GPS NAVIGATION SIGNAL MULTIPATH INTERFERENCE

by

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The GPS monitor station antenna at Cape Canaveral exhibits multipath interference. This interference is directionally dependent and continues unabated in spite of having cut foliage and trees in the predominant signal paths. The base antenna location is below the height of the nearby tree line and is in the vicinity of numerous potentially reflective structures. This investigation attempts to show potential causes of the interference. Antenna relocation possibilities are entertained to reduce or eliminate the interference.

A recently developed multipath meter is used to take measurements. NovAtel Inc. implemented a Multipath Meter (MPM) feature within the Multipath Estimation Delay Lock Loop (MEDLL) portion of Wide Area Augmentation System (WAAS) type receivers. The MPM outputs data that describes the multipath environment that an antenna is experiencing. It uses NovAtel's MEDLL technology that is able to model and remove multipath signals from the direct signal. MEDLL generates enough information to calculate residuals from the modeling process and outputs them in a standard log format, along with multipath amplitude, delay and phase for each satellite signal currently being tracked. This data is tracked every second.
The MEDLL receiver uses narrow code correlators and maximum likelihood estimation to resolve direct and indirect signal phenomenon as well as a unique software package to easily gather and analyze the resulting data. In the case of the Cape Canaveral Monitor Station antenna, comparisons at three locations (base, high, and remote) will indicate factors leading to reduced interference. Reduced interference is important since the Cape Canaveral Monitor Station can be used as an input to the GPS control system’s satellite position estimates. This, in turn, can affect the GPS user’s navigation performance.
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CHAPTER I

INTRODUCTION

GPS System Background

The Global Positioning System (GPS) provides space-based radio positioning, time transfer, and nuclear detonation detection functions. The GPS is composed of four segments: Space, Control, Navigation User, and Nuclear Detection. The Control segment’s primary elements are a Master Control Station (MCS), five Monitor Stations (MS), and three Ground Antennas (GA). (United States, 1995) Monitor Stations are spread geographically throughout the world to receive radio frequency signals from Space segment satellites. Each MS collects satellite tracking and status data and local meteorological data and forwards this data to the MCS. The GPS system uses “pseudorange and accumulated delta range” tracking data to simultaneously compute precise ephemeris and clock state estimates and to compute predictions for all GPS operational satellites.” (United States, 1989) Clearly, the overall GPS system depends on Monitor Station tracking data that is free of uncorrelated errors that cannot be estimated or otherwise reduced in a Kalman filter. One such source of tracking data error that may exist in the system is a phenomenon known as “multipath interference.”

* Pseudorange is defined to be the time difference between the epoch of the received satellite pseudorandom code and a locally generated epoch. Accumulated delta range is defined to be the accumulated phase of the signal carrier sampled at the code epoch.
Multipath is a condition such that a radio frequency signal arrives at the receiving antenna from more than one propagation route. The effect of multipath is to skew and bias the ranging measurement. (Command Descriptions Manual, 2001) Multipath phenomenon has been suspected at both the Cape Canaveral Monitor Station and the Colorado Springs Monitor Station, based on pseudorange residual data. Problems at these two sites appear to involve line-of-sight obscura impairments as well as multipath interference. (United States, 2001)

Typical Multipath Calculation Method

The typical method for computing multipath effects is based on data from both the code and carrier tracking loops. Multipath has previously been estimated by examining carrier phases at both L1 (1575 MHz) and L2 (1227 MHz) frequencies and noting the corresponding pseudorange. Thus, the following equations, where \( p_1 \) is pseudorange, have been applied:

\[
MP_1 = p_1 - (1 + \frac{2}{\alpha} - 1)\Phi_1 + (\frac{2}{\alpha} - 1)\Phi_2
\]

\[
\alpha = \left(\frac{f_1}{f_2}\right)^2 \text{ where } f_1 = 1.57542 \text{ GHz; } f_2 = 1.2276 \text{ GHz}
\]

\[
\lambda_1 = 0.1903 \text{ m; } \lambda_2 = 0.2442 \text{ m; } \Phi_1 = \lambda_1 L_1 \text{(cycles); } \Phi_2 = \lambda_2 L_2 \text{(cycles)}
\]

This calculated multipath data has “a combination of low frequency change due to multipath and high frequency change due to receiver measurement noise” as shown in Fig. 1. According to this data, multipath variation is “around 3 minutes in period.” (Allen Osborne and STI/VEGA)
Sam Storm van Leeuwen summarized traditional multipath calculations in the following way:

1. Collect pseudoranges and carrier phases for several hours until the full range of satellite elevations has been covered.

2. Convert pseudoranges and carrier phases to units of length (i.e., multiply carrier cycles by speed of light and divide by carrier frequency)

3. Subtract carrier range from pseudorange for each satellite measurement. Common errors will cancel and only ionospheric, pseudorange multipath, carrier phase multipath, noise terms, and carrier phase ambiguity remain.

4. Fit a second order polynomial to the resulting data and subtract it from the data to retain primarily pseudorange multipath and some noise terms.
5. At the average elevation over the 15 to 20 minute interval, determine standard deviation of residuals and subtract the pseudorange noise contribution using \( S_{\text{multipath}} = \sqrt{S_{\text{residual}}^2 - S_{\text{noise}}^2} \).

**Multipath Rejection and Restriction**

Research into the specifications shows that the topic is presented in paragraph 3.4.1.2.2, Multipath Rejection, in the Monitor Station prime item specification. The specification requires multipath rejection of greater than 14db at all Monitor Stations except the Cape Canaveral Monitor Station “where it shall be 8db at elevation angles of less than minus 15°.” Paragraph 3.4.1.2.6, MS antenna element receiving antenna function, provides further information to require greater than or equal to 8 db at all elevation angles less than or equal to -15° and greater than or equal to 2db at elevation angles less than or equal to -5°. (United States, 1980)

The Monitor Station data is restricted in terms of its use. Per the specification, paragraph 6.2.3, Monitor Station elevation mask, satellites will be tracked above 5° elevation for the purpose of assuring performance and navigation service integrity. In terms of using the data for navigation computations, the specification says:

System error analysis has indicated that data below 15 degrees adds no significant information to the estimation of ephemeris, clock, and troposphere state parameters. This is due to the large
troposphere component of measurement error encountered near
the horizon which is correlated over the smoothing interval.
Therefore, with realistic a priori measurement error profiles, the
Kalman estimation filter will utilize only that data collected above
15 degree elevations, and the precision corrections (i.e.,
troposphere) are of CS [Control Segment] performance interest at
15 degrees and above. (United States, 1980)

The Monitor Station specification for multipath rejection reads as a
requirement only on antenna gain pattern below the horizon. The processing
restriction for use in navigation computations limits the lowest elevation angle to
15°. However, data base changes have been incorporated into the system,
without changing the specifications, so that the current limits are different. In
fact, data from all Monitor Stations, except Cape Canaveral, are incorporated into
the Kalman filter at 10° elevation and above. The Cape Canaveral Monitor
Station has a limit at 25° because of interference problems. The MCS uses status
data from all stations down to the lowest acquisition or tracking elevation, which
can be below the horizon. (P.J. Mendicki) The question is, “Is there a reasonable
way to mitigate multipath effects at Cape Canaveral so that its limit can be
changed from 25° to 10°?”

Antenna Characteristics

The Cape Canaveral Monitor Station was originally a dedicated test
station and, as such, was not built with the same operational Monitor Station
antenna or receiver used at the other sites. However, in 1998, the site was upgraded with a new AOA receiver and antenna. The new receiver is the same that will be used in the other stations operationally, but the antenna is not. By the late-1990s, the Cape Canaveral Monitor Station was used as a test asset to support major new developments in the system, but it periodically returns to operational use, for short periods, when live operational test needs dictate. (Hermanson) Over the years, at least two different antennas have been used at the site. The current antenna is a choke ring design intended to minimize multipath interference.

![Figure 2. Choke Ring Antenna](image)

Generic antenna elements of this type are designed with broadband radiating elements and a quadrature feed network. The broadband element allows the antenna to provide continuous coverage from L1 (1560 to 1590 MHz) to L2 (1212 to 1242 MHz) frequencies without regard for operating temperature. The quadrature feed network has characteristics providing excellent circular
polarization, minimum axial ratio, low phase ripple, good pattern symmetry, and a stable phase center. (EDO Corp) The antenna element is coupled with a choke ring to mitigate multipath interference. A choke ring is a ground plane utilizing a series of concentric rings to minimize gain below the horizon. A comparison (Fig. 3 and Fig. 4) of elevation gain patterns (1227 MHz, isotropic level = 10.3 db) with and without the choke ring demonstrates the usefulness of the choke ring. (Technical Data Package)

Figure 3. Antenna Element Without Choke Ring
The choke ring has a diameter of 15 inches in comparison to the approximately 60-inch diameter ground plane at the other Monitor Station sites. The standard antenna at other sites is shown in Fig. 5.
Purpose

This paper focuses on multipath interference characteristics at Cape Canaveral Monitor Station using a previously unused technique to measure multipath directly. The measurement uses a separate but identical antenna element and choke ring (AOA antenna) and separate Novatel Multipath Estimating Delay-Lock-Loop (MEDLL) receiver. No test or operational assets at Cape Canaveral are used.

This investigation examines antenna location as a principle means of minimizing multipath interference. To that end, the measurement plan is to collect data at the base location (as near to the current operational antenna as is reasonable), at a high location directly above the base location, and at a remote location in a clear area at the same height as the operational antenna. This combination allows the base multipath environment to be measured as well as allowing a measure of how greater height can minimize multipath. The remote location allows a verification of what a “no multipath” environment should look like in this area. “To combat multipath, antenna siting is of prime importance.” (Kaplan, 259)
CHAPTER II
MULTIPATH ESTIMATING DELAY-LOCK-LOOP

Multipath Model

Novatel’s MEDLL receiver accomplishes real-time signal quality monitoring, including an indication of multipath interference, by separating received signals into the line-of-sight and multipath (reflected) components. The key parameters are delay, relative amplitude, and phase of the multipath signal, along with the residual values for each correlator used for multipath estimation. (Townsend, 2002)

Bryan Townsend describes some important characteristics of multipath, which is the basis for multipath measurement:

a. The multipath signal will always arrive after the direct path signal because it must travel a longer distance over the propagation path.

b. The multipath signal will normally be weaker than the direct path signal since some signal power will be lost from the reflection.

c. If the delay of the multipath is less than two PRN code chip lengths, the internally generated receiver signal will partially correlate with it. If the delay is greater than 2 chips the correlation power will be negligible.
J. M. Kelly and M. S. Braasch at Ohio University considered a similar model for multipath. They recognized that the increased precision of GPS could make uncorrelated errors, such as multipath, significant. A range bias will exist in the widely used code tracking method in the presence of fast fading multipath signals. As shown in Figure 6, fading of multipath will cause a shifted, scaled autocorrelation lobe to fade in and out of phase with respect to the direct lobe.

(J.M. Kelly)

\[ \text{SMR} = 3 \text{dB, delay} = 0.75 \text{ chips} \]

Figure 6. Multipath Model

Kelly quantified multipath fading through simulation as follows:

Figure 7. Multipath Fading

* Fading refers to the bandwidth of the spectral components that are dependent on angular frequency of the direct signal and the phase rate of the reflections.
Typical receivers use early-late slope detection as follows:

![Early Late Slope Technique](image)

**Figure 8. Early Late Slope Technique**

Pseudorange is measured as the time shift required to align the internally generated signal with the IF signal, scaled by the speed of light. Three replica codes are used for the correlation purposes: one is directly aligned with the IF signal (punctual), one is delayed (late) and one is advanced (early). The early and late codes lay on the slope of the autocorrelation function either side of the peak and are used to aid the continuous tracking of the code, and to reduce the tracking error. Two or three correlators may be used in a typical receiver.

**Correlation Characteristics**

Townsend uses this same model, based on his important characteristics, in expressing the basis for MEDLL technology. He focuses on the question of whether the direct and indirect components can be reasonably measured and/or determined. A multipath free reference function is subtracted from the observed correlation function to leave multipath and noise. An estimate is made of most likely multipath delay, phase, and amplitude. A correlation function based on
those estimates is then subtracted from the function used to make the estimate. The sum of the squares of the correlator values generates multipath residuals. (Jakab)

Modern digital correlators are relatively inexpensive so that many correlators can be used to improve performance. (Kaplan, 150) MEDLL dedicates 10 or more correlators to each channel as shown in Figure 9. (Townsend, 1995)

Figure 9. Multiple Correlator Sampling

The procedure depends on describing the signal at the input of the receiver as:

\[ r = \sum_{m=0}^{M} a_m p(t - \tau_m) \cos(\omega t + \theta_m) + n(t) \]

where

- \( M \) = number of signals
- \( t \) = time
\begin{equation}
\begin{aligned}
p(t) &= \text{spread-spectrum code} \\
n(t) &= \text{noise} \\
a_m &= \text{component signal amplitude} \\
\tau_m &= \text{component signal delay} \\
\theta_m &= \text{component signal phase} \quad (\text{Townsend, 2001})
\end{aligned}
\end{equation}

The MEDLL receiver computes the multipath estimation several times within a second and outputs the data once a second for all satellites in view. Since the measurement technique does not depend on code minus carrier techniques, only the L1 C/A code is used.

**Effectiveness**

Townsend shows the effectiveness of this technique by simulating the relationship between pseudorange error and multipath delay. In the following plot, the multipath amplitude is 0.5 of the direct amplitude.
Figure 10. Theoretical pseudorange error for MEDLL.

In comparison, similar results are obtained for the code minus carrier multipath simulation in Figure 11. (Townsend, 2000)

Figure 11. Code Minus Carrier Multipath
Multipath power can be taken from this data in terms of the ratio of desired signal power over undesired signal power (D/U), expressed in decibels. It should be clear that the computed parameters of multipath delay, amplitude, and phase can only be useful when there is an appreciable loss of D/U level (that is, a significant multipath component exists). The point to observe is that MEDLL can make good estimates of multipath down to about 0.2 chip delay. (Townsend, 2000)
CHAPTER III

DATA COLLECTION AND ANALYSIS TOOLS

Satellite Geometry

The data collection plan for this effort requires that a reasonably complete set of satellite visibility angles be obtained. Ideally, a complete set of all unique trajectories for all satellites should be obtained. Such a set would require about 24 hours of data collection for each measurement location. Another 24 hours for each location would be needed if the original measurement were to be verified to assure the best possible measurement accuracy. (Jaksic) In this case, 144 hours would be needed for the three locations (base, high, and remote). A reasonable time frame was developed since resources did not permit such an extensive collection effort. An approximate twelve-hour period provides one orbit revolution of the constellation and would be the minimum needed to represent each satellite. The criteria used here is to obtain close to the 24-hour period subject to time constraints. About 21 hours, on average, of data was collected for each location.

As shown in Figures 12, 13, and 14, the sky views (orientation is as if you are looking skyward from the site) show the satellite positions at start and end times, as well as trajectories, during the data collection effort for each location. The plot is scaled in terms of azimuth and elevation. This collection should provide a reasonably complete survey of multipath reflection possibilities. Refer to the Appendix for calculated individual satellite visibility timelines.
Figure 12. Base Start and End Sky Views
Figure 13. High Start and End Sky Views
Hardware Details

The two primary hardware items are the AOA antenna and the NovAtel MEDLL receiver. Since the equipment was to be located at three different locations and elevated to a maximum of 43 feet, the package needed to be relatively self-contained with minimum teardown and reassembly. Figure 15 shows the antenna and receiver package as one assembly. The left view shows the overall package and subsequent views show details of the package. When mounted on the boom lift, as shown in Figures 16, 17, and 18, the package is highly mobile and capable of quick repositioning with no teardown. The package is connected by cabling to ground based computer (115 KBPS serial link), TV monitor (coax cable), and 115-volt power (extension cord). A 100-foot fiberglass tape measure was attached to bottom of the boom lift to determine height above ground (the antenna base is the reference point).

The current antenna is mounted on the side of a building at 13 feet above ground. So the base measurement antenna and the remote measurement antenna are at the same height. The high measurement antenna height is 43 feet. The boom lift package was wrapped and sealed in plastic to protect the equipment from rain.

The equipment package includes a video camera focused on a bubble level so that the antenna can be assured of being level (the boom lift has a self leveling control feature for the platform in one axis). The bubble level has reticules at one and two degrees. In practice, if the platform is leveled in the ground position, it
maintains near level conditions as it is raised. Unfortunately, the tests were conducted during high ambient temperatures that, in combination with the enclosing plastic wrap, rendered the video camera inoperative. No confirmation of correct leveling during test periods was possible.

Figure 15. Equipment Arrangement

Figure 16. Base Location Showing Operational and Test Antenna
Figure 17. High Location View With Insert
NovAtel’s Multipath Assessment Tool (MAT) is a Windows based program to collect and display multipath parameters, including signal and satellite information. The software accepts and stores real-time data from the serial port of a WAAS-type (Wide Area Augmentation System) MEDLL receiver. MAT provides several tools to aid multipath analysis, ranging from top-level “data-consolidation” plots to detail signal plots. (MAT User Manual)

Top level plots show average multipath power and pseudorange error parameters in polar plot azimuth-elevation form. The average value is color coded to scale and the azimuth-elevation cells represent the general location of the satellites. Minimum multipath power and maximum pseudorange error can also be shown in this same form. Such plots allow the entire set of data to be
viewed to quickly identify and isolate multipath problems. Signal plots and histograms allow more specific problem analysis.

Specific signal plots are available for multipath strength, phase, delay, and residuals as well as pseudorange error and signal-to-noise ratio. Satellite azimuth and elevation plots complete the picture.

Histograms are available to show statistical results for all the primary parameters. Although no histograms are used here, they can help group characteristics and show trends.

Site Layout

Figure 19 shows the site layout with bearings centered on the test antenna for base and high cases. The top-level polar plots from MAT can be related to the bearing shown in the site layout and aerial photographs. For example, if the minimum multipath D/U polar plot shows a significant multipath signal from a satellite at a bearing of 135°, a probability is that a reflecting surface lies along the line of this bearing. Thus, although there are no satellites to the North at sufficiently low elevations to be concerned about multipath, it does not mean that reflectors to the North can't be sources of multipath. It should be understood that this measurement equipment has no means of detecting direction of the multipath signal. We safely assume the direct signal is line-of-sight between the antenna and the satellite and the reflected signal may take any path or direction relative to the antenna, except the direct path.
Figure 19 shows the base layout with several structures in the vicinity of the test antenna. Since the height of the antenna is 13 feet, many of the surrounding surfaces are close to or above the zero elevation horizon of the antenna. A sample list of above-horizon potential reflectors in the vicinity is:

- 28 foot diameter S-band antenna at 350°
- 2 large metal ventilation ducts on the roof at 10°
- 75 foot microwave tower at 243°
- 15 foot diameter communication antenna at 280°
- 25 foot tree line to the south
By elevating the antenna thirty feet above the base measurement case, the high measurement antenna is positioned so that many of these same potential reflectors are at much lower elevation angles relative to the antenna.

Figures 20 and 21 show aerial views at the measurement sites. The purpose of these figures is to ensure that the environment around the measurement location is fully considered. With these figures, we can see beyond the immediate tree line and account for objects not directly visible from the test site. For example, Figure 20 shows a large three-story hangar building at just over 200 meters on a bearing of 130° relative to the test antenna. It also shows how close the tree line, particularly to the south, is to the antenna location. Figure 21 shows the remote location and shows that location relative to the base location. Small one-story buildings are over 200 meters away at bearings of 20° and 160° from the remote antenna location.

In summary, the base test location is used to assess the multipath environment near the operational antenna. The high test location is used to assess the mitigation effects of lowering the elevation angles of potential reflectors relative to the antenna. The remote test location is used to assess a clear field situation and to provide a relative measure to compare with the other two cases.
Figure 20. Base Aerial Layout

Figure 21. Remote Aerial Layout
CHAPTER IV
MULTIPATH MEASUREMENT RESULTS

Overview

Figure 22 presents the top-level “big picture” results for all testing. The figure summarizes minimum D/U and average D/U for each test case. Inspection shows immediately that the base case has some multipath interference, while the high and remote cases are relatively free of multipath effects. The interest region is along a band from $0^\circ$ to $25^\circ$ elevation. In general, the D/U power in the region is 3 to 6 db lower in the base case compared to either the high or remote case. Note that the remote case is the “cleanest” multipath case, as expected. The effect of raising the base antenna to the high antenna height is reduced multipath, as expected. The remote case shows several decibels greater D/U power in the interest region compared to the high case, but, in general, both cases are better than the base case.

Figures 23 and 24 compare the base case to the high case and the remote case, respectively, by showing differences in power level for D/U and minimum D/U in the interest region. The comparison plots show a green cell if the corresponding high or remote cell is 3 db or greater than the corresponding base cell. Black represents the same level and red indicates -3 db or less. Plots from Figure 22 are reproduced in these two figures to aid in visual comparison. As explained, both the high and remote cases show an overall more favorable multipath situation. The apparent bias in the plots northwest to southeast is
likely from inaccuracies in leveling the antenna in the respective test cases. While this “tilt” is not desirable, it does not obscure the fact that the high and remote locations are significantly superior.

Figure 25 summarizes maximum pseudorange error and average pseudorange error for each test case. The indications are similar to the D/U data with average pseudorange errors for high and remote cases in the 1-meter range. Maximum pseudorange error for high and remote cases rarely exceed 2 meters. Conversely, the base case average pseudorange errors reach into the 2-meter range and maximum pseudorange error is shown as high as 5 meters.

Several azimuths in the base case show significant multipath interference in the interest region. Strong indications are at 60° to 100° and at 200° to 230° azimuth. Worst case interference seems to exist near 10° elevation. While there may be reflectors along these bearings, it is virtually impossible to associate the data with specific (obvious) reflectors in the area with any certainty. The easterly indication could be the result of glancing reflections from the building roof in that direction. The southwesterly indication could be from the 75-foot microwave tower in that general direction. The southeasterly indication might be from the distant three-story hangar in that general direction. Since we are not proposing to remove the reflectors, but, rather, to move the antenna, there is no compelling reason to try to isolate individual reflectors.
Figure 22. Minimum D/U and D/U (Average) Plots for Base, High, Remote
Figure 23. Base and High Difference, Region of Interest
Figure 24. Base and Remote Difference, Region of Interest
Figure 25. Maximum PS Error (Average) and PS Error for Base, High, Remote
It is significant to note that there are no major variations showing strong indications in the interest region of the high case. The remote case shows one such variation at 130° azimuth, but it is a singular, readily explained exception. Refer to Figure 42 in the Appendix and Figure 21 to see the likely reflector as a parked aircraft at this azimuth. Clearly, the base case shows multipath interference and the high and remote cases show relatively free conditions.

Selected Cases

Figures 22 and 25 provide clues to where further investigation could be beneficial. For selected strong indications, detail signal plots will show what is actually occurring. Refer to the Appendix for a breakdown of the minimum D/U polar plot for each satellite. Each selected case, by individual satellite, will present a series of eight signal plots: multipath phase, multipath D/U, elevation, azimuth, carrier noise ratio, pseudorange error, multipath delay, and multipath residuals.

Phase is the shift between the multipath and direct signal in the range from \(-\pi\) to \(+\pi\). Strength is the relative power of the desired signal compared to the undesired signal, as previously discussed. Carrier noise ratio is carrier to noise density ratio in dB-Hz. Pseudorange error is an indication of pseudorange error expressed in meters. Delay is the time delay between multipath and direct signal expressed in course/acquisition code chips. Residuals provide an indication of confidence in the multipath strength calculation.
First, for comparison sake, Figure 24 shows a high elevation condition with virtually no multipath. It is presented so that “multipath-free” can be compared with later multipath indications. Figure 24 shows almost no pseudorange error and high D/U readings with the satellite near zenith. Multipath phase tends toward zero, with some noise, since there is not a strong multipath component. Residuals are low and carrier noise ratio is high.

Strong multipath indications exist for PRN 29 in the easterly direction at low elevation (see Figure 38). Figure 27 presents the eight-parameter data for this satellite while the satellite traverses from about 30° to about 5° elevation. Multipath phase shows a definite pattern intermixed with noise. Multipath D/U shows a significant multipath component with minimums below 20 db for most of the excursion below 25° elevation. Carrier noise ratio drops off as elevation drops, as expected. During the worst-case interval, pseudorange error exceeds 3 meters. This is an example of sustained (7000 seconds) multipath interference in the easterly direction.
Figure 26. Selected Case PRN 02 Base, High Elevation
Figure 27. Selected Case PRN 29 Base, Low Elevation
Looking in a more westward direction, Figure 28 shows PRN 07 rising from about 7° elevation at a bearing of 235°. There is an initial strong multipath component up to about 10° as shown by the low D/U level under 20 db. The signal continues to exhibit some multipath strength even up to 20° elevation, but the effect on pseudorange error is generally in the 1-meter range. The multipath delay plot shows a somewhat different pattern suggesting that the average delay is mid-range rather than low-range as was the case in Figure 27. Multipath phase shows a strong pattern. This is an example of sustained (2600 seconds) multipath interference in the easterly direction.
Figure 28. Selected Case PRN 07 Base, Low Elevation
Finally, Figure 29 shows PRN 06 with visibility from about 5° to 12° elevation on the eastern horizon. Multipath indications are very strong with excursions below 10 db D/U. Multipath phase is a well-defined pattern. Carrier noise ratio is in the expected range for this elevation. Multipath delay tends toward the low-range suggesting a relatively close reflector. Pseudorange error is dramatic as 10° elevation is approached. Multipath residuals are high. This is a worst-case example of strong multipath interference.

For comparison purposes, PRN 06 is shown in the high test case along this same trajectory in Figure 30. As expected, the plot shows significantly reduced multipath effects. Multipath D/U is well above 20 db for the full 7000 seconds. Carrier noise ratio appears about the same as with the base test case. There is less of a pattern to the multipath phase and multipath delay is less defined. Pseudorange error is generally in the 1-meter range with no major excursions. Multipath residuals are reasonably well contained over the range.

For further comparison, PRN 06 is shown in the remote test case along this same trajectory in Figure 31. The characteristics are generally the same as for the high test case shown in Figure 30. This tends to confirm that the base case is exhibiting multipath interference that is not present in either of the other test cases.
Figure 29. Selected Case PRN 06 Base, Low Elevation
Figure 30. Selected Case PRN 06 High, Low Elevation
Figure 31. Selected Case PRN 06 Remote, Low Elevation
A closer inspection of the specific difference between base and high test cases is shown in Figure 32 by comparing D/U for base with high. The signal overlays show that the base case sustains a generally lower D/U level with some strong lower excursions.

Figure 32. Compare D/U for PRN 06 Base and High, Same Trajectory

Figure 33 performs the same comparison on pseudorange error by showing the base case excursion generally into the 2 meter range, with peaks as high as 6, while the high case remains stable in the 1 meter range. Figure 34 shows that the elevation in this comparison was essentially the same for both base and high cases.
Figure 33. Compare PS Error for PRN 06 Base and High, Same Trajectory

Figure 34. Compare Elevation for PRN 06 Base and High, Same Trajectory
The same type of comparison is made between high and remote cases. It has been established that the remote case is generally free of significant multipath components and can represent the “multipath free” environment. By comparing the remote case to the high case, a measure of the marginal multipath strength at the high location is established. Figure 35 shows the remote case has a slightly higher D/U level with the high case, but the difference is relatively small. Neither case exhibits strong variations.

Figure 35. Compare D/U for PRN 06 Remote and High, Same Trajectory

Figure 36 shows a comparison between high and remote cases in terms of pseudorange error. Figure 37 shows the elevation comparison between high and remote and indicates that the measurements were taken at approximately the
same elevations. For this worst-case environment for the base test case, these plots show that the high test case is nearly as multipath-free as the remote case, either of which has significantly less multipath interference than the base test case.

Figure 36. Compare PS Error for PRN 06 Remote and High, Same Trajectory
Summary and Conclusions

This paper has reviewed the unique environment of the Cape Canaveral Monitor Station by describing how its equipment is different than other such stations and by identifying potential multipath reflectors surrounding this antenna. The unique multipath measurement technique of the Novatel receiver and software was presented to show that a credible “full scope” analysis of multipath was undertaken. The measurement results at three specific locations have been thoroughly reviewed and differences noted.

The data shows that the best solution to reduce or remove multipath effects would be to move the antenna to a remote location. If that were not practical from a cost or technical viewpoint, then a good alternative would be to
elevate the antenna well above the surrounding potential reflectors. In this case, all significant multipath effects would be removed. Either solution should allow the Cape Canaveral Monitor Station to provide data suitable for use in the Master Control Station in the same manner as other monitor stations.
Appendix

Figure 38. Base Individual Minimum D/ U Plots
Figure 41. Visibility Timeline Remote

Figure 42. Source of Remote Singular Multipath Event: Aircraft
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