COMPARISON OF GPS PSEUDORANGE AND BIASED DOPPLER RANGE MEASUREMENTS TO DEMONSTRATE SIGNAL MULTIPATH EFFECTS

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SUMMARY

The TI 4100 Geodetic Global Positioning System (GPS) Receiver has been field tested in several environments. These include collocation rooftop tests near reflective equipment, isolated desert positioning tests, and shipboard survey tests. The receiver data consisted of pseudorange (code) and biased Doppler range (phase) measurements on both L1 and L2 frequency channels. This paper compares differences between ionospherically corrected pseudorange and biased Doppler range measurements to demonstrate the significant effects of signal multipath on the pseudorange measurements. That is, pseudorange signal multipath effects can be isolated, detected, and statistically modeled using only the above measurements. Examples are given for various receiver antenna locations. Day-to-day comparisons are made to demonstrate the repeated multipath effects due to repeated satellite-to-antenna geometries. The results can be used to analyze and statistically model pseudorange multipath effects for possible improved positioning and GPS satellite orbit determination accuracy.

INTRODUCTION

The Defense Mapping Agency, in cooperation with the United States Geological Survey and the National Oceanic and Atmospheric Administration, have sponsored the development of the TI 4100 Geodetic Receiver. The receiver was built by Texas Instruments, Incorporated, of Lewisville, Texas. Except for the controlling software, the Geodetic Receiver is similar to the commercial version. That is, the receivers track up to four satellites Simultaneously by sampling segments of broadcast signals of different satellites in a time multiplexing sense. Pseudorange and phase measurements are obtained on both the L1 and L2 GPS channels. Using interpolation procedures, up to a total of 16 measurements can be obtained for the same time instant.

The pseudorange is obtained by multiplying the received minus transmit time by the speed of light. This value must be corrected for a number of error sources to obtain the true range. These include the effects due to the ionosphere, troposphere, satellite and receiver clock error, and relativity. In addition to these error sources, the pseudorange has a receiver measurement only error of 0.6 to 1.0 m. for L1 only [1].

Phase measurements in cycles are accumulated and then differenced over a given time interval. These differences are converted to a corresponding Doppler change in range. This is done by removing any cycle counts due to biased frequencies and then multiplying by the speed of light divided by the transmission frequency. The receiver phase has a measurement only error of between 1 and 3 mm. for L1 only. This, of course, is much more accurate than the L1 pseudorange standard deviation. Except for the ionospheric effect, the above error sources affect a change in pseudorange values the same as a Doppler change in range over the same time interval. Therefore, to have equivalent values of change in pseudorange and Doppler range, first order ionospheric corrections are made to both values using dual frequency measurements [2].

This paper investigates the differences between ionospherically corrected pseudoranges and biased Doppler ranges, denoted as pseudo-Doppler ranges. For convenience, the initial value of a series of biased Doppler ranges is taken as the pseudorange for the corresponding time. The Doppler change in range values are then added to this initial value to obtain the biased Doppler ranges. The pseudo minus Doppler range data is then modified to have zero mean. If the receiver antenna is in a reflective environment, the pseudo-Doppler ranges are found to be much larger than receiver measurement accuracy. Comparisons obtained from receivers in different configurations and locations indicate that these large pseudo-Doppler range differences are due to signal multipath. Further, a comparison of the double difference residuals of a 25-m. baseline relative positioning experiment demonstrates that the variations of the pseudorange residuals (about 4 m.) are much larger than that expected from measurement noise (about 1 m.) and that of the phase range measurements (about 2 cm.). Consequently, subtracting the Doppler measurements from pseudoranges is close to subtracting true satellite to antenna ranges. System errors such as receiver clock and tropospheric error also cancel. This leaves, for the most part, pseudorange signal multipath effects, pseudorange receiver measurement noise, and a bias.

An analysis of pseudo-Doppler ranges for the Spring 1985 GPS Precision Baseline Test is presented. This test has the advantage of having data from both low reflective desert areas and highly reflective rooftop locations spaced across the continental United States. Also, data was taken over several days that enables cross correlations to be made day-to-day. If the multipath is due to highly reflective objects, this effect is repeated the next day only about 4 min. earlier due to the repeated satellite-to-receiver geometries. This effect is seen in the cross-correlation function. Since the pseudorange multipath effect is isolated, the

correlation functions can be statistically modeled and incorporated into the Kalman filter estimation procedure. Therefore, the results have applications to both survey position estimation and GPS satellite trajectory estimation procedures that currently use the pseudorange measurements.

The above procedure to isolate the pseudorange signal multipath effects (with measurement noise) is not limited to fixed site locations. The procedure works just as well for dynamic cases since movements affect both the pseudo and Doppler ranges and are canceled when the two ranges are differenced (see shipboard test [3]). This reference demonstrates the combined use of pseudo and Doppler ranges to improve absolute positioning over the standard pseudorange-only procedure in a high multipath environment.

The next section describes the Spring 1985 Test and the test locations. Then the pseudo-Doppler range differences are presented and analyzed. The correlation procedures are applied to the data in the fourth section. The conclusion summarizes the testing results and correlation analysis.

TEST DESCRIPTIONS

This paper analyzes only the data from the TI 4100 receivers that were used in the Spring 1985 High Precision Baseline Test. The testing interval was between 29 March and 5 April. The analysis herein consists of the last 3 days of the test, days 93 to 95. These days were selected due to the larger availability and higher continuity of the data. The TI 4100 receivers were located at the 10 sites given in Table 1. Also given in the table are the station numbers, the designated receiver identification, and a brief description of the location.

The receivers at each site collected both pseudorange and phase measurements on both frequency channels every 30 sec. Although a slightly faster sampling rate would have been preferable, this rate appears sufficient to demonstrate the multipath effects. The sampling rate was varied in a different data set from 12 sec. to 36 sec. This produced about a 10 percent variation, down and back up, in the cross-correlation terms. Also, to reduce the amount of data processing, one satellite, SV11, was selected for data analysis at each site. Similar types of results would be expected from the other satellites.

TABLE 1. SPRING 1985 PRECISION BASELINE TEST SITE LOCATIONS

Station	Station Number	Receiver Identification	Description
Mammoth, Cal.	85084	9	Rural location
Big Pine, Cal.	85082	V	Rural location
Mojave, Cal.	85081	Y	Rural location
Hat Creek, Cal.	85083	Z	Rural location
Ft. Davis, Tex.	85080	X	Polaris site
Haystack, Mass.	85078	A	Polaris site
Richmond, Fla.	85079	8	Polaris site
ARL/SW, Austin, Tex.	85016	7	R & D Lab
Pt. Mugu, Cal.	85086	W	R & D Lab
NSWC, Dahlgren, Va.	85085	3	R & D Lab

PSEUDO-DOPPLER RANGE COMPARISONS

To demonstrate the effects of signal Multipath, plots of pseudo-ranges minus doppler ranges are presented for a low reflectivity desert location, Mojave, and a high reflectivity rooftop location, Naval Surface Weapons Center, Dahlgren, Va. (NSWC). Figures 1 and 2 are plots of Mojave for days 94 and 95, respectively. Note the low values of standard deviation, 1.25 and 1.67 m. These figures are contrasted with the plots for the same days at the high reflectivity location at NSWC given in Figures 3 and 4. Note the large variation of the NSWC plots whose standard deviations are 4.02 and 5.82 m., respectively. Note that the signature of Figures 3 and 4 is similar. The strong dips and peaks occur in both plots except the effects on day 95 occur about 4 min. earlier. This indicates a day-to-day correlation that is discussed in the next section.

Plots for the highly reflective Pt. Mugu rooftop location are given in Figures 5 and 6 for days 94 and 95, respectively. Note at both the NSWC and Pt. Mugu sites that the receivers lost lock (resulting in a lack data) for 1 day while it was experiencing high signal multipath effects, as seen on its next day plots. This demonstrates that multipath effects can be sufficiently extreme as to cause receiver to lose lock with the satellite.

Standard deviations are determined for the remainder of the sites and are given in Table 2 for days 93, 94, and 95. Note the fairly good consistency between the day-to-day standard deviations for each site.

CORRELATION ANALYSIS

To demonstrate the repeated day-to-day signal multipath effects, cross-correlation coefficient functions are determined for 2 days of pseudo minus Doppler range data. The cross-correlation coefficient function [4] is defined as the standard cross correlation divided by the standard deviation of each data set. This normalizes its values to be between −1 and +1. Figures 7, 8, and 9 present the cross-correlation coefficient function for low, intermediate, and high signal reflectivity sites of Mojave, Richmond, and NSWC, respectively. For Mojave, the cross-correlation coefficient function stays in the noise level. For Richmond, there is a peak of .45 at a delay of −240 sec. For NSWC, the time scale is the delay in the GPS time of day in sec. A large peak (.632) occurs in Figure 9 at the same −240 sec. delay. These results demonstrate that the data from the higher signal reflectivity location is correlated day-to-day occurring approximately 4 min. earlier due to the earlier repeated satellite orbit-to-antenna geometries. Here, it is worth noting that the orbit repeats itself at 3 min. and 56 sec. earlier. This is approximated by −240 sec. due to the 30-sec. sampling interval.

Cross-correlation coefficient functions have been determined at the different sites for both days 93 to 94 and 94 to 95, where data is available. The value of the functions at delay −240 sec. denotes the day-to-day correlation and, correspondingly, indicates the level of signal multipath that exists at the site. The computed values at the −240 sec. delay for each site are given in Table 3. Again, note the consistency between the two 2-day data sets.

TABLE 2. STANDARD DEVIATION OF PSEUDO MINUS DOPPLER RANGES

Site	Day 93 (m)	Day 94 (m)	Day 95 (m)
Mammoth, Cal.	1.92	2.00	1.93
Big Pine, Cal.	2.75	2.63	2.96
Mojave, Cal.	1.44	1.25	1.67
Hat Creek, Cal.	2.10	2.12	2.00
Ft. Davis, Tex.	1.82	1.96	1.97
Haystack, Mass.	(not available)	2.71	2.55
Richmond, Fla.	2.54	2.60	2.48
ARL/SW, Austin, Tex.	2.08	2.21	2.20
Pt. Mugu, Cal.	(not available)	4.36	3.31
NSWC, Dahlgren, Va.	4.53	4.02	5.82

TABLE 3. CROSS-CORRELATION FUNCTION COEFFICIENT FOR PSEUDO MINUS DOPPLER RANGE DATA AT A DELAY OF −240 SECONDS

Site	Days 93-94	Days 94-95
Mammoth, Cal.	.058	.079
Big Pine, Cal.	.104	.140
Mojave, Cal.	.144	.162
Hat Creek, Cal.	.260	.306
Ft. Davis, Tex.	.079	.096
Haystack, Mass.	(not available)	.405
Richmond, Fla.	.500	.453
ARL/SW, Austin, Tex.	.645	.632
Pt. Mugu, Cal.	(not available)	.566
NSWC, Dahlgren, Va.	.750	.632

An example of the normalized autocorrelation function of the NSWC pseudo-Doppler range data is given in Figure 10. This appears to be modeled by a simple exponential autocorrelation function with a correlation length of about 50 sec.

CONCLUSION

This paper analyzes the differences between ionospherically corrected pseudorange and biased Doppler range data taken with Texas Instruments, Inc., TI 4100 receivers during the Spring 1985 GPS Precision Baseline Test. Data from low through high signal reflectivity environments were examined. In a high reflectivity environment, such as a laboratory rooftop, these range differences are shown to vary significantly, for example, up to 20 m. in a 30-sec. time interval. In the low reflectivity environment, such as a flat desert location, the variations are about the level expected due to the receiver measurement noise. By this differencing of data, error sources and true values are canceled leaving essentially only pseudorange receiver measurement errors, pseudorange signal multipath effects, and a bias. The signal multipath affects the code measurements significantly more than phase measurements.

The effects of significant signal reflectors are seen to be similar on 2 consecutive days. It is noted that the effects occur about 4 min. earlier on the second day due to the earlier repetition of the satellite-to-antenna geometries. This repetition is demonstrated by the cross-correlation coefficient function of the two day-to-day sets of data. Values of about 0.1, that are in the noise level for low reflective environments, to above 0.6 for high reflective environments are obtained for time delays of −240 sec. (−4 min.).

Additionally, the autocorrelation of the pseudorange minus Doppler range data is presented for a high reflectivity location. From the above results, it appears that each satellite's signal multipath effects on pseudorange can be statistically modeled for a stationary site. This model could be incorporated into a Kalman filter estimation procedure that uses pseudorange measurement data to minimize the multipath effects. This has applications to positioning and to GPS satellite orbit determination. Current procedures that use averaging techniques [5], [6] with the pseudorange and Doppler data reduce, but do not minimize, the signal multipath effects.

At two of the highly reflective sites the pseudo and Doppler range differences were above the 10 m. scale of the plots. At corresponding times (plus or minus 4 min.) on adjacent days, the receiver lost lock with the satellite. This indicates that the receiver has difficulty trucking in a high multipath environment.

In summary, by isolating the pseudorange signal multipath effects it is demonstrated that (1) these effects can be very large in high signal reflectivity environments; (2) for a stationary site, these effects on pseudorange measurements can be statistically modeled to possibly improve estimation procedures; and (3) the multipath effects can be large enough to cause the receiver to lose lock. Further analysis should be performed on antenna design, for example, with or without a ground plane or absorption material, and on receiver design to be less susceptible to signal multipath.

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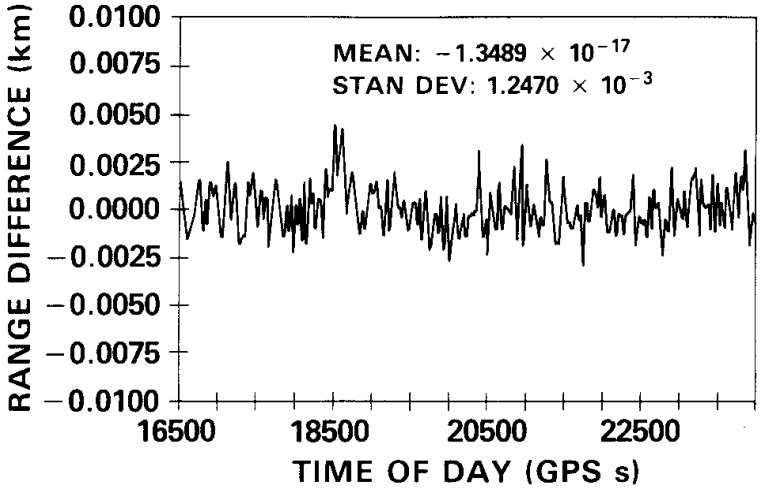


FIGURE 1. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN VALUE SET TO ZERO), DAY 94, MOJAVE

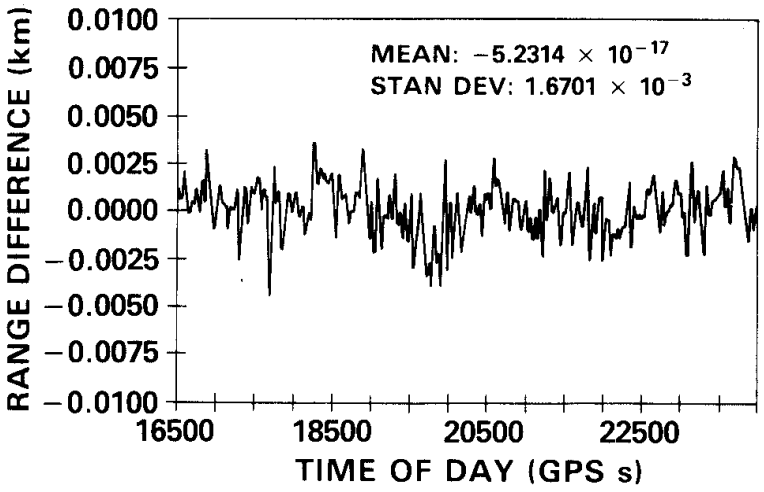


FIGURE 2. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN VALUE SET TO ZERO), DAY 95, MOJAVE

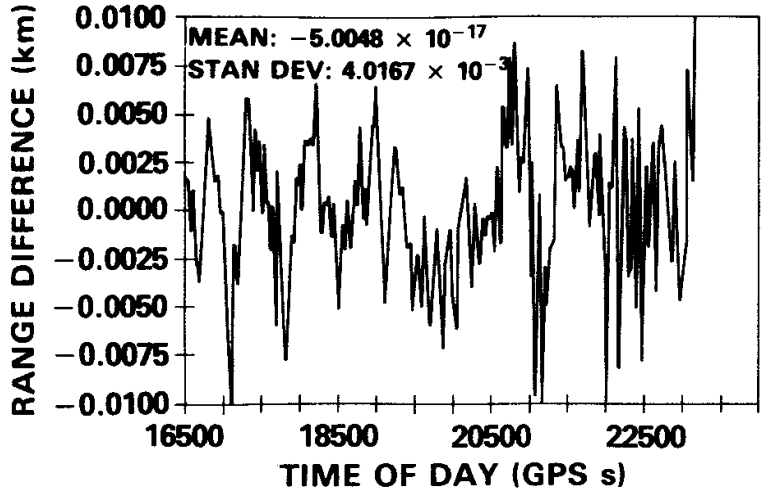


FIGURE 3. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN VALUE SET TO ZERO), DAY 94, NSWC

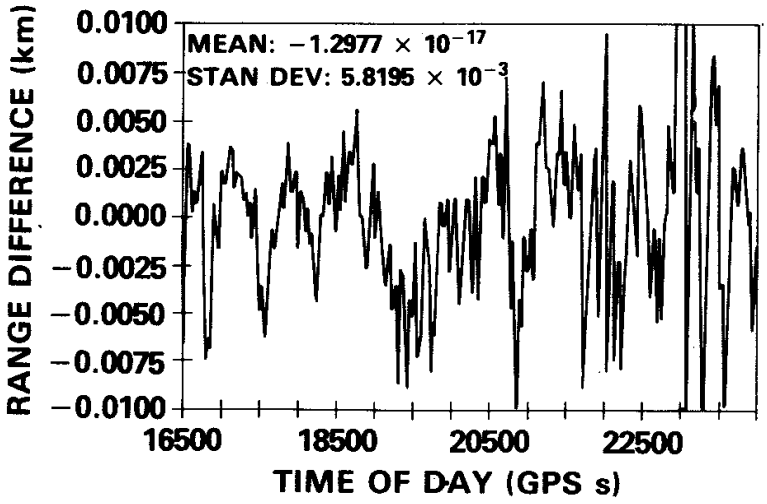


FIGURE 4. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN VALUE SET TO ZERO), DAY 95, NSWC

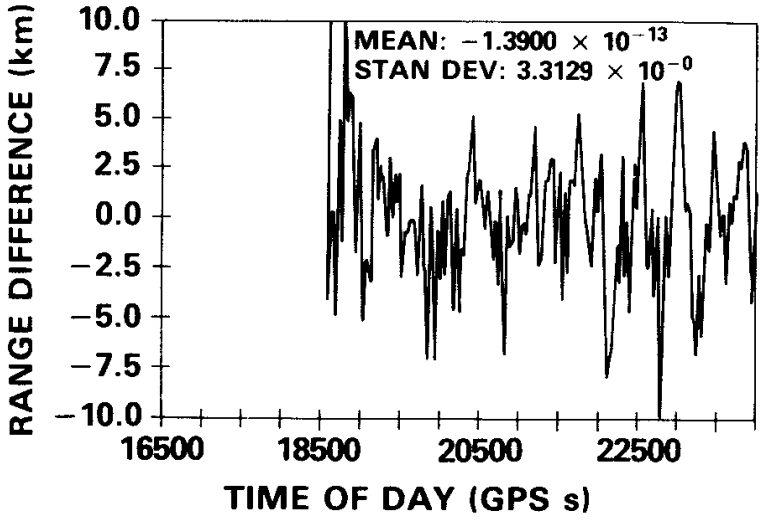


FIGURE 5. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN SET TO ZERO), DAY 94, PT. MUGU VALUE

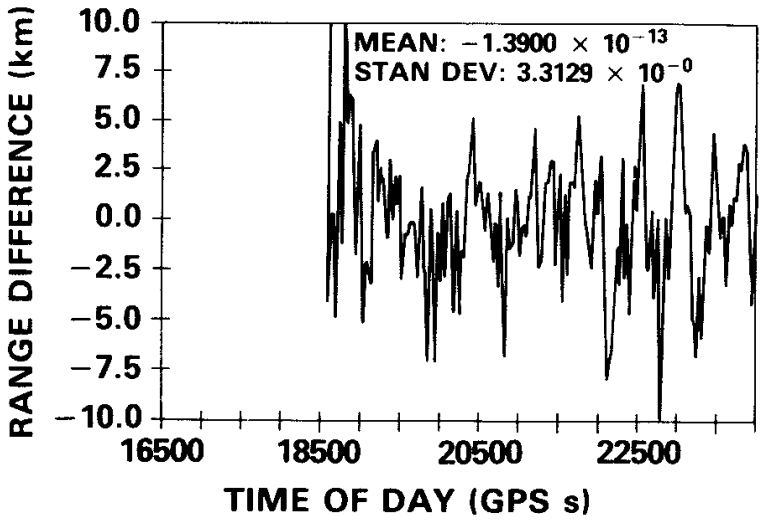


FIGURE 6. DIFFERENCE BETWEEN PRN AND CCI RANGES (MEAN VALUE SET TO ZERO), DAY 95, PT. MUGU

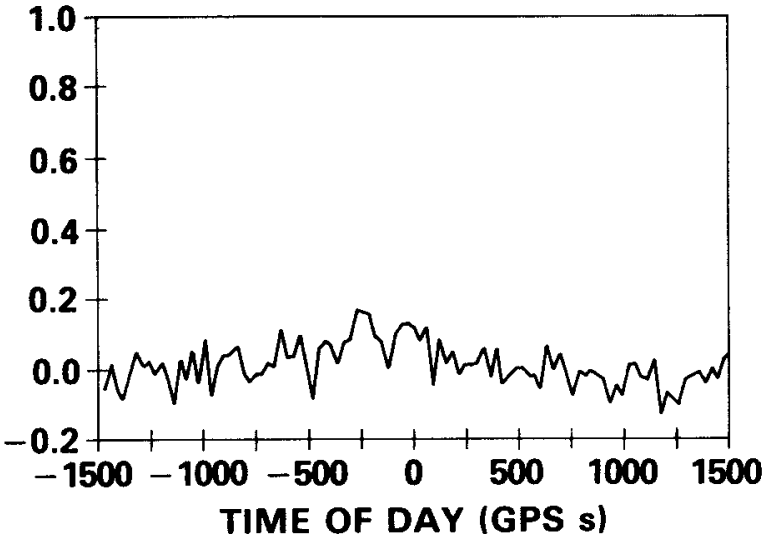
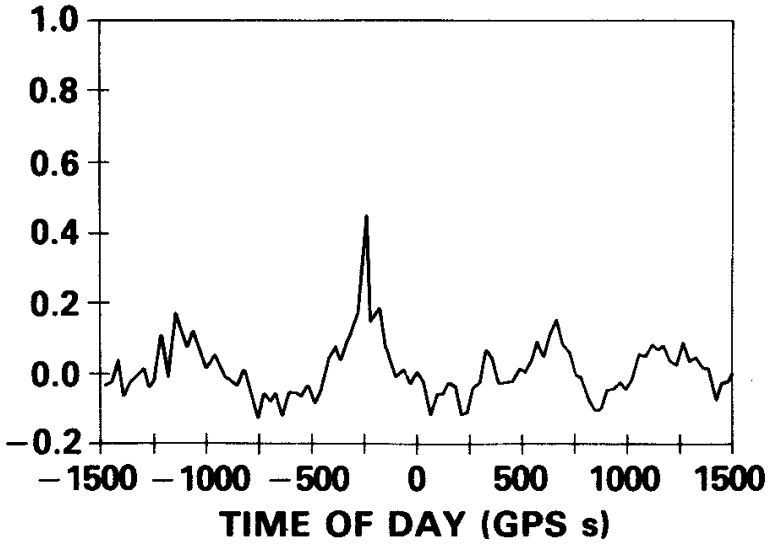


FIGURE 7. CROSS-CORRELATION FUNCTION COEFFICIENT, DAYS 94 AND 95, MOJAVE



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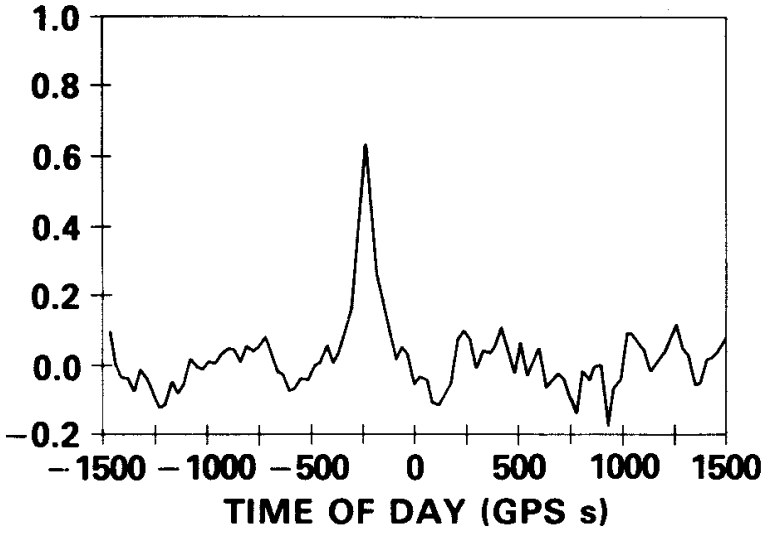

FIGURE 9. CROSS-CORRELATION FUNCTION COEFFICIENT, DAYS 93 AND 94, NSWC

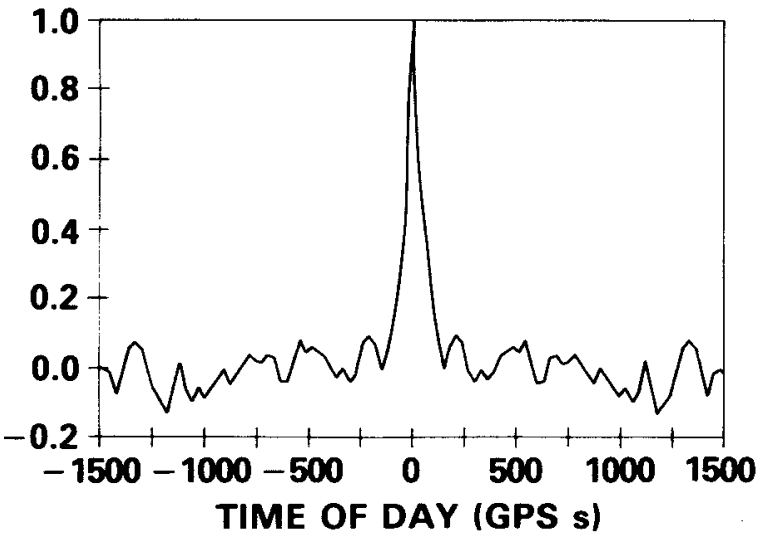

FIGURE 10. AUTOCORRELATION FUNCTION COEFFICIENT, DAY 94, NSWC