TEST REPORT: LOW-COST ACCESS TO TDRS USING TOPEX TO EMULATE SMALL SATELLITE PERFORMANCE

Stephen Horan

NMSU-ECE-97-013 August 1997

TEST REPORT: LOW-COST ACCESS TO TDRS USING TOPEX TO EMULATE SMALL SATELLITE PERFORMANCE

Prepared by:

Stephen Horan
Manuel Lujan Space Tele-Engineering Program
Klipsch School of Electrical and Computer Engineering
New Mexico State University
Box 30001, MSC 3-0
Las Cruces, NM 88003

NMSU-ECE-97-013

Work performed as part of NASA Grant NAG 5-1491

August 29, 1997

TABLE OF CONTENTS

ACRONYM LIST

BER	Bit Error Rate
HPBW	Half Power Beam Width
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
NMSU	New Mexico State University
STK	Satellite Tool Kit
TDRS	Tracking and Data Relay Satellite
TLE	Two Line Element
WSC	White Sands Complex

I. EXECUTIVE SUMMARY

This report lists the objectives and conclusions of a series of experimental contacts between the TOPEX and the TDRS satellites. These experiments are designed to verify the theoretical prediction that a spin-stabilized satellite with a broad-beam, zenith-pointing antenna can have regular, significant contacts with the TDRS and use those contacts for data services. This series of experiments is a joint project between the experimenters at New Mexico State University (NMSU), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), and the Jet Propulsion Laboratory (JPL).

In these experiments, we show that

1. The satellite contacts during the experiment begin and end as predicted prior to the experiment
2. The data contact is held for the desired contact duration
3. The data quality through the contact is high and similar to that required by actual project needs
4. The receiving hardware at the White Sands Complex (WSC) is able to track the signals better than expected by analysis of the antenna pattern effects alone predict.

We believe that these experiments successfully demonstrate the basic concept and its validity with actual spacecraft systems.

II. TEST OBJECTIVES

The pointing experiment conducted between the TOPEX (see Figure 1) spacecraft and the Tracking and Data Relay Satellites (TDRS) was designed to provide experimental verification to the theoretical studies made earlier [1] - [4] into the potential for non-gimbaled antennas to point at the TDRS satellites in the Space Network constellation and provide useful data throughput. The test was designed to show that

1. A user satellite using a fixed-pointed antenna will be able to initiate and maintain contact with a TDRS when that antenna is pointed at the user satellite's local zenith position
2. This will occur on those orbits where the user satellite's orbit passes near the TDRS subsatellite point (see Figure 2)
3. The contact duration and data quality will be sufficient to provide a reasonable data service.

While the concept was originally developed using low-gain, non-directional antennas, this experiment is being conducted with a high-gain antenna on the TOPEX. While the high-gain antenna will have a Half Power Beam Width (HPBW) greater than the 40-degree beamwidth used in the theoretical analysis, it is expected that the TOPEX system will have sufficient margin to maintain

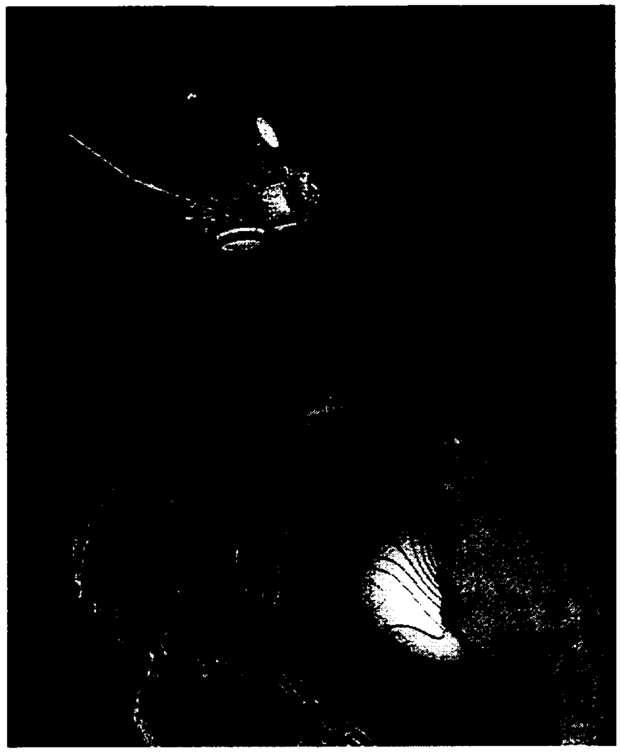

Figure 1 - TOPEX spacecraft.

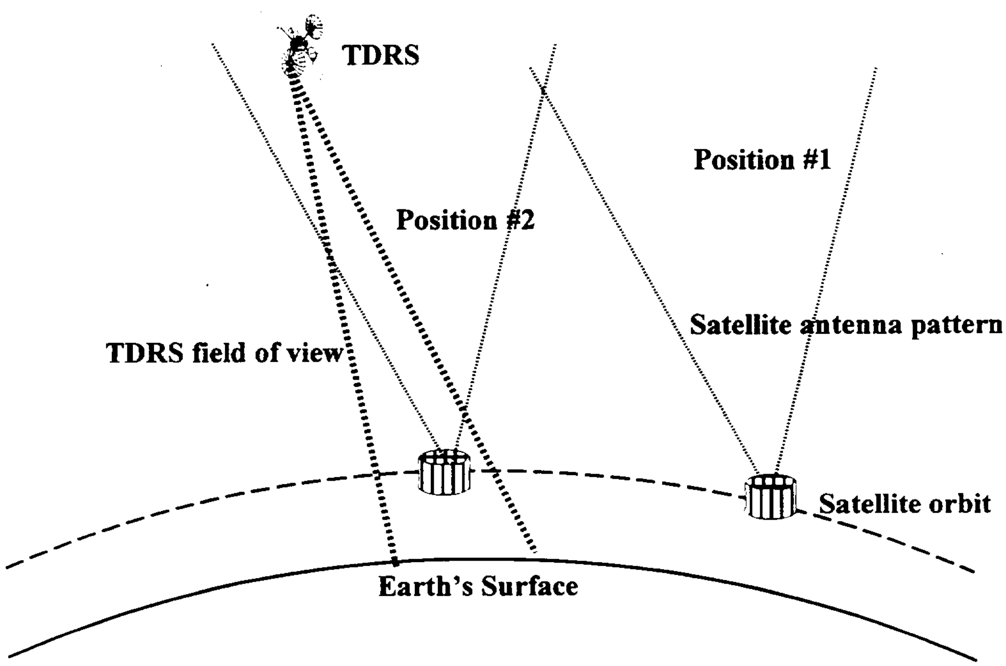

Figure 2 - Fixed antenna access by a satellite sweeping past the TDRS position.

a contact even when operating on an antenna side lobe and not the antenna main lobe.

III. TEST PARTICIPANTS

The test participants included:

1. Stephen Horan - NMSU: experiment design
2. Leslie Ambrose - NASA/GSFC: network interface and scheduling
3. Pat Sanatar - JPL: TOPEX project interface
4. Bruno Calanche - JPL: TOPEX communications analysis

Other test personnel were called upon as need by the respective GSFC and JPL organizations. There was no requirement for explicit support at the White Sands Complex (WSC) beyond normal TOPEX user support. Orbital predictions and data analysis were performed both at NMSU and JPL.

IV. TEST DATA TO BE GATHERED

During the experiment runs, two major data sets were to be collected during the contacts between TOPEX and the assigned TDRS: signal strength indicators and data quality indicators. This data was developed at JPL based on the normal performance monitoring data supplied from the WSC to a user. In particular, the minimum data set to be collected included

1. Signal strength indication at the WSC receivers
2. An estimate of the received signal Bit Error Rate (BER)
3. Signal start and stop times.

JPL elected to collect other data, in particular, the forward link AGC voltage to give an indication of the forward-link signal strength.

During the experiment time, the TOPEX was configured to send a test data set on the Q channel with a data rate of 16 kbps.

V. SELECTION OF EXPERIMENT OPPORTUNITIES

The times for the experiment opportunities were determined by

1. Non-interference with scheduled operations at WSC and for TOPEX
2. TOPEX passing within 20° of a TDRS subsatellite point at closest approach
3. Ability to try communications with both TDRS East and TDRS West

4. Attempt to have two passes close in time on different TDRS satellites.

The duration of the experiment was determined by the time for the TOPEX to travel the distance along its orbit corresponding to a pointing angle range of ± 20° from a given TDRS. From these general constraints, a list of potential dates and times in June 1997 were submitted to JPL for investigation of potential access times. From the general list, the dates and times listed in Table 1 were selected by JPL as experiment windows for data collection. Figures 3 through 7 illustrate the ground tracks for TOPEX, TDRS East and TDRS West during these experiment windows. The orbital ground tracks were generated at NMSU using Satellite Tool Kit (STK) [5]. The ephemeris data for both the TDRS satellites and TOPEX were obtained from the Air Force Institute of Technology ftp server [6] in the form of standard two-line element (TLE) files. Table 2 lists the orbital elements used in the predictions.

Table 1. TOPEX Experiment Windows of Opportunity

Day Number	Date	Start Time	End Time	TDRS
174	23 June 1997	3:42:30	3:55:00	West
175	24 June 1997	6:54:30	7:06:00	East
176	25 June 1997	7:15:15	7:29:00	East
178	27 June 1997	15:27:30	15:40:30	West
178	27 June 1997	18:15:30	18:29:30	East

Table 2. TOPEX and TDRS Orbital Elements

Orbital Element	TOPEX	TDRS-East	TDRS-West
spacecraft identifier	22076	19883	21639
epoch	97173.53461370	97176.06688969	97176.29836412
inclination angle (degrees)	66.0378	0.6707	0.0813
eccentricity	0.0008359	0.0002370	0.0004207
Right Ascension of Ascending Node (degrees)	163.4372	85.5045	101.0808
Argument of Perigee (degrees)	278.7732	26.4777	27.5138
Mean Anomaly (degrees)	81.2337	144.3773	77.9855
Mean Motion (rev/day)	12.80930736	1.00270071	1.00274832

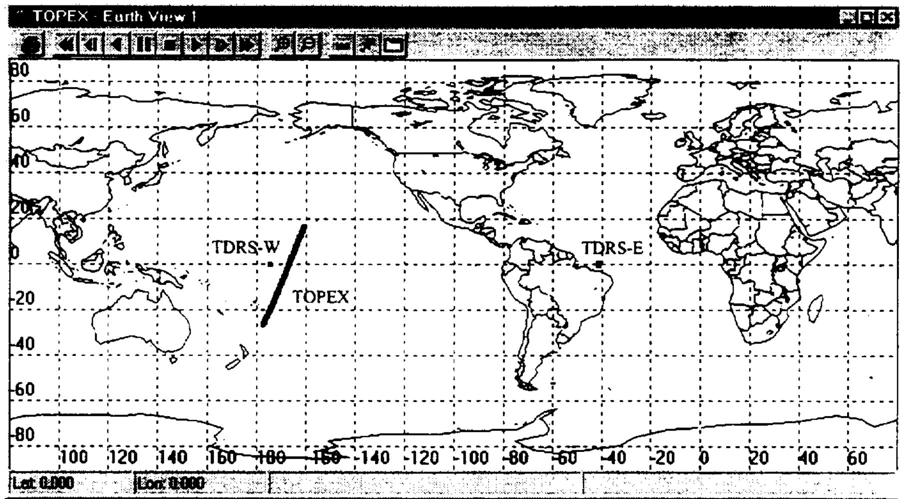

Figure 3 - TOPEX ground track for day 174 and access to TDRS-W.

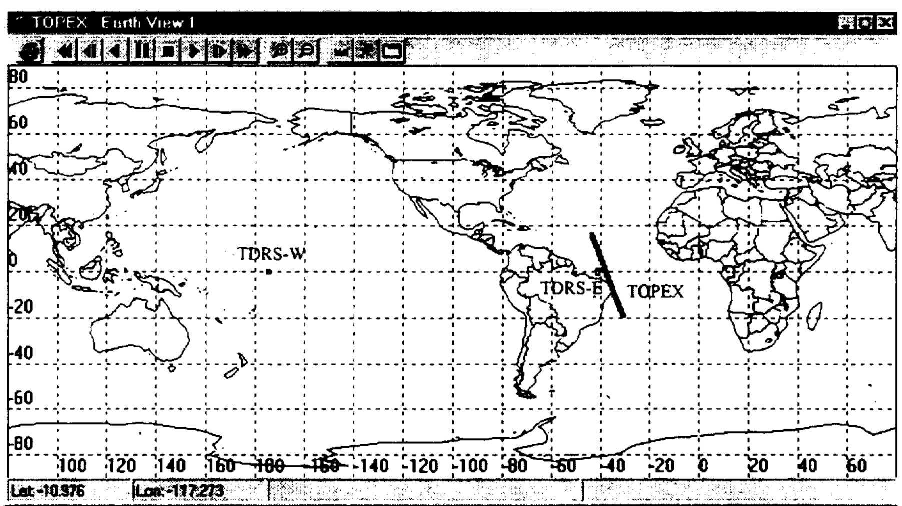

Figure 4 - TOPEX ground track for day 175 and access to TDRS-E.

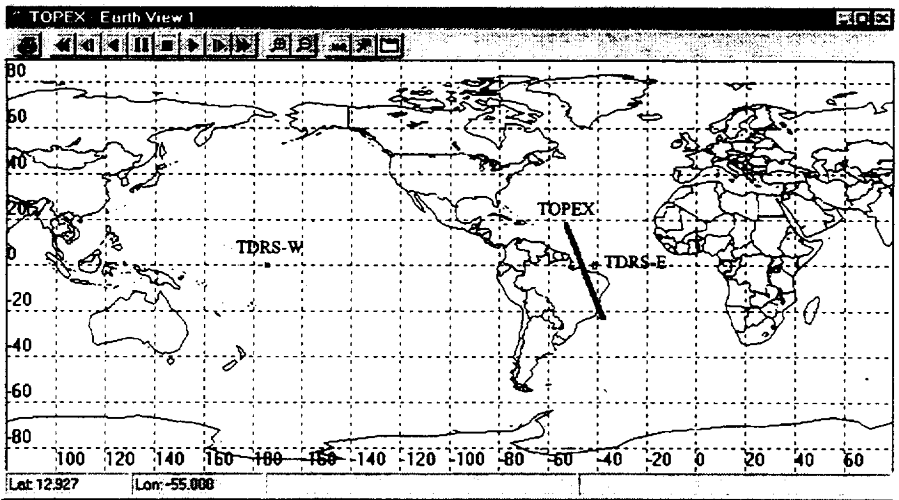

Figure 5 - TOPEX ground track for day 176 and access to TDRS-E.

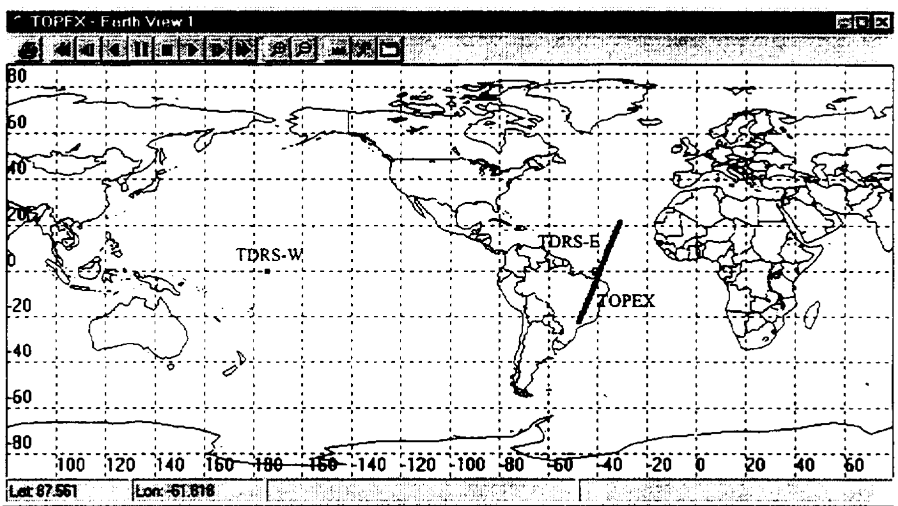

Figure 6 - TOPEX ground track for day 178 and access to TDRS-E.

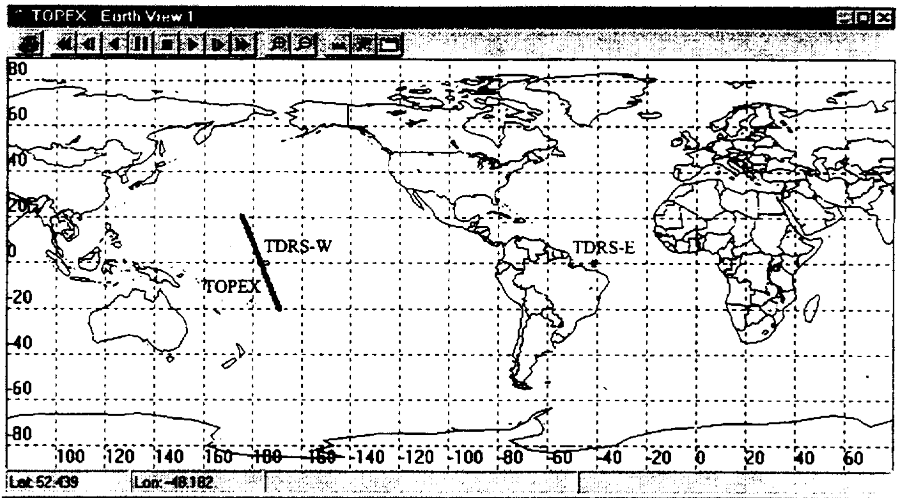

Figure 7 - TOPEX ground track for day 178 and access to TDRS-W.

VI. TEST RESULTS

VI.1 Pointing Angles and Access Times

The first check made on the experiment was to cross check the predicted pointing from TOPEX to TDRS for each pass. These pointing angles were used to estimate the start and stop times for each pass. This was given to the scheduling office for scheduling the experiment times. Figures 8 through 12 show the reported zenith angle between the TOPEX high gain antenna boresight pointing and the TDRS used for the contact. Also given is the predicted pointing angle estimated by STK. The STK analysis did not have the actual TOPEX attitude so the difference between the measured and the predicted would be expected to have an uncertainty of a few degrees. This is what is seen in these graphs. STK also generated predictions of the TOPEX azimuth pointing angle to TDRS and these can be compared with the TOPEX results but that result does not prove a reasonable accuracy check because the TOPEX attitude in true, three-dimensional space was unknown to the experimenters at NMSU and, therefore, there is a considerable angular offset between the STK results and the TOPEX data.

The predicted access times for each pass were generated prior to the experiment window based on when the TOPEX would enter or leave the 20-degree circle around the TDRS subsatellite point. The pass durations were chosen to be approximately 10 minutes (see Table 1) with the expectation that we would observe the receiver lock-up process at the WSC. The return link from TOPEX through TDRS receiver lock status is indicated in Figures 13 through 17 where a

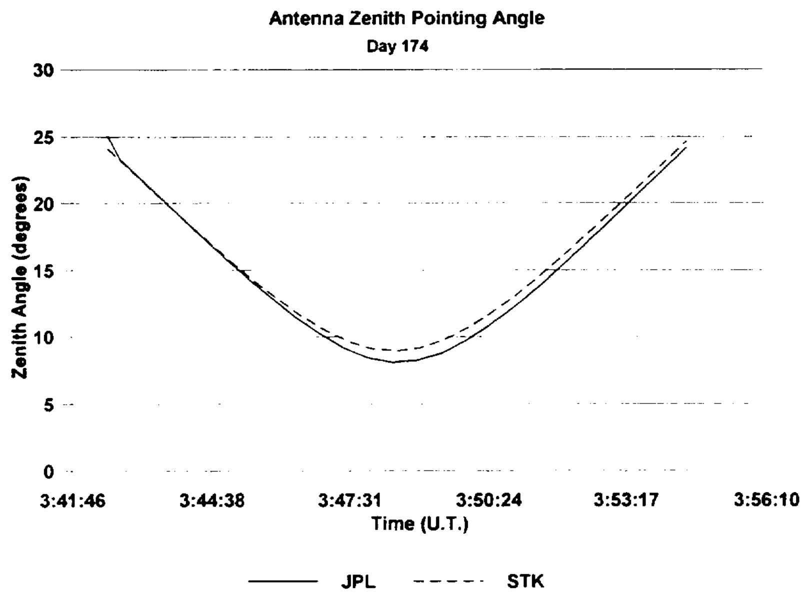

Figure 8 - TOPEX to TDRS antenna pointing relative to boresight for day174.

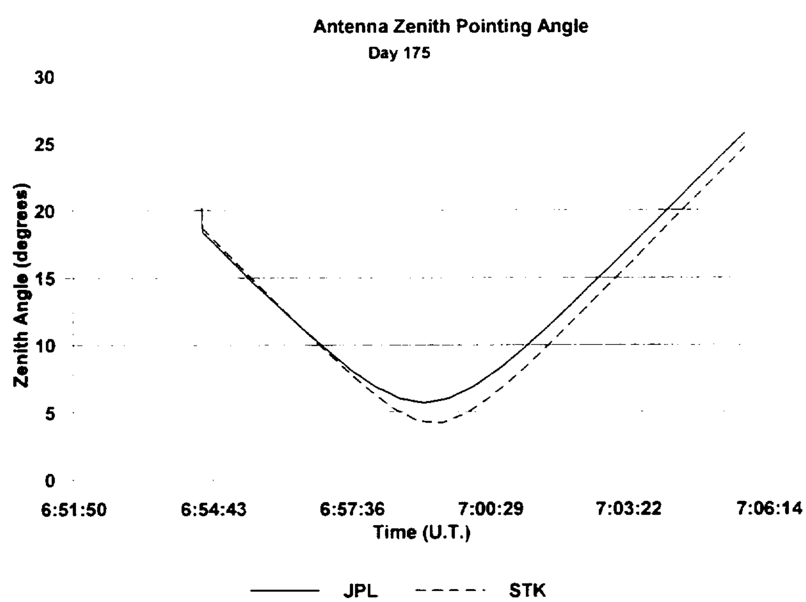

Figure 9 - TOPEX to TDRS antenna pointing relative to boresight for day175.

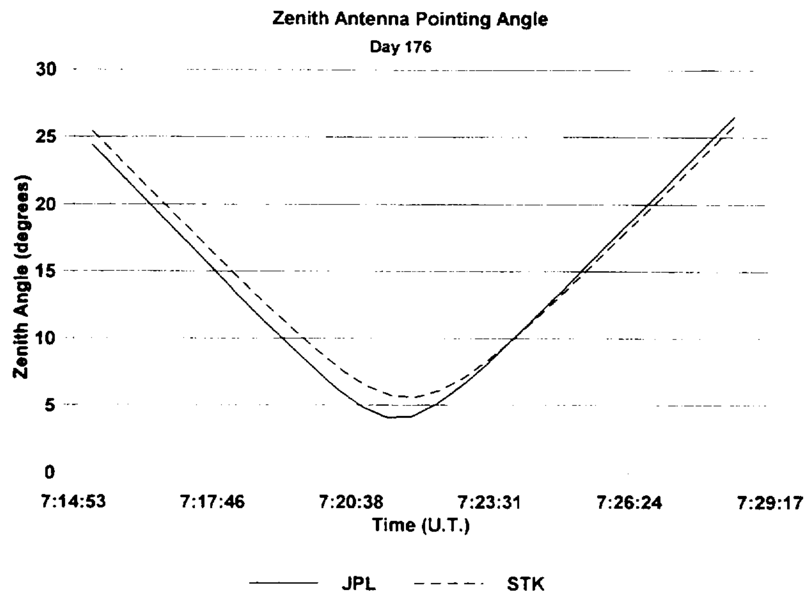

Figure 10 - TOPEX to TDRS antenna pointing relative to boresight for day176.

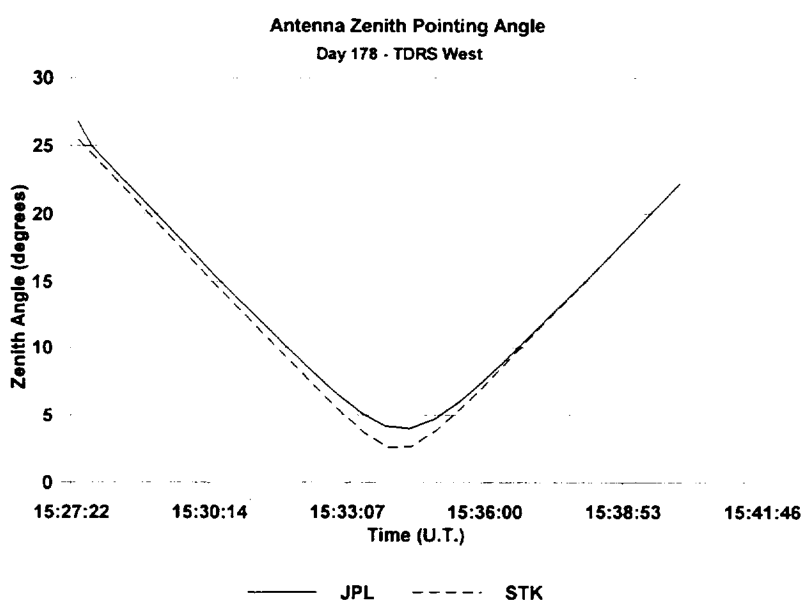

Figure 11 - TOPEX to TDRS antenna pointing relative to boresight for day178.

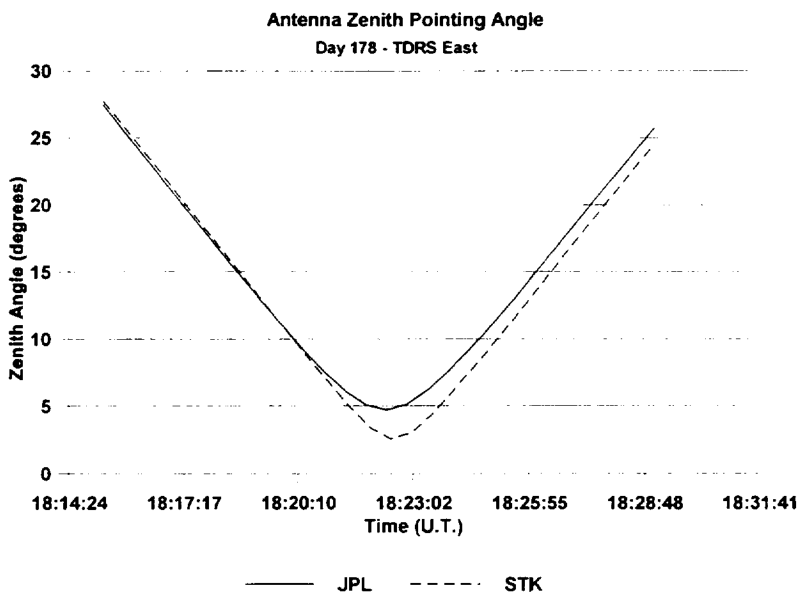

Figure 12 - TOPEX to TDRS antenna pointing relative to boresight for day178.

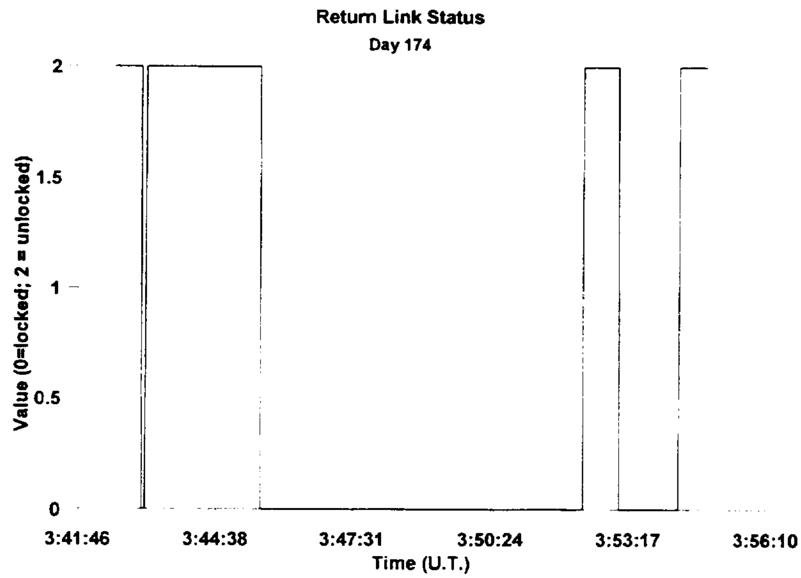

Figure 13 - Receiver lock status at the WSC for day 174.

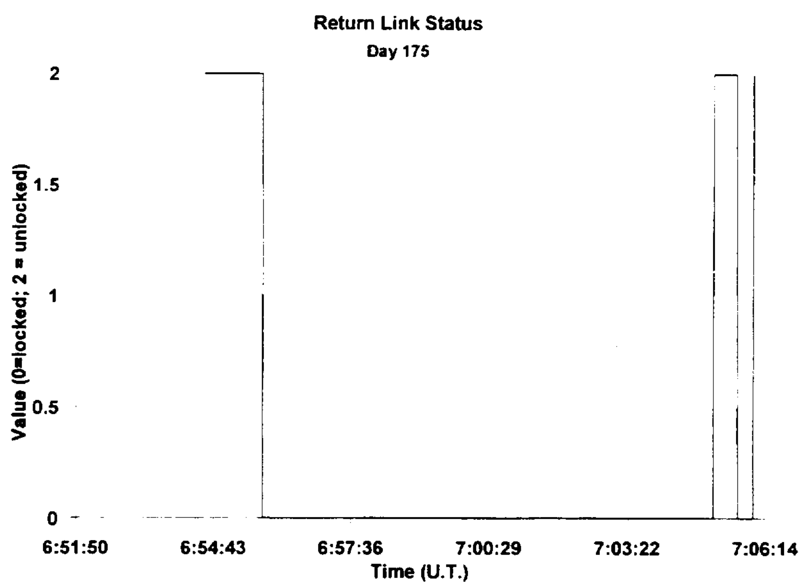

Figure 14 - Receiver lock status at the WSC for day 175.

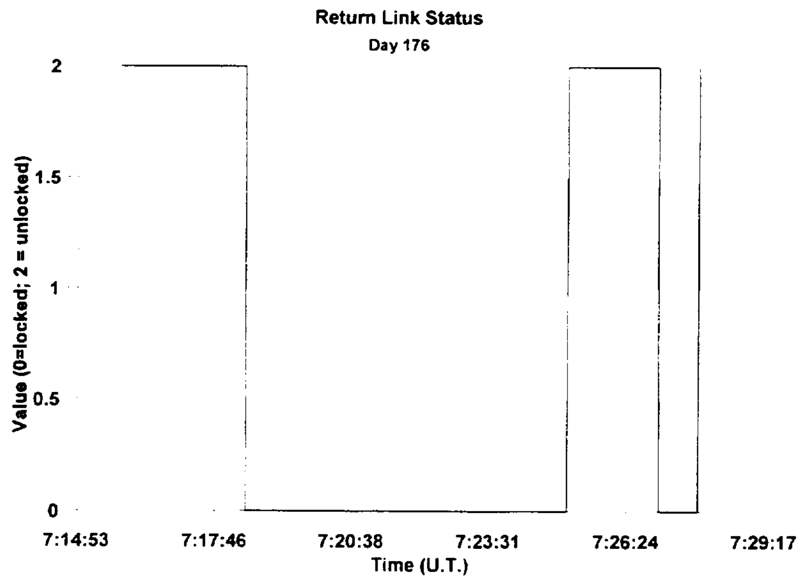

Figure 15 - Receiver lock status at the WSC for day 176.

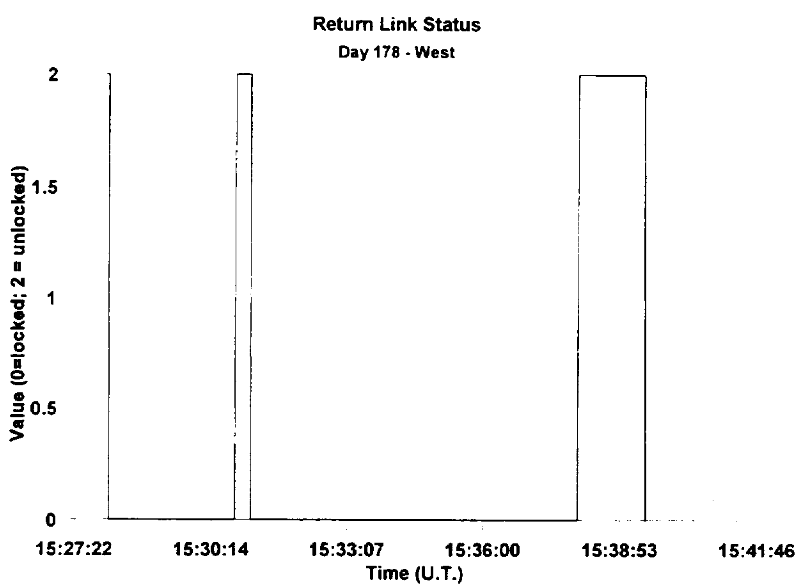

Figure 16 - Receiver lock status at the WSC for day 178 and TDRS West.

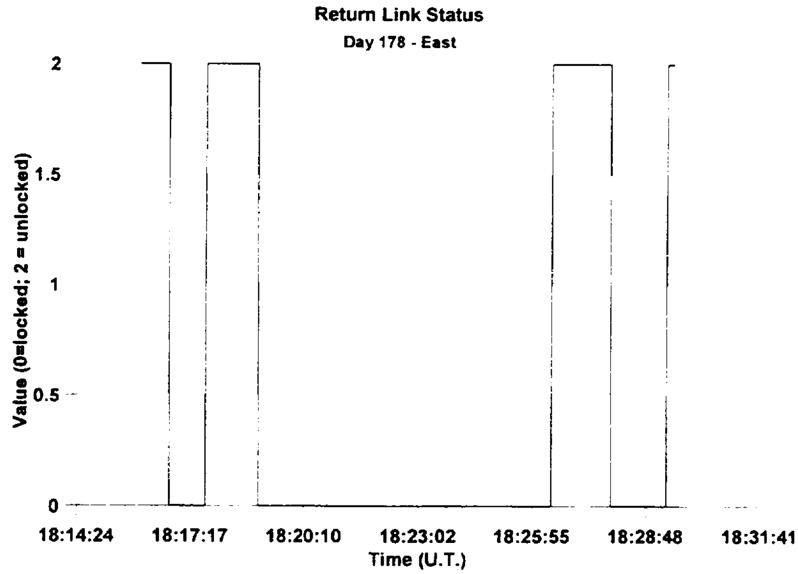

Figure 17 - Receiver lock status at the WSC for day 178 and TDRS East.

value of 0 indicates receiver lock while a value of 2 indicates that the receiver is not locked. The plots generally indicate a main region of receiver lock around the center of the pass time and a shorter region on either side of this where the receiver has short lock periods. Table 3 gives the return link primary access regions and an indication of secondary access regions for each pass. Table 4 gives the total time in each region. There was not a similar measurement available for the forward link to TOPEX through TDRS.

Table 3. TOPEX Return Link Access Times Based on Receiver Lock Status

Pass Day	Primary Start	Primary Stop	Secondary Start	Secondary Stop
174	3:45:35	3:52:19	3:53:05	3:54:19
175	6:55:45	7:05:09	7:05:40	7:06:00*
176	7:18:25	7:25:09	7:27:05	7:27:54
178-W	15:31:05	15:37:59	15:28:05 15:39:25	15:30:44 15:40:25*
178-E	18:19:00	18:26:24	18:16:45 18:27:55	18:17:39 18:29:19

* scheduled end of pass time

Table 4. TOPEX Return Link Access Durations		
Pass Day	**Primary Duration (minutes)**	**Secondary Duration (minutes)**
174	6.73	1.23
175	9.40	0.33*
176	6.73	0.82
178-W	6.90	2.65, 1.00*
178-E	7.40	0.9, 1.40

* terminated by scheduled end of pass

VI.2 BER Performance

The estimated Bit Error Rate (BER) performance of the data sets is illustrated in Figures 18 through 22. This data is derived from ODM data for the TOPEX Q channel and was supplied from the WSC. As can be seen from these plots and the receiver lock status plots, when the receiver was in lock, the BER generally was at the 8 level corresponding to an estimated maximum BER of 10^{-8}.

VII. ANALYSIS OF RESULTS

VII.1 Expected Effects of Antenna Pattern and Space Loss

The antenna pattern and the change in the link distance over the pass time are expected to modify the observed signal strengths from that seen in boresight alignment at closest approach between the TOPEX and the TDRS. These effects would be observable on both the forward and return data links through TDRS to the TOPEX. In this section, we will outline the expected contributions of both of these effects.

The antenna pattern will exhibit relative gain variations because we have fixed the pointing of the TOPEX antenna towards the local zenith. Normally, this antenna would be tracking the relative TDRS position and provide close to boresight pointing for the data service. In this experiment, the TOPEX will suffer a considerable pointing loss towards the TDRS directions because the tracking has been disabled. We can estimate the size of the pointing loss by approximating it with a symmetrical pattern and use the following relationship for the pointing loss, L_p, [7],[8]:

$$L_p = 64\left|\frac{J_2(u)}{u^2}\right|^2$$

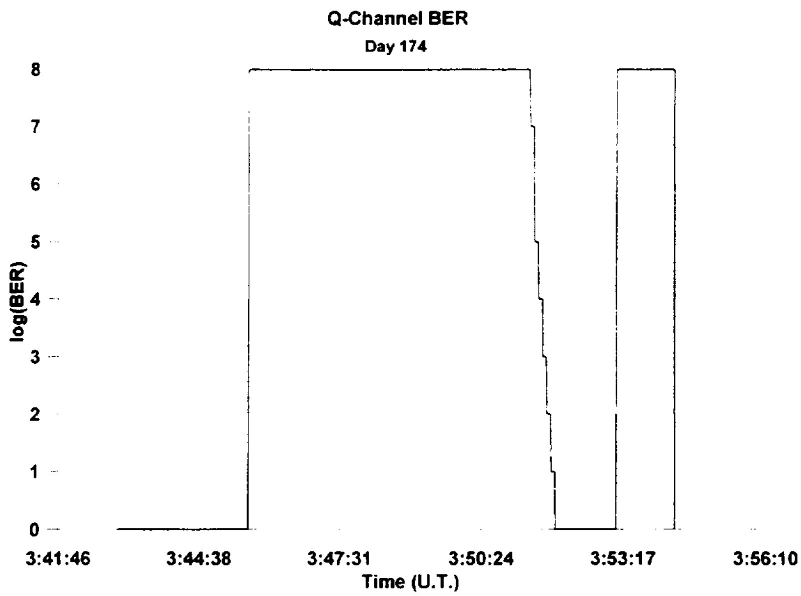

Figure 18 - Q-Channel BER Status for day 174.

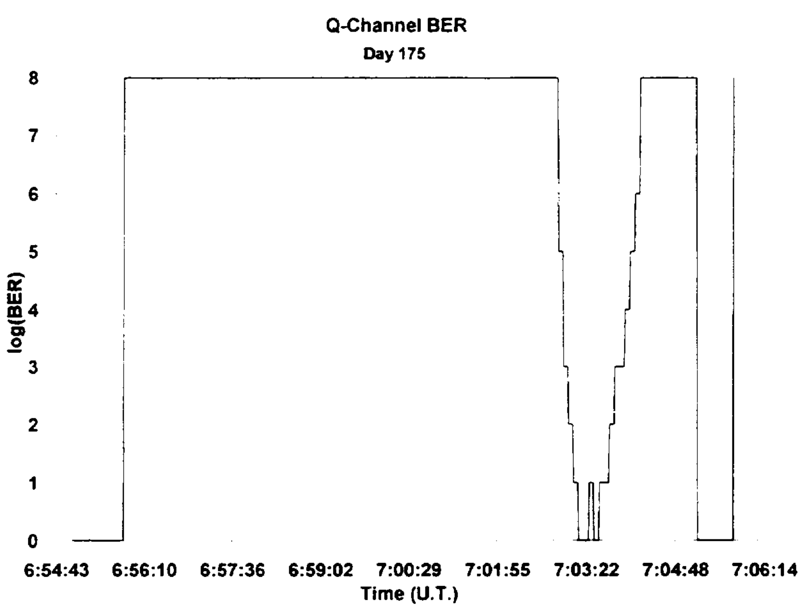

Figure 19 - Q-Channel BER Status for day 175.

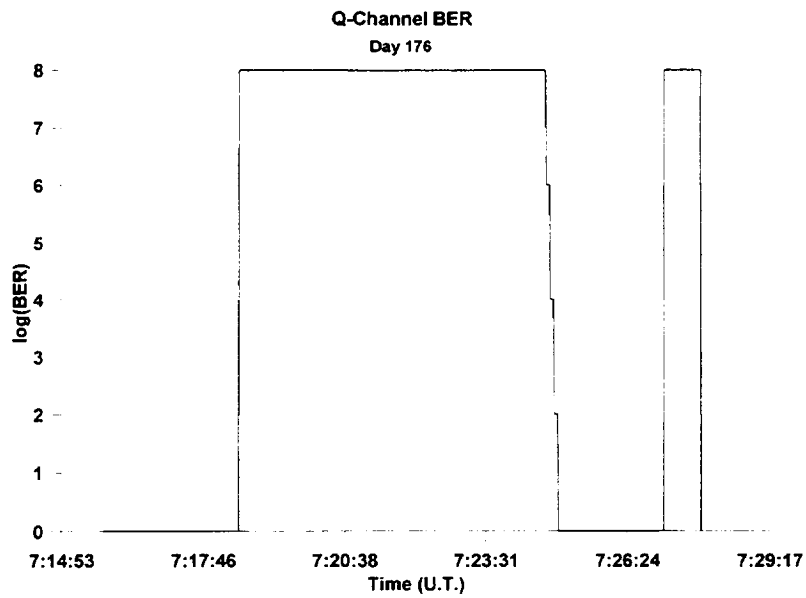

Figure 20 - Q-Channel BER Status for day 176.

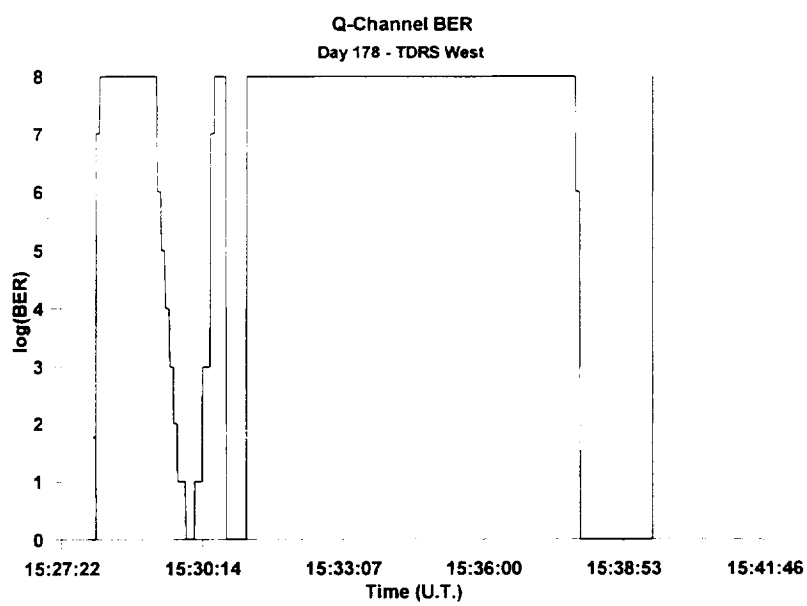

Figure 21 - Q-Channel BER Status for day 178 and TDRS West.

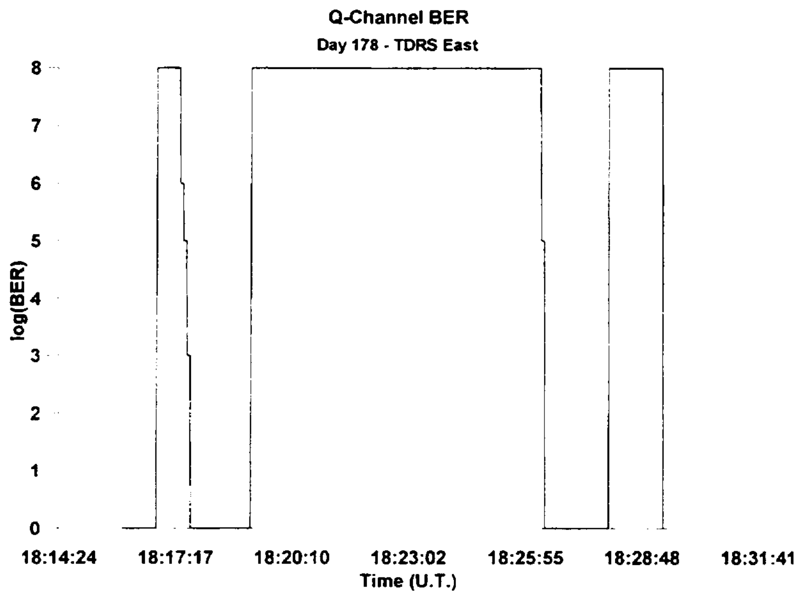

Figure 22 - Q-Channel BER Status for day 178 and TDRS East.

where u = $\sin(\theta)\lambda/D$ given that θ is the pointing angle from boresight (the same angles as plotted in Figures 8 through 12), λ is the radiation wavelength corresponding to a carrier frequency of 2287 MHz, and D is the TOPEX antenna diameter of 1.29 meters [9].

The space loss, L_s, effect can be computed from

$$Ls = (4\pi R/\lambda)^2$$

where λ is the radiation wavelength and R is the link distance.

When working in dB units, both losses can be added together for a combined expected loss value. In Figures 23 through 27, the relative value of the combined loss is plotted. This is the difference in dB between the computed loss at every moment in time through the pass and the minimum loss occurring at the mid-point of the pass. As can be seen for each pass, there is a central lobe centered near the mid-pass point and several side lobes. The side lobes arise from the antenna pattern. The space loss provides a nearly-constant offset because the range does not change substantially over the 10-minute pass.

VII.2 Comparison with Actual Results

We can estimate the HPBW of the TOPEX high-gain antenna by [10]

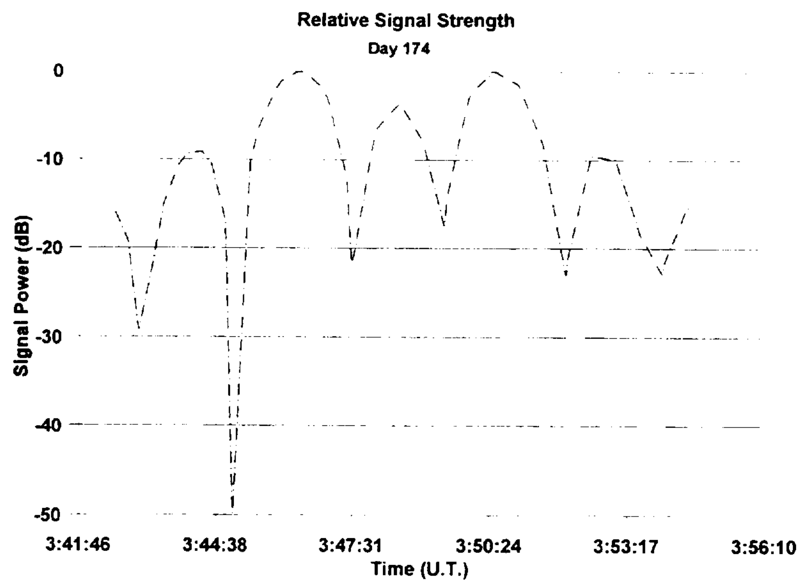

Figure 23 - Pointing loss and space loss for day 174.

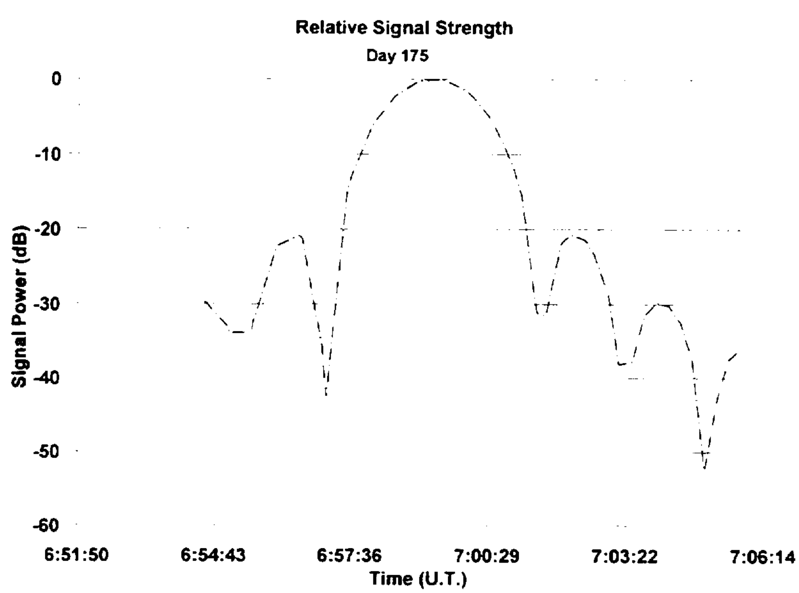

Figure 24 - Pointing loss and space loss for day 175.

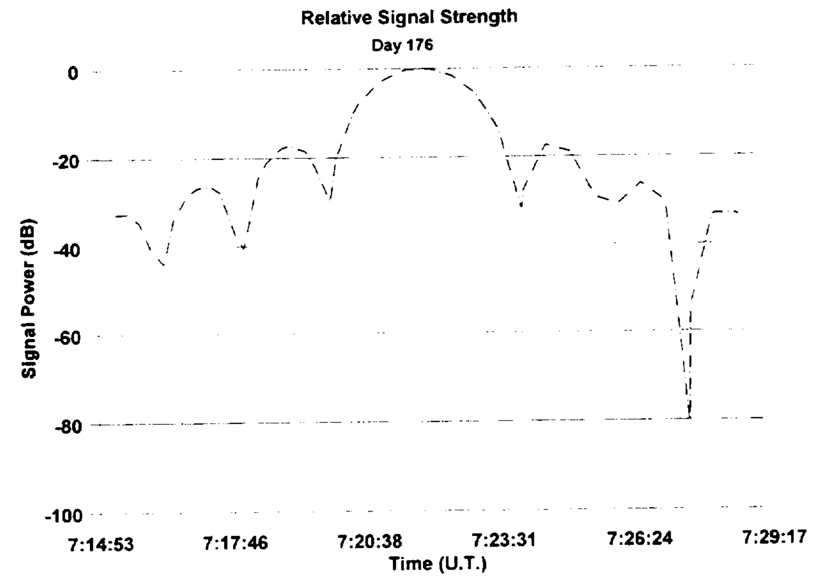

Figure 25 - Pointing loss and space loss for day 176.

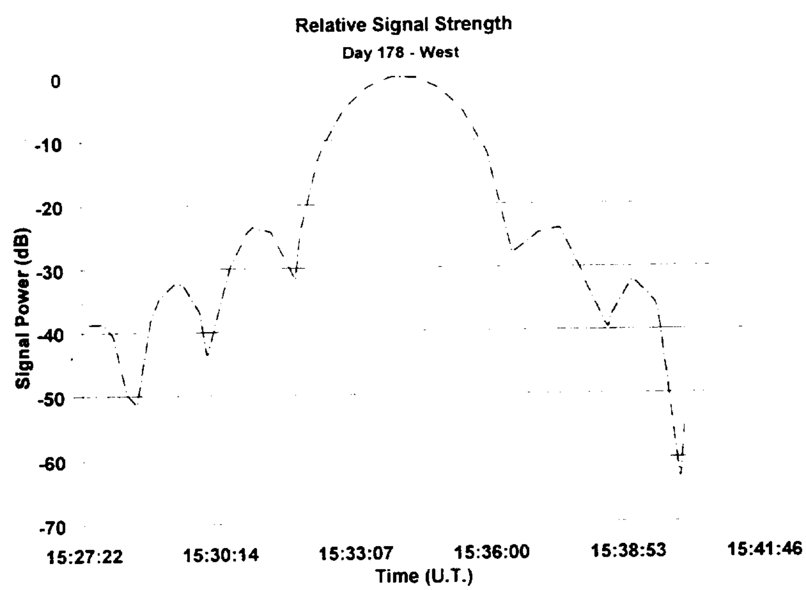

Figure 26 - Pointing loss and space loss for day 178 and TDRS West.

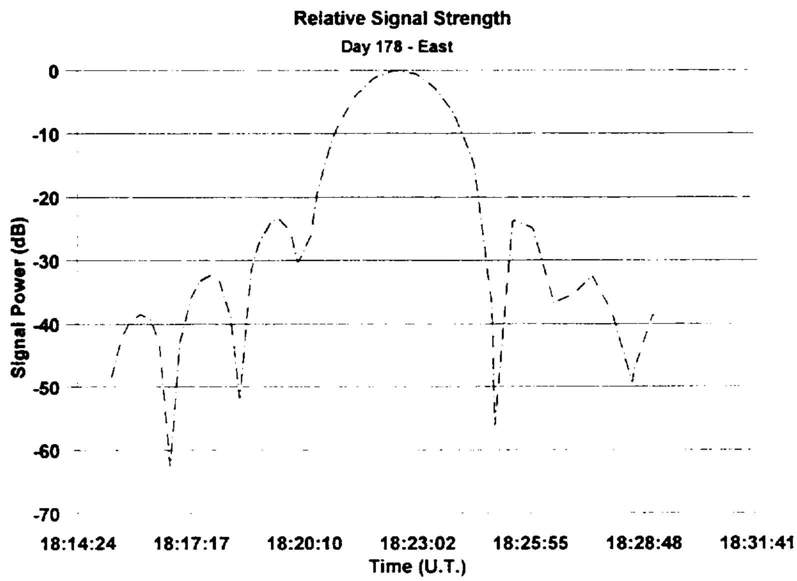

Figure 27 - Pointing loss and space loss for day 178 and TDRS East.

$$\text{HPBW} = \frac{72.8^\circ\ \lambda}{D}$$

where D is the antenna diameter of 1.29 meter and λ is the wavelength of 0.131 meter. The initial predictions were made assuming an antenna HPBW of 40°. The actual TOPEX antenna would have a HPBW of 7.4°. Based on the more restrictive HPBW than the initial analysis was expecting, the indicated lock status would be expected to cover a more narrow range in time than that observed. By comparing the lock status plots shown in Figures 28 to 32 with the predicted relative signal strength plots, we observe that the lock times cover the main antenna lobe and most of the first side lobe on either side of the main lobe. Typically, the receiver falls out of lock around the time of the second null in the antenna pattern.

The integrated receiver signal strength remained high during the period when the receiver at the WSC was in lock. During these periods, the estimated BER was on the order of 10^{-8}. This indicates that the system has sufficient margin to produce a reliable output even when the received signal strength varies by several dB. This leads us to hypothesize that the expected performance for systems using this method of TDRS access would be better than that limited to access times within the HPBW alone.

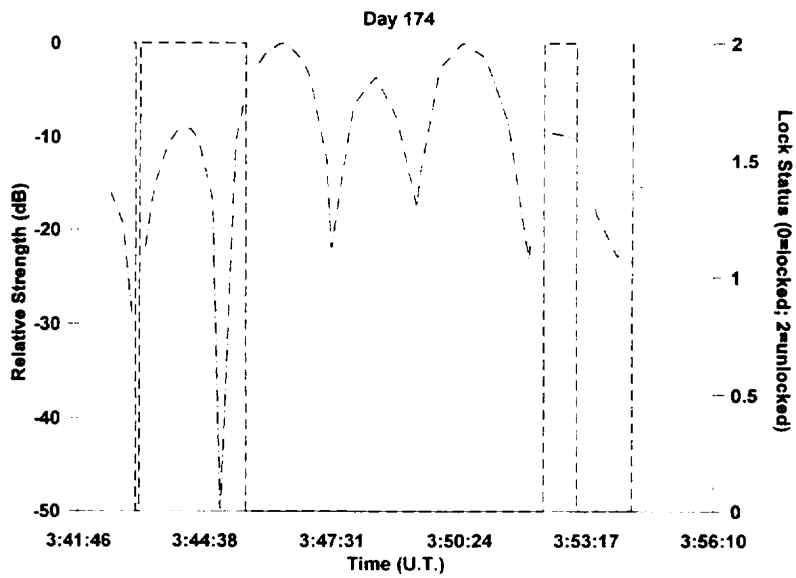

Figure 28 - Correlation of the signal strength with the receiver lock status for day 174

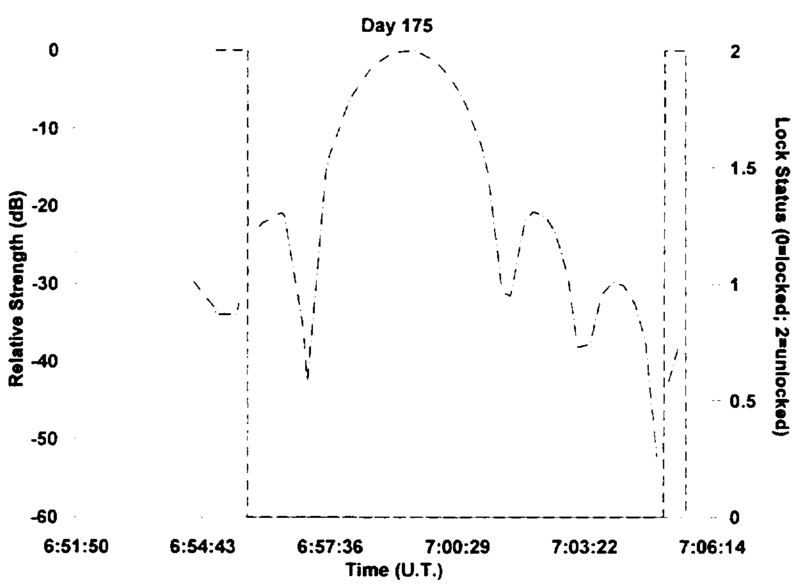

Figure 29 - Correlation of the signal strength with the receiver lock status for day 175

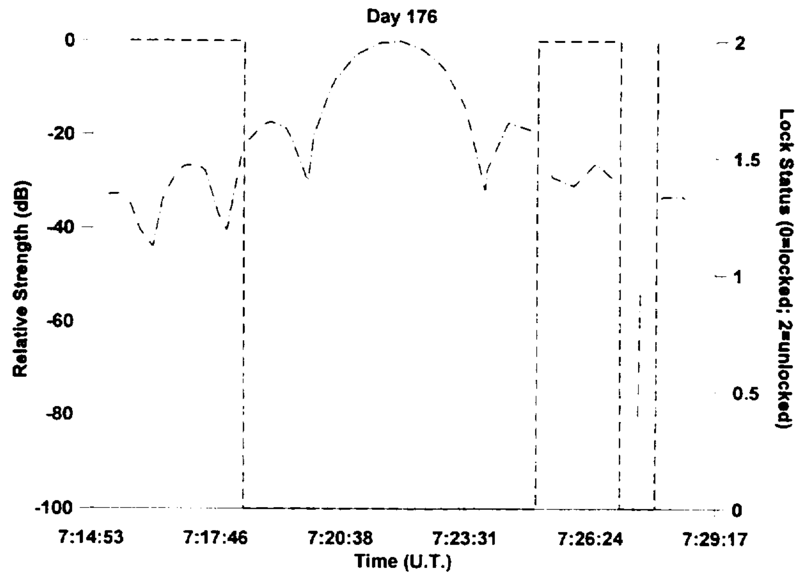

Figure 30 - Correlation of the signal strength with the receiver lock status for day 176

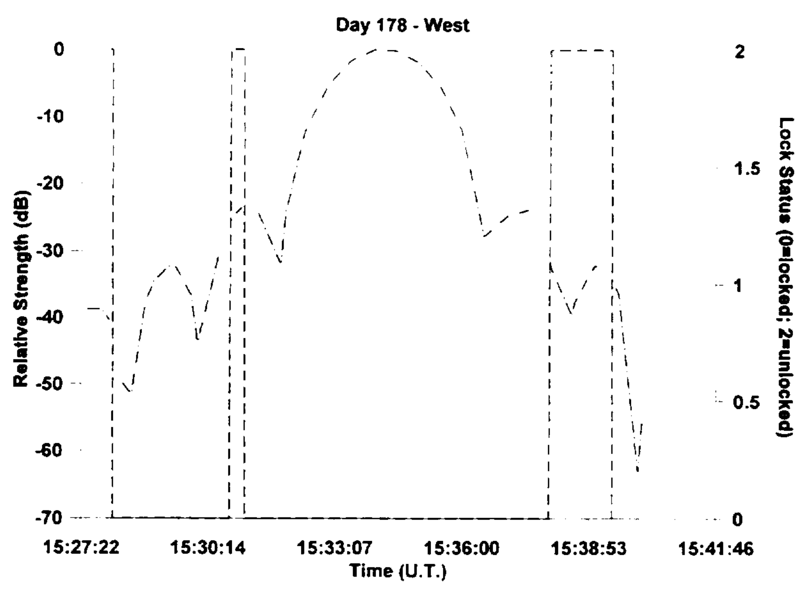

Figure 31 - Correlation of the signal strength with the receiver lock status for day 178 and TDRS West

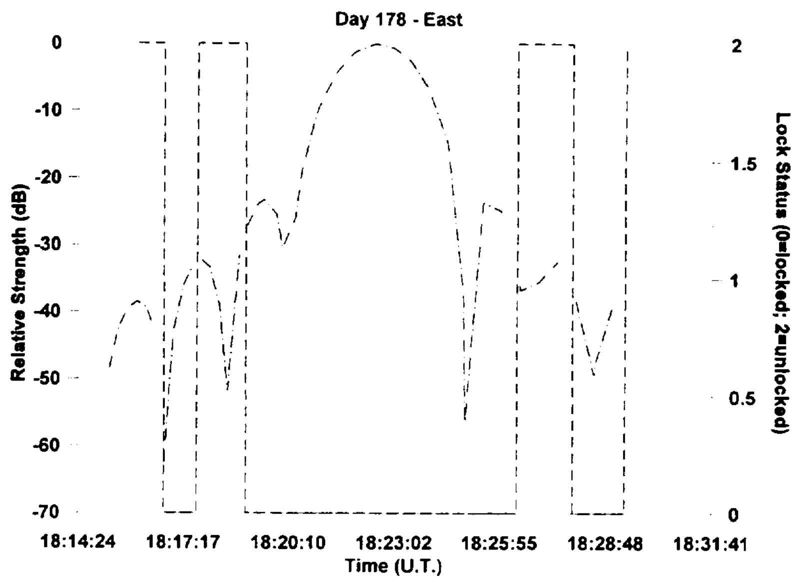

Figure 32 - Correlation of the signal strength with the receiver lock status for day 178 and TDRS East

VIII. CONCLUSIONS

From this series of experiments, we conclude that

1. The basic access concept of using a zenith-pointing antenna as it sweeps past the TDRS subsatellite point is validated because the observed contacts occurred at the predicted times and were of the predicted duration
2. The system has sufficient margin to allow for access beyond the HPBW limits and into the antenna side lobes for contact
3. An antenna with higher gain and more narrow HPBW can be used to give contact durations expected for lower gain, wider bandwidth antennas. This implies that the higher-gain antennas should be pursued because they can support higher data rates and therefore, higher daily data volumes to the ground.

From the performance observed in these experiments, we conclude that the series of experiments was a success.

IV. ACKNOWLEDGMENTS

This research is supported via NASA grant NAG 5-1491 to New Mexico State University. We wish to thank NASA/GSFC for providing the satellite time to conduct the experiment. We also wish to thank the support from JPL to coordinate the TOPEX use. JPL also provided the results of their analysis for this report.

V. REFERENCES

[1] S. Horan and T. Minnix, "Small Satellite Access of the Space Network," *Proceedings of the International Telemetering Conference,* Vol. XXX, p. 78.

[2] S. Horan, W.P. Osborne, T. Minnix, "Improved Small Satellite Access of the Space Network," NMSU-ECE-94-, December 1994.

[3] S. Horan, "Small Satellite Access of the Space Network," *Space Technology and Applications International Forum*, part one, p. 501, January 1996.

[4] S. Horan, J. Vigil, and T. Minnix, "Small Satellite Access of the Space Network," submitted to the *IEEE Transactions on Aerospace and Electronic Systems*.

[5] Analytical Graphics, "Satellite Tool Kit," version 4, August 1997.

[6] TLE.019 obtained from archive.afit.af.mil, June 1997.

[7] W. L. Stutzman and G. A. Theile, *Antenna Theory and Design*, New York: John Wiley & Sons, 1981, p. 420.

[8] T.T. Ha, *Digital Satellite Communications*, 2nd ed., New York: McGraw-Hill, 1990, p. 80.

[9] P. Sanatar, Jet Propulsion Laboratory, private communication.

[10] Stutzman and Theile, *ibid.*