GPS MULTIPATH DETECTION WITH VARYING ANTENNA HEIGHT

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ABSTRACT

Multipath errors on GPS single frequency carrier phase observations are discussed in this report. Theory on how this potentially harmful influence affects GPS measurements is shown. An experiment was performed where a short baseline was measured in a reflective environment. The results, mainly the double difference residuals, were analysed and compared to demonstrate how and when multipath occurs. Multipath detection is performed in three different ways to prove its occurrance on the specific reflective surface. All of the analyses were performed with a particular satellite which was deemed to have the best geometry for this study.

TABLE OF CONTENTS

Page

LIST OF FIGURES

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CHAPTER 1
INTRODUCTION

The Navstar Global Positioning System (GPS) has become very popular in the last few years. The full constellation of satellites has almost been achieved and with it increased use of the system has shown that in specific cases the accuracies reached may be inadequate. The increasing affordability of this system has brought on many uses, such as land surveying in urban areas and precise engineering surveys. These types of surveys often require the precise determination of short baselines (less than 2 km). These same survey uses often bring on a potentially damaging effect called multipath due mostly to the environment in which they are conducted.

"Multipath errors occur if the received signal is composed of the direct line of sight signal and one or more constituents which have propagated along paths of a different length" (Georgiadou and Kleusberg, 1988). This is the result of the signals bouncing off reflective surfaces near the antenna and finding their way to the antenna. Multipath is purely a function of site selection and antenna design.

This report will show how multipath error noise is detected and will show the results of an experiment conducted over nine days atop the roofs of Gillin Hall and Head Hall on the U.N.B. campus. This experiment featured a short baseline measurement with Ashtech L-XII GPS receivers in a highly reflective environment with three different antenna heights to show the geometry of the occurring multipath signal. The experiment setup is shown in Figure 1.1. The collected single frequency GPS carrier phase data was processed using the Ashtech GPS Post-Processing System (GPPS) software and the resulting residuals were analyzed to show their multipath contamination.

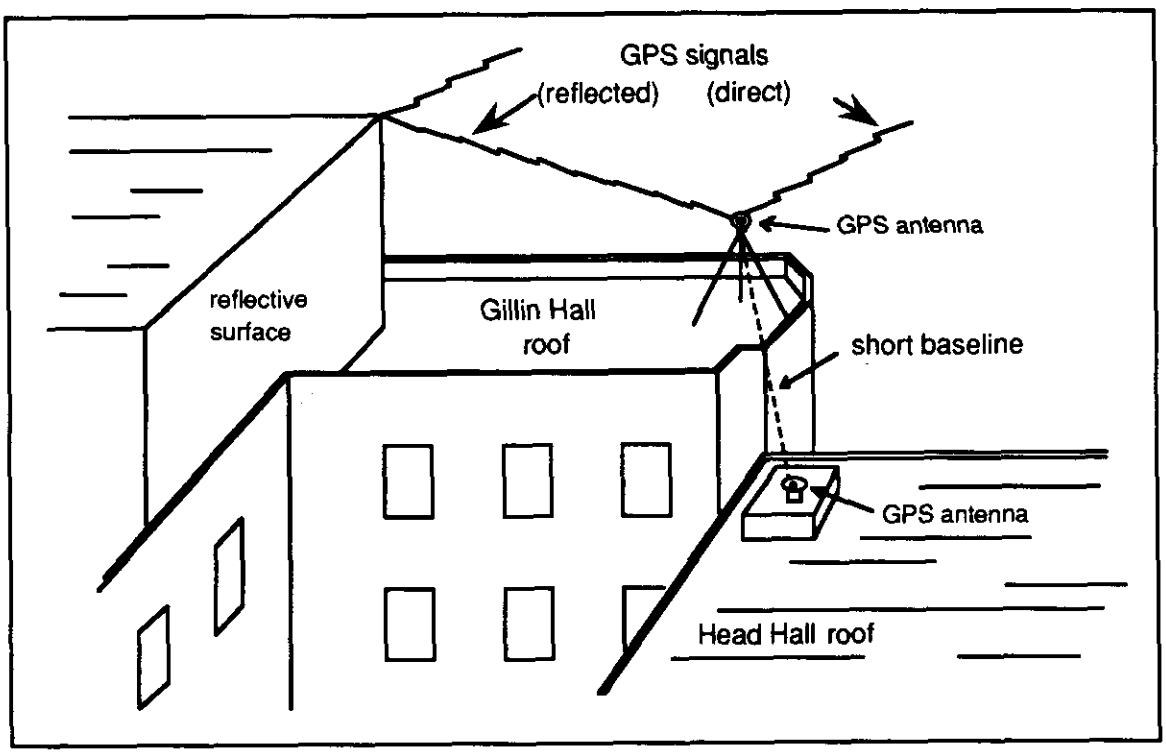

Figure 1.1 Experiment setup showing GPS signals.

Other errors found in GPS observations may be greatly reduced or removed either by mathematical modelling or observation procedures such as double differencing (Wells et al., 1986). Georgiadou and Kleusberg (1988) have derived a multipath induced carrier phase mathematical model; however, since the environment for multipath changes with every new site, this is not practical for normal survey applications, nor would it be applicable to kinematic GPS surveying where the satellite - reflector - antenna geometry is forever changing.

Since multipath is site dependent and not baseline-length dependent, it is especially harmful when it occurs during short baseline measurement. Georgiadou and Kleusberg (1988) obtained a theoretical maximum of 4.8 cm (1/4 cycle) at the L1 frequency for carrier phase observations. No errors of that magnitude show up in this experiment; however, with plot comparisons and statistical analysis the multipath error will be evident.

Two other errors usually go hand in hand with multipath. These are antenna imaging and antenna phase centre variations. Antenna imaging occurs when a change in the antenna phase pattern is caused by some type of conducting material in close proximity to the antenna (Tranquilla, 1986). Antenna phase centre variations occur when the phase centre of the antenna is different for signals arriving from different directions. Both these errors will inseparably be detected with multipath if the antenna orientation is left unchanged. For this reason, imaging and phase centre variations will be accepted as being part of multipath in this experiment since they are inseparable.

CHAPTER 2
DATA COLLECTION AND PROCESSING

2.1 Field Procedures

The main purpose of this experiment was to show how GPS multipath could be detected and how it would be affected by changing the antenna height. Many GPS users are unaware of the situations in which reflective objects might lead to bad results because of multipath. These reflective objects could range from the tin roof of a nearby house, a grain silo, or even the roof or side of a car or truck parked nearby. GPS on airplanes may get multipath from the surface of the aircraft while ships could easily obtain the multipath effects from the water surface or parts of the ship superstructure. The type and duration of the observations dictate how much any amount of multipath will affect the desired results.

In many cases the site locations or survey points were selected before GPS was known or considered for any type of high precision surveying. No thought was given to the proximity of reflective surfaces. Urban areas provide the users with little recourse in some instances and sites with good satellite visibility may have a reflective environment.

2.1.1 Planning

Before the observations were performed, the Ashtech software Mission Planner was used. This program is updated with the almanac files obtained directly from the GPS satellites by the GPS receivers. It is primarily used to inform the users on the optimum times for satellite availability. In this case, it was used to ensure that some satellites would be favorably situated for the purpose of this experiment.

As a result of using Mission Planner the window of observation was selected to be from 2 p.m. to 4 p.m. (ADT). This 2 hour window would ensure that enough satellite data would be available to detect the multipath in question. Due to the time difference between the solar and sidereal day (GPS satellite orbits have a period of almost exactly half a sidereal day), the window of observation was advanced by 4 minutes each day.

2.1.2 Location

The location chosen for this experiment was a short baseline between station Hamilton on the roof of Head Hall and station Gillin on the roof of Gillin Hall. The reasons for this choice were that there was a 6 metre high reflective wall about 15 metres south of station Gillin and the coordinates of station Hamilton were already known. This would be needed in later processing. The length of the baseline was approximately 47 metres. Station Hamilton had no reflective surfaces above it; however, the flat pebble roof extended to the northeast which may have caused reflected signals to be received by the antenna from below the antenna horizon. The antenna, however, was less than 0.3 metres above the roof and so it is unlikely that the roof would cause any significant multipath error.

2.1.3 Observations

During the observation window of 2 hours, 10 different satellites were visible. The satellites or space vehicles (sv) were: 03, 05, 13, 16, 17, 18, 20, 24, 26, and 27. The GPS receiver can be set to stop recording data from satellites when they fall below a specified elevation angle. In this case the cutoff angle was set at a 10 degree elevation mask. At no time in this experiment were there any fewer than 4 satellites visible. An average of 6 were visible at any particular time. A recording interval of 20 seconds was used and this yielded an average of 400 epochs of data per day.

Since the main purpose behind this experiment was to show the changing effects of multipath by changing the antenna height, the height of the antenna on station Gillin, near the reflective wall, was altered to three different positions. Heights of approximately 1, 2, and 3 metres above the roof were used for 3 days each consecutively. The total of 9 days were observed in consecutive order. The orientations of the antenna were not disturbed other than for changing the height to avoid antenna phase centre variations from possibly contaminating the results. This, along with the 4 minute advance in the observation window each day, ensured that the same satellite geometry was observed for the entire experiment.

When the antenna was set at the 2 and 3 metre heights on the roof of Gillin Hall, a tall extended tripod was used. The 3 metre high setup was particularly challenging to achieve safely on a windy rooftop, about 2 metres from the edge. (The $ 5,200.00 antenna and $ 22,000.00 receivers were insured by the university before this setup was installed for the final 3 day period!) The tall tripod was levelled with a leg in the top of each of 3 regular tripods set up on the roof. Sandbags were placed over each of the 9 tripod legs on the surface of the roof. Duct tape, ropes, and wooden braces were used to anchor down the 3 metre high setup which had to be levelled using a stepladder.

Ground plane extenders are sometimes attached to certain GPS antennas. These extenders are used to help reduce the sensitivity to signals reaching the antenna from below the antenna horizon. They are sometimes coated with an absorbing material to prevent diffraction interference (Tranquilla et al., 1986). No ground plane extenders were used in this experiment.

2.2 Equipment

Two Ashtech L-XII GPS receivers were used in this experiment. They belong to the Department of Surveying Engineering at the University of New Brunswick. These C/A code tracking receivers were used to make the carrier phase measurements.

A Wild precision optical plummet was used to aid in levelling the antenna directly above the station on the roof of Gillin Hall. Only the level bubble on this plummet could be used due to the lack of an appropriate tribrach at the time. Four Wild tripods were used, one of which was an extended tall tripod.

Any cycle slips which may have happened during the experiment were removed automatically by the Ashtech GPS Post-Processing System (GPPS) software which was used to process the raw data on an IBM 80486 personal computer.

A Zenith 80286 laptop computer was used to download the data from the receivers after each day's observations. The raw data was immediately transferred to floppy diskettes for safe storage and for further processing. Microsoft Excel 4.0 was used on an IBM 80486 personal computer and Microsoft Excel 2.0 was used on a Macintosh IIci personal computer along with Cricketgraph and MacDraw to analyze and portray the multipath effects.

2.3 Data Processing

The raw single frequency carrier phase measurement data was processed using the Ashtech GPS Post- Processing System (GPPS) software. Each of the nine observed days contained approximately the same amount of data. With the recording interval set at 20 seconds for both data collection and processing, this amounted to about 400 epochs for each day. The IBM 80486 personal computer processed each day's data in less than a minute. The coordinates of the station on the roof of Head Hall were known and held fixed in the processing. This relative positioning technique was used to eliminate some of the errors associated with GPS positioning.

The data was first processed with an elevation cutoff angle set at 15 degrees. This angle is taken from the horizon to the satellite and in this case proved to be too high. The satellite-reflector-antenna geometry would require an elevation cutoff angle to be below 10 degrees; however, the data was recorded with an elevation cutoff angle of 10 degrees. Reprocessing of each day was done with an elevation cutoff angle set at 7 degrees to ensure that all the data was included.

2.3.1 Error Elimination

The GPPS program uses the double differencing process to eliminate some of the errors. This is a linear combination of the observation equations for continuous carrier phase observation types. The receiver - satellite double differencing process removes, or greatly reduces, the effects of receiver clock errors and satellite clock errors (Wells et al., 1986). By observing a short baseline, satellite orbit errors, ionospheric and tropospheric delay errors were also removed or greatly reduced. Other errors like multipath, cycle slips, and random observation errors remain. They are carried on through the adjustments and show up in the double difference residual output Cycle slips are corrected by the GPPS program.

Random observation errors remain random while multipath shows a systematic occurrance from one day to the next.

2.3.2 Residual Analysis

After careful study of the residual plots from the GPPS program and consultation with Ashtech's Mission Planner program, it was found that satellite PRN 18 would be in an ideal position to propagate a reflected signal off the intended wall. Figure 2.1 shows a polar plot of the GPS satellites available during the observation period.

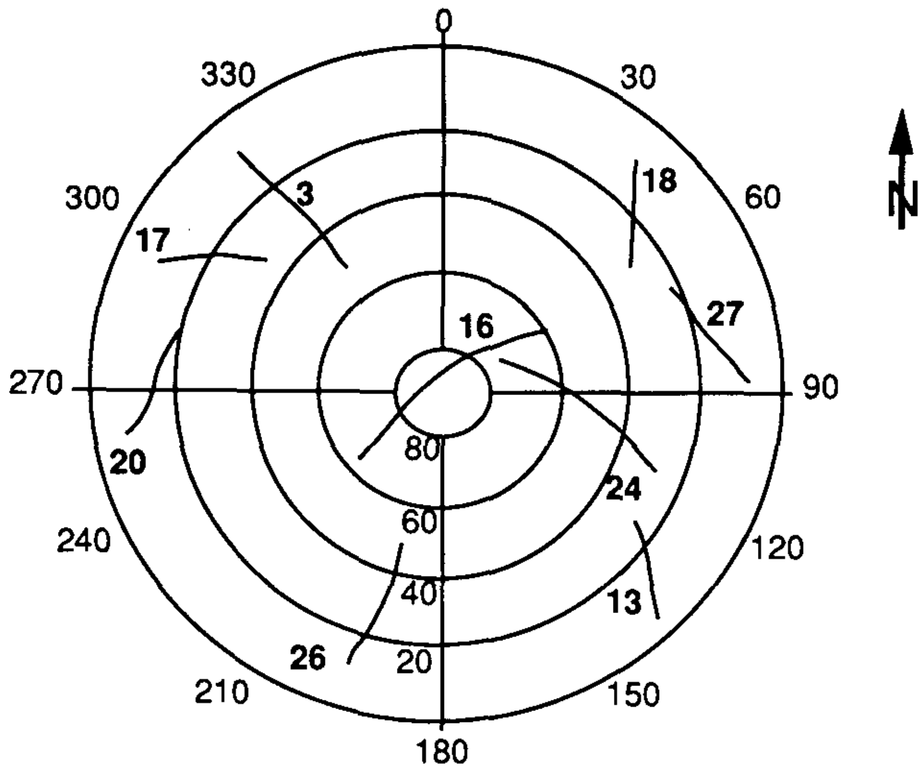

Figure 2.1 Satellite polar plot, Sept 22, 1993, 17:00 - 19:00 UT.

The wall was to the south east of the antenna on Gillin Hall and the satellite PRN 18 was to the northeast and at a low elevation.

The residual output files from GPPS were manipulated using Microsoft Excel 4.0 on an IBM 80486 personal computer. The residual data was parsed, sorted, cut and pasted to the desired format with only data from PRN 18 in the final file.

The CORREL function was used to calculate the correlation coefficients between the arrays of residuals from day to day. It should be noted that the correlation coefficients were calculated using output from the GPPS program with the processing elevation cutoff angle set at 15 degrees. Due to time constraints this could not be redone after reprocessing using 10 degrees.

The values from the residual files of PRN 18 and the correlation coefficients were then transferred to Macintosh text files and plotted using the Cricketgraph program.. The plots were then imported into MacDraw for the final presentation as shown in this report.

CHAPTER 3
MULTIPATH ON CARRIER PHASE

It should be kept in mind that this experiment was performed with GPS carrier phase measurements. As the reflected signal arrives at the antenna, it is biased by a phase shift which is different from that of the direct signal due to the excess in path length. These two signals are then effectively superimposed and depending on the level at which the reflected signal is reduced in the process of reflection, the resultant measured phase of the combined becomes biased due to multipath. This is directly shown in the amplitude of the multipath carrier phase error (Georgiadou and Kleusberg, 1988), which for the most part is carried through the processing adjustments into the residuals. If the reflected signal voltage was not decreased, then the maximum phase error would be equivalent to 90 degrees which is 1/4 the wavelength, or 4.8 cm for the L1 frequency of the 1.57542 GHz GPS signal (Georgiadou and Kleusberg, 1988).

"The frequency of the multipath error depends on the change of excess path length with time " (Muller and Campbell, 1989). They also state that the periods of multipath typically range from a few to several minutes. In this experiment, the multipath seemed to follow a 2 to 3 minute periodicity; however, due to a lack of ground plane extenders and possible contamination by multiple reflections these values were simply interpolated from the residual plots and not derived mathematically.

"Multipath effects, when averaged over a long enough time for the relative phase of the direct and reflected signals to have changed by at least one cycle, will considerably reduce any biases in the measurements " (Wells et al., 1986). In this case, with the geometry relating the satellite, reflector, and antenna, the 2 hour observation period was well sufficient for a precise baseline measurement.

CHAPTER 4
MULTIPATH DETECTION

4.1 Residual Plot Comparisons

We know that multipath error is systematic and repeated from day to day if the satellite-reflector-antenna geometry is left unchanged. Only the antenna height was changed in this experiment after days 3 and 6 of the observation period. The multipath error was carried on through the processing and is found in the double difference residuals. As mentioned earlier, the double difference residuals for PRN 18 and 16 were the optimal pair to study for this particular reflector location. It should be noted that direct comparisons should only be made between plots at the same antenna heights. Figures 4.1, 4.2, and 4.3 show these residuals for the 1, 2, and 3 metre heights respectively.

It can clearly be seen that by comparing the plots of the double difference residuals there is a common trend in the three plots for each antenna height. By looking a little closer it can be seen that in each successive plot the systematic trend occurs earlier by about 240 seconds. This is due to the repeated satellite orbit every sidereal day which is 236 seconds shorter than the solar day.

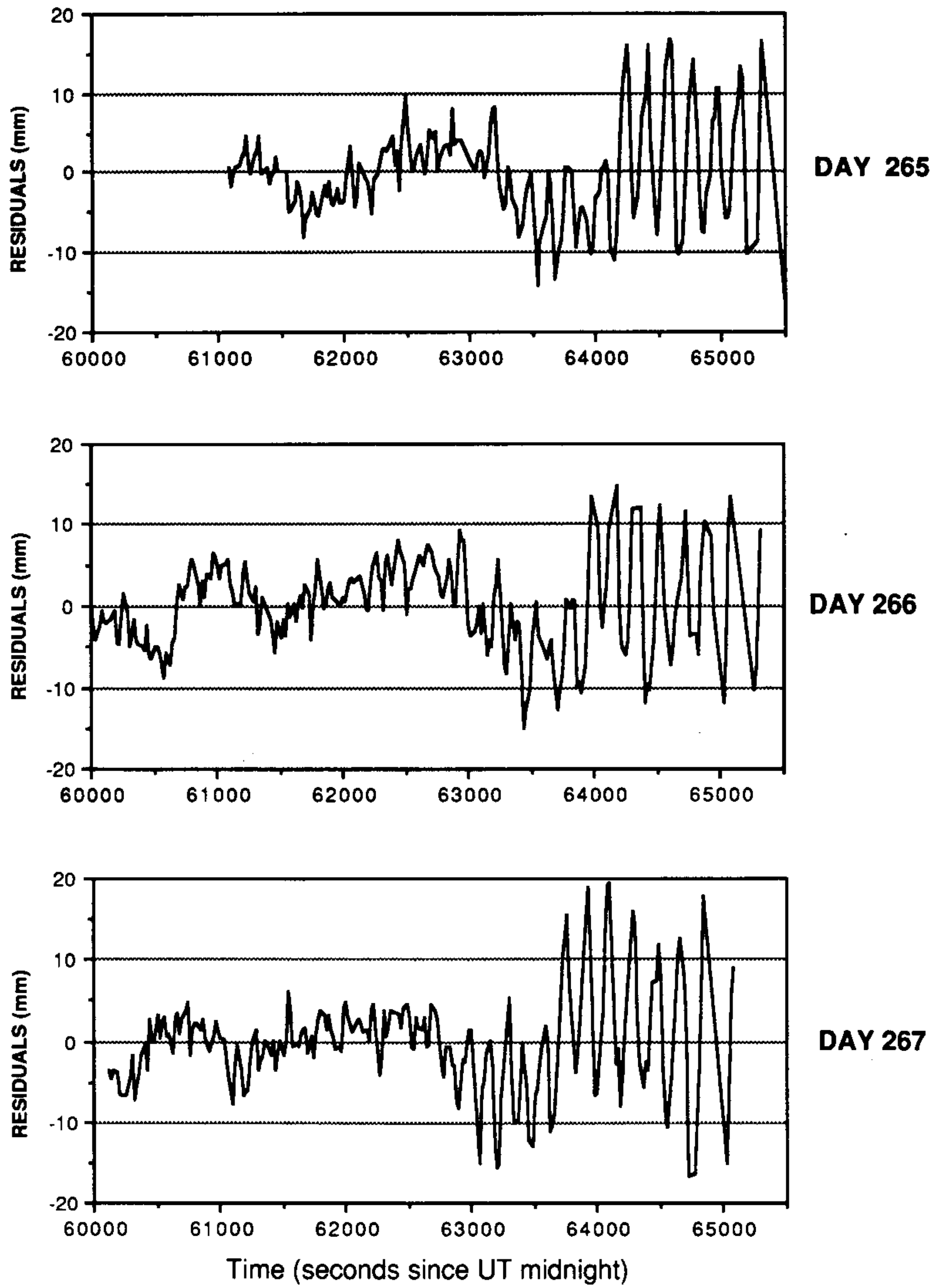

Figure 4.1 Double difference residuals of PRNs18-16 (days 265-67)

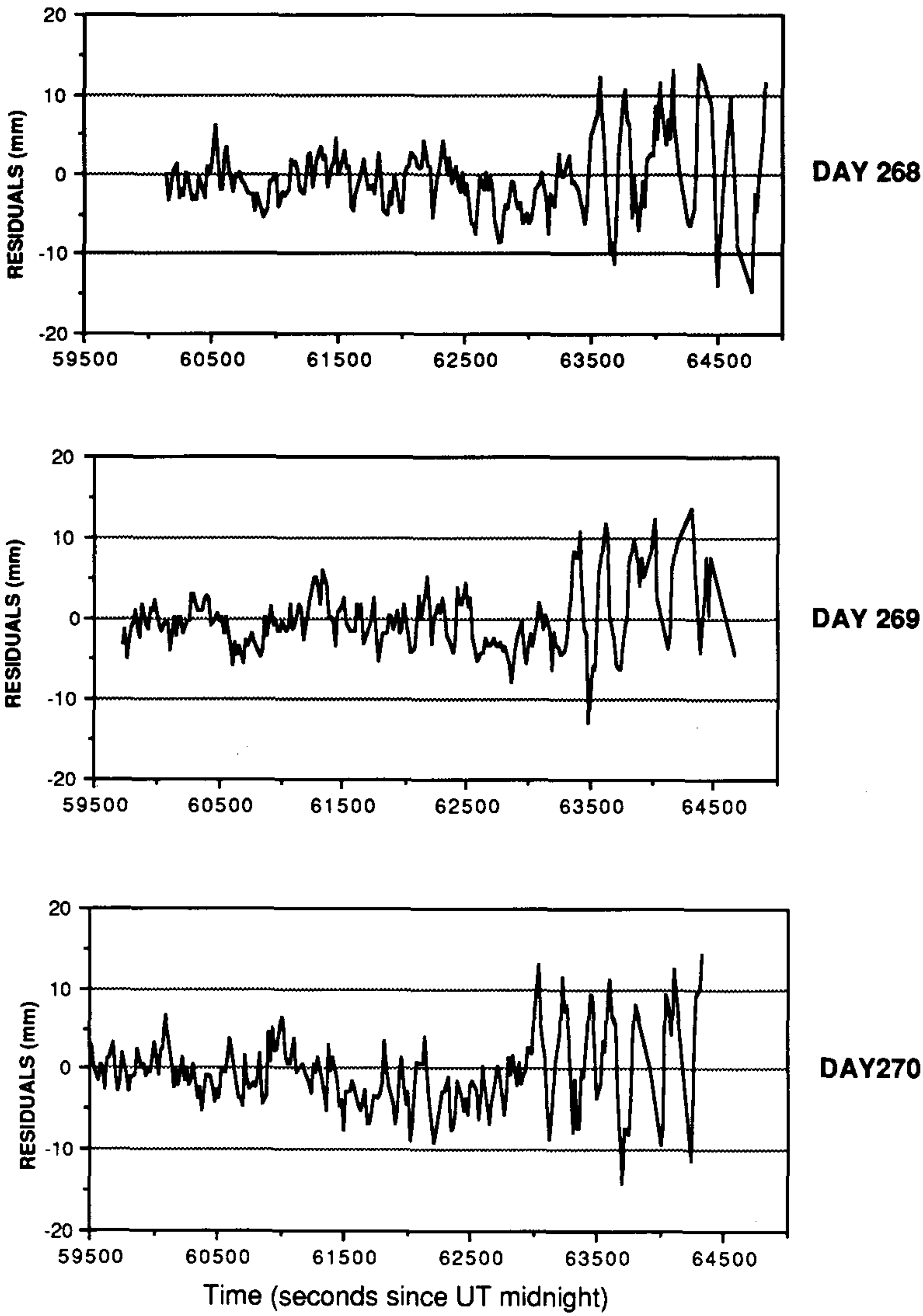

Figure 4.2 Double difference residuals of PRNs 18-16 (days 268-70)

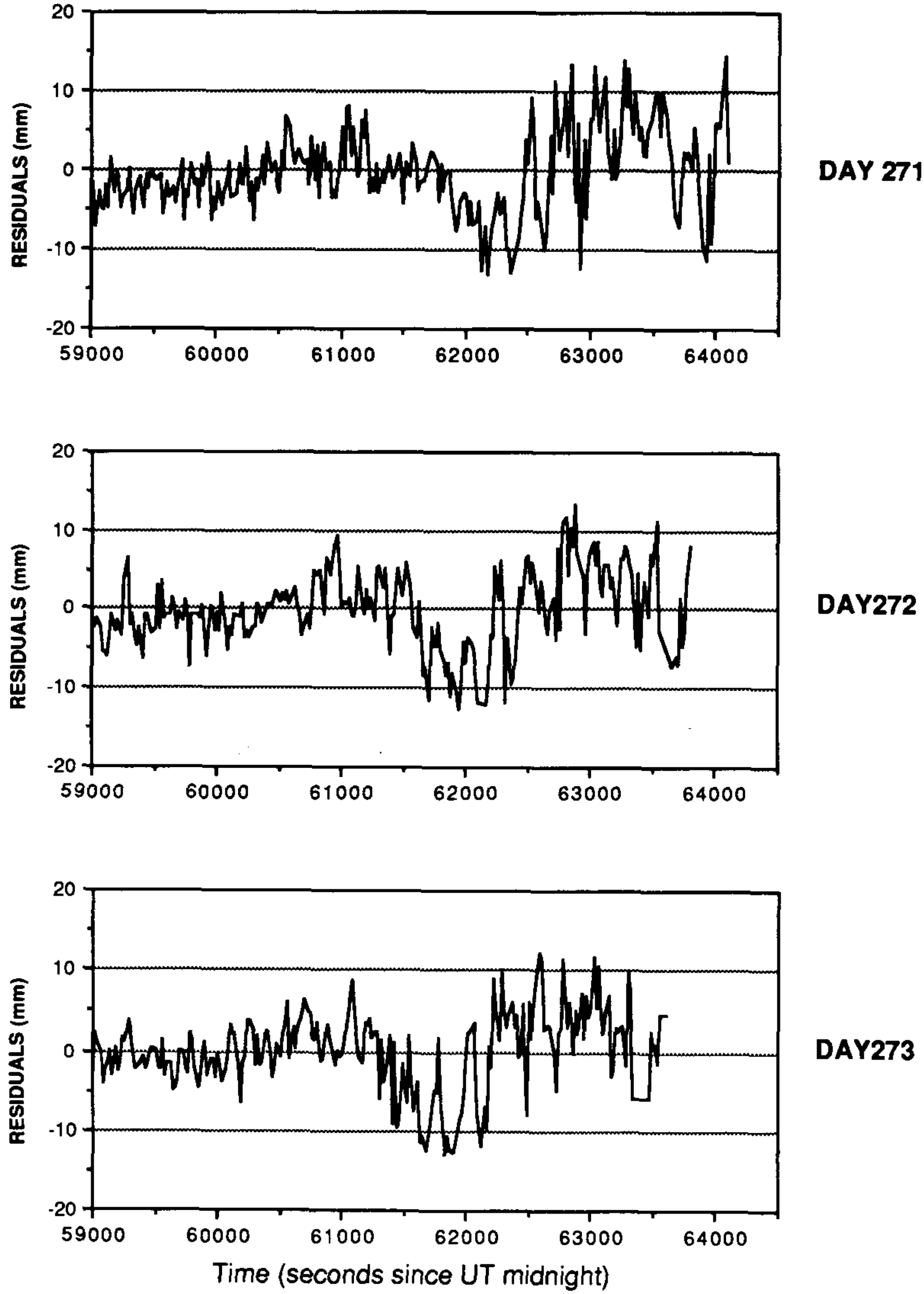

Figure 4.3 Double difference residuals of PRNs 18-16 (days 271-73)

4.2 Correlation Analysis

Cross correlations were performed to statistically prove the existence of systematic trends within the residual plots for the same heights. "The cross-correlation coefficient function is defined as the standard cross correlation divided by the standard deviation of each data set. This normalizes its value to be between -1 and +1 " (Evans, 1986). Figures 4.4, 4.5, and 4.6 each show the plots of the correlation coefficients versus the time lag (in seconds) for two chosen days. For each antenna height set of data, the data from the first day was cross correlated with that for the second and third day respectively.

As expected, the correlation coefficients peaked up to 0.61 near time lags of 240 seconds for comparisons from the first days to the second days. The correlation coefficients were lower for the comparisons from the first days to the third days; however, they still peaked near the expected 480 seconds time lag. The peaks of these cross correlation plots do not occur exactly at the expected 240 and 480 seconds time lags because the GPPS program omitted some epochs of data when correcting for cycle slips. These cycle slips occur mostly during the low elevation tracking of the satellites mainly due to excessive multipath. The missing epochs in one day had to be omitted in the correlated day to ensure that each data set was of equal dimensions. The correct procedure would have been to interpolate residual values where they were omitted; however, this was not done. Also, an exact 236 second delay would

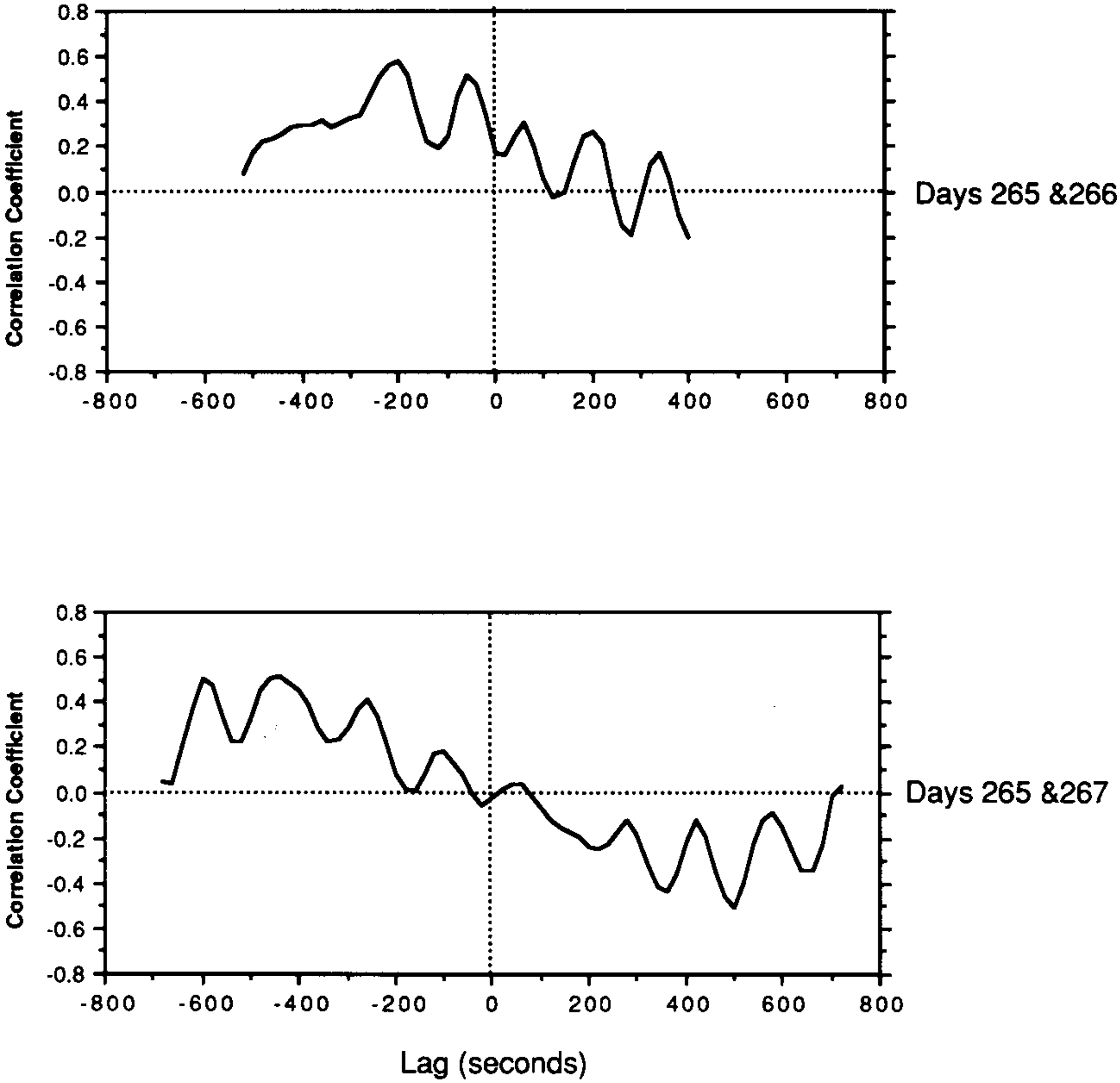

Figure 4.4 Cross correlations of double difference residuals for PRNs 18-16 (days 265-266 and days 265-267).

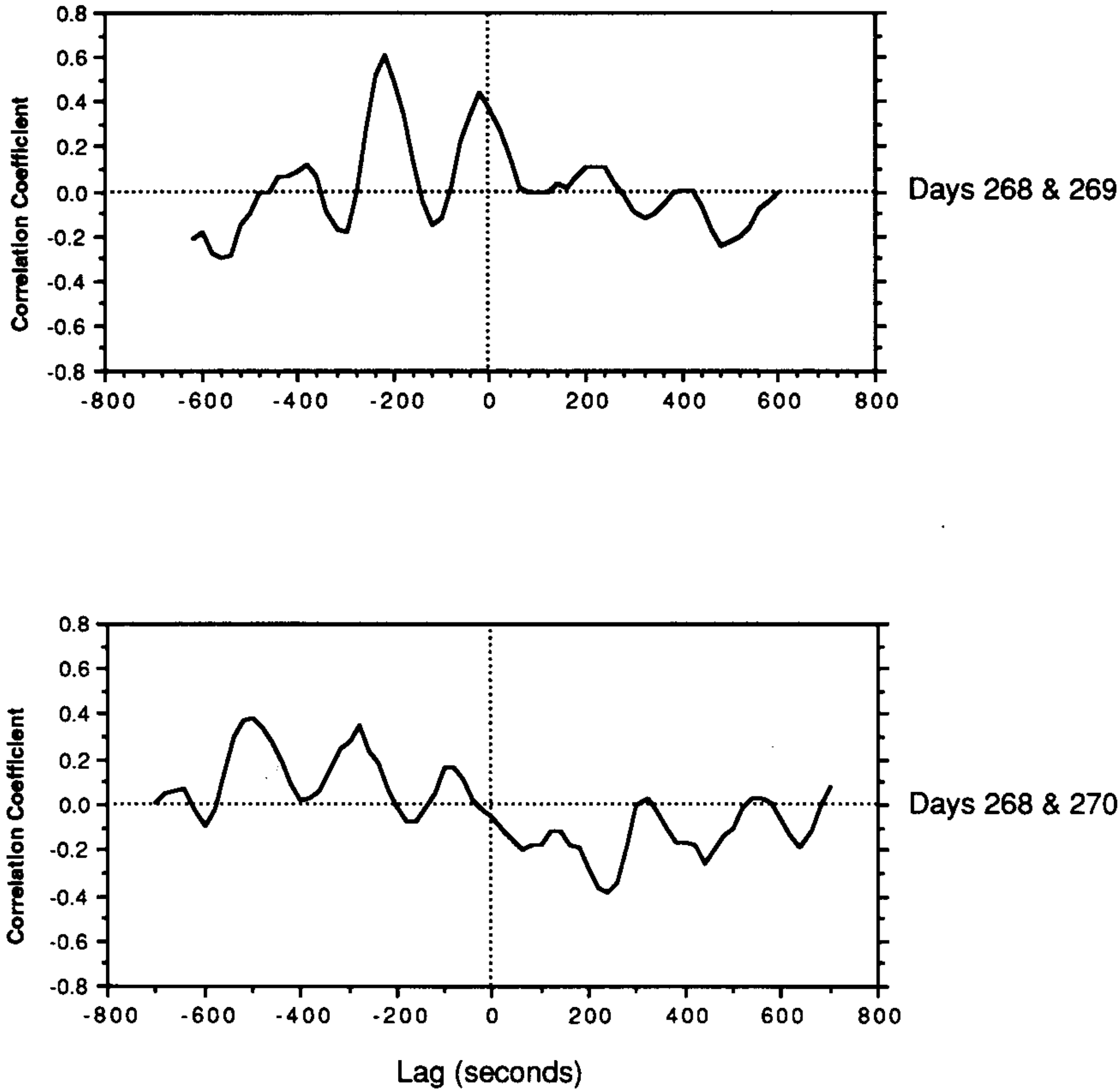

Figure 4.5 Cross correlations of double difference residuals for PRNs 18-16 (days 268-269 and days 268-270).

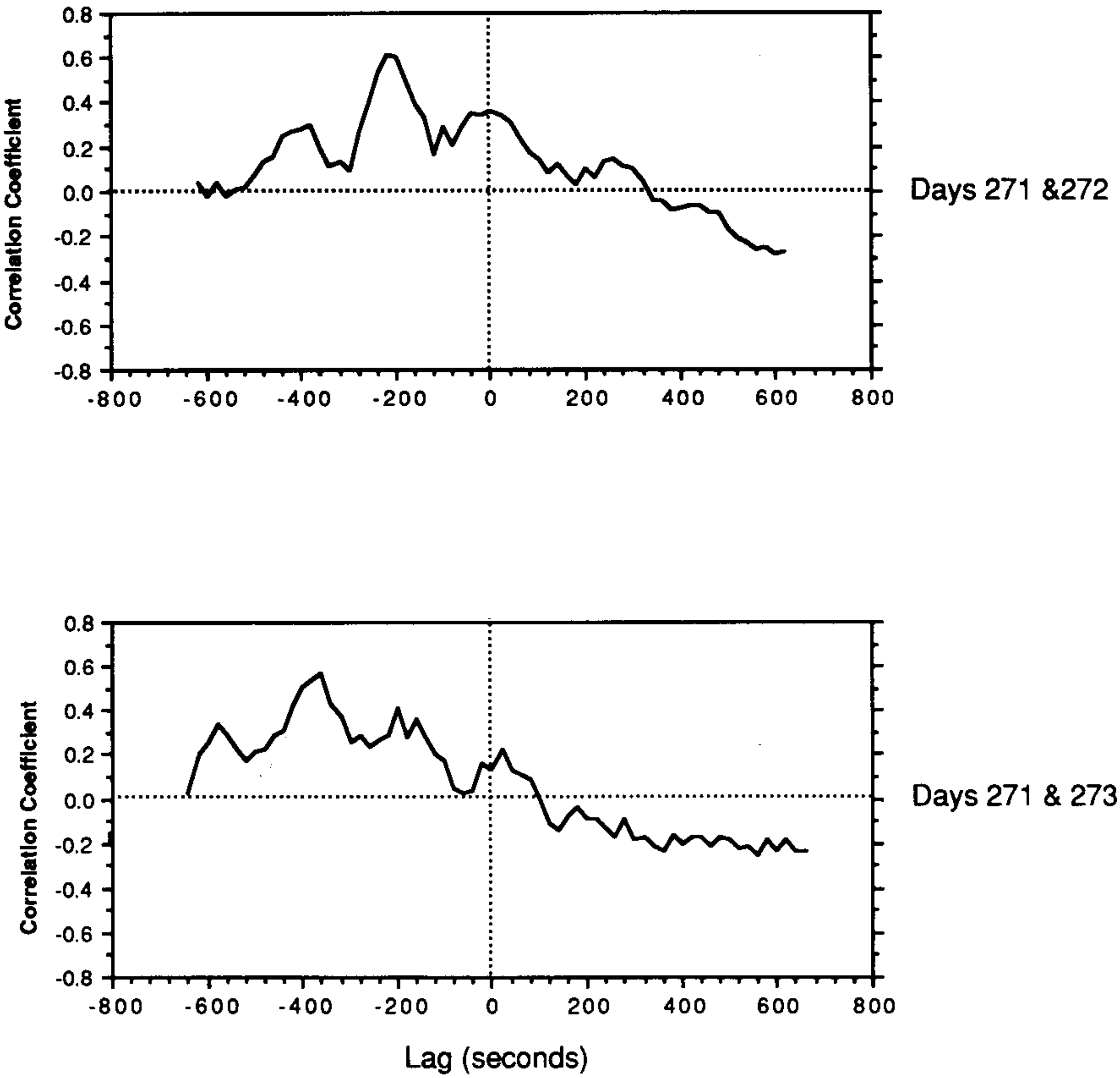

Figure 4.6 Cross correlations of double difference residuals for PRNs 18-16 (days 271-272 and days 271-273).

never be seen (exact time difference between solar and sidereal days) because the data was collected and processed at 20 second intervals. The closest offset observable would be 240 seconds. It should also be mentioned that the satellite orbit periods are not exactly 12 sidereal hours; therefore, another small time difference is introduced.

4.3 Geometric Comparisons

Where the residual plots show a significant increase in amplitude (Figures 4.1, 4.2 4.3), it is assumed that this is caused by the multipath signal reflecting off the wall in question.

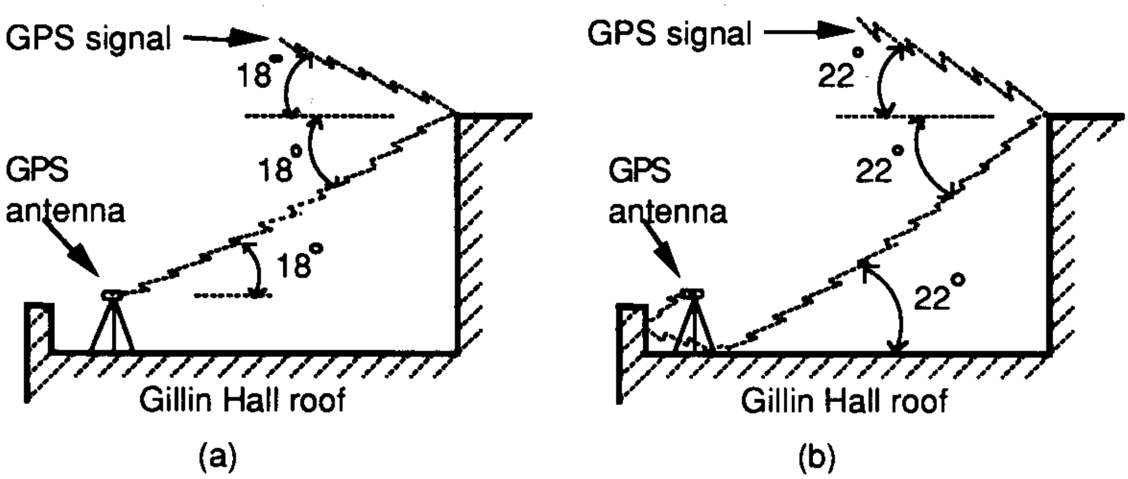

Figure 4.7 Signal reflections: Single (a), Multiple (b).

The signal reflection elevation angle for the 1 metre antenna height was predicted and found to be at 18 degrees when significant multipath began (see Figure 4.7 (a)). In the residual plots for the 1 and 2 metre antenna heights the amplitude increases, decreases, and increases again when the satellite is getting very low on the horizon. By marking the times where these increases in amplitude occurred (multipath) and obtaining the satellite elevation at that time, it was noticed that significant multipath occurred before the predicted time.

For example, at the 2 metre height, the predicted time of multipath off the reflecting wall was found to be correct; however, multipath also seemed to occur, to a lesser degree, with the satellite elevation 4 degrees above the predicted 18 degree elevation. This translates to about 10 minutes earlier than the predicted time. This is mainly because the ground plane extenders were not used. The geometry suggests that the reflected signals also bounced off surfaces below the antenna and not only the reflecting wall(see Figure 4.7 (b)). The signal could bounce off the top of the guard rail or have multiple bounces off the reflecting wall and the concrete floor overlying the building's metal roof. If ground plane extenders were used, perhaps there would not have been as much multiple reflection contamination.

With the elevation cutoff angle set at 10 degrees in the data collection, direct multipath off the reflecting wall was not permitted to happen for the 3 metre antenna height setup. The geometry suggests that this multipath would begin at a satellite elevation of 11 degrees; however, the data is cutoff before any large amplitude occurs. The presence of multipath from other sources, such as multiple reflections, is apparent but at a smaller level.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

"Multipath and imaging effects in a highly reflective environment are likely to be limiting factors for... static carrier applications at the few centimetre level " (Wells et al., 1986). In this report, these two effects were grouped together and referred to as multipath. The multipath effect was the only major error remaining after the double differencing process was performed by the GPPS software on this short baseline. This effect is baseline-length independent; therefore, it becomes a major part of the total error budget for the short baseline determination (Wells et al., 1986).

Multipath detection is not very difficult if the same baseline is observed on consecutive days at the same sidereal time. Comparisons of residual plots and cross correlations can show the systematic repeatability of the multipath induced errors. One can even predict the time and elevation angle at which particular multipath errors should occur. In this case, the data was contaminated by extra multipath which was neither expected nor wanted. This occurred mostly due to the lack of ground plane extenders on the antenna. The elevation cutoff angle in the data collection should have been much lower than 10 degrees to accurately show the multipath errors with the 3 metre antenna height.

The GPPS software is a very user friendly program; however, it is not intended for research purposes and has too much of a black box type of processing. The user cannot obtain proper plots for same scale comparisons of residuals and the program cannot perform the needed statistical analysis of the data.

Math models exist for the prediction of multipath; however, they remain impractical to use, as was the case in this experiment. Each site location is unique and with multiple reflections this modelling becomes almost impossible.

Although this report did not focus on the length of time of observations required for precise determination of a short baseline, the repeatability of these measurements was within 1 mm. The 2 hour observation period was long enough to mean out almost all the effects of multipath. This length of time may be uneconomical for the private industry. With more GPS surveying being performed in urban areas and highly reflective environments, the need for proper antenna design and appropriate length of observation periods will be more pressing.

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