Specify Satellite Configuration
Elements	Enter Orbital Elements for Each Satellite
Duration	Enter Simulation Duration in Days
Execute	Begin Simulation Execution
Exit	Exit Program

```
DefInt I-N
DefDbl A-H, O-Z
Dim ECISat(0 To 2)                 ' Earth-Centered Coordinates (Satellite)
Dim ECITE(0 To 2)                  '              "            (TDRS East)
Dim ECITW(0 To 2)                  '              "            (TDRS West)
Dim ISTRT120(0 To 20) As Long      'TDRS East 20-degree access start
Dim ISTRT140(0 To 20) As Long      '          40
Dim ISTRT160(0 To 20) As Long      '          60
Dim ISTRT220(0 To 20) As Long      'TDRS West 20-degree access start
Dim ISTRT240(0 To 20) As Long      '          40
Dim ISTRT260(0 To 20) As Long      '          60
Dim ISTOP120(0 To 20) As Long      'TDRS East 20-degree access stop
Dim ISTOP140(0 To 20) As Long      '          40
Dim ISTOP160(0 To 20) As Long      '          60
Dim ISTOP220(0 To 20) As Long      'TDRS West 20-degree access stop
Dim ISTOP240(0 To 20) As Long      '          40
Dim ISTOP260(0 To 20) As Long      '          60
Dim ACCMIN120(0 To 20)             'TDRS East 20-degree access minutes
Dim ACCMIN140(0 To 20)             '          40
Dim ACCMIN160(0 To 20)             '          60
Dim ACCMIN220(0 To 20)             'TDRS West 20-degree access minutes
Dim ACCMIN240(0 To 20)             '          40
Dim ACCMIN260(0 To 20)             '          60
Dim Minutes120(0 To 32)            'TDRS East 20-degree cumulative access minutes
Dim Minutes140(0 To 32)            '          40
Dim Minutes160(0 To 32)            '          60
Dim Minutes220(0 To 32)            'TDRS West 20-degree cumulative access minutes
Dim Minutes240(0 To 32)            '          40
Dim Minutes260(0 To 32)            '          60
Dim Slant120(0 To 20)              'TDRS East 20-degree maximum slant path
Dim Slant140(0 To 20)              '          40
Dim Slant160(0 To 20)              '          60
Dim Slant220(0 To 20)              'TDRS West 20-degree maximum slant path
Dim Slant240(0 To 20)              '          40
Dim Slant260(0 To 20)              '          60


Sub ConfigCommand_Click ()
    Form1.Show 1
End Sub

Sub ExitCommand_Click ()
    End
End Sub

Sub ElementsCommand_Click ()
'Get the file with the set of elements
    Open "elements.dat" For Input Access Read As #1
    Input #1, DataStr$
    nsats = Val(DataStr$)
    Input #1, DataStr$
    iSat = Val(DataStr$)
```

```
    Input #1, DataStr$
    RAANSat = Val(DataStr$)
    Input #1, DataStr$
    eSat = Val(DataStr$)
    Input #1, DataStr$
    ArgSat = Val(DataStr$)
    Input #1, DataStr$
    MAnomSat = Val(DataStr$)
    Input #1, DataStr$
    MMotSat = Val(DataStr$)
    If nsats > 1 Then
        Input #1, DataStr$
        iTE = Val(DataStr$)
        Input #1, DataStr$
        RAANTE = Val(DataStr$)
        Input #1, DataStr$
        eTE = Val(DataStr$)
        Input #1, DataStr$
        ArgTE = Val(DataStr$)
        Input #1, DataStr$
        MAnomTE = Val(DataStr$)
        Input #1, DataStr$
        MMotTE = Val(DataStr$)
    Else
        iTE = 0#
        RAANTE = 0#
        eTE = 0#
        ArgTE = 0#
        MAnomTE = 0#
        MMotTE = 0#
    End If
    If nsats > 2 Then
        Input #1, DataStr$
        iTW = Val(DataStr$)
        Input #1, DataStr$
        RAANTW = Val(DataStr$)
        Input #1, DataStr$
        eTW = Val(DataStr$)
        Input #1, DataStr$
        ArgTW = Val(DataStr$)
        Input #1, DataStr$
        MAnomTW = Val(DataStr$)
        Input #1, DataStr$
        MMotTW = Val(DataStr$)
    Else
        iTW = 0#
        RAANTW = 0#
        eTW = 0#
        ArgTW = 0#
        MAnomTW = 0#
        MMotTW = 0#
    End If
```

```
'Close the input file
    Close #1
    If TS = 1 Then
        Sat$ = "Test Satellite"
        Inclin = iSat
        RAAN = RAANSat
        Eccen = eSat
        Arg = ArgSat
        MAnom = MAnomSat
        MMot = MMotSat
        Form2.Show 1
        iSat = Inclin
        RAANSat = RAAN
        eSat = Eccen
        ArgSat = Arg
        MAnomSat = MAnom
        MMotSat = MMot
    End If
    If TE = 1 Then
        Sat$ = "TDRS East"
        Inclin = iTE
        RAAN = RAANTE
        Eccen = eTE
        Arg = ArgTE
        MAnom = MAnomTE
        MMot = MMotTE
        Form2.Show 1
        iTE = Inclin
        RAANTE = RAAN
        eTE = Eccen
        ArgTE = Arg
        MAnomTE = MAnom
        MMotTE = MMot
    End If
    If TW = 1 Then
        Sat$ = "TDRS West"
        Inclin = iTW
        RAAN = RAANTW
        Eccen = eTW
        Arg = ArgTW
        MAnom = MAnomTW
        MMot = MMotTW
        Form2.Show 1
        iTW = Inclin
        RAANTW = RAAN
        eTW = Eccen
        ArgTW = Arg
        MAnomTW = MAnom
        MMotTW = MMot
    End If
'Write out the results
    Open "elements.dat" For Output Access Write As #1
```

```
    Print #1, Format$(3, "#0")
    Print #1, Format$(iSat, "##0.0#####")
    Print #1, Format$(RAANSat, "##0.0#####")
    Print #1, Format$(eSat, "#0.0#####")
    Print #1, Format$(ArgSat, "##0.0#####")
    Print #1, Format$(MAnomSat, "##0.0#####")
    Print #1, Format$(MMotSat, "#0.0#")
    Print #1, Format$(iTE, "##0.0#####")
    Print #1, Format$(RAANTE, "##0.0#####")
    Print #1, Format$(eTE, "#0.0#####")
    Print #1, Format$(ArgTE, "##0.0#####")
    Print #1, Format$(MAnomTE, "##0.0#####")
    Print #1, Format$(MMotTE, "#0.0#######")
    Print #1, Format$(iTW, "#0.0#####")
    Print #1, Format$(RAANTW, "##0.0#####")
    Print #1, Format$(eTW, "#0.0#####")
    Print #1, Format$(ArgTW, "##0.0#####")
    Print #1, Format$(MAnomTW, "##0.0######")
    Print #1, Format$(MMotTW, "#0.0#######")
    Close #1
End Sub

Sub DurationCommand_Click ()
    Form5.Show 1
End Sub

Sub ExecCommand_Click ()
Dim lim20 As Double     '20-degree poiniting angle (radians)
Dim lim40 As Double     '40
Dim lim60 As Double     '60
Dim MASat As Double     'Instantaneous Mean Anomaly (Satellite)
Dim MATE As Double      '                 "           (TDRS East)
Dim MATW As Double      '                 "           (TDRS West)
Dim in As Double        'Simulation index
Dim nSat As Double      'Mean Motion Parameter (Satellite)
Dim nTE As Double       '              "        (TDRS East)
Dim nTW As Double       '              "        (TDRS West)
    Screen.MousePointer = 11  'Set pointer to hour glass icon (busy)
    DtoR = Pi / 180#
    thresh = 81.3 * DtoR
    lim20 = 20# * DtoR
    lim40 = 40# * DtoR
    lim60 = 60# * DtoR
'Define output file
    Open out$ For Output Access Write As 1
    Open res$ For Output Access Write As 2
'Document the input parameters
    Print #1, Format$(Now, "mmmm dd, yyyy")
    Print #1, "Satellite Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANSat, "##0.0#####"), "degrees"
    Print #1, "Argument of Perigee", Format$(ArgSat, "##0.0#####"), "degrees"
    Print #1, "Mean Anomaly        ", Format$(MAnomSat, "##0.0#####"), "degrees"
```

```
    Print #1, "Eccentricity         ", Format$(eSat, "##0.0#####")
    Print #1, "Inclination Angle    ", Format$(iSat, "##0.0#####"), "degrees"
    Print #1, "Mean Motion          ", Format$(MMotSat, "##0.0##"), "orbits/day"
    Print #1, "TDRS East Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANTE, "##0.0#####"), "degrees"
    Print #1, "Argument of Perigee", Format$(ArgTE, "##0.0#####"), "degrees"
    Print #1, "Mean Anomaly         ", Format$(MAnomTE, "##0.0#####"), "degrees"
    Print #1, "Eccentricity         ", Format$(eTE, "##0.0#####")
    Print #1, "Inclination Angle    ", Format$(iTE, "##0.0#####"), "degrees"
    Print #1, "Mean Motion          ", Format$(MMotTE, "##0.0#######"), "orbits/da
y"
    Print #1, "TDRS West Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANTW, "##0.0#####"), "degrees"
    Print #1, "Argument of Perigee", Format$(ArgTW, "##0.0#####"), "degrees"
    Print #1, "Mean Anomaly         ", Format$(MAnomTW, "##0.0#####"), "degrees"
    Print #1, "Eccentricity         ", Format$(eTW, "##0.0#####")
    Print #1, "Inclination Angle    ", Format$(iTW, "##0.0#####"), "degrees"
    Print #1, "Mean Motion          ", Format$(MMotTW, "##0.0########"), "orbits/d
ay"
' Convert the angles from degrees to radians and initialize values.
    RAAN0Sat = RAANSat * DtoR
    Arg0Sat = ArgSat * DtoR
    iSat = iSat * DtoR
    MAnomSat = MAnomSat * DtoR
    RAAN0TE = RAANTE * DtoR
    Arg0TE = ArgTE * DtoR
    iTE = iTE * DtoR
    MAnomTE = MAnomTE * DtoR
    RAAN0TW = RAANTW * DtoR
    Arg0TW = ArgTW * DtoR
    iTW = iTW * DtoR
    MAnomTW = MAnomTW * DtoR
' Compute the semi-major axis for each orbit
    aSat = K3(MMotSat)
    aTE = K3(MMotTE)
    aTW = K3(MMotTW)
    Print #1, "Satellite Semimajor Axis", Format$(aSat, "######0.0"), "kilometer
s"
    Print #1, "TDRS East Semimajor Axis", Format$(aTE, "######0.0"), "kilometers
"
    Print #1, "TDRS West Semimajor Axis", Format$(aTW, "######0.0"), "kilometers
"
' Compute the Regression of Nodes Rate
    dRAANSat = RAAN_Rate(aSat, iSat, eSat)
    dRAANTE = RAAN_Rate(aTE, iTE, eTE)
    dRAANTW = RAAN_Rate(aTW, iTW, eTW)
    Print #1, "Satellite RAAN_Rate", Format$(dRAANSat, "00.000000E+00"), "Radian
s/sec"
    Print #1, "TDRS East RAAN_Rate", Format$(dRAANTE, "00.000000E+00"), "Radians
/sec"
    Print #1, "TDRS West RAAN_Rate", Format$(dRAANTW, "00.000000E+00"), "Radians
/sec"
```

```
'Compute Apsidal Rate
    dArgSat = Apsidal_Rate(aSat, iSat, eSat)
    dArgTE = Apsidal_Rate(aTE, iTE, eTE)
    dArgTW = Apsidal_Rate(aTW, iTW, eTW)
    Print #1, "Satellite Apsidal_Rate", Format$(dArgSat, "00.000000E+00"), "Radi
ans/sec"
    Print #1, "TDRS East Apsidal_Rate", Format$(dArgTE, "00.000000E+00"), "Radia
ns/sec"
    Print #1, "TDRS West Apsidal_Rate", Format$(dArgTW, "00.000000E+00"), "Radia
ns/sec"
' Define the computation range
    PPO& = 100#
    OPD& = MMotSat
    NDays& = Days
    PPD& = PPO& * OPD&
    dt = 1# / (PPD&)
'Change of units and combination of multiplication factors
    dRAANSat = dRAANSat * dt * 86400#
    dRAANTE = dRAANTE * dt * 86400#
    dRAANTW = dRAANTW * dt * 86400#
    dArgSat = dArgSat * dt * 86400#
    dArgTE = dArgTE * dt * 86400#
    dArgTW = dArgTW * dt * 86400#
    MMotSat = 2# * Pi * MMotSat * dt
    MMotTE = 2# * Pi * MMotTE * dt
    MMotTW = 2# * Pi * MMotTW * dt
    For I& = 0 To (NDays& - 1)
'Initialize Counters for keeping track of orbital access results per orbit
        For j& = 0 To 20
            ISTRT120(j&) = -100#
            ISTRT140(j&) = -100#
            ISTRT160(j&) = -100#
            ISTRT220(j&) = -100#
            ISTRT240(j&) = -100#
            ISTRT260(j&) = -100#
            ISTOP120(j&) = -100#
            ISTOP140(j&) = -100#
            ISTOP160(j&) = -100#
            ISTOP220(j&) = -100#
            ISTOP240(j&) = -100#
            ISTOP260(j&) = -100#
            ACCMIN120(j&) = 0#
            ACCMIN140(j&) = 0#
            ACCMIN160(j&) = 0#
            ACCMIN220(j&) = 0#
            ACCMIN240(j&) = 0#
            ACCMIN260(j&) = 0#
            Slant120(j&) = 0#
            Slant140(j&) = 0#
            Slant160(j&) = 0#
            Slant220(j&) = 0#
            Slant240(j&) = 0#
```

```
            Slant260(j&) = 0#
        Next j&
            jj120 = 0#
            jj140 = jj120
            jj160 = jj120
            jj220 = jj120
            jj240 = jj120
            jj260 = jj120
        For j& = 0 To (OPD& - 1)
            For K& = 0 To (PPO& - 1)
'Compute the index for where in the simulation we are
            in = K& + j& * (PPO&) + I& * (PPD&)
'Compute the correction to the RAAN and the argument of perigee
            RAANSat = RAAN0Sat + dRAANSat * in
            RAANTE = RAAN0TE + dRAANTE * in
            RAANTW = RAAN0TW + dRAANTW * in
            ArgSat = Arg0Sat + dArgSat * in
            ArgTE = Arg0TE + dArgTE * in
            ArgTW = Arg0TW + dArgTW * in
'Compute Current Mean Anomalies for Each Satellite
            MASat = (in * MMotSat) + MAnomSat
            MATE = (in * MMotTE) + MAnomTE
            MATW = (in * MMotTW) + MAnomTW
'Compute Current Guess for the Eccentric Anomaly for Each Satellite
            EASat = MASat
            EATE = MATE
            EATW = MATW
'Then Update the Estimate By Solving Kepler's Equation
            EASat = Kepler(MASat, EASat, eSat)
            EATE = Kepler(MATE, EATE, eTE)
            EATW = Kepler(MATW, EATW, eTW)
'Compute the True Anomaly for Each Satellite
            TASat = TrueA(EASat, eSat)
            TATE = TrueA(EATE, eTE)
            TATW = TrueA(EATW, eTW)
'Compute the Longitude for Each Satellite
            uSat = ArgSat + TASat
            uTE = ArgTE + TATE
            uTW = ArgTW + TATW
'Compute the ECI unit vector for each satellite
            Call UnitVec(RAANSat, uSat, iSat, ECISat())
            Call UnitVec(RAANTE, uTE, iTE, ECITE())
            Call UnitVec(RAANTW, uTW, iTW, ECITW())
'Compute the vector dot products
            DP1 = Dot3x1(ECISat(), ECITE())
            DP2 = Dot3x1(ECISat(), ECITW())
' Compute the central angle between the vectors
            Gamma1 = Acos(DP1)
            Gamma2 = Acos(DP2)
' Compute the radial vector for each satellite
            radSat = Pos(aSat, eSat, TASat)
            radTE = Pos(aTE, eTE, TATE)
```

```
            radTW = Pos(aTW, eTW, TATW)
' Compute the slant path difference
            SP1 = slant(radSat, ECISat(), radTE, ECITE())
            SP2 = slant(radSat, ECISat(), radTW, ECITW())
'Compute the local elevation angle
            If (Gamma1 > thresh) Then
'Adjust the angle for the cases of "over the horizon"
                Phi1 = (Pi / 2#)
            Else
                Phi1 = (Pi / 2#) - Acos(radTE * Sin(Gamma1) / SP1)
            End If
            If (Gamma2 > thresh) Then
                Phi2 = (Pi / 2#)
            Else
                Phi2 = (Pi / 2#) - Acos(radTW * Sin(Gamma2) / SP2)
            End If
'See if the angle is within the 20,40, or 60 degree pointing
            If Phi1 <= lim20 Then
                If ISTRT120(jj120) = -100 Then
                    ISTRT120(jj120) = in
                    ISTOP120(jj120) = in
                    Slant120(jj120) = SP1
                Else
                    ISTOP120(jj120) = in
                End If
            Else
                If ISTOP120(jj120) <> -100 Then jj120 = jj120 + 1
            End If
            If Phi1 <= lim40 Then
                If ISTRT140(jj140) = -100 Then
                    ISTRT140(jj140) = in
                    ISTOP140(jj140) = in
                    Slant140(jj140) = SP1
                Else
                    ISTOP140(jj140) = in
                End If
            Else
                If ISTOP140(jj140) <> -100 Then jj140 = jj140 + 1
            End If
            If Phi1 <= lim60 Then
                If ISTRT160(jj160) = -100 Then
                    ISTRT160(jj160) = in
                    ISTOP160(jj160) = in
                    Slant160(jj160) = SP1
                Else
                    ISTOP160(jj160) = in
                End If
            Else
                If ISTOP160(jj160) <> -100 Then jj160 = jj160 + 1
            End If
            If Phi2 <= lim20 Then
                If ISTRT220(jj220) = -100 Then
```

```
            ISTRT220(jj220) = in
            ISTOP220(jj220) = in
            Slant220(jj220) = SP2
        Else
            ISTOP220(jj220) = in
        End If
    Else
        If ISTOP220(jj220) <> -100 Then jj220 = jj220 + 1
    End If
    If Phi2 <= lim40 Then
        If ISTRT240(jj240) = -100 Then
            ISTRT240(jj240) = in
            ISTOP240(jj240) = in
            Slant240(jj240) = SP2
        Else
            ISTOP240(jj240) = in
        End If
    Else
        If ISTOP240(jj240) <> -100 Then jj240 = jj240 + 1
    End If
    If Phi2 <= lim60 Then
        If ISTRT260(jj260) = -100 Then
            ISTRT260(jj260) = in
            ISTOP260(jj260) = in
            Slant260(jj260) = SP2
        Else
            ISTOP260(jj260) = in
        End If
    Else
        If ISTOP260(jj260) <> -100 Then jj260 = jj260 + 1
    End If
    Next K&
    Next j&
    sum120 = 0#
    sum140 = sum120
    sum160 = sum120
    sum220 = sum120
    sum240 = sum120
    sum260 = sum120
    For j& = 0 To OPD&
    ACCMIN120(j&) = (ISTOP120(j&) - ISTRT120(j&)) * dt * 24 * 60
    ACCMIN140(j&) = (ISTOP140(j&) - ISTRT140(j&)) * dt * 24 * 60
    ACCMIN160(j&) = (ISTOP160(j&) - ISTRT160(j&)) * dt * 24 * 60
    ACCMIN220(j&) = (ISTOP220(j&) - ISTRT220(j&)) * dt * 24 * 60
    ACCMIN240(j&) = (ISTOP240(j&) - ISTRT240(j&)) * dt * 24 * 60
    ACCMIN260(j&) = (ISTOP260(j&) - ISTRT260(j&)) * dt * 24 * 60
    sum120 = sum120 + ACCMIN120(j&)
    sum140 = sum140 + ACCMIN140(j&)
    sum160 = sum160 + ACCMIN160(j&)
    sum220 = sum220 + ACCMIN220(j&)
    sum240 = sum240 + ACCMIN240(j&)
    sum260 = sum260 + ACCMIN260(j&)
```

```
        Print #1, "TDRS East Access Summary on Orbit", Format$(j&, "##0"), "and
Day", Format$(I&, "##0")
        Print #1, "20-Degree Access Minutes:", Format$(ACCMIN120(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT120(j&), "and ending at index", ISTO
P120(j&)
        Print #1, "Maximum Slant Path:", Slant120(j&)
        Print #1, "40-Degree Access Minutes:", Format$(ACCMIN140(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT140(j&), "and ending at index", ISTO
P140(j&)
        Print #1, "Maximum Slant Path:", Slant140(j&)
        Print #1, "60-Degree Access Minutes:", Format$(ACCMIN160(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT160(j&), "and ending at index", ISTO
P160(j&)
        Print #1, "Maximum Slant Path:", Slant160(j&)
        Print #1, "TDRS West Access Summary on Orbit and Day"
        Print #1, "20-Degree Access Minutes:", Format$(ACCMIN220(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT220(j&), "and ending at index", ISTO
P220(j&)
        Print #1, "Maximum Slant Path:", Slant220(j&)
        Print #1, "40-Degree Access Minutes:", Format$(ACCMIN240(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT240(j&), "and ending at index", ISTO
P240(j&)
        Print #1, "Maximum Slant Path:", Slant240(j&)
        Print #1, "60-Degree Access Minutes:", Format$(ACCMIN260(j&), "###0.0#")
        Print #1, "Starting at index", ISTRT260(j&), "and ending at index", ISTO
P260(j&)
        Print #1, "Maximum Slant Path:", Slant260(j&)
        Next j&
'Analyze the results
        Print #2, "Day Number:", I&, "Inclination Angle:", iSat / DtoR, "Mean Mo
tion:", OPD&
        For ii = 0 To 32
            Minutes120(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN120(j&) > ii Then Minutes120(ii) = Minutes120(ii) +
1

                Next j&
            Minutes140(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN140(j&) > ii Then Minutes140(ii) = Minutes140(ii) +
1

                Next j&
            Minutes160(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN160(j&) > ii Then Minutes160(ii) = Minutes160(ii) +
1

                Next j&
            Minutes220(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN220(j&) > ii Then Minutes220(ii) = Minutes220(ii) +
1

                Next j&
```

```
            Minutes240(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN240(j&) > ii Then Minutes240(ii) = Minutes240(ii) +
 1
                Next j&
            Minutes260(ii) = 0#
                For j& = 0 To (OPD& - 1)
                    If ACCMIN260(j&) > ii Then Minutes260(ii) = Minutes260(ii) +
 1
                Next j&
            Print #2, ii, Minutes120(ii), Minutes140(ii), Minutes160(ii), Minute
s220(ii), Minutes240(ii), Minutes260(ii)
        Next ii
        Print #2, "Total Access Time for TDRS East at 20 Degrees: "; Format$(sum
120, "##0.0#"); " minutes"
        Print #2, "Total Access Time for TDRS East at 40 Degrees: "; Format$(sum
140, "##0.0#"); " minutes"
        Print #2, "Total Access Time for TDRS East at 60 Degrees: "; Format$(sum
160, "##0.0#"); " minutes"
        Print #2, "Total Access Time for TDRS West at 20 Degrees: "; Format$(sum
220, "##0.0#"); " minutes"
        Print #2, "Total Access Time for TDRS West at 40 Degrees: "; Format$(sum
240, "##0.0#"); "minutes"
        Print #2, "Total Access Time for TDRS West at 60 Degrees: "; Format$(sum
260, "##0.0#"); "minutes"
    Next I&
    Print #1, "Final Satellite Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANSat / DtoR, "##0.0#####"), "deg
rees"
    Print #1, "Argument of Perigee", Format$(ArgSat / DtoR, "##0.0#####"), "degr
ees"
    Print #1, "Mean Anomaly         ", Format$(MAnomSat / DtoR, "##0.0#####"), "de
grees"
    Print #1, "Eccentricity         ", Format$(eSat, "##0.0#####")
    Print #1, "Inclination Angle    ", Format$(iSat / DtoR, "##0.0#####"), "degree
s"
    Print #1, "Mean Motion          ", Format$(MMotSat, "##0.0##"), "orbits/day"
    Print #1, "Final TDRS East Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANTE / DtoR, "##0.0#####"), "degr
ees"
    Print #1, "Argument of Perigee", Format$(ArgTE / DtoR, "##0.0#####"), "degre
es"
    Print #1, "Mean Anomaly         ", Format$(MAnomTE / DtoR, "##0.0#####"), "deg
rees"
    Print #1, "Eccentricity         ", Format$(eTE, "##0.0#####")
    Print #1, "Inclination Angle    ", Format$(iTE / DtoR, "##0.0#####"), "degrees
"
    Print #1, "Mean Motion          ", Format$(MMotTE, "##0.0#######"), "orbits/da
y"
    Print #1, "Final TDRS West Orbital Parameters"
    Print #1, "RAAN:                ", Format$(RAANTW / DtoR, "##0.0#####"), "degr
ees"
```

```
    Print #1, "Argument of Perigee", Format$(ArgTW / DtoR, "##0.0#####"), "degre
es"
    Print #1, "Mean Anomaly        ", Format$(MAnomTW / DtoR, "##0.0#####"), "deg
rees"
    Print #1, "Eccentricity        ", Format$(eTW, "##0.0#####")
    Print #1, "Inclination Angle   ", Format$(iTW / DtoR, "##0.0#####"), "degrees
"
    Print #1, "Mean Motion         ", Format$(MMotTW, "##0.0########"), "orbits/d
ay"
    Close #1
    Close #2
    Screen.MousePointer = 0
    MsgBox "Run Completed", 0, "Simulation Status"
End Sub


Function Kepler (MA#, EA, ecc) As Double
 ' Computes a solution to Kepler's Equation by using Newton's
 ' Method for finding the roots of a non-linear equation
Dim e As Double
Dim fuzz As Double
Dim fun As Double
Dim fun1 As Double
Dim dE As Double
    e = EA
    fuzz = .00000001
    For I = 1 To 100
        fun = e - ecc * Sin(e) - MA#
        fun1 = 1# - ecc * Cos(e)
        dE = -(fun / fun1)
        e = e + dE
        If Abs(dE) < fuzz Then Exit For
    Next I
    Kepler = e
End Function

Function TrueA (EA, ecc) As Double
Dim s As Double
Dim c As Double
Dim x As Double
    s = Sqr(1# - ecc * ecc) * Sin(EA)
    c = Cos(EA) - ecc
    x = Atn(s / c)
    If c < 0 Then
        x = x + Pi
    End If
    TrueA = x
End Function

Sub UnitVec (Omega, u, inc#, Vec())
```

```
    Vec(0) = Cos(Omega) * Cos(u) - Sin(Omega) * Cos(inc#) * Sin(u)
    Vec(1) = Sin(Omega) * Cos(u) + Cos(Omega) * Cos(inc#) * Sin(u)
    Vec(2) = Sin(inc#) * Sin(u)
End Sub

Function Dot3x1 (v1(), v2()) As Double
    Dot3x1 = v1(0) * v2(0) + v1(1) * v2(1) + v1(2) * v2(2)
End Function

Function Acos (x) As Double
    Acos = Pi / 2# - Atn(x / Sqr(1# - (x * x)))
End Function

Function K3 (xx) As Double
Dim x As Double
    x = (86400# / (xx * 2# * Pi)) ^ 2
    x = x * 398600.8
    K3 = x ^ (1# / 3#)
End Function

Function Pos (a, e, TA) As Double
    Pos = (a * (1# - e * e)) / (1# + e * Cos(TA))
End Function

Function slant (r1, v1(), r2, v2()) As Double
Dim x As Double
Dim y As Double
Dim z As Double
    x = r1 * v1(0) - r2 * v2(0)
    y = r1 * v1(1) - r2 * v2(1)
    z = r1 * v1(2) - r2 * v2(2)
    slant = Sqr(x * x + y * y + z * z)
End Function

Sub Form_Load ()
    out$ = "output.dat"
    Pi = 4# * Atn(1#)
End Sub

Function RAAN_Rate (a, inc#, ecc) As Double
Dim n As Double
Dim x As Double
Dim y As Double
    n = Sqr(398600.4 / (a ^ 3))
    x = -1.5 * n * .00108263 * (6378.14 ^ 2) * Cos(inc#)
    y = (a ^ 2) * ((1# - (ecc ^ 2)) ^ 2)
    RAAN_Rate = x / y
End Function

Function Apsidal_Rate (a, inc#, ecc) As Double
Dim x As Double
Dim y As Double
```

```
Dim n As Double
    n = Sqr(398600.4 / (a ^ 3))
    x = .75 * n * .00108263 * (6378.14 ^ 2) * (4# - 5# * (Sin(inc#) ^ 2))
    y = (a ^ 2) * ((1# - (ecc ^ 2)) ^ 2)
    Apsidal_Rate = x / y
End Function
```

Click on Satellites to Include in the Simulation

- [ ] Test Satellite
- [ ] TDRS East
- [ ] TDRS West

Output File Specification:

[ ]

[Continue]

```
Sub Continue_Click ()
    out$ = OutFile.Text
    Dot% = InStr(1, out$, ".")
    res$ = Left$(out$, Dot%) + "res"
    Form1.Hide
    Unload Form1
End Sub

Sub TDRSWCheck_Click ()
    TW = 1
End Sub

Sub TDRSECheck_Click ()
    TE = 1
End Sub

Sub SatCheck_Click ()
    TS = 1
End Sub

Sub Form_Load ()
    OutFile.Text = out$
End Sub
```

Enter the Orbital Elements in NORAD Two-Line Order

Inclination (degrees):

RAAN (degrees):

Orbital Eccentricity:

Argument of Perigee (degrees):

Mean Anomaly (degrees):

Mean Motion (revs/day):

Continue

```
Sub Continue_Click ()
    Inclin = Val(InclinText.Text)
    RAAN = Val(RAANText.Text)
    Eccen = Val(EccenText.Text)
    Arg = Val(ArgPerText.Text)
    MAnom = Val(MeAnomText.Text)
    MMot = Val(MeanMotText.Text)
    Hide
    Unload Form2
End Sub

Sub Form_Load ()
    Text1.Text = Sat$
    InclinText.Text = Format$(Inclin, "##0.0#####")
    RAANText.Text = Format$(RAAN, "##0.0#####")
    EccenText.Text = Format$(Eccen, "#0.0#####")
    ArgPerText.Text = Format$(Arg, "##0.0#####")
    MeAnomText.Text = Format$(MAnom, "##0.0#####")
    MeanMotText.Text = Format$(MMot, "##0.0#######")
End Sub
```

Enter the Simulation Duration in Days

Done

```
Sub Command1_Click ()
    Days = Val(DurDay.Text)
    Hide
    Unload Form5
End Sub

Sub Text2_Change ()

End Sub
```

SECTION 3 - PAYLOAD SIMULATION CONCEPT

The results for the circular orbit studies presented here were applied to simulate the performance of an actual payload. The payload was assumed to be configured as follows:

a) an on-board Solid State Recorder (SSR) was used to store data between passes
b) instruments in the payload communicated with the payload command and control system using a MIL-STD-1553 bus
c) TDRS access was scheduled using the access times for a one-day simulation run derived from a 15-orbit per day satellite access simulation.

The simulations were performed using the CACI product Network II.5. The full text of the research report based on this work is given in the supplemental report "CCSDS Service Models for Small Space Payloads". In this work, the desired objectives to be met were determining the necessary buffer sizes in the payload, the potential daily throughput, and the interaction of control structures with payload performance. In the simulations, at total of 8,640 CCSDS packets were generated each day and then "sent to the ground" during access windows. The major results were found to be:

a) the on-board SSR required a size between 24.0 Mbit and 29.5 Mbit to buffer the data depending upon control methodology,
b) the most efficient payload usage came from allowing the Remote Terminals (RT) in the payload to only be concerned with data gathering and to allow the communications interface with the Space Network handle all of the CCSDS-related functions and packetization, and
c) the MIL-STD-1553 bus protocol was not an important factor at this low of a data rate.

This simulation study was limited in scope but the basic models developed can be used and modified to support different access configurations and control modes with minimal programming effort.

SECTION 4 - POTENTIAL FOR TRANSPONDER DESIGN IMPROVEMENT

Small Satellite User Transponder

- **The objective of this task is to examine the savings in size, weight, power and cost that maybe achieved by the use of custom VLSI in the design of a TDRSS user transponder for small satellites.**
- **Initially examined the CEI and Motorola designs for use as a baseline in the study.**

Initial Results

Motorola Design:

87 Vintage Technology

14 x 7 x 6 Box which weighs 16 lb.

Power-- 18 watts Rx. and 50 watts Tx.

CEI Design:

92 Vintage Technology

8 x 5 x 5 Box which weighs 10 lb.

Power-- 9.7 watts Rx. and 32 watts Tx.

Basic Result

- CEI's design was chosen as the baseline for our study.
- But, this almost ended our study as the digital portion of the CEI design consists of a DSP chip for spread spectrum processing and a large FPGA for PN code generation and some glue logic.
- The digital part of the CEI design cannot benefit much from custom VLSI.

New Direction

- **Decided to broaden the question to ask what could be done to improve the transponder design for small satellite missions if the only constraint on the transponder is that we must use TDRSS as is.**
- **Initial results of this kind of thinking are somewhat encouraging but still need scrubbing**

- One thought is to use GPS for navigation and attitude control, this means we could eliminate the PN on the command link and reduce the number of contacts from 4 to 1 per day.
- This could reduce the receiver power draw in half to 5 watts or so. It also means that the receiver could be shut down part of the time since the spacecraft knows where it is.
- The NASA Microelectronics Center at UNM is working on a space qualified GPS chip set for JPL which might be used for this purpose.

- **Another idea we are testing on the computer is an antenna for the user spacecraft that is fix pointed away from the earth and it's beam is allowed to sweep as the user spacecraft orbits. The idea is that the antenna will point at TDRSS sometimes and when it does we will transmit the data. Question is when and for how long.**

User Transponder Status

- **Work is continuing on the potential impact of custom VLSI on the RF part of the transponder.**
- **Work also continues on determining the minimum set of features that a user transponder needs to service the small satellite market.**
- **Final report will be available in August.**

SECTION 5 - CONCLUSIONS AND RECOMMENDATIONS

This study originated as an investigation into the possibilities for Space Network transponder improvement by modifying the hardware. The conclusion of that effort was that major improvements leading to dramatic data throughput increases would not be possible and maintain the features and compatibility necessary for the Space Network. Given that, we began investigating how the overall operation of a small satellite could be improved and still maintain usage of the Space Network rather than proprietary ground stations. We investigated the concept of a small satellite using a simple, non-gimballed antenna system with a 10 W SN transponder. We performed the orbital analysis to determine if this configuration could provide the desired 10 kbps average throughput over one day. From the analysis we make the following conclusions:

- a small satellite using a non-gimballed antenna can have sufficient contact time through the Space Network to achieve the desired goal of 10 kbps throughput averaged over one day (data throughput exceeds 864 Mbits/day)
- both TDRS in the SN will probably be required to achieve this
- a broader antenna HPBW will give greater contact potential but at a lower data rate
- broad antenna patterns will probably not be able to realize the required scheduled access time in the SN to achieve their potential for aggregate data throughput

From the analysis and considering the operational considerations, we believe that the optimal configuration will be to use a higher-gain antenna with short contacts rather than a low-gain antenna with long contacts.

In this study, we based all analysis upon the assumption that the data rate would be set by the minimal EIRP of the system at the margins of the contact and the distance between the satellite and the TDRS at the margins. If a variable data rate methodology can be devised, then the throughput of the system can be increased. This is worth further study to parameterize the methodology of variable data rates and the gain in throughput to be expected.

The basic initial analysis was performed for circular orbits. Similar orbital results are obtained for eccentric orbits having low eccentricity. High-eccentricity orbits may be better served with fixed ground stations rather than through the Space Network. This will need more study based on mission models to determine the exact tradeoffs required.