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ANALYSIS OF EUVE EXPERIMENT RESULTS

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ABSTRACT

A series of tests to validate an antenna pointing concept for spin-stabilized satellites using a data relay satellite are described. These tests show that proper antenna pointing on an inertially-stabilized spacecraft can lead to significant access time through the relay satellite even without active antenna pointing. We summarize the test results, the simulations to model the effects of antenna pattern and space loss, and the expected contact times. We also show how antenna beam width affects the results.

SECTION I - INTRODUCTION

Designers of small satellites often prefer to use direct communications links to ground stations rather than using a data relay satellite to minimize the power, weight, and complexity required for gimbaled antennas and the associated pointing electronics required to maintain the link through the relay satellite. To allow for the use of existing relay satellites and to avoid the construction of new, single-mission ground terminals, a technique was developed [1] for using broad-beam, non-gimbaled antennas for accessing a Tracking and Data Relay Satellite (TDRS) within the Space Network (SN). The relay technique being investigated is based on the assumption that the satellite requiring space-to-ground communications is spin-stabilized, has a zenith-pointing communications antenna, and is in a typical Low-Earth Orbit (LEO). The SN has six TDRS on orbit with three satellites in an operational constellation. The TDRS satellite to be used for relaying data is located in a standard geostationary orbit and that either the TDRS East at 41° or TDRS West at 174° west longitude is available to support the communications link. With this configuration, the LEO satellite is able to communicate through the relay satellite for several minutes when the antenna systems on the two satellites are mutually visible as shown in Figure 1. At the first LEO position in this figure, the antennas are not

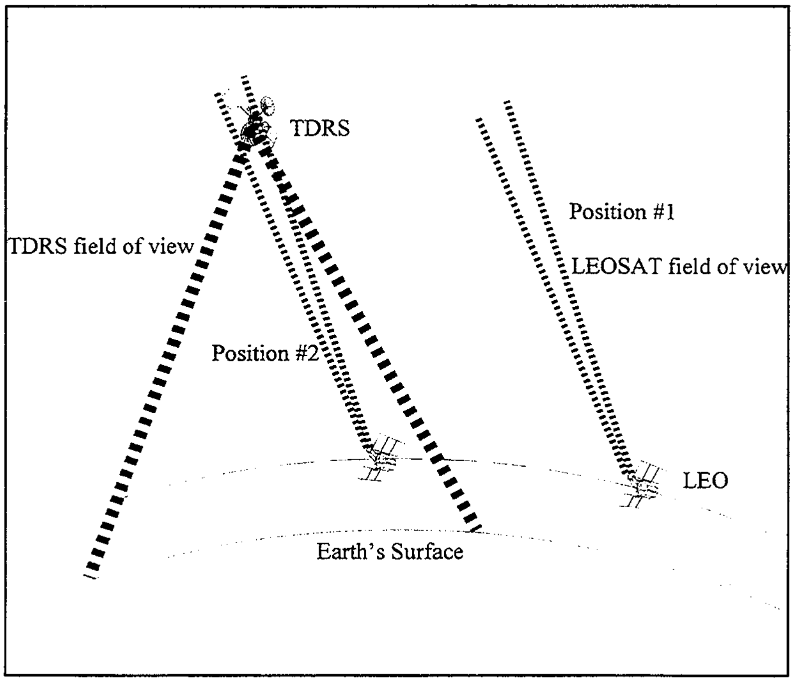


Figure 1 - TDRS/EUVE Access Geometry.

mutually visible while at the second position, the two antennas mutually point at each other. This time of mutual visibility occurs whenever the TDRS subsatellite point is located near either the ascending or descending node of the LEO satellite's orbit. This report describes the results of testing this concept with the Extreme Ultra Violet Explorer (EUVE) satellite. EUVE differs from the desired configuration in that EUVE has a relatively high-gain parabolic antenna rather than a broad-beam antenna and, most importantly, EUVE has an inertially-stabilized attitude control system rather than a spin-stabilized attitude control system. Prior to the testing, it was believed that these limitations would not affect the basic proof-of-concept test that we were trying to achieve. A total of six EUVE communication passes through the West TDRS over two consecutive days was provided by NASA to perform the testing. The necessary equipment was configured for data collection at the Second TDRS Ground Terminal, also known as *Danzante*, at the White Sands Complex, New Mexico. Details of the test configuration are given in [2] and the test report is contained in [3] .

During the test passes, the expected access time was predicted to be approximately five minutes centered on the time when EUVE was closest to TDRS West. Because the EUVE antenna system has a significant gain and a correspondingly narrow antenna pattern, an accommodation was needed to make the test similar to that predicted to be found with a broad-beam antenna sweeping past the TDRS location. To accomplish this, the EUVE control center pointed the spacecraft antenna to the TDRS position at the time of closest approach and fixed it there for the pass duration. This pointing was done prior to the start of the pass and active pointing during the pass was disabled by ground command. During the test passes, it was expected that, as EUVE moved along its orbit, it would sweep past the TDRS position and emulate the desired contact profile.

The results of these test contacts were that the contact times greatly exceeded the predicted value of five minutes. To allow for timing uncertainties and to allow for tracking of the receiver acquisition process, data were collected for a period of 30 minutes centered around the expected contact mid-point. The data gathered consisted of EUVE data files, and ground station receiver estimates of the signal E_b/N_o and EUVE Doppler offset. The received E_b/N_o for these passes is illustrated in Figure 2 (pass #2 had no data recorded due to configuration checks). Instead of a gradual acquisition and loss process at the start and end of the data acquisition interval during each pass, the ground station receivers immediately locked onto the EUVE communications signal relayed through TDRS at the scheduled start of the communications service time and stayed locked until the scheduled end of the service time. Therefore, instead of a five-minute pass, we recorded thirty-minute passes during each contact period. This opens the potential for using this concept for spacecraft operations.

In this report, we examine the basis for the extended passive pointing observed with EUVE and TDRS. Based on simulations, we will show the minimum antenna pattern width needed to accomplish passive

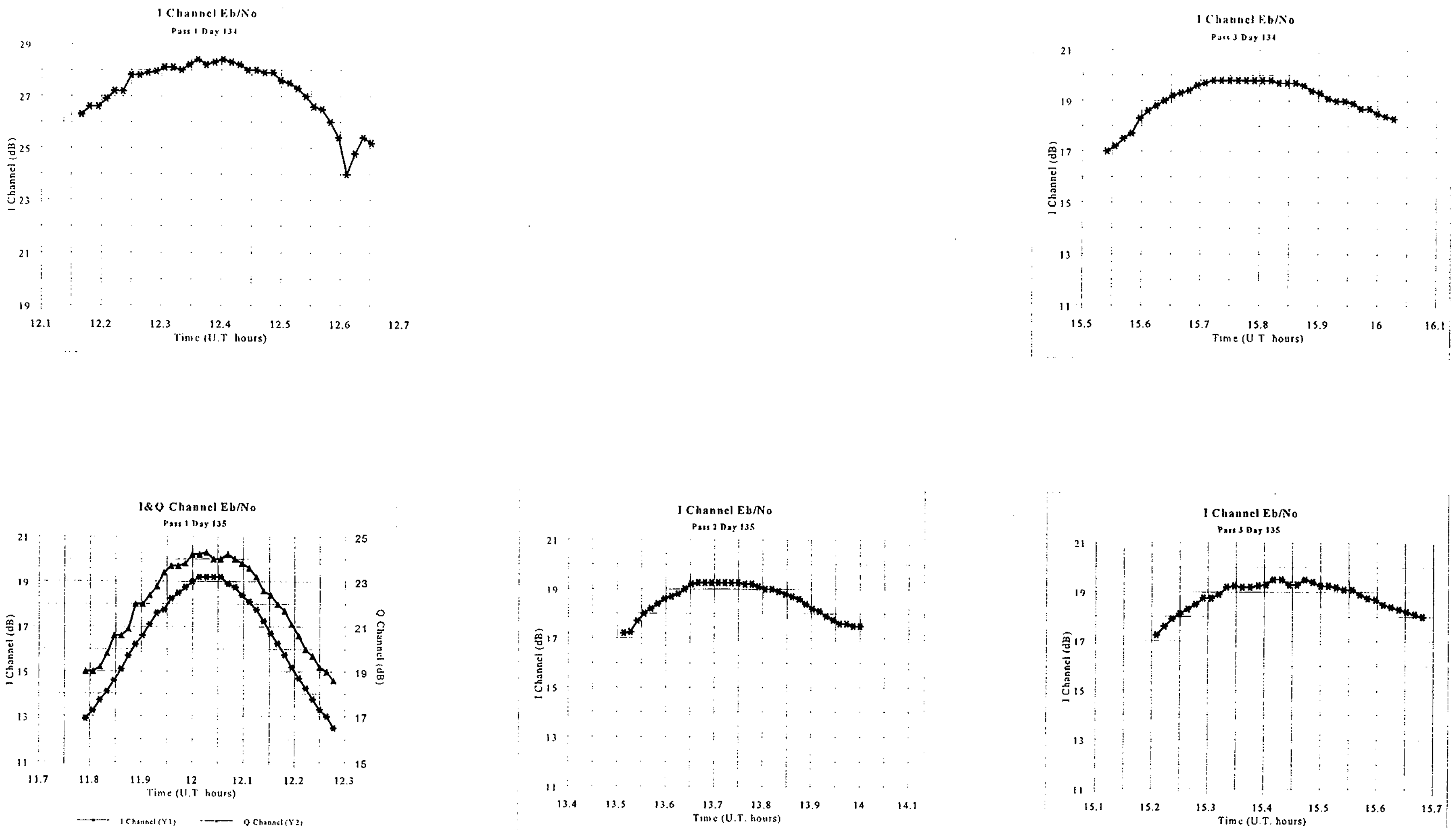


Figure 2 - E_b/N_o measurements for each EUVE pass as measured at WSC.

pointing. We will also show effects of broader antenna patterns and offset-pointing from the optimal case. Finally, we will show the effects of antenna pattern and space loss on the received signal strength. From these considerations, we can draw conclusions on how these results can be used in an operational satellite.

SECTION II - ANALYSIS

II.1 EXPLANATION OF RESULTS

The purpose of the test program was to validate the concept of accessing TDRS by using only a satellite's orbital motion to position the communications antenna. From previous analysis, it was expected that this concept would allow for brief, but significant, contacts similar to those found for a LEO satellite communicating with a fixed ground station. The results of the test with the EUVE did not show the expected short contact times but significantly-longer contact times. In subsequent discussions during the test debriefing, the reason for the unexpectedly long contact results became clear. The initial conceptual model for the test assumed that the communications antenna mounted on the EUVE spacecraft would act in a sweeping motion with respect to the TDRS Multiple Access (MA) antenna since the EUVE antenna did not employ active tracking during the contact time. To accomplish this, the EUVE antenna was pre-positioned to point directly at TDRS West as EUVE swept under the TDRS. During the test pass, the antenna would not be moved to track the apparent TDRS position. However, this model neglects the effects of having an inertially-stabilized attitude control system in EUVE. An inertially-stabilized attitude control system tries to maintain a constant pointing of the spacecraft with respect to an inertial coordinate system. While TDRS is still in earth orbit, its orbital altitude of 42,164 km with respect to the center of the earth and in excess of 35,000 km from EUVE, places it effectively at a distance of infinity with respect to EUVE and nearly motionless in an inertial coordinate system as seen from EUVE. Therefore, EUVE's inertial attitude control system maintains nearly-constant antenna pointing during a whole TDRS visibility period even though active antenna tracking has been disabled. With this type of spacecraft, the sweeping motion of a spinning satellite cannot be replicated without actively pointing the antenna during the pass. This also implies that active tracking during the pass may not be necessary to maintain communications contact between an orbiting spacecraft and TDRS.

II.2 SIMULATED EVENTS

In order to better understand the test results and validate the hypothesis for the antenna pointing, a series of simulations using the package Satellite Tool Kit [4] were performed. The simulations were configured for a geostationary satellite and a LEO satellite communicating with it. The geostationary satellite was given the TDRS West orbital characteristics while the LEO satellite was given the EUVE orbital characteristics. The orbital elements given in Table 1, which were obtained from the Air Force Institute of Technology Internet archive site [5], were used to generate the TDRS and EUVE positions corresponding to the time of the actual satellite passes. The simulation used an inertial attitude control model for the LEO spacecraft. The antenna systems on both satellites were modeled as sensor-objects within the simulation. In Satellite Tool Kit, sensor objects have an associated acceptance cone with a user-controller central angle which defines their field of view. For antennas, this acceptance cone usually will be related to the antenna Half Power Beam Width (HPBW). Contact times between the satellites in the simulation were based upon each being within the acceptance cone of the other for the contact duration. The simulated TDRS was modeled as having an acceptance cone width of ±13°

Table 1. NORAD Two-Line Elements

Satellite	Mean Orbital Elements
EUVE	`1 21987U 92031A   96133.75979634  .00000715  00000-0  23180-4 0  5418` `2 21987  28.4307  61.1763 0008917  26.4215 333.6854 15.19769324218282`
TDRS 4 West	`1 21639U 91054B   96134.58492492  .00000067  00000-0  00000+0 0   326` `2 21639   0.0894  72.6418 0004855 340.4259 214.7824  1.00274365111549`

corresponding to the actual TDRS MA antenna system pointing range. An acceptance cone with an angular width of ±6.2° was found to be the minimum necessary on the simulated LEO satellite to have contact with the simulated TDRS during whole time the TDRS was in view of the LEO satellite. A narrower acceptance cone angular width reduced the simulated contact time while a wider acceptance cone angular width did not increase the simulated contact time. By way of comparison, the actual EUVE antenna has a HPBW of approximately 7° which corresponds to an acceptance cone of only one half that found necessary to maintain contact over the simulated duration. However, there is significantly more than 3 dB of link margin so the antenna actually performed more like the simulated one than the HPBW would indicate. In the simulations, the acceptance cone angular width is considered to be an absolute constraint for determining the start and stop of the contact. For real systems, the beamwidth allowed by the link margin is the relevant beamwidth to be used. This will typically be more than the HPBW but the exact amount needs to be determined by the system designer based on the available link performance margin.

To compare the validity of the simulations with the actual test measurements, we give the times for the contacts over the period of the actual tests based on the simulations in Table 2. In this table, the contact times, as predicted by NASA prior to the tests, are also listed to show that they compare quite well. Ground tracks for all six of the simulated EUVE passes (light and heavy sinusoidal lines) and

Table 2. EUVE-to-TDRS Pass Log					
		Simulated (UT)		Predicted (UT)	
Day	**Pass**	**Start of Pass**	**End of Pass**	**AOS**	**LOS**
134	1	11:54:17	12:52:07	11:58:00	12:48:00
	2	13:34:46	14:33:04	13:39:00	14:29:00
	3	15:15:37	16:14:50	15:20:00	16:11:00
135	1	11:33:15	12:31:07	11:37:00	12:27:00
	2	13:13:44	14:12:08	13:18:00	14:08:00
	3	14:54:40	15:53:58	14:59:00	15:50:00

TDRS West (dot at the equator at -174° longitude) corresponding to the times of the experiment in May 1996 are shown in Figure 3 with similar results being obtained for the other five passes in the test series. The heavy-lined section of the ground track for EUVE indicates the portion of a pass when a contact through TDRS West would be possible. The Acquisition of Signal (AOS) and Loss of Signal (LOS) points along the simulated ground track are indicated. To produce the ground track, the user must enter the orbital element sets into the simulation program and adjust the simulated EUVE yaw, pitch, and roll attitude to give boresight antenna pointing to the TDRS West position at the time of closest approach. This simulates the configuration of the actual EUVE antenna pointing during the passes.

From these results, we can predict that the entire 58-minute pass should have been observable and not just the 30 minutes over which data was collected. For the actual test passes, all but one were observed to have actual measurements during the entirety of the scheduled test time. The one that did not was due to a ground hardware configuration problem. This implies that non-active pointing for spacecraft antennas on inertially-stabilized satellites has a potential use in satellite communication

(a) Pass #1 of Day 134

(b) Pass #3 of Day 134

(c) Pass #1 of Day 135

(d) Pass #2 of Day 135

(e) Pass #3 of Day 135

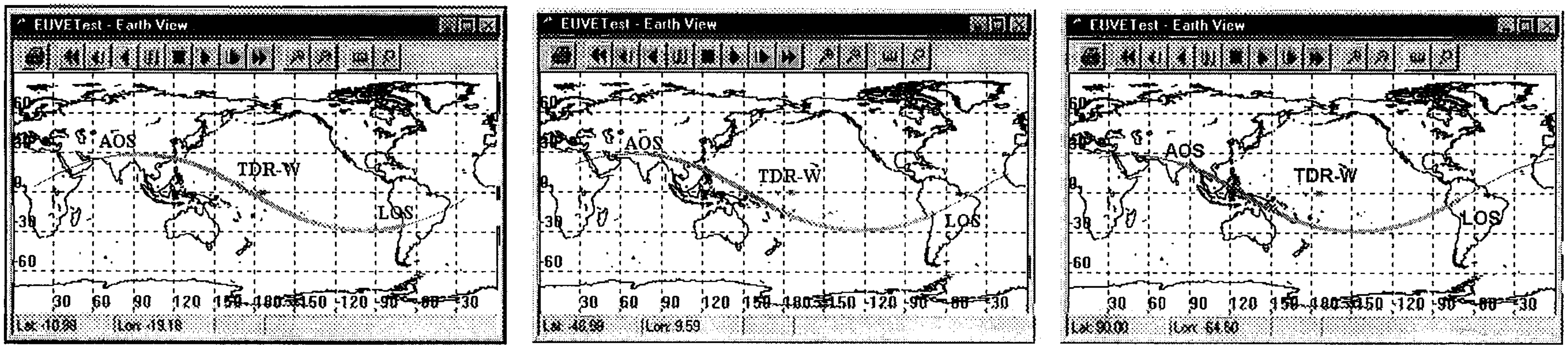


Figure 3 - Simulated EUVE Passes; EUVE Ground Track Shown as a Sinusoid with Darker Shading Indicating the Contact Region

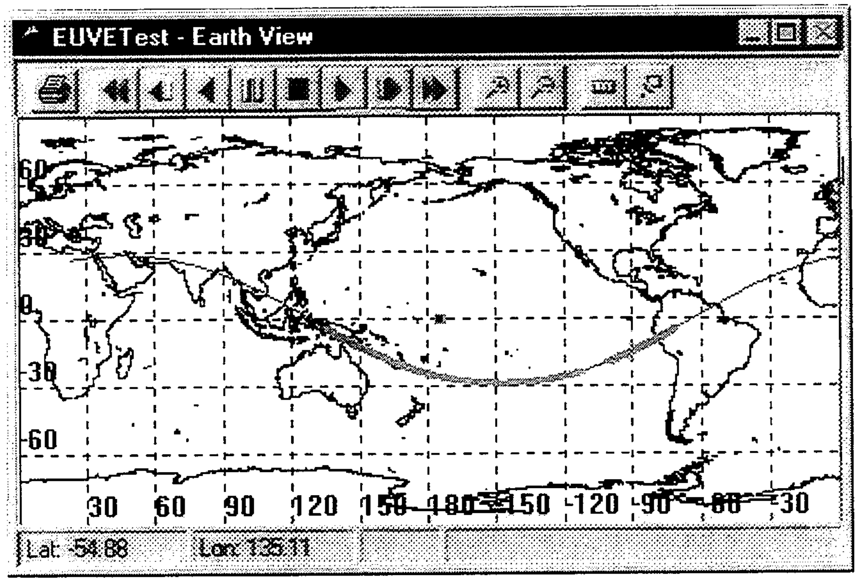
system design.

From an inspection of the simulated azimuth and elevation angles of the TDRS with respect to the EUVE, we find that they change over the pass time by up to 7° from boresight. To investigate limits on the performance in this configuration, several test simulations beyond those used to establish minimum acceptance cone profiles were developed. The first case investigated was that of a misaligned antenna with the results illustrated in Figure 4. Here, the simulated LEO satellite antenna is offset by 5° in yaw from its optimal value. As can be seen by a gap in the coverage near -110° longitude, the full-pass coverage is not obtained. However, if the acceptance cone angle is increased from ±6.2° to ±10°, the full pass coverage is again achieved as if the antenna had correct pointing. A second case considered was that of the antenna acceptance cone angle being set to ±32° with optimal antenna pointing being fixed at that needed for the second orbit of a three-orbit sequence. In this case, all three orbits are covered from the one pointing position as shown in Figure 5. In this case, all three passes for the second day of testing could have been covered with a suitable broad-beam antenna.

So far, we have only considered the pointing geometry for the access. To determine the actual communications performance, we need to also examine the effects of the orbit link power budget. We examine those issues in the next section.

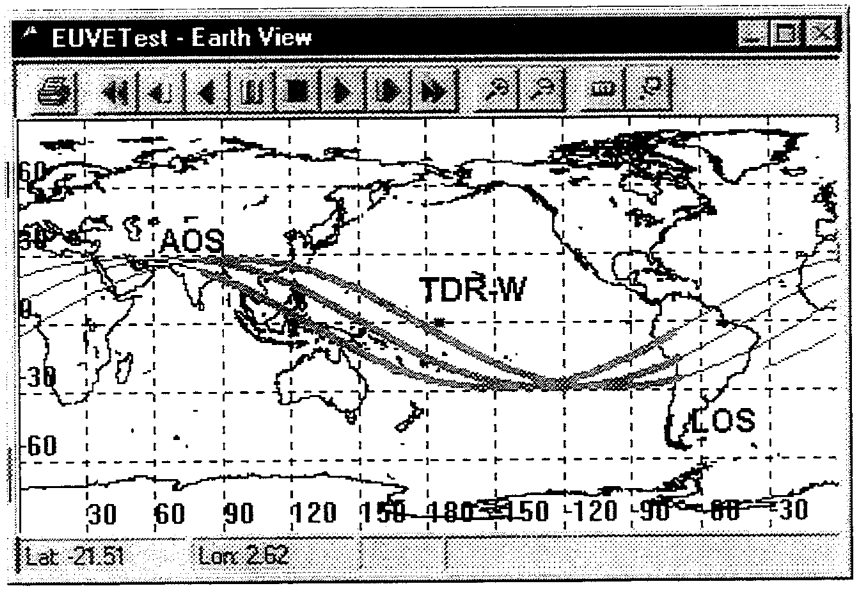
II.3 SPACE LOSS AND ANTENNA PATTERN CONTRIBUTION

During the six data collection passes between EUVE and TDRS West, it was noticed that the estimated the energy-per-bit to noise density ratio, E_b/N_o, as measured at the ground station receiving equipment, varied by several dB. In an effort to better understand the E_b/N_o results, it was decided to investigate



Lat: -54.88 Lon: 135.11

Figure 4 - Same simulated pass as Figure 3(e) but with the spacecraft off-pointed by 5° in yaw. The coverage gap occurs near -110° longitude.



Lat: -21.51 Lon: 2.62

Figure 5 - Simulation of three consecutive passes for 14 May 1996 with the antenna acceptance cone angle set to ±32°. The thick lines represent simulated contact times.

the space loss and antenna pattern contributions to the link as a function of the small variations in pointing during a pass. The variation in the received E_b/N_o should be a function of two effects: the changing distance between the LEO satellite and the relay satellite due to orbital motion and the changing gain in the LEO satellite antenna because the relay satellite is not always aligned with the antenna boresight pointing. Here, we examine both of these effects.

The variation in received signal power due to link distance is normally computed in the link power budget by the space loss term. The normal definition for the space loss, L_s, in a link is given by

$$L_s = 20 \log (4\pi R/\lambda) \qquad (1)$$

where R is the link range and λ is the operating wavelength. To compute the power variation relative to that at the minimum range, R_o, the relative space loss, L_{sr}, is computed using

$$L_{sr} = 20 \log (R/R_o) \qquad (2)$$

The link range, R, will vary over the contact time due to the orbital motion of the LEO satellite. Using this equation, and the range between the LEO satellite and the relay satellite from the simulation studies, the relative contribution to the overall observed E_b/N_o variation due to range variation was computed.

The antenna pattern variation was computed using an assumed tapered parabolic feed for the antenna. Under this assumption, the normalized gain pattern in dB units as a function of the off-axis pointing angle, θ, is given by

$$G = 10\log\left(64\left|\frac{J_2(u)}{u^2}\right|^2\right) \qquad (3)$$

where $u = \pi D \sin(\theta)/\lambda$ and D is the antenna diameter, and λ is the operating carrier wavelength [6],[7].

In these computations, the local elevation angle from the LEO satellite to the simulated TDRS position, as determined in the simulation, is used as the off-axis pointing angle.

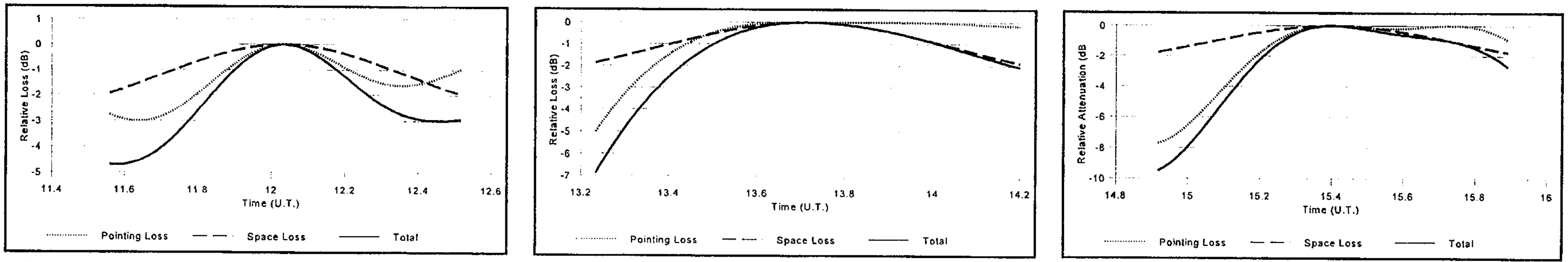
The predicted variation in the received E_b/N_o is based on the addition of the space loss and antenna pattern loss in dB units over time and is illustrated for each pass in Figure 6. This can be compared with the observed measurements as shown in Figure 7 which illustrates the normalized, predicted and observed E_b/N_o attenuation for all passes in the series. In most cases, the agreement is to within 1 dB. During the observed contact time, the space loss typically accounts for approximately 1 dB of the total signal variation while the antenna pattern gain variation accounts for the rest. Over the whole simulated contact time, the total variation in E_b/N_o is predicted to be approximately 6 dB with the space loss amounting to approximately 2 dB of the variation and the antenna pointing loss contributing the remainder. Because we are inferring the EUVE attitude and antenna pointing within the simulation and do not have access to the actual pointing vectors and spacecraft attitude, we expect there to be some variations between the predicted signal variations and the actual measurements. Also, no special care was taken at the WSC to calibrate the measurement devices for exact E_b/N_o measurements so some variation is expected here as well. Given these uncertainties, we find this level of agreement to be reasonable for this experiment configuration.

SECTION III - LONG-TERM RESULTS

An extended set of simulations was run to determine the effectiveness of the non-active antenna pointing over a 31-day period. In these simulations, both the TDRS East and TDRS West satellites were used as potential targets for the inertially-controlled LEO satellite. The antenna position was fixed at that for an orbit whose descending node was near the TDRS West subsatellite location. Figure

(a) Pass #1, Day 134

(b) Pass #3, Day 134



(c) Pass #1, Day 135

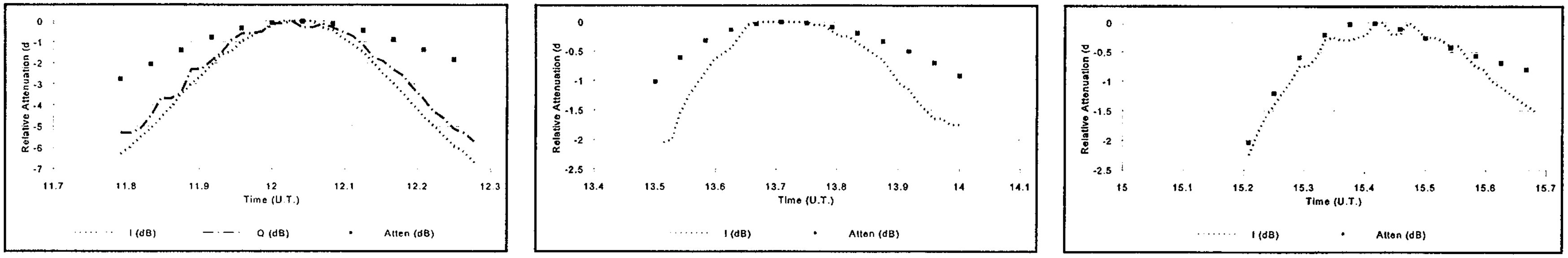
(d) Pass #2, Day 135

(e) Pass #3, Day 135

Figure 6 - Predicted Pointing Loss and Space Loss Variations over the Simulated Contacts

(a) Pass #1, Day 134

(b) Pass #3 Day 134



(c) Pass #1, Day 135

(d) Pass #2, Day 135

(e) Pass #3, Day 135

Figure 7 - Predicted and Observed Signal Variation over the Contact Duration

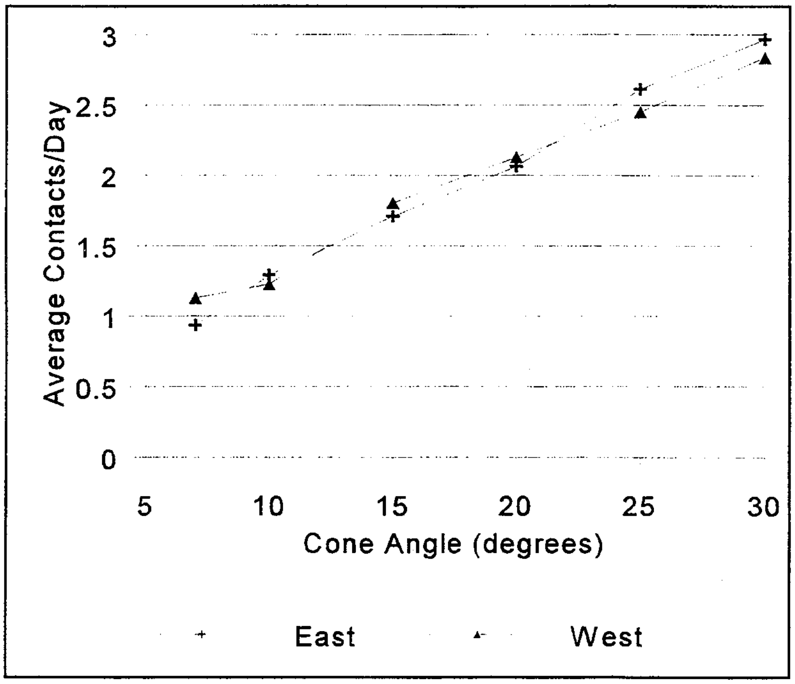


Figure 8 - Simulated Number of Daily Contacts through the East and West TDRS as a Function of Acceptance Cone Angle.

8 illustrates the average number of contacts per day as a function of the antenna acceptance cone angle. For narrow cone angles, the LEO satellite is able to make one contact per day through each TDRS. As the acceptance cone angle increases, the number of contacts per day increases through approximately three contacts per day at an acceptance cone angle of ±30°. As can be seen, the number of contacts per day is the same for both TDRS even though the pointing was optimized for TDRS West. In all cases, the contacts through TDRS East and West did not occur on the same orbits.

Related to the number of contacts per day is the duration of each contact. Figure 9 illustrates the average and maximum contact durations over the same 31-day simulation period used above. As can be seen, the maximum duration is approximately 60 minutes and is not a function of antenna acceptance cone angle. This occurs on orbits where the pointing is optimized for boresight pointing. The second part of the plot is the average contact duration which is a function of the antenna

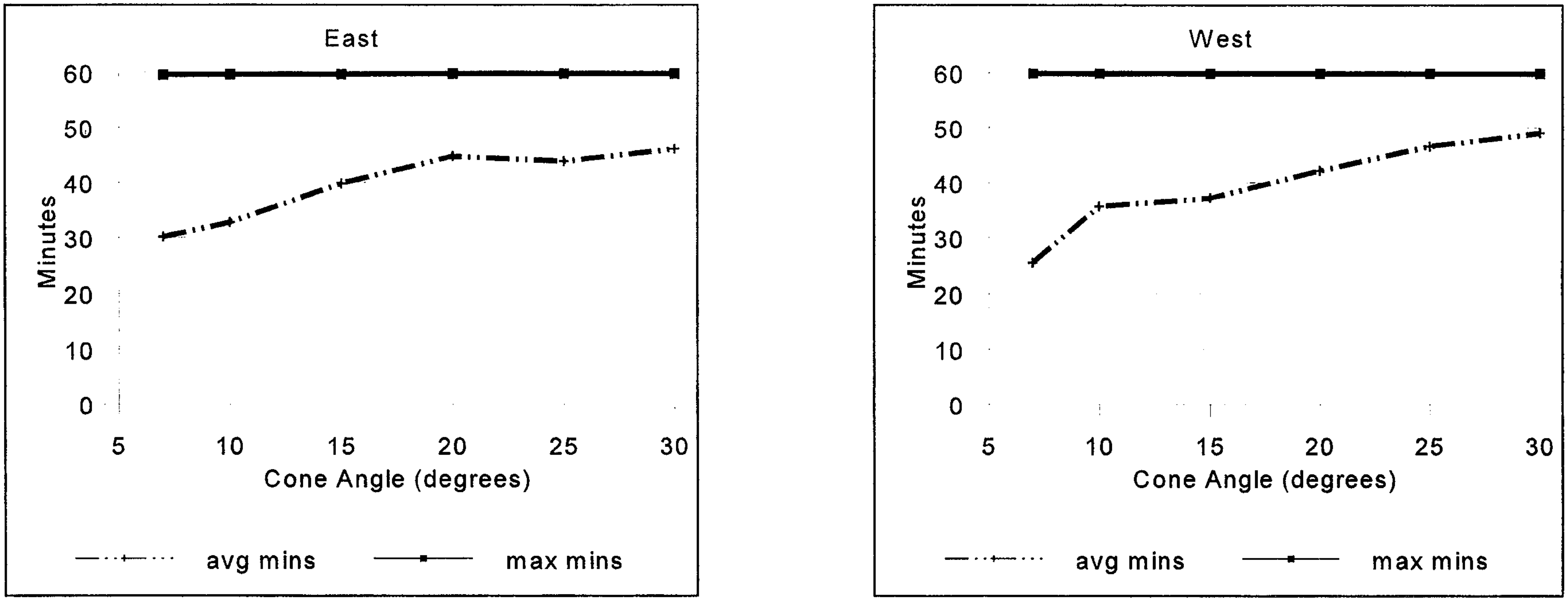


Figure 9 - Simulated Average and Maximum Contact Duration through TDRS East and TDRS West.

acceptance cone angle. For the single contact per day with the narrow cone angle, the average time is 25 minutes. For the large acceptance cone angles, the average contact duration rises to nearly 50 minutes. These results are illustrated for TDRS West and are similar for TDRS East.

SECTION IV - IMPLICATIONS

The test brought out a significant, unexpected result: inertially-stabilized spacecraft can achieve full-pass access to a given TDRS under the following conditions:

a. Based upon the simulation results, the antenna for the transmitting satellite needs to have a useful beamwidth exceeding ±6.2°

b. For narrow-beam antennas, the pointing angle needs to be exact from the transmitting satellite to TDRS

c. If the beamwidth is wider, the pointing does not need to be as exact and in fact can cover several orbits with one pointing angle if the beamwidth is broad enough

d. If a single antenna pointing angle is used over an extended period, significant contacts can be obtained each day with the exact number of contacts and contact duration being a function antenna acceptance cone angle.

These conclusions are based on the simulation results but their agreement with the actual events is encouraging. These results can be considered in the design of satellites with low-gain antenna systems.

Based on the simulations and the actual test results, new possibilities for antenna pointing on inertially controlled satellites are indicated. For example:

a. Satellites having antenna systems which have lost their tracking capability could be prepointed to obtain useful passes,

b. Emergency backup antennas could be made and permanently mounted on a satellite,

c. If minimizing the wear on antenna gimbals or having the need to operate in reduced-power mode is necessary in a satellite, then support using a limited series of contacts through TDRS for data services is still possible despite the reduced capacity of the satellite.

Other potential uses may become apparent based on a detailed study of the satellite operations concept.

SECTION V - ACKNOWLEDGMENTS

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SECTION VI - REFERENCES

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