DETECTION AND CORRECTION OF GLOBAL POSITIONAL SYSTEM CARRIER
PHASE MEASUREMENT ANOMALIES

A thesis presented to
The faculty of the Fritz J. and Dolores H. Russ
College of Engineering and Technology of
Ohio University

In partial fulfillment
of the requirements for the degree
Master of Science

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June 2004
This thesis entitled
DETECTION AND CORRECTION OF GLOBAL POSITIONAL SYSTEM CARRIER
PHASE MEASUREMENT ANOMALIES

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ABSTRACT


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GPS carrier phase measurements are widely used in high accuracy navigation and timing applications. However, anomalies can exist in these measurements, which if not accounted for, can degrade their integrity and accuracy and make them unsuitable for high accuracy applications.

The research contained in this document was performed to identify carrier phase measurement anomalies and develop algorithms that can detect and possibly correct these anomalies. Following the identification of carrier phase anomalies, two types of detectors were developed for their detection along with logic to combine the outputs of the detectors, including appropriate corrective action upon the detection of one or more anomalies. Anomalies were simulated by introducing errors into the GPS data sets collected at Ohio University.

Approved:

Frank van Graas

Fritz J. and Dolores H. Russ Professor of Electrical Engineering
ACKNOWLEDGEMENTS

First of all I would like to thank God for everything that he has given me in my life. I am so very grateful to Him for giving me this ability to find my inner strength and bounce back from disastrous situations time and again. I thank my family back home for their constant support during the tumultuous years and for making their presence felt in spite of the physical separation. I owe a lot to my sister and brother-in-law Naina and Rajiv Sharma, for pulling me out of the abyss and helping me rediscover myself. Without their help I would not have found the motivation that was badly needed to go through with this work.

My sincere and heartfelt thanks to Dr. Frank van Graas for being my advisor and backbone in this endeavor. His patience, understanding and the flexibility that he provided me with have been invaluable throughout my Master’s program and especially in completing this thesis work. I consider it a privilege to have worked under him. I thank Dr. Michael Braasch and Dr. Chris Bartone for lending me their assistance in the numerous courses that I took under them and for being members in my defense committee. I also thank Dr. William Kaufman for agreeing to be the external representation in the defense committee. Special thanks to Lukas Marti for his help with some of the tough-to-crack homework assignments and also for his general philosophical guidance. Finally I thank one and all at the Avionics Engineering Center for all the support that I have received from each one of you and for making this an unforgettable experience for me.
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1 INTRODUCTION

The Standard Positioning Service (SPS) of the Global Positioning System (GPS) does not satisfy the accuracy and integrity requirements for aircraft precision approach and landing. For example, the GPS SPS horizontal accuracy is 25 m (2\text{drms}) and the vertical accuracy is 43 m (95\%) [1], while the least demanding precision approach operation (Category I), requires vertical position accuracy of 4 m. [2]

During the last decade, much research has been performed by the GPS industry to develop various techniques that improve the performance of standalone GPS. Most of these techniques use satellite ranging corrections (also called differential corrections) from a GPS receiver at a known location or networks of GPS receivers to improve the accuracy of the standalone GPS user receiver. Examples of early test and evaluation systems include the Local Area Differential Global Positioning System (LADGPS), Wide Area Differential Global Positioning System (WADGPS), and GPS interferometry. [1] The latter technique achieves accuracies at the sub-decimeter level. At the time of this writing, many national as well as international government and industry services exist that provide differential GPS corrections, such as StarFire\textsuperscript{TM}, OmniStar\textsuperscript{TM}, and Eurofix. Although these systems are very accurate, they are not designed to satisfy demanding aviation requirements. The Federal Aviation Administration (FAA) has also been involved in the development of two augmentation systems for standalone GPS; the Local Area Augmentation System (LAAS) and the Wide Area Augmentation System (WAAS). The WAAS is designed to increase both the accuracy and integrity of GPS SPS over most of the Conterminous United States (CONUS) to support precise horizontal and vertical
aircraft guidance up to Category I Precision Approaches. The LAAS is designed to support aircraft approach and landing with high availability up to Category III Precision Approaches.

Although the concept of augmentation systems was conceived to enhance the performance of standalone GPS, these systems themselves also must meet the stringent accuracy, integrity, continuity and availability requirements that are set for high-accuracy applications. In the computation of the differential corrections, extensive use is made of the carrier-phase measurements of the received GPS signals. These measurements have noise that is below the centimeter-level. However, carrier phase measurements may contain errors that cannot be properly represented by a stochastic model. [3] Some of these errors, such as cycle slips, may be caused by factors external to the receiver, including signal obstruction and multipath, while others, such as receiver clock jumps and data gaps, may be caused by irregularities in the receiver or data collection hardware. Irrespective of their cause, the proper detection and, if possible, correction of such anomalies is necessary to guarantee the accuracy and the integrity of the differential corrections that are generated by an augmentation system. This thesis is focused on the development of carrier phase anomaly detection and correction algorithms for stationary receivers, by the simultaneous use of detection algorithms that operate on carrier phase measurements from both the L1 and L2 GPS frequencies. Although the algorithms developed for this thesis were tested in a post-processing scenario, the algorithms were designed for real-time operation.
1.1 GPS Overview

GPS is a satellite-based radio navigation system, which was developed by the Department of Defense (DoD) of the United States of America. Although GPS was primarily developed for military applications, civilian use of GPS continues to increase at a rapid pace. GPS is primarily used to determine user position (under both static and dynamic conditions) in terms of latitude, longitude and height (above the earth’s ellipsoid or with respect to mean sea level), velocity and precise time. GPS can be broadly classified into three segments; the space segment, the control segment and the user segment, as shown in Figure 1.1 below.
At the time of this writing, the satellite segment consists of 28 satellites in 6 orbits that are inclined at an angle of 55 degrees with respect to the earth’s equatorial plane. The satellites revolve in these orbits at an altitude of approximately 11,000 nautical miles (~20,000 km) with an orbital period of 11 hours 57 minutes and 57.27 seconds. Radio navigation signals are transmitted by the satellites that enable the user to calculate its 3-dimensional position and clock offset relative to GPS system time.

The control segment consists of a network of five monitor stations (located at Colorado Springs, Ascension Island, Diego Garcia, Kwajalein and Hawaii), four ground antenna upload stations (located at Ascension Island, Diego Garcia, Kwajalein and the Eastern Launch Site) and a Master Control station (located at Schriever AFB, Colorado). The monitor stations track the GPS satellites; collect the dual frequency pseudorange and carrier phase measurements, and decode the navigation message. The results are forwarded to the Master Control Station. The Master Control Station is the operations center for the GPS. Here, the data received from the Monitor Stations are processed for the accomplishment of various tasks, the most significant of which is the computation and upload of the orbital and clock correction data (ephemeris) for each satellite being tracked. This information is transmitted to the ground antenna upload stations, which upload the data to satellites in view of the station. The satellites, in turn, process the data and transmit updated information back to the earth, which is used by the user segment in solving for the 4D navigation solution. [4]

The community (both military and civilian) that makes use of these GPS ranging signals for calculating their position on or near the earth surface forms the user segment.
GPS uses the Direct Sequence Spread Spectrum (DS-SS) technique in transmitting navigation data. Here, the navigation data (which has a bit rate of 50 bps) is Binary Phase Shift Keyed (BPSK) modulated on to a 1,023,000 bps random noise-like signal known as pseudo random noise or PRN codes (this is equivalent to modulo-2 adding the navigation data onto the PRN sequence). The high chipping rate of the PRN code also spreads the bandwidth of the carrier signal. The GPS satellites transmit their signals on two primary frequencies, Link 1 (L1) frequency which is centered at 1575.42 MHz and Link 2 (L2) frequency, which is centered at 1227.6 MHz. Two different PRN sequences are used to spread the bandwidth of the carrier signals in GPS. These are the Coarse Acquisition code or the C/A-code and the precision code or the P-code. While both these signals are used to modulate the L1 carrier, only one of them (usually the P-code) is used to modulate the L2 carrier.

The C/A-code, which is unique for each satellite, is chosen from a set of Gold codes having a sequence length of 1023 bits with a chipping rate of 1.023 MHz. Hence, the C/A-code repeats every 1 millisecond. The Gold codes were selected because of their excellent cross correlation properties, which provide for a minimum level of interference among the various C/A-codes.

The P-code is unique for each satellite, and has a time period of 1 week with a chipping rate of 10.23 Mbps. The P-code is normally encrypted to form what is called the Y-code. A special decryption key is required to acquire and track the Y-code.
The GPS provides two types of positioning services, the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). While the SPS is designed for civilian use and can be used by any user across the globe, the PPS is only available to authorized users, including military personnel. The accuracy specifications for both these services are presented in Table 1.1. [1]

<table>
<thead>
<tr>
<th>GPS Service Type</th>
<th>Vertical Accuracy (meters) (95%)</th>
<th>Horizontal Accuracy (meters) (2drms, 95%)</th>
<th>UTC Time Transfer Accuracy (nsec) (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>156</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>PPS</td>
<td>27.7</td>
<td>22</td>
<td>200</td>
</tr>
</tbody>
</table>

1.2 GPS Error Sources

The accuracy of GPS depends on the quality of the code and carrier measurements along with that of the ephemeris data. [1] Various errors affect the performance of the GPS. These are listed below

1. Satellite Clock Error
2. Ephemeris Prediction Error
3. Relativistic Effects
4. Ionospheric Error
5. Tropospheric Error
6. Receiver Noise and Resolution
7. Multipath
Errors in the pseudorange measurements occur due to the deviation of the satellite clocks from GPS system time in spite of the use of highly stable atomic clocks. The deviation can be as large as 1 millisecond (which translates to an error of approximately 300 km in the pseudorange domain). [1] The satellites broadcast estimates of the clock errors to the GPS receiver, which implements a second-order polynomial to remove most of the satellite clock error. The satellites also broadcast orbital parameters, which enable the GPS receiver to reduce the ephemeris pseudorange error to approx. 4.2 m (1σ). [1]

The special and general relativity (SR and BR) corrections became non-trivial for the GPS where the desired accuracy is in the order of centimeters. These effects cause an average increase in the satellite frequency as observed by a user on the earth. This can be compensated by purposefully lowering the satellite clock frequency prior to their launch.

The other relativistic effects include those due to the eccentricity of the satellite orbit and the Sagnac effect. A detailed explanation of these errors and their correction procedures can be found in [1].

The ionosphere is a dispersive media (since the velocity of a wave propagating through it is dependent on its frequency) filled with free electrons that are formed due to the ionization of gas molecules by the sun’s ultraviolet radiation energy. The ionosphere advances the phase velocity $v_p$ (velocity of the carrier component) of the GPS signal while simultaneously delaying the group velocity $v_g$ (velocity of the modulating signal). Hence, the refractive index of the ionosphere deviates from the ideal value of unity. The signal passing through the ionosphere layer undergoes refraction, which causes the path
length to vary. When only the first-order approximations are considered, this path length difference varies as a function of Total Electron Content (TEC) and the inverse of the square of the frequency \(1/f^2\). Therefore, by making range measurements on both the GPS frequencies (L1 and L2), the ionospheric delay error can be removed to a large extent. For single frequency users, various correction models have been developed, which can be used to reduce the ionospheric delay error. [1]

The troposphere, unlike the ionosphere is, however, a non-dispersive medium. Hence, the phase and group velocities of the GPS signals passing through this layer are delayed by the same amount as compared to their respective velocities in free space. The tropospheric delay has two components; a dry component that makes up for approximately 90% of the total delay and a wet component that makes up for the remaining 10% of the delay. The dry component of the delay can be modeled very well because of its predictability, unlike the wet component. Numerous models exist for the computation of the tropospheric delay that can be used in reducing this error. [1]

As is the case with all receiver systems, the GPS receiver is affected by thermal noise. Thermal noise jitter and the effects of dynamic stress error are the two primary sources of error effecting both the pseudorange measurements made by the code lock loop (also known as the Delay Lock Loop (DLL)) and the carrier phase measurements made by the carrier lock loops (which can either be the Phase Lock Loop (PLL) or the Frequency Lock Loop (FLL). Other receiver factors that affect the measurement accuracy are hardware and software resolution and oscillator stability. [1]
“Multipath is defined as the presence of multiple signal paths between a transmitter and a receiver due to reflection and diffraction”. [5] Multipath is highly undesirable because it introduces errors in pseudorange measurement values by distorting the discriminator output thus shifting the zero crossing of the discriminator. This results in an erroneous shift in the locally generated PRN code that has to be aligned with the incoming PRN code. Multipath error can be reduced, but not eliminated. One of the most efficient ways of achieving this is through the proper design and placement of the GPS receiving antenna. Multipath error can also be reduced through proper design of the receiver. In summary, Table 1.2 lists the error sources in each of the GPS segments. [1]

<table>
<thead>
<tr>
<th>Segment Source</th>
<th>Error Source</th>
<th>GPS 1σ error (m) without SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Satellite clock stability</td>
<td>3.0</td>
</tr>
<tr>
<td>Space</td>
<td>Satellite perturbations</td>
<td>1.0</td>
</tr>
<tr>
<td>Space</td>
<td>Other (thermal radiation, etc.)</td>
<td>0.5</td>
</tr>
<tr>
<td>Control</td>
<td>Ephemeris prediction error</td>
<td>4.2</td>
</tr>
<tr>
<td>Control</td>
<td>Other (thruster performance, etc.)</td>
<td>0.9</td>
</tr>
<tr>
<td>User</td>
<td>Ionospheric delay</td>
<td>5.0</td>
</tr>
<tr>
<td>User</td>
<td>Tropospheric delay</td>
<td>1.5</td>
</tr>
<tr>
<td>User</td>
<td>Receiver Noise and resolution</td>
<td>1.5</td>
</tr>
<tr>
<td>User</td>
<td>Multipath</td>
<td>2.5</td>
</tr>
<tr>
<td>User</td>
<td>Other (interchannel bias, etc.)</td>
<td>0.5</td>
</tr>
<tr>
<td>System UERE</td>
<td>Total (RSS)</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 1.2 GPS Error Sources [1]
A Ground-Based Augmentation System (GBAS) is one in which the user receives augmentation information from a ground-based transmitter, while a Satellite-Based Augmentation System (SBAS) is a wide-area coverage augmentation system in which the user receives augmentation information from a satellite. [6]

Before discussing the functionality of the augmentation systems, it is essential to understand the four Required Navigation Performance (RNP) parameters namely accuracy, time availability, integrity and continuity. Accuracy is defined as “the difference between the estimated and true aircraft position”. [7] Integrity is the ability of the system to warn the users, if the errors in the position solution cross a certain threshold or alarm limit (AL). [8] The warning has to be issued within a specific period of time following the crossing of the AL. This time limit is termed as time-to-alarm. Continuity can be interpreted as the ability of the system, to provide uninterrupted measurements throughout the execution of a flight operation. Finally, “time availability is the fraction of time for which the system is operational – providing position fixes with the specified accuracy, integrity and continuity”. [7]
2.1 Differential Global Positioning System

Both the ground and the satellite-based augmentation systems function on the principles of DGPS, which are explained below.

Figure 2.1 depicts the concept of DGPS. The signals transmitted by the GPS satellites are received by a reference receiver that is placed at a known (surveyed) position.

The reference receiver makes ranging measurements to all satellites in view. With the knowledge of the true reference receiver position, the true geometric range to each satellite can be calculated. By comparing the true with the actual range measurements,
the error or bias in each of the pseudorange measurements can be estimated. Next, the biases are corrected for the satellite clock offsets that are calculated from the navigation data broadcast by the satellites. The remaining biases are the sum of the errors introduced by the ionosphere, the troposphere, multipath, satellite orbit error, satellite clock error, receiver noise, and receiver clock offset. [1] Measurement biases that are common between the reference receiver and the user receiver form the differential corrections. These differential corrections are then broadcast to the user receiver, also known as the rover, which implements them into its position solution. Assuming that the distance between the reference receiver and the rover is sufficiently small (typically ≤ 100 km) [1], the errors common to both the receivers, such as SV orbit and clock errors, tropospheric delays and ionospheric delays, are mostly cancelled. However, errors such as receiver noise and multipath remain in the position solution and are not cancelled. These errors can be minimized but cannot be eliminated. [1]

Based on the type of corrections broadcast by the reference receiver, DGPS systems can be broadly classified as code-based differential GPS and carrier-based differential GPS. Examples of code-based DGPS are Local Area Differential GPS (LADGPS) and Wide Area Differential GPS (WADGPS). It is noted that all code-based DGPS systems use the carrier phase to reduce the noise on the pseudorange measurements. Therefore, code-based systems could also be referred to as carrier-smoothed code-based DGPS. A LADGPS system generally consists of multiple reference receivers with antennas placed at surveyed locations and separated by a small distance (typically tens or hundreds of meters). The coverage area of a LADGPS system is limited owing to the fact that some of
the pseudorange errors are subject to spatial decorrelation. For example, the difference between the reference receiver and the rover of the projection of satellite orbit errors on the line-of-sight directions increases as the distance between the reference receiver and the rover increases.

The Wide Area Differential Global Positioning System (WADGPS) is another form of code-phase DGPS. It consists of multiple wide-area reference stations (WRSs) that are widely separated from each other. These stations make pseudorange measurements, which are sent to the wide-area master station (WMS). The WMS generates multiple sets of corrections known as vector corrections and transmits them to the user receivers within the coverage area. As opposed to the scalar corrections generated in the LADGPS, the vector corrections are better suited to capture the local error and its spatial gradient thus providing a wider coverage area. [7] For a given wide area of coverage, the number of WRSs required by the WADGPS would be significantly less as compared to those required by the LADGPS. Examples of WADGPS include the US Coast Guard’s National DGPS [1], WAAS [9], Thales’ Landstar [10], NavCom’s StarFire™ [11], OmniSTAR™ Inc., [12], Australian Maritime Safety Authority (AMSA) DGPS [13], and DCI [1].

Instead of relying solely on carrier-smoothed code-phase (pseudorange) measurements, the differential corrections can also be computed from the highly accurate but ambiguous carrier-phase measurements. Here, both the reference and rover receivers measure the discrepancy between the carrier phases of the received signal and the locally-generated replica signal. The ambiguity in the carrier-phase measurements arises due to the
unknown number of integer carrier cycles present along the line-of-sight path joining the satellite and the receiver. If the integer ambiguity could be resolved then the precise carrier phase measurements could be used in attaining real time positioning accuracies on the order of a fraction of a wavelength. In order to resolve the integer ambiguities, a double differenced pseudorange measurement is formed. This measurement is then smoothed by a corresponding double-differenced carrier phase measurement. Various computationally intensive techniques are then used to search through the smoothed pseudorange double-differenced carrier phase measurements for the correct integer ambiguity set. [1] The carrier-based DGPS technique is extensively used in both static and dynamic surveying. [1]

2.1.1 Local Area Augmentation System

LAAS is a GBAS, functioning on the principle of LADGPS. The LAAS Ground Facility (LGF) is placed at an airport to facilitate the precision landing and take off of aircraft. The LGF consists of four high-quality reference receiver and antenna pairs, Very High Frequency Data Broadcast (VDB) equipment feeding a single VDB antenna, and equipment racks. Ranging measurements are fed into the ground station from the reference receivers. Ground monitoring is performed by comparing measurements from two or more receivers. This aids in detecting faulty measurements and improving the accuracy of the corrections. [7] The LGF forms a single set of corrections, or scalar corrections, for each satellite. Scalar corrections capture all of the important error components close to the reference station and hence, are very suitable for high accuracy applications. [7] Integrity of GPS is enhanced with the generation of integrity parameters.
that estimate the quality of the corrections and warn the user of any system malfunctions.

[7] Continuity of GPS may be improved with the integration of inertial systems and ground-based pseudolites. Pseudolites also aid in increasing the availability of ranging sources for precision approach. The corrections along with the integrity parameters are transmitted to the airborne user through the VHF data broadcast (VDB). Table 2.1 delineates the vertical requirements for the aircraft precision approach using LAAS. [2]

It is seen that the requirements become more demanding from CAT I to CAT III Precision Approach operations. Over 400 test flight approaches were performed in 1995 using both, the code-phase and carrier-phase LADGPS techniques to investigate the feasibility of using GPS along with a local augmentation for Category II/III precision approach of aircraft. [14, 15] Results from these tests show that both techniques provide the required accuracy level for CAT IIIb automatic landings.

**Table 2.1 Tentative Ground Facility Requirements for Precision Approach Using LAAS [2]**

<table>
<thead>
<tr>
<th>Precision Approach Type</th>
<th>Decision Height (DH) (ft)</th>
<th>NSE Vertical Accuracy (95%) (m)</th>
<th>Continuity</th>
<th>Integrity</th>
<th>Vertical Alert Limit (VAL) (m)</th>
<th>Time To Alert (TTA) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT I</td>
<td>&gt; 200</td>
<td>4</td>
<td>8 x 10^{-6}/15 seconds</td>
<td>2 x 10^{-7}/ approach</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>CAT II</td>
<td>100-200</td>
<td>2</td>
<td>4 x 10^{-6}/15 seconds</td>
<td>10^{-9}/15 seconds</td>
<td>5.3</td>
<td>1</td>
</tr>
<tr>
<td>CAT IIIa</td>
<td>≤ 100</td>
<td>2</td>
<td>4 x 10^{-6}/15 seconds</td>
<td>10^{-9}/15 seconds</td>
<td>5.3</td>
<td>1</td>
</tr>
<tr>
<td>CAT IIIb</td>
<td>≤ 50</td>
<td>2</td>
<td>Vertical: 2 x 10^{-6}/15 seconds</td>
<td>Vertical: 10^{-9}/15 seconds</td>
<td>5.3</td>
<td>1</td>
</tr>
</tbody>
</table>
2.1.2 Wide Area Augmentation System

2.1.2.1 Principle of Operation

WAAS is a space-based Augmentation System and is an extension of WADGPS. Figure 2.2 illustrates the various WAAS segments and its overall functioning.

Table 2.2 lists the various services provided by WAAS and the purpose that each of these serves in augmenting GPS. [16]
Table 2.2 WAAS Service

<table>
<thead>
<tr>
<th>WAAS Service</th>
<th>RNP Parameter Augmented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranging Function</td>
<td>Availability and Reliability</td>
</tr>
<tr>
<td>Differential GPS Corrections</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Integrity Monitoring</td>
<td>Integrity and Safety</td>
</tr>
</tbody>
</table>

For the initial phase of operation (Phase I), WAAS consists of two GEO (INMARSAT) satellites, a network of 25 WAAS Reference Stations (WRSs) and two WAAS Master Stations (WMSs). The WRSs are spread across the Conterminous United States (CONUS), Hawaii, Alaska and San Juan, Puerto Rico. The reference stations make ranging measurements from the GPS and GEO satellites and transmit them to the WAAS Master Stations. All the WAAS corrections such as the GPS and GEO orbits, clocks and the L1 frequency ionospheric vertical delays at the Ionosphere Grid Points (IGPs) are calculated for each of the visible satellites. These corrections are subsequently uplinked to the GEO satellites through the Ground Uplink Stations (GUSs). The WAAS GEO satellites transmit signals on the L1 frequency with C/A-code modulation.

2.1.2.2 CNMP Monitor

Since WAAS was intended to be used for CAT I Precision Approach of aircraft, the information provided to the users must be accurate and reliable. The probability that a user experiences misleading information at any point in space and time must be less than $10^{-7}$ per hour. [17] In order to achieve this requirement, multiple integrity monitors are used in the WMSs, which operate on the WAAS corrections and integrity data. Multipath and code noise are two sources of error that are inherent to the pseudorange
measurements. For the proper functioning of the integrity monitors, it is necessary to mitigate multipath error and device a method to statistically characterize the residual pseudorange noise. Moreover, the integrity monitors were designed with the assumption that the pseudorange noise can be modeled as a normal, zero mean random variable. [17] This was achieved with the help of the Code Noise and Multipath Estimator (CNMP) monitor. The CNMP monitor computes the standard deviation value of the code noise and multipath error ($\sigma_{MP}$) on each satellite track for each measurement that is received from the WRS. This is done using the standard CNMP relationship as shown in Equation 2.1 below. [17]

$$MP = PR - AD - 2 \times d_{iono} + \lambda \times N$$  \hspace{1cm} (2.1)

where

- $MP$ is the Multipath Error and code noise (m)
- $PR$ is the measured Pseudorange between the satellite and the receiver (m)
- $d_{iono}$ is the ionospheric delay for the satellite signal (m)
- $N$ is the unknown integer ambiguity in cycles
- $\lambda$ is the wavelength of the satellite signal (meters per cycle)

One important aspect of the CNMP algorithm is the carrier phase anomaly detection. Anomalies in the carrier phase corrupt the multipath error estimation. This might lead to the improper characterization of the multipath error by the CNMP monitor. Hence, the need for the proper detection and correction of all such anomalies. A detailed discussion about carrier phase anomaly detection is presented in Section 4 of this document.
2.1.3 EGNOS

The European Geostationary Navigation Overlay System (EGNOS) is also a space-based augmentation system. It is a joint project of the European Space Agency (ESA), the European Commission, Eurocontrol and the European Organization for the Safety of Air Navigation. When fully operational, it will consist of three geostationary satellites (INMARSAT – 3), 30 Ranging and Integrity Monitoring Stations (RIMSs), four master control centers and six up-link stations. Similar to the INMARSAT satellites of WAAS, the EGNOS satellites do not have signal generators onboard. Instead the signals transmitted by them are up-linked from the complex network of ground stations. The RIMS compute the position of the EGNOS satellites and compare the position measurements of the GPS and GLONASS satellites with the measurements obtained from the satellite’s signals. This information is sent to one of the Master Control Centers where the measurements are processed. The up-link stations receive the corrections through a secure communications network and transmit them to the EGNOS satellites. The EGNOS System Test Bed (ESTB) has been operational since February 2000. A test signal is being transmitted by one of the EGNOS satellites to enable potential users to test the capabilities of EGNOS. [18]
3 CARRIER PHASE ANOMALIES

Figure 3.1 illustrates the process of the integrated Doppler frequency shift measurement. Once the receiver acquires a satellite, it tracks the Doppler-shifted carrier phase using either a PLL or an FLL. The difference of the received frequency and the locally-generated frequency is termed the beat frequency. If the receiver oscillator frequency is the same as the satellite oscillator frequency, the beat frequency represents the Doppler frequency shift due to the relative, line-of-sight motion between the satellite and the receiver.

\[
\text{Integrated \_ Doppler} = \int_{t_1}^{t_2} (f_R - f_o) dt
\]

where

- \( f_R \) is the received frequency
- \( f_o \) is the locally generated frequency

Figure 3.1 Integrated Doppler frequency shift measurement
The beat frequency is integrated over time, and the resulting measurement is called the integrated Doppler frequency shift. In a digital receiver, this measurement is also referred to as the accumulated Doppler frequency shift, or simply the accumulated Doppler. Many publications also refer to this measurement as the carrier phase observable.

The efficacy of the carrier phase measurements could be reduced in high accuracy applications due to the several types of anomalies. The following carrier phase anomalies have been identified during this research.

1. **Cycle Slips**
2. **Loss of Lock**
3. **Missing measurements in a satellite data set**
4. **Corrupted or Bad measurement data**

### 3.1 Cycle Slips

Cycle slips are caused when the receiver tracking loop fails to continuously monitor the number of Doppler cycles being accumulated over a period of time. This could either cause an unspecified number of cycles to pass through the system undetected, or too many cycles could be counted. [19] Cycle slips can be of three types, Integer whole cycle slips, half cycle slip and slow cycle slips. Integer whole cycle slips represent the case where the receiver slips single or multiple whole cycles of the incoming signal at any instant of time. This is illustrated in Figure 3.2. Half cycle slips are similar to integer whole cycle slips but in this case the receiver slips exactly one half of a whole cycle of the incoming signal at any instant of time.
Carrier Phase (m)

Figure 3.2 Integer Cycle Slip

The receiver may also experience a slip that is just a fraction of a whole carrier cycle. Repeated occurrence of such fractional slips over successive time epochs could lead to one or more half cycle slips. This phenomenon is termed a slow cycle slip, which is illustrated in Figure 3.3.

Cycle slips are primarily caused by low signal to noise ratios and signal fading, but can also result from radio frequency interference (RFI) or high receiver dynamics. While multipath and low satellite elevation angles can cause a reduction in the satellite signal to noise ratio, ionospheric scintillation is cited as the primary cause of signal fading.
High receiver dynamics that exceed the ability of the receiver’s tracking loop to maintain lock on the received signal are also a cause of cycle slips. [19, 20] RFI can be caused by intentional or unintentional signal radiation in or near the GPS band. RFI can be wideband, a single frequency, or something in between. The interfering signals can also be continuous or pulsed. Wide-band interference reduces the SNR, but narrow-band interference could also affect the integrated Doppler measurements. [21] In addition to signal obstruction, irregularities in satellite and receiver oscillators can also cause cycle slips. [20]

Slow cycle slips could be caused by multipath or by narrow band RFI. In this scenario, the carrier-tracking loop is slowly taken over by the multipath or RFI signal. After some
time, the receiver will detect this condition, but the time to detection could easily exceed
the time-to-alert of a few seconds. [22]

Numerous methods have been developed for the detection and correction of cycle slips in
the past. A detection method consists of setting up a test statistic, which is used in testing
the satellite data for cycle slips. Most of the commonly used test statistics are different
permutations of dual frequency carrier phase measurement differences or a combination
of carrier phase and code phase measurements. These include ionospheric residual,
geometry free phase measurements, triple differenced phase measurements, range
residual and difference of wide lane phase and narrow lane pseudorange measurements.
Each of these is discussed in detail below.

The Accumulated Doppler measurements on the L1 and L2 frequencies, for a particular
time instant, are given by the following equations

\[
AD_{L1,i}(t) = d_{s,i}(t) + \Delta t_{r_{L1}}(t) - c_{t_{L1}} + d_{s_{L1}}(t) + d_{t_{L1}}(t) - d_{i}\times N_{L1,i}
\]

\[
AD_{L2,i}(t) = d_{s,i}(t) + \Delta t_{r_{L2}}(t) - c_{t_{L2}} + d_{s_{L2}}(t) + d_{t_{L2}}(t) - d_{i}\times N_{L2,i}
\]

where:

\[AD_{L1,i}(t) = \text{Accumulated Doppler measurement of satellite ‘i’ for the time instant ‘t’ (m)}\]
\[ d_{s,1}(t) = \text{true line of sight range from the satellite} \; \text{‘i’} \; \text{to the user (m)} \]

\[ t_{\text{rcvr}}(t) = \text{the receiver clock offset from GPS system time (s)} \]

\[ t_{\text{sv},i}(t) = \text{the satellite clock offset from GPS system time (s)} \]

\[ d_{\text{tropo},i}(t) = \text{the apparent path length increase due to propagation through troposphere (m)} \]

\[ d_{\text{iono},i}(t) = \text{the apparent path length increase due to propagation through ionosphere (m)} \]

\[ d_{\text{orbit},i}(t) = \text{the satellite orbit error in the line-of-sight direction (m)} \]

\[ d_{\text{survey},i}(t) = \text{the error in position coordinates of the reference point due to inaccurate survey in the line-of-sight direction (m)} \]

\[ \Phi = \text{is the phase noise (in cycles) due to the receiver measurement errors (hardware and noise), diffuse and non-diffuse multipath, etc.,} \]

\[ \lambda = \text{is the wavelength of the received signal in cycles} \]

\[ N_i = \text{is the initial unknown integer number of carrier cycles from the satellite} \; \text{‘i’} \; \text{to the receiver} \]

The expression for the ionospheric residual can be derived as follows.

Differencing equations 3.1 and 3.2, Equation 3.3 is obtained as shown below.
\[
\text{AD}_{L1,i}(t) - \text{AD}_{L2,i}(t) = \Delta ct_{\text{recvr},L1-L2}(t) - \Delta ct_{\text{sv},L1-L2,i}(t) - \\
\left( d_{\text{iono},L1,i}(t) - d_{\text{iono},L2,i}(t) \right) + \left( \Phi_{L1}(t) - \Phi_{L2}(t) \right) + \\
\left( \lambda_{L1} N_{L1,i} - \lambda_{L2} N_{L2,i} \right)
\]  

(3.3)

Note that the AD measurement as expressed above is in meters. Also since phase noise is small when compared to ionosphere error and phase ambiguities, it could be neglected in all the subsequent equations. Rewriting Equation 3.3, expressing AD in cycles, results in Equation 3.4 as shown below.

\[
\lambda_{L1} AD_{L1,i}(t) - \lambda_{L2} AD_{L2,i}(t) = \left( d_{\text{iono},L1,i}(t) - d_{\text{iono},L2,i}(t) \right) + \\
\left( \lambda_{L1} N_{L1,i} - \lambda_{L2} N_{L2,i} \right)
\]  

(3.4)

where, \( AD^c(t) \) is the accumulated Doppler measurement in units of cycles. Dividing by \( \lambda_{L1} \) throughout and recognizing that \( \frac{\lambda_{L1}}{\lambda_{L2}} = \frac{f_{L1}}{f_{L2}} \) Equation 3.5 is obtained.

\[
AD^c_{L1,i}(t) - \frac{f_{L1}}{f_{L2}} AD^c_{L2,i}(t) = \frac{1}{\lambda_{L1}} \left( d_{\text{iono},L1,i}(t) - d_{\text{iono},L2,i}(t) \right) + \\
\left( N_{L1,i} - \frac{f_{L1}}{f_{L2}} N_{L2,i} \right)
\]  

(3.5)
It is seen here that the only time varying term remaining in the expression is the ionospheric delay term. Hence, this statistic is termed the ionospheric residual. The ionosphere is expected to vary slowly under nominal conditions making the above statistic a smooth quantity. Any cycle slips that are present in the dual frequency ambiguities could then be easily detected by this statistic. Since the cycle slips can occur on either or both of the frequencies, the isolation of the slip to its corresponding frequency becomes a challenge when using ionospheric residuals for cycle slip correction. Assuming that $\Delta N_{L1}$ and $\Delta N_{L2}$ represent the magnitude of cycle slips occurring on the L1 and L2 measurements, respectively, the last term in Equation 3.5, in the presence of cycle slips becomes

$$L1 \Delta N_{L1} + L2 \Delta N_{L2}$$

This represents one equation with two unknowns, which can produce an infinite number of solutions. The number of solutions could be narrowed down to a finite number by computing the estimates for both $\Delta N_{L1}$ and $\Delta N_{L2}$. Either time-differenced pseudorange measurements [19] or time-differenced range rate residuals [23] could be used for this purpose. Once the approximate values are established, the search for the precise slip values could then be fine tuned by varying the approximate values such that the difference in the ionospheric residual values before and after the cycle slip occurrence is minimized. Approximations to the slip values can also be obtained by applying Kalman filtering to the range rate residuals before and after the cycle slip occurrence. By applying Kalman filtering to the ionospheric residuals before and after the cycle slip and by using the approximation obtained earlier, the correct slip values could be determined. [23] An
analytical study was undertaken in [20] to establish the limits of the search. It can be concluded from this study that the L1 and L2 cycle slips can be uniquely identified from each other only if the approximate values are established with an accuracy of ± 4 cycles. Similar conclusions are also made in [19, 23].

The second statistic involving phase measurements is the geometry free phase also known as narrow lane phase. It can be defined as the difference of the double difference L1 and L2 carrier phase measurements. The double differenced measurements are obtained by differencing the carrier phase measurements from two receivers followed by differencing them for two satellites for every epoch. The expression for this statistic is given in Equation 3.6.

\[
\nabla \Delta AD_{L1-L2}(t) = \left[ (AD_{L1,i}^1(t) - AD_{L1,j}^2(t)) - (AD_{L1,i}^1(t) - AD_{L1,j}^2(t)) \right] - \left[ (AD_{L2,i}^1(t) - AD_{L2,j}^2(t)) - (AD_{L2,i}^1(t) - AD_{L2,j}^2(t)) \right]
\]

where ‘1’ and ‘2’ represent the stationary and rover receivers and ‘i’ and ‘j’ represent the satellites, respectively. Expanding each of the bracketed terms above using equations 3.1 and 3.2 and simplifying them, Equation 3.7 is obtained as shown below.

\[
\nabla \Delta AD_{L1-L2}(t) = -\Delta d_{\text{iono},L1-L2,i-j}^{1-2}(t) + \Delta \Phi_{L1-L2,i-j}^{1-2}(t) + \left( \lambda_{L1} \times \Delta N_{L1,i-j}^{1-2} - \lambda_{L2} \times \Delta N_{L2,i-j}^{1-2} \right)
\]
It is seem here that this statistic consists of residual ionospheric error, residual phase noise, and residual integer phase ambiguities but is free of the satellite-receiver geometry effects. Under nominal ionospheric conditions, Equation 3.7 represents a slowly varying, low noise residual. However in the presence of cycle slips, an appreciable change would be seen in the third term of Equation 3.7, thus facilitating detection.

A detection and correction method utilizing this statistic is documented in [24]. First, the concept of time differencing is applied in detecting the cycle slips, since time differencing is analogous to high pass filtering. [20] In order to correct the cycle slips the precise slip values have to be calculated. This is done by combining the geometry free residual statistic with the wide lane phase minus narrow lane pseudorange statistic into a Chebyshev polynomial, least-squares fitting scheme. Though this method was successfully applied in cycle slip detection and correction in both static and kinematic scenarios, it was found to be ineffective in detecting dual frequency cycle slips that satisfy the following inequality.

\[
\left| \lambda_{L1} \delta N_{L1} - \lambda_{L2} \delta N_{L2} \right| \leq \Delta \Phi_{1-2, i-j}^{L1-L2, i-j}(t) \tag{3.8}
\]

Here \( \delta N_{L1} \) and \( \delta N_{L2} \) represent cycle slips on L1 and L2 frequencies, respectively. The double differenced carrier phase measurements expressed by Equation 3.7 that are computed for two consecutive time epochs could be subtracted to form an inter-frequency triple differenced statistic. The expression for the triple difference is given by Equation 3.9 below.
\[
\delta \nabla \Delta AD_{L1-L2} = \nabla \Delta AD_{L1-L2}(t1) - \nabla \Delta AD_{L1-L2}(t)
\]
\[
- \Delta d^{1-2}_{\text{iono}, L1-L2, i-j, t1-t} + \Delta \Phi^{1-2}_{L1-L2, i-j, t1-t} \]

(3.9)

where \( \delta \nabla \Delta \) is the triple difference operator, \( t1 \) and \( t \) represent consecutive measurement epochs, respectively. It is seen that this statistic is free of residual integer ambiguities and consists of ionospheric effects and residual phase noise. Under nominal atmospheric conditions when ionospheric variation is relatively small, cycle slips could be detected by a simple comparison of the two consecutive epoch values of this statistic. However, under active ionospheric conditions, this method becomes impractical because of large variations in the ionospheric residual value. If it is assumed that the carrier phase multipath value could be averaged out over a short period of time then a reasonably good estimate of ionospheric variation over that short time period could be obtained by averaging Equation 3.9 over that time period. [25, 26] Thus, this statistic could be used even during active ionospheric time periods. However the same limitation that applies to the geometry free phase statistic is also applicable in this case since the latter is derived from the former.

Alternatively, carrier phase measurements made on only one frequency (either L1 or L2) could be used in forming another triple differenced statistic. The expressions for L1 and L2 triple differenced measurements are shown below in equations 3.10 and 3.11, respectively.
\[
\delta \nabla \Delta \Delta_{L1} = \left\{ \left[ AD_{L1,i}^1(t_l) - AD_{L1,i}^2(t_l) \right] - \left[ AD_{L1,j}^1(t_l) - AD_{L1,j}^2(t_l) \right] \right\} - \\
\left\{ \left[ AD_{L1,i}^1(t) - AD_{L1,i}^2(t) \right] - \left[ AD_{L1,j}^1(t) - AD_{L1,j}^2(t) \right] \right\}
\]

(3.10)

\[
\delta \nabla \Delta \Delta_{L2} = \left\{ \left[ AD_{L2,i}^1(t_l) - AD_{L2,i}^2(t_l) \right] - \left[ AD_{L2,j}^1(t_l) - AD_{L2,j}^2(t_l) \right] \right\} - \\
\left\{ \left[ AD_{L2,i}^1(t) - AD_{L2,i}^2(t) \right] - \left[ AD_{L2,j}^1(t) - AD_{L2,j}^2(t) \right] \right\}
\]

(3.11)

where \( \delta \nabla \Delta \) is the triple difference operator, \( t_l \) and \( t \) represent consecutive measurement epochs, respectively. Substituting equations 3.1 and 3.2 into equations 3.10 and 3.11, respectively, and simplifying the resulting terms, the following equations are obtained for this statistic.

\[
\delta \nabla \Delta \Delta_{L1} = \Delta d_{i-j,t_l-t}^{1-2} + \Delta d_{\text{tropo},i-j,t_l-t}^{1-2} - \Delta d_{\text{iono},L1,i-j,t_l-t}^{1-2} + \\
\Delta d_{\text{survey},i-j,t_l-t}^{1-2} + \Delta \Phi_{L1,t_l-t,i-j}^{1-2}
\]

(3.12)

\[
\delta \nabla \Delta \Delta_{L2} = \Delta d_{i-j,t_l-t}^{1-2} + \Delta d_{\text{tropo},i-j,t_l-t}^{1-2} - \Delta d_{\text{iono},L2,i-j,t_l-t}^{1-2} + \\
\Delta d_{\text{survey},i-j,t_l-t}^{1-2} + \Delta \Phi_{L2,t_l-t,i-j}^{1-2}
\]

(3.13)

Assuming that the survey error is negligible, the geometric range between the receivers and the satellites could then be estimated with high accuracy. The geometric range values could then be subtracted from the above equations and what remains would
predominantly consist of atmospheric errors and phase noise. Under nominal atmospheric conditions this represents a smooth value, which could be used in detecting any abrupt changes caused by cycle slips. The use of this statistic is documented in [3] for detecting cycle slips in both static and kinematic scenarios.

Phase and pseudorange measurements could be combined to form various test statistics for detecting cycle slips. Significant among them are range rate residual and narrow lane phase minus wide lane pseudorange.

The expression for the range rate residual is given below in Equation 3.14. [23]

\[
\text{Range Rate} = \left( AD_1(t_1) - AD_1(t) \right) - \left( PR_1(t_1) - PR_1(t) \right)
\]

(3.14)

This expression holds good for both the L1 and L2 frequency measurements. The L1 and L2 pseudorange measurements can be expressed as shown in equations 3.15 and 3.16, respectively.

\[
PR_{L1,i}(t) = d_{s,i}(t) + ct_{rcvr,L1}(t) - ct_{sv,L1,i}(t) + d_{tropo,i}(t) + d_{iono,L1,i}(t) + d_{orbital,i}(t) + d_{survey,i}(t) + \left( \psi_{L1}(t) \right)
\]

(3.15)

\[
PR_{L2,i}(t) = d_{s,i}(t) + ct_{rcvr,L2}(t) - ct_{sv,L2,i}(t) + d_{tropo,i}(t) + d_{iono,L2,i}(t) + d_{orbital,i}(t) + d_{survey,i}(t) + \left( \psi_{L2}(t) \right)
\]

(3.16)
Note that equations 3.15 and 3.16 are similar to equations 3.1 and 3.2 respectively, with the exception that the pseudorange measurements do not possess the unknown integer ambiguities as is the case with the accumulated Doppler measurements and the code noise is much higher than the carrier phase noise. The code phase noise is denoted as $\Psi(t)$ in the pseudorange equations. Substituting equations 3.15 and 3.16 into 3.14 and simplifying, Equation 3.17 is obtained for the range residual as shown below.

$$\text{Range Rate} = -2d_{\text{iono,iot},t1-t} + \Delta \Phi_{t1-t} - \Delta \Psi_{t1-t}$$

(3.17)

Wide lane phase minus narrow lane pseudorange can be expressed by Equation 3.18. [24]

$$\lambda_4 \left[ \nabla \Delta \text{AD}^c_{L1} - \nabla \Delta \text{AD}^c_{L2} \right] - \lambda_5 \left[ \frac{\nabla \text{PR}^L_{L1}}{\lambda_{L1}} + \frac{\nabla \text{PR}^L_{L2}}{\lambda_{L2}} \right]$$

(3.18)

where $\lambda_4 = \left( \frac{1}{\lambda_{L1}} - \frac{1}{\lambda_{L2}} \right)^{-1} = 86.2$ cm is known as the wide lane wavelength, $\lambda_5 = \left( \frac{1}{\lambda_{L1}} + \frac{1}{\lambda_{L2}} \right)^{-1} = 10.7$ cm is known as the narrow lane wavelength, respectively.

$\nabla \Delta \text{AD}^c_{L1}$ and $\nabla \Delta \text{AD}^c_{L2}$ are the double differenced $L1$ and $L2$ accumulated Doppler measurements in units of cycles, respectively. The expressions for these variables are given by equations 3.19 and 3.20 below.
\[ \nabla \Delta d_{s, i-j}^{L1} = \frac{\Delta d_{s, i-j}^{L1}(t)}{\lambda_{L1}} + \frac{\Delta d_{tropo, i-j}^{L1}(t)}{\lambda_{L1}} - \frac{\Delta d_{iono, L1, i-j}^{L1}(t)}{\lambda_{L1}} + \]

(3.19)

\[ \frac{\Delta \Phi_{L1, i-j}}{\lambda_{L1}} + \Delta N_{L1, i-j} \]

\[ \nabla \Delta d_{s, i-j}^{L2} = \frac{\Delta d_{s, i-j}^{L2}(t)}{\lambda_{L2}} + \frac{\Delta d_{tropo, i-j}^{L2}(t)}{\lambda_{L2}} - \frac{\Delta d_{iono, L2, i-j}^{L2}(t)}{\lambda_{L2}} + \]

(3.20)

\[ \frac{\Delta \Phi_{L2, i-j}}{\lambda_{L2}} + \Delta N_{L2, i-j} \]

\( \nabla \Delta PR_{L1} \) and \( \nabla \Delta PR_{L2} \) are the double differenced L1 and L2 pseudorange measurements, respectively, which can be expressed by the following equations.

\[ \frac{\nabla \Delta PR_{L1}}{\lambda_{L1}} = \frac{1}{\lambda_{L1}} \times \left[ PR_{L1, i}^{1}(t) - PR_{L1, i}^{2}(t) \right] - \frac{1}{\lambda_{L1}} \times \left[ PR_{L1, j}^{1}(t) - PR_{L1, j}^{2}(t) \right] \]

\[ = \frac{\Delta d_{s, i-j}^{L1}(t)}{\lambda_{L1}} + \frac{\Delta d_{tropo, i-j}^{L1}(t)}{\lambda_{L1}} + \frac{\Delta d_{iono, L1, i-j}^{L1}(t)}{\lambda_{L1}} + \]

(3.21)

\[ \frac{\Delta d_{orbital, i-j}^{L1}(t)}{\lambda_{L1}} + \frac{\Delta \psi_{L1, i-j}^{L1}(t)}{\lambda_{L1}} \]
\[
\frac{\nabla \Delta PR_{L2}}{\lambda_{L2}} = \frac{1}{\lambda_{L2}} \times \left( PR_{L2,i}^{1}(t) - PR_{L2,j}^{2}(t) \right) - \frac{1}{\lambda_{L2}} \times \left( PR_{L2,i}^{1}(t) - PR_{L2,j}^{2}(t) \right)
\]

\[
= \frac{\Delta d_{i,j}^{1-2}}{\lambda_{L2}} + \frac{\Delta d_{i,j}^{tropo}}{\lambda_{L2}} + \frac{\Delta d_{i,j}^{tropo, L2, i-j(t)}}{\lambda_{L2}} + \frac{\Delta d_{i,j}^{tropo, L2, i-j(t)}}{\lambda_{L2}} + \frac{\Delta d_{i,j}^{tropo, L2, i-j(t)}}{\lambda_{L2}}
\]

(3.22)

Substituting equations 3.19 through 3.22 into Equation 3.18 and simplifying the terms, Equation 3.23 is obtained for the wide lane phase minus narrow lane pseudorange.

\[
\lambda_{4} \left[ \nabla \Delta AD_{L1}^{C} - \nabla \Delta AD_{L2}^{C} \right] - \lambda_{5} \left[ \nabla \Delta PR_{L1}^{1, i-j(t)} + \nabla \Delta PR_{L2}^{1, i-j(t)} \right] = \lambda_{4} \left( \nabla \Delta N_{L1}^{1} - \nabla \Delta N_{L2}^{1} \right)
\]

(3.23)

It is seen here that this statistic contains double differenced carrier phase ambiguities along with residual code and carrier noise terms. Since the code phase noise is several orders of magnitudes larger than the carrier phase noise, the performance of this test statistic for cycle slip detection depends of the accuracy of the code phase measurements.

[25] A solution to this problem is proposed in [26]. Here a running average filter is used to smooth the double differenced measurements. The standard deviation value (σ) of the smoothed measurements is computed and the unfiltered double differenced measurements are compared against a ±4σ limit. A slip is declared when any unfiltered data point is found to be outside the confidence interval. Once the slip is declared, the
size is calculated by integrating this statistic with the geometry free residual into a Chebyshev polynomial, least-squares fitting scheme as mentioned earlier. As is the case with the geometry free residual, this statistic is found to be ineffective in detecting dual frequency cycle slips when the following inequality is satisfied.

\[ \lambda_4 \left( \nabla \Delta N_{L1} - \nabla \Delta N_{L2} \right) \leq \lambda_4 \left( \frac{\nabla \Delta \Phi_{L1,i-j}^{1-2}(t)}{\lambda_{L1}} - \frac{\nabla \Delta \Phi_{L2,i-j}^{1-2}(t)}{\lambda_{L2}} \right) \tag{3.24} \]

Though the efficacy of each of these methods in detecting and correcting cycle slips has been well documented, none of them have been designed to detect the remainder of the carrier phase anomalies that were identified earlier.

### 3.2 Loss of Lock

Loss of lock occurs when the receiver tracking loop loses the satellite signal. This phenomenon is caused by the same factors that result in cycle slips. Under normal conditions, the receiver tracking the signal properly detects the loss of lock and the lock counter is appropriately reset. However, the receiver could fail to report the signal loss. Hence, the lock counter is not always reset. Since there would be an appreciable change in the accumulated Doppler value for the signal upon re-acquisition, the latter case poses a potential problem as it could easily be misdiagnosed as a cycle slip and an inappropriate action might be initiated to correct it. It is further noted that a loss-of-lock would not necessarily result in the equivalent of slipping a whole number of cycles. An illustration of receiver loss of lock is shown in Figure 3.4.
3.3 Data Gaps

Data gaps are missing measurements that exist in satellite data sets. This is illustrated in Figure 3.5. Data gaps occur primarily due to miscommunication between the receiver and the data recording equipment, or due to a receiver processing or communication channel overload. Throughout the text of this document the terms ‘data gaps’ and ‘missing measurements’ are used interchangeably.
3.4 Corrupted Measurements Data

Corrupted measurement data occurs when a measurement value is wrong for one epoch. The value can either be set to zero, or it can take on any arbitrary value. This condition can either be caused by a receiver glitch, or because of communications problems between the receiver and the data recording equipment. Figure 3.6 illustrates corrupted measurement data.
Time (s)

Size = $\alpha$
Where $\alpha$ is any real number

Figure 3.6 Corrupted Measurement Data
4 CARRIER PHASE ANOMALY DETECTION AND CORRECTION

The focus of the research reported in this thesis is the development of an algorithm to detect various carrier phase anomalies discussed in Section 3. In addition, if an anomaly is detected, it should either be corrected or flagged. Two types of anomaly detectors were developed and are listed below.

1. Dual frequency (L1 and L2) anomaly detector
2. Single frequency (L1 or L2 only) anomaly detector

The most significant among all anomalies considered for this research are the cycle slips. The detectors listed above, were developed to detect whole and half carrier cycle slips as well as slow cycle slips in addition to all the other anomalies identified in Section 3 of this document. The dual frequency detector uses both the L1 and the L2 carrier phase measurements from the data set of a single satellite to detect the presence of anomalies. The single frequency detector uses L1 or L2 carrier phase measurements from the data sets of two or more simultaneously tracked satellites. Anomalies present in either or both the data sets can be detected using this detector. The slow cycle slip detector also uses either L1 or L2 measurements.

4.1 Dual Frequency Anomaly Detector

The dual frequency anomaly detector is based on the following principle. [27] For each satellite that is examined for anomalies, the L1 and L2 carrier phase measurements are differenced, both expressed in units of length. Next, a curve is fit through the differences.
The curve fit is used to extrapolate the value of the next measurement. The difference of the actual and the extrapolated values yields a test statistic, which is compared against a predetermined threshold. In the presence of an anomaly, the test statistic will exceed the threshold. The satellite from which the test statistic was formed is correspondingly tagged. This process is repeated for each satellite tracked and for every instant of time for which it was tracked. The equation for the test statistic is derived below.

The expressions for accumulated Doppler measurements on the L1 and L2 frequencies that are contained in equations 3.1 and 3.2 are reproduced here for convenience.

\[
\begin{align*}
AD_{L1,i}(t) &= d_{s,i}(t) + c_{rcvr,L1}(t) - c_{sv,L1,i}(t) + d_{tropo,i}(t) - d_{iono,L1,i}(t) + \\
& \quad d_{\text{orbital},i}(t) + d_{\text{survey},i}(t) + \left(\Phi_{L1}(t) + \lambda_{L1,i} \times N_{L1,i}\right) \\
\end{align*}
\] (4.1)

\[
\begin{align*}
AD_{L2,i}(t) &= d_{s,i}(t) + c_{rcvr,L2}(t) - c_{sv,L2,i}(t) + d_{tropo,i}(t) - d_{iono,L2,i}(t) + \\
& \quad d_{\text{orbital},i}(t) + d_{\text{survey},i}(t) + \left(\Phi_{L2}(t) + \lambda_{L2,i} \times N_{L2,i}\right) \\
\end{align*}
\] (4.2)

The difference of the L1 and L2 carrier phase measurements can be expressed by Equation 4.3 shown below.

\[
D_{i,m}(t) = AD_{L1,i,m}(t) - AD_{L2,i,m}(t)
\] (4.3)

Next, a curve is fit through successive differences and the fitted curve is then used to predict the next measurement by extrapolating the curve to the next measurement. If \(D_{i,e}(t)\) represents the difference of the extrapolated measurement values, then the test
statistic is obtained by differencing the measured and extrapolated differences as shown below in Equation 4.4.

\[ \text{residual}(t) = D_{i,m}(t) - D_{i,e}(t) \] (4.4)

In the absence of anomalies, the test statistic primarily contains the effects of L1 and L2 carrier phase noise, since all other terms change slowly during the time between measurements. The noise on the test statistic is typically on the order of millimeters. Figure 4.1 shows the dual frequency test statistic obtained for satellite 27 based on data collected on September 7, 2001. In Figure 4.1, a 1st order curve fit was used over 6 successive measurements at a 5 second update rate.

![Figure 4.1 Example of Dual Frequency Test Statistic (satellite 27)]
It is observed in Figure 4.1 that the residual values are typically noisier near the edges of the plot. This is due to the fact that these residuals are formed from the measurements that were taken when the satellite was at lower elevation angles. Thus, the signal-to-noise ratio of the measurements was typically lower as compared to the measurements taken when the satellite was at higher elevation angles (represented by the residuals in the middle of the plot). In order to properly characterize the distribution of the residuals the above residuals were normalized using the signal-to-noise ratio values. The normalized residuals are shown in Figure 4.2 below.

![Figure 4.2 Example of Normalized Dual Frequency Test Statistic (Satellite 27)](image)

Any anomaly greater than 10 mm in the residual data will produce an observable value in the dual frequency test statistic. Three key parameters must be determined in order to complete the detection algorithm. These are listed as follows.
1. The order of the curve fit
2. The number of successive measurements to be used in the curve fit
3. The detection threshold for the test statistic.

In order to compute the order of the curve fit and the number of measurements, multiple sets of the test statistics were formed, for every satellite, by varying both the order of the curve fit and the number of measurements in the fit. The combination of the fit order and the number of measurements that resulted in a minimum standard deviation of the calculated test statistics was used in the dual frequency algorithm.

Results obtained for this thesis are derived from two 24-hour data sets, one collected on June 8, 2000 and the second collected on September 7, 2001. Two data sets were used to verify the consistency of the results. Linear (1st order) and quadratic (2nd order) curves were fitted through the test statistics, for each of the satellites, with the number of measurements being varied from 2 to 10. Higher-order curve fits were not used because they were found to produce large values for the residuals.

Figures 4.3 and 4.4 show the stem plots of the standard deviations of the residuals for satellites 1 and 3, respectively. The June 8, 2000 data were used for these plots. Note that for satellite 1, a linear curve fit with 4 points in each fit resulted in the lowest test statistic values, while a linear curve fit with 2 fit points produced the best results for satellite 3.

The same analysis was performed using the September 7, 2001 data. Data pertaining to satellites 1 and 27 were selected. The linear curve fit resulted in the minimum standard deviation for both the satellite test statistics as shown in figures 4.5 and 4.6.
Figure 4.3 Stem plot of the test statistic standard deviation for satellite 1 (June 8, 2000 data)

Figure 4.4 Stem plot of the test statistic standard deviation for satellite 3 (June 8, 2000 data)
Figure 4.5 Stem plot of the test statistic standard deviation for satellite 1
(September 7, 2001 data)

Figure 4.6 Stem plot of the test statistic standard deviation for satellite 27
(September 7, 2001)
The fit points required in producing these minima were 4 and 6 for satellites 1 and 27, respectively.

In order to characterize the dual frequency test statistics of all the satellites and ascertain the assumption that these residuals exhibit Gaussian (or nearly Gaussian) properties, histograms and normal probability plots were generated for each of them. The normal probability plots give a graphical assessment of how Gaussian the residual data set is. The measurements are plotted (as a set of ‘+’ dots) against their respective Cumulative Distribution Function (CDF) probabilities over a linear line that is representative of a perfectly Gaussian distribution. If the residual were to be perfectly Gaussian then the ‘+’ dots would perfectly overlie the underlying linear plot. Other distributions, however, would introduce a curvature. Figures 4.7 and 4.8 show the histogram plots generated for satellites 1 and 27 data, respectively, collected on September 7, 2001. The corresponding normal probability plots are shown in figures 4.9 and 4.10. These plots were generated prior to normalizing the satellite residuals values. Hence, it can be seen that the distribution of the residuals in non-Gaussian near the tails while being Gaussian near the core of the distribution. However the normalized residuals exhibit near Gaussian properties as shown in Figures 4.11 – 4.14. To further validate the consistency of this result, the same analysis was performed on some of the dual frequency satellite data sets derived from the June 8, 2000 data. Observations made on these results resulted in similar conclusions.
Figure 4.7 Histogram of un-normalized dual frequency test statistic for satellite 1
(September 7, 2001 data)

Figure 4.8 Histogram of un-normalized dual frequency test statistic for satellite 27
(September 7, 2001 data)
Figure 4.9 Normal Probability plot of un-normalized dual frequency test statistic for satellite 1 (September 7, 2001 data)

Figure 4.10 Normal Probability plot of un-normalized dual frequency test statistic for satellite 27 (September 7, 2001 data)
Figure 4.11 Histogram of normalized dual frequency test statistic for satellite 1 (September 7, 2001 data)

Figure 4.12 Histogram of normalized dual frequency test statistic for satellite 27 (September 7, 2001 data)
Figure 4.13 Normal Probability plot of normalized dual frequency test statistic for satellite 1 (September 7, 2001 data)

Figure 4.14 Normal Probability plot of normalized dual frequency test statistic for satellite 27 (September 7, 2001 data)
The detection threshold for the test statistic is computed to satisfy the probability of false detection. [8] The probability of false detection was set to $10^{-7}$, in accordance with approximate continuity requirements for GPS augmentation systems. Since a false anomaly detection of one satellite on one receiver does not result in a loss-of-continuity, the false detection probability does not need to be set based on the continuity requirement listed in Table 2.1. The full derivation of the exact false detection probability for this monitor is beyond the scope of this thesis. The relationship between the detection threshold and the probability of false detection for a normally distributed statistic is given by Equation 4.5. [8]

$$P_{FD} = \text{erfc} \left[ \frac{T_D}{\sigma \sqrt{2}} \right] \tag{4.5}$$

where

- $P_{FD}$ is the probability of false detection
- $T_D$ is the detection threshold for the residual
- $\sigma$ is the standard deviation of the residual
- $\text{erfc}$ is the complementary error function which is given by Equation 4.6 below.

$$\text{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_z^\infty e^{-\lambda^2} d\lambda \tag{4.6}$$

Equation 4.5 is solved for $T_D$, given by Equation 4.7 below.

$$T_D = \sigma \sqrt{2} \text{erfc}^{-1}(P_{FD}) \tag{4.7}$$
Substituting the value of $P_{FD}$ as $10^{-7}$ and simplifying the above expression, the detection threshold becomes

$$T_{Pre_D} = 5.32\sigma$$  \hspace{1cm} (4.8)

Using Equation 4.8, the detection threshold for every satellite was calculated. The highest valued threshold was chosen among all the calculated thresholds for the dual frequency detector. Once an anomaly is detected in the residual values for a particular satellite, an appropriate corrective action is initiated, which is outlined in Section 4.4 of this document. Following the corrective action, the test statistic is recalculated and tested against a tighter threshold. The reason for a tighter threshold is that if detection occurred, an anomaly exists with a high probability. In avoiding a missed detection, credit can no longer be taken for the prior probability of an anomaly occurring. The second threshold is computed using a probability of false alarm of $10^{-3}$. [8] The expression for the second threshold was derived using Equation 4.7. This is given by Equation 4.9 below.

$$T_{Post_D} = 3.29\sigma$$  \hspace{1cm} (4.9)

Table 4.1 below lists the pre and post detection threshold obtained using the above expressions for both, the June 8, 2000 as well as September 7, 2001 data sets.

**Table 4.1 Threshold settings for the dual frequency detector**

<table>
<thead>
<tr>
<th>Date of data collection</th>
<th>Pre-detection threshold (cms)</th>
<th>Post-detection threshold (cms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/08/2000</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>09/07/2001</td>
<td>1.1</td>
<td>0.67</td>
</tr>
</tbody>
</table>
The dual frequency detector fails to detect certain statistically unique combinations of integer cycle slips occurring in the carrier phase measurements on both the frequencies. Consider the case when ‘m’ and ‘n’ would represent the magnitude of cycle slips occurring on the L1 and L2 carrier phase measurements of the received signal, respectively. Equations 4.11 and 4.12 below give the mathematical representation of this situation.

\[
AD_{i,L1}(t) = AD_{i,L1}(t) + m\lambda_1
\]  
\[
AD_{i,L2}(t) = AD_{i,L2}(t) + n\lambda_2
\]  

The dual frequency detector would fail in detecting these cycle slips if the following inequality is satisfied.

\[
|m\lambda_{L1} - n\lambda_{L2} + \Phi| \leq T_D
\]  

where m and n are expressed in cycles and \(\Phi\) represents the phase noise from the receiver measurements (hardware and software), diffuse and non-diffuse multipath, etc.

Table 4.2 lists undetected dual frequency cycle slip combinations occurring in the range of 0 to +100 L1 and L2 cycle slips. Note that only those slip combinations whose difference is less than 1.5 centimeter is shown in this table. The magnitude of such candidate combinations depends on the type of cycle slip detector being used and the corresponding threshold values established to detect the slips.
Table 4.2 List of undetected combinations of L1 and L2 cycle slips

<table>
<thead>
<tr>
<th>Slip on L1 frequency (m)</th>
<th>Slip on L2 frequency (n)</th>
<th>$m\lambda_{L1} - n\lambda_{L2}$ (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>7</td>
<td>0.0032</td>
</tr>
<tr>
<td>18</td>
<td>14</td>
<td>0.0063</td>
</tr>
<tr>
<td>27</td>
<td>21</td>
<td>0.0095</td>
</tr>
<tr>
<td>36</td>
<td>28</td>
<td>0.0127</td>
</tr>
<tr>
<td>41</td>
<td>32</td>
<td>-0.0127</td>
</tr>
<tr>
<td>50</td>
<td>39</td>
<td>-0.0095</td>
</tr>
<tr>
<td>59</td>
<td>46</td>
<td>-0.0063</td>
</tr>
<tr>
<td>68</td>
<td>53</td>
<td>-0.0032</td>
</tr>
<tr>
<td>77</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>86</td>
<td>67</td>
<td>0.0032</td>
</tr>
<tr>
<td>95</td>
<td>74</td>
<td>0.0063</td>
</tr>
</tbody>
</table>

4.2 Single Frequency Anomaly Detector

The single frequency anomaly detector is based on the following principle. A low noise statistic is formed by computing the triple difference of three consecutive L1 or L2 carrier phase measurements made on two simultaneously tracked satellites. Individual test statistic values are formed using the carrier phase measurements of the reference satellite and each of the non-reference satellites. These test statistics are then checked against a predetermined threshold value. A test statistic value that is higher than the set threshold indicates the presence of an anomaly. The corresponding satellite pair is tagged.

A reference satellite is chosen among all the satellites that are being tracked at a given instant of time. The reference satellite is chosen with the elevation angle as the criterion.

Since the data of the reference satellite is involved in forming all the single frequency residuals for every time instant, it is imperative that the reference satellite data remains
free of anomalies such as data gaps and bad measurements. Also a satellite that is being tracked at a high elevation angle is least likely to experience a loss of lock due to signal obstruction. Any anomalies detected in the reference satellite data would result in its replacement by the satellite that is next in the elevation angle hierarchy as the next reference satellite. The equation for the test statistic can be derived in the following manner. Since the equations pertaining to the single frequency detector derived in this section are applicable to both the L1 and L2 frequency detectors, the frequency subscript is not included in the equations.

Computing the triple difference residual is a three-step process. First, two sets of single difference measurements are formed by successively differencing three consecutive carrier phase measurements for each of the two satellites as shown in equations 4.13 through 4.16.

\[
\Delta AD_{\text{ref}, t3-t2} = AD_{\text{ref}, t3} - AD_{\text{ref}, t2}
\]

\[
= \left( d_{s, \text{ref}, t3} - d_{s, \text{ref}, t2} \right) + \left( c\tau_{\text{rcvr}, t3} - c\tau_{\text{rcvr}, t2} \right) -
\]

\[
\left( c\tau_{\text{sv}, \text{ref}, t3} - c\tau_{\text{sv}, \text{ref}, t2} \right) + \left( d_{\text{tropo,ref}, t3} - d_{\text{tropo,ref}, t2} \right) -
\]

\[
\left( d_{\text{iono,ref}, t3} - d_{\text{iono,ref}, t2} \right) + \left( d_{\text{orbit,ref}, t3} - d_{\text{orbit,ref}, t2} \right) +
\]

\[
\left( d_{\text{survey,ref}, t3} - d_{\text{survey,ref}, t2} \right) + \left( \Phi_{\text{ref}, t3} - \Phi_{\text{ref}, t2} \right)
\]

(4.13)
\[ \Delta AD_{\text{ref}, t2-t1} = AD_{\text{ref}, t2} - AD_{\text{ref}, t1} \]

\[ = \left( d_{s, \text{ref}, t2} - d_{s, \text{ref}, t1} \right) + \left( c_{\text{rcvr}, t2} - c_{\text{rcvr}, t1} \right) - \left( c_{\text{sv, ref}, t2} - c_{\text{sv, ref}, t1} \right) + \left( d_{\text{tropo, ref}, t2} - d_{\text{tropo, ref}, t1} \right) - \left( d_{\text{iono, ref}, t2} - d_{\text{iono, ref}, t1} \right) + \left( d_{\text{orbit, ref}, t2} - d_{\text{orbit, ref}, t1} \right) + \left( d_{\text{survey, ref}, t2} - d_{\text{survey, ref}, t1} \right) + \left( \Phi_{\text{ref}, t2} - (\Phi)_{\text{ref}, t1} \right) \]

\[ \Delta AD_{i, t3-t2} = AD_{i, t3} - AD_{i, t2} \]

\[ = \left( d_{s, i, t3} - d_{s, i, t2} \right) + \left( c_{\text{rcvr}, t3} - c_{\text{rcvr}, t2} \right) - \left( c_{\text{sv, i}, t3} - c_{\text{sv, i}, t2} \right) + \left( d_{\text{tropo, i}, t3} - d_{\text{tropo, i}, t2} \right) - \left( d_{\text{iono, i}, t3} - d_{\text{iono, i}, t2} \right) + \left( d_{\text{orbit, i}, t3} - d_{\text{orbit, i}, t2} \right) + \left( d_{\text{survey, i}, t3} - d_{\text{survey, i}, t2} \right) + \left( (\Phi)_{i, t3} - (\Phi)_{i, t2} \right) \]
\[ \Delta AD_{i, t_2 - t_1} = AD_i(t_2) - AD_i(t_1) \]

\[ = \left( d_{s, i}(t_2) - d_{s, i}(t_1) \right) + \left( ct_{\text{rcvr}, i}(t_2) - ct_{\text{rcvr}, i}(t_1) \right) - \left( ct_{\text{sv}, i}(t_2) - ct_{\text{sv}, i}(t_1) \right) + \left( d_{\text{tropo}, i}(t_2) - d_{\text{tropo}, i}(t_1) \right) - \left( d_{\text{iono}, i}(t_2) - d_{\text{iono}, i}(t_1) \right) + \left( d_{\text{orbit}, i}(t_2) - d_{\text{orbit}, i}(t_1) \right) + \left( d_{\text{survey}, i}(t_2) - d_{\text{survey}, i}(t_1) \right) + \left( (\Phi)_i(t_2) - (\Phi)_i(t_1) \right) \]

where ‘t1’, ‘t2’ and ‘t3’ represent three consecutive measurement epochs. The single difference represents the change in the range between the satellite and the receiver between two consecutive time epochs. It is seen from the above equations that the single difference eliminates the integer ambiguity assuming that the satellite was continuously tracked between the two epochs. In the second step, the single differenced measurements of the reference and the non-reference satellites are subtracted to form two double differenced measurements as shown in equations 4.17 and 4.18.
Double differencing removes the error induced by the receiver clock bias in the carrier phase measurements. Finally subtracting the double difference measurements as shown in Equation 4.19 forms the triple differenced residual.

\[
\text{residual}(3) = \left( \Delta AD_{\text{ref, } t3-t2} - \Delta AD_{i, t3-t2} \right) - \left( \Delta AD_{\text{ref, } t2-t1} - \Delta AD_{i, t2-t1} \right)
\]  

(4.19)

In the absence of any high atmospheric activity, the tropospheric and ionospheric errors do not vary rapidly with time. Hence, the double differenced tropospheric and
ionospheric errors in equations 4.17 and 4.18 tend to cancel each other out when the triple difference is computed. Substituting equations 4.17 and 4.18 into Equation 4.19, the expression for the residual is obtained as shown in Equation 4.20 below.

\[
\text{residual}(t3) = \left( \left( d_{s, \text{ref - i}}(t3) - d_{s, \text{ref - i}}(t2) \right) - \left( d_{s, \text{ref - i}}(t2) - d_{s, \text{ref - i}}(t1) \right) \right) -
\]

\[
\left( \left( t_{sv, \text{ref - i}}(t3) - t_{sv, \text{ref - i}}(t2) \right) - \left( t_{sv, \text{ref - i}}(t2) - t_{sv, \text{ref - i}}(t1) \right) \right) +
\]

\[
\left( \left( d_{\text{orbit, ref - i}}(t3) - d_{\text{orbit, ref - i}}(t2) \right) - \left( d_{\text{orbit, ref - i}}(t2) - d_{\text{orbit, ref - i}}(t1) \right) \right) +
\]

\[
\left( \left( d_{\text{survey, ref - i}}(t3) - d_{\text{survey, ref - i}}(t2) \right) - \left( d_{\text{survey, ref - i}}(t2) - d_{\text{survey, ref - i}}(t1) \right) \right) +
\]

\[
\left( \left( \Phi_{\text{ref - i}}(t3) - \Phi_{\text{ref - i}}(t2) \right) - \left( \Phi_{\text{ref - i}}(t2) - \Phi_{\text{ref - i}}(t3) \right) \right) \left( \Phi_{\text{ref - i}}(t2) - \Phi_{\text{ref - i}}(t1) \right) \right) \right)
\]

(4.20)

The geometric range between the receiver and the satellite is calculated using the two-point formula as shown in Equation 4.21 below.

\[
\text{range}(t3) = \sqrt{(x_s(t3) - x_u(t3))^2 + (y_s(t3) - y_u(t3))^2 + (z_s(t3) - z_u(t3))^2}
\]

(4.21)

where

\([x_s(t3) \ y_s(t3) \ z_s(t3)]\) is the satellite position in ECEF coordinate system for time instant ‘t3’

\([x_u(t3) \ y_u(t3) \ z_u(t3)]\) is the user receiver position in the ECEF coordinate system for time instant ‘t3’
A detailed description of the satellite position computation process can be found in [1, 27]. The geometric range between the reference and the non-reference satellite and the receiver is calculated for all three epochs and subtracted from Equation 4.20. It is noted that the ephemeris data transmitted by the satellite can change every hour. The satellite positions for all three successive measurement epochs should always be computed using the same ephemeris data. The orbit error is mostly accounted for by computing the triple difference of the geometric range to the satellite. By using the surveyed coordinates for the user receiver position, the survey error is minimized. The satellite clock bias for each time instant is calculated from the ephemeris data transmitted by the satellite and is also subtracted from Equation 4.20. A detailed description of the satellite clock bias is also contained in [1, 27]. After removing all the known quantities from Equation 4.20, what is left predominantly represents phase noise difference, which is represented in Equation 4.22 below.

\[
\text{residual}(t_3) = [\Phi_{\text{ref} - 1}(t_3) - \Phi_{\text{ref} - 1}(t_2)] - [\Phi_{\text{ref} - 1}(t_2) - \Phi_{\text{ref} - 1}(t_1)]
\]  \hspace{1cm} (4.22)

Figures 4.15 and 4.16 show the un-normalized anomaly free L1 and L2 frequency residuals for satellite pair 10-30, which are on the order of millimeters. September 7, 2001 data are used for these plots.
Figure 4.15 Un-normalized single frequency (L1) residuals for the satellite pair 10-30 (September 7, 2001 data)

Figure 4.16 Un-normalized single frequency (L2) residuals for the satellite pair 10-30 (September 7, 2001 data)
The procedure followed in setting up the threshold value for the single frequency detector is similar to the one followed for the dual frequency detector. The single frequency residuals were characterized in a way similar to characterization of the dual frequency residuals. Figures 4.17 and 4.18 show the histogram plots of the un-normalized L1 and L2 residuals computed for satellite pair 10-30 from the September 7, 2001 data. The corresponding normal probability plots are shown in figures 4.19 and 4.20. It is observed that unlike the case of the dual frequency residuals, the normal probability plots for the single frequency residuals remain fairly linear not only at the core of the distribution but also near the tails. This is because the triple differencing of the carrier phase measurements cancels the effect of low frequency multipath noise, which is highly correlated between measurement epochs. What remains predominantly consists of white noise, which is uncorrelated between measurement epochs. To verify this assertion, the single frequency statistics for the satellite pair 10-30 were normalized using the Signal-to-Noise ratio values. These results are plotted in Figures 4.21 through 4.26. By comparing Figures 4.19 and 4.25 as well as Figures 4.20 and 4.26, it is seen that there is very little derived benefit in normalizing the single frequency residuals. To further validate the consistency of this result, the same analysis was performed on another single frequency statistics set derived from the June 8, 2000 data. Observations made on these results resulted in similar conclusions.
Figure 4.17 Histogram of un-normalized single frequency (L1) residuals for satellite pair 10-30 (September 7, 2001 data)

Figure 4.18 Histogram of un-normalized single frequency (L2) residuals for satellite pair 10-30 (September 7, 2001 data)
Figure 4.19 Normal Probability plot of the un-normalized single residuals (L1) for satellite pair 10-30 (September 7, 2001)

Figure 4.20 Normal Probability plot of the un-normalized single residuals (L2) for satellite pair 10-30 (September 7, 2001 data)
Figure 4.21 Normalized single frequency residuals (L1) for satellite pair 10-30 (September 7, 2001 data)

Figure 4.22 Normalized single frequency residuals (L2) for satellite pair 10-30 (September 7, 2001 data)
Figure 4.23 Histogram of the normalized single frequency residuals (L1) for satellite pair 10-30 (September 7, 2001 data)

Figure 4.24 Histogram of the normalized single frequency residuals (L2) for satellite pair 10-30 (September 7, 2001 data)
Figure 4.25 Normal probability plot of the normalized single frequency residuals (L1) for satellite 10-30 (September 7, 2001 data)

Figure 4.26 Normal probability plot of the normalized single frequency residuals (L2) for satellite 10-30 (September 7, 2001 data)
Table 4.3 lists the pre-detection and post-detection threshold values for the single frequency detectors. The first detection threshold for both detectors was computed to be 1.1 cm.

Table 4.3 Calculated Threshold Values for Single Frequency Detectors

<table>
<thead>
<tr>
<th>Date of data collection</th>
<th>L1 detector</th>
<th>L2 detector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
<td>Second</td>
</tr>
<tr>
<td></td>
<td>Threshold</td>
<td>Threshold</td>
</tr>
<tr>
<td></td>
<td>(cms)</td>
<td>(cms)</td>
</tr>
<tr>
<td>06/08/00</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>09/07/01</td>
<td>1.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

The single frequency detector cannot detect identical slips occurring on the L1/L2 measurements of both the reference and the non-reference satellites. This condition can be analyzed as follows. It is assumed that ‘m’ and ‘n’ represent the magnitude of the cycle slips on the L1 and L2 frequencies of the reference satellite. Similarly ‘p’ and ‘q’ are assumed to represent the cycle slips on the L1 and L2 frequencies for the non-reference satellite, respectively. All cycle slips are assumed to have occurred between the second (t2) and the third (t3) time instants. The single difference equations for L1 are given by:

\[
\Delta AD_{\text{ref, } t3 - t2} = \Delta AD_{\text{ref, } t3 - t2} + m\lambda_1 \tag{4.23}
\]

\[
\Delta AD_{i, t3 - t2} = \Delta AD_{i, t3 - t2} + p\lambda_1 \tag{4.24}
\]

The L2 equations are obtained by replacing ‘m’ by ‘n’ and ‘p’ by ‘q’. The double differenced equation for L1 is given by:
\[\Delta AD'_{\text{ref}, t3 - t2} - \Delta AD'_{i, t3 - t2} = \left( \Delta AD_{\text{ref}, t3 - t2} - \Delta AD_{i, t3 - t2} \right) + (m - p)\lambda_1 \] (4.25)

It is observed that the cycle slips pass through the L1 detector when |m| = |p| and \(\Delta \Phi_{\text{ref} - i, t3 - t2} < T_D\).

Simultaneous cycle slips do not affect the position solution as such a slip would. This would, however, be a problem for a timing user or for the data analysis (e.g., multipath estimation). It can thus be concluded that the sole use of single frequency detectors would be sufficient for a positioning user, while the simultaneous use of single and dual frequency detectors is required for timing users and for data analysis.

### 4.3 Slow Cycle Slip Detector

The single and dual frequency statistics obtained from their respective detectors are used in detecting the slow cycle slip as well. Note here that a separate threshold for detecting slow cycle slips is not developed. This is because the pre-detection thresholds for the single and dual frequency detectors are set to 1.1 cms, which is sensitive enough to detect both the integer as well as slow cycle slips. If the satellite experiences a slow cycle slip, then theoretically it would be detected by any/all of these three integer whole cycle slip detectors. However none of them would succeed in correcting it as they are designed to correct only the integer cycle slips. Hence, the satellite in question would be tagged and excluded. For the slow cycle slips that are not detected, the most likely cause is a low Signal-to-Noise ratio or Radio Frequency Interference. Under such conditions, it is unlikely that multiple receivers would have correlated errors. Therefore, a multiple
receiver cross-check would detect this condition. Another option for slow cycle slip detection would be the use of Receiver Autonomous Integrity Monitoring (RAIM) on the carrier phase measurements. [8] The scope of this document, however, is limited to single and dual frequency detectors.

4.4 Carrier Phase Anomaly Correction

This section describes the correction procedures developed to deal with all the identified carrier phase anomalies in this research. These procedures are implemented in the comprehensive carrier phase detector described in the Section 4.5.

4.4.1 Loss of Lock

The duration of the loss of lock plays a crucial role in determining the further usage of the satellite data. A satellite with frequent loss of lock is not a desirable candidate for the residual formations. Such a situation might occur with those satellites that are being tracked at low elevation angles with a low SNR. If the duration of the loss of lock is on the order of a few seconds then the satellite is tagged and not used. For the purpose of this research, the minimum duration of a continuous satellite data segment is set at 30 seconds. No attempt is made to recover the data during a very short loss of lock, by means such as data extrapolation through curve fitting etc. This is because it is difficult to determine how good the recovered data is in terms of residual errors.

Two possibilities arise for the loss of satellite data in between successive epochs. One is a genuine loss of lock of the satellite by the receiver and the other is the loss of
communication between the receiver and the data recording software, causing a data gap in the measurement set. One way of differentiating between the two is by observing the trend of the carrier phase measurements before and after the duration time of loss of data. In the case of loss of lock, however brief, there will be a discernable jump in the accumulated Doppler measurement value before and after the loss of lock while in the case of missing data the accumulated Doppler retains its smooth trend throughout.

4.4.2 Data Gaps

Data gaps in a given satellite data set can be corrected by calculating the value of the missing measurement using carrier measurements from a second satellite. This is done using the single frequency residual values. Since the reference satellite is specifically chosen to be free of data gaps, its data are used in filling in the missing measurement value for any simultaneously tracked non-reference satellite. The expression for the filled-in accumulated Doppler value of the non-reference satellite can be derived by first considering the expression for the single frequency residual as shown below in Equation 4.26.
residual \((t3)\) = \left( \frac{\Delta AD_{\text{ref} - \text{i}, t3 - t2}}{t3 - t2} - \frac{\Delta AD_{\text{ref} - \text{i}, t2 - t1}}{t2 - t1} \right) - \\
\left( \frac{\Delta range_{\text{ref} - \text{i}, t3 - t2}}{t3 - t1} - \frac{\Delta range_{\text{ref} - \text{i}, t2 - t1}}{t2 - t1} \right) + (4.26)
\\
\left( \frac{\Delta clk\_bias_{\text{ref} - \text{i}, t3 - t2}}{t3 - t2} - \frac{\Delta clk\_bias_{\text{ref} - \text{i}, t2 - t1}}{t2 - t1} \right)

where

\[
\Delta AD_{\text{ref} - \text{i}, t3 - t2} = \Delta AD_{\text{ref}, t3 - t2} - \Delta AD_{\text{i}, t3 - t2}
\]

\[\Delta AD_{\text{ref} - \text{i}, t2 - t1} = \Delta AD_{\text{ref}, t2 - t1} - \Delta AD_{\text{i}, t2 - t1} \tag{4.27}\]

\[
\Delta range_{\text{ref} - \text{i}, t3 - t2} = \Delta range_{\text{ref}, t3 - t2} - \Delta range_{\text{i}, t3 - t2}
\]

\[\Delta range_{\text{ref} - \text{i}, t2 - t1} = \Delta range_{\text{ref}, t2 - t1} - \Delta range_{\text{i}, t2 - t1} \tag{4.29}\]

\[
\Delta clk\_bias_{\text{ref} - \text{i}, t3 - t2} = \Delta clk\_bias_{\text{ref}, t3 - t2} - \Delta clk\_bias_{\text{i}, t3 - t2}
\]

\[\Delta clk\_bias_{\text{ref} - \text{i}, t2 - t1} = \Delta clk\_bias_{\text{ref}, t2 - t1} - \Delta clk\_bias_{\text{i}, t2 - t1} \tag{4.31}\]

\[\Delta range_{\text{ref}, t3 - t2} \] is the computed change in the range between the reference satellite and user receiver between the 2\textsuperscript{nd} and the 3\textsuperscript{rd} tracking instants.

\[\Delta range_{\text{ref}, t2 - t1} \] is the computed change in the range between the reference satellite and user receiver between the 1\textsuperscript{st} and the 2\textsuperscript{nd} tracking instants.
Δrange_{i,t3-t2} is the computed change in the range between the non-reference satellite and user receiver between the 2\textsuperscript{nd} and the 3\textsuperscript{rd} tracking instants.

Δrange_{i,t2-t1} is the computed change in the range between the non-reference satellite and user receiver between the 1\textsuperscript{st} and the 2\textsuperscript{nd} tracking instants.

Δclk\_bias\textsubscript{ref,t3-t2} is the computed change of the reference satellite clock bias between the 2\textsuperscript{nd} and the 3\textsuperscript{rd} tracking instants.

Δclk\_bias\textsubscript{ref,t2-t1} is the computed change of the reference satellite clock bias between the 1\textsuperscript{st} and the 2\textsuperscript{nd} tracking instants.

Δclk\_bias\textsubscript{i,t3-t2} is the computed change of the non-reference satellite clock bias between the 2\textsuperscript{nd} and the 3\textsuperscript{rd} tracking instants.

Δclk\_bias\textsubscript{i,t2-t1} is the computed change of the non-reference satellite clock bias between the 1\textsuperscript{st} and the 2\textsuperscript{nd} tracking instants.

By setting the residual in Equation 4.26 to zero, the required non-reference satellite carrier phase measurement \((AD_i(t3))\) is obtained as shown in Equation 4.33 below.

\[
AD_i(t3) = [\left(\Gamma + \Theta - \Omega\right) \times (t3 - t2)] + AD_i(t2)
\]  \hspace{1cm} (4.33)

where

\[
\Gamma = \left(\frac{\Delta AD\textsubscript{ref,t3-t2}}{t3 - t2}\right) - \left(\frac{\Delta AD\textsubscript{ref-i,t2-t1}}{t2 - t1}\right)
\]  \hspace{1cm} (4.34)
\[ \Theta = \frac{(\Delta \text{clk}_{\text{bias}}_{\text{ref}-i,t3-t2})}{t3 - t2} - \frac{(\Delta \text{clk}_{\text{bias}}_{\text{ref}-i,t2-t1})}{t2 - t1} \quad (4.35) \]

\[ \Omega = \frac{(\Delta \text{range}_{\text{ref}-i,t3-t2})}{t3 - t2} - \frac{(\Delta \text{range}_{\text{ref}-i,t2-t1})}{t2 - t1} \quad (4.36) \]

It is recognized that Equation 4.33 represents the estimated noise-free carrier phase measurement for the current epoch. When fed into the single frequency detector this estimated measurement produces a zero value for the single frequency residual. Since carrier phase noise is considered to be in the order of millimeters, such a measurement value could be used for a short period of time. For the current research, a satellite whose data is found to contain successive missing measurements is flagged and not used until 30 seconds of continuous data is recorded by the receiver.

### 4.4.3 Cycle Slips

Cycle slip correction for the current research is a four-step process. The first step involves the calculation of the estimated satellite carrier phase measurement using the same procedure as described in Section 4.4.2 of this document, for missing measurements. The estimated measurement is then subtracted from the anomalous measurement. The difference consists of the integer cycle slips along with the phase noise. The integer cycle slips are estimated from this difference and subtracted from the measurement. Since the goal is to correct the cycle slips the phase noise is left untouched in the anomalous measurement.
4.4.4 Corrupted Data

The procedure followed for the correction of corrupted measurement data is similar to the one followed for the missing measurement data. However as explained in Section 3 of this document, the corrupted carrier phase measurements can take either a zero or a non-zero value. If the measurement equals zero, it is replaced by its estimated value using Equation 4.33. If the corrupted measurement takes on a non-zero value it is treated as an integer cycle slip and the corresponding correctional procedure is initiated. Note that this method will only work in those cases where the non-zero valued corrupted measurement equals an integer cycle plus the usual phase noise. In other situations this method will fail to rectify the anomaly, and the satellite in question would be tagged and barred from further usage.

4.5 Comprehensive Carrier Phase Anomaly Detector

The single and dual frequency detectors are combined with the slow cycle slip detector in forming the comprehensive carrier phase anomaly detector. Figure 4.27 shows the flow chart of the comprehensive detector algorithm.

In the initial phase, the data for all the satellites is taken and the current GPS time is computed for them. The presence of three consecutive carrier phase measurements is needed for the formation of the single frequency residuals. Therefore, a memory state is set up to determine the satellites that are being tracked for three consecutive time epochs.
Figure 4.27 Flow Chart of the comprehensive carrier phase anomaly detection and correction algorithm
The same memory state stores the corresponding satellite elevation angles, which are used in choosing the reference satellite. The dual frequency residual formation depends on the number of consecutive measurements to be used in the curve fit. If ‘n’ consecutive measurements are to be used for a particular satellite then the dual frequency residual formation commences at the \((n+1)^{th}\) time instant from the first tracking instant for that satellite.

Since all three detectors are operated in tandem, the anomaly detection and correction process for the satellite commences at the \((n+1)^{th}\) instant. The satellites tracked for the present time epoch are identified and compared with those tracked for the previous time epoch. The absence of satellite data for the current epoch could mean either a receiver loss of lock or a missing measurement. Hence, each of these occurrences is further investigated. For those satellites with receiver loss of lock, a memory state is formed containing the time of loss of lock. This is shown as memory_state_1 in the flow diagram. If a single carrier phase measurement is found to be missing for a satellite, then its id is stored in a second memory state and the carrier phase measurement is filled in at a later stage in the algorithm.

This is shown as memory_state_2 in the flow diagram. On the other hand, if multiple carrier phase measurements are found to be missing for a satellite then it is flagged and not used unless it is reacquired by the receiver.

If any satellite is added for the current epoch, then memory_state_1 is used to determine if it is being tracked for the very first time or if it is being reacquired after a loss of lock.
New acquisitions as well as satellites that are reacquired after a considerable time period following a loss of lock are used in the residual formation. Satellites that are reacquired after a brief loss of lock are flagged and not used till continuous data are available for 30 seconds. Next, the reference satellite is selected from all satellites being tracked for the current instant.

Before the carrier phase measurements can be used in forming the triple difference residual, they must be corrected for potential receiver clock jumps introduced by the Ashtech Z-12 receiver. Appendix A contains details regarding the receiver clock jumps and their correction.

The carrier phase measurements of all the non-reference satellites are checked for the presence of anomalies such as data gaps and corrupted measurement points. The memory_state_2 that was set up earlier is used in detecting data gaps. It was mentioned earlier that a corrupted measurement could take on a zero value or any other arbitrary measurement value. At this stage of the algorithm, only the zero valued corrupted measurements are filled in. A memory state is formed (shown as memory_state_3 in Figure 4.27) to discriminate isolated instances of the corrupted measurements from consecutive instances for the satellite(s) in question. Satellite(s) containing consecutive corrupted measurements are flagged and not used until they are reacquired after a considerable time period following a loss of lock. On the other hand, isolated instances of data gaps and zero-valued corrupted measurements are corrected by filling in the
corresponding measurements. Corrupted measurements that take on arbitrary values are
duly detected and corrected at a later stage in the algorithm.

The satellite measurements are then sent to the single and dual frequency anomaly
detectors where the corresponding single and dual frequency residuals are formed. These
are then checked against their respective pre-detection thresholds. In the absence of
anomalies in any of the measurements, none of the pre-detection thresholds are breached
by any of the residuals. However, any residuals crossing their respective thresholds
indicate the presence of an anomaly in one or more satellites. Note that up to this point
the only anomalies not accounted for are the non-zero valued corrupted measurements
and cycle slips. A memory state is formed (shown as memory_state_4 in Figure 4.27) in
differentiating between isolated and consecutive instances of non-zero valued corrupted
measurement occurrences. While integer cycle slips and isolated instances of non-zero
valued corrupted measurements are corrected for appropriately, satellites whose data are
identified as containing slow cycle slips and/or consecutive non-zero valued corrupted
measurements are flagged and not used until they are reacquired after a long loss of lock.
Single and dual frequency residuals are recomputed using the carrier phase measurements
that are corrected for integer cycle slips and non-zero valued corrupted measurements.
These recomputed residuals are checked against their respective post-detection
thresholds. Satellites whose residuals cross the post-detection threshold values are
suitably flagged and not used until they are reacquired after a long loss of lock. On the
other hand, the satellites whose residuals stay below the post-detection threshold values
are retained in the anomaly detection process. The corrected measurements and the residuals are subsequently stored and the entire process is repeated for the next epoch.

Table 4.4 summarizes the capabilities, advantages and disadvantages of each of the single and dual frequency anomaly detectors. For navigation users, the single frequency detectors are sufficient, while for timing users and for data analysis, both single and dual-frequency detectors must be used to guarantee the detection of all feasible cycle slip combinations.

**Table 4.4 Summary of the capabilities of various carrier phase anomaly detectors**

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>General Capabilities</th>
<th>Advantage</th>
<th>Drawback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Frequency (L1)</td>
<td>Detects integer as well as slow cycle slips occurring in the carrier phase measurements on the L1 frequency for reference and/or non-reference satellites</td>
<td>Detects cycle slips occurring simultaneously on the L1 and L2 measurements in certain unique combinations, which could evade detection by the dual frequency detector</td>
<td>Does not detect cycle slips of the same magnitude and direction occurring in the carrier phase measurements on the L1 frequency of all satellites</td>
</tr>
<tr>
<td>Single Frequency (L2)</td>
<td>Detects integer as well as slow cycle slips occurring in the carrier phase measurements on the L2 frequency for reference and/or non-reference satellites</td>
<td>Detects cycle slips occurring simultaneously on the L1 and L2 measurements in certain unique combinations, which could evade detection by the dual frequency detector</td>
<td>Does not detect cycle slips of the same magnitude and direction occurring in the carrier phase measurements on the L2 frequency of all satellites</td>
</tr>
<tr>
<td>Dual Frequency</td>
<td>Detects integer as well as slow cycle slips occurring in the carrier phase measurements on the L1 and/or L2 frequency for one or more satellites</td>
<td>Detects cycle slips occurring with the same magnitude and direction on either the L1 and/or the L2 frequency, which could evade detection from the L1 and/or L2 detectors</td>
<td>Does not detect cycle slips occurring simultaneously on the L1 and L2 measurements in certain unique combinations for one or more satellites</td>
</tr>
</tbody>
</table>
5 DATA COLLECTION PROCEDURE

The Avionics Engineering Center (AEC) of Ohio University maintains two DGPS ground reference stations. One is located at the Ohio University’s airport in Albany, OH and the other at Stocker Center on the university’s campus. Presented below is a brief description of the data collection procedure at both these locations.

5.1 Data Collection at the University Airport

The LAAS Ground Facility (LGF) at the Ohio University airport (KUNI) collects single frequency GPS data, using a network of four Integrated Multipath Limiting Antennas (IMLAs) and a Ziatech dedicated data collection computer. Figure 5.1 is a photograph of one of the four IMLAs installed at the Ohio University’s airport. The IMLA consists of two different antennas, the Multipath Limiting Antenna (MLA) and the High Zenith Antenna (HZA). The MLA is used to track low elevation satellites in the range of approximately $3^0-35^0$ above the horizon and has excellent multipath rejection capability while tracking satellites within this elevation range. The HZA is used to track high elevation satellites in the range of $30^0-90^0$ above the horizon. The hand off angle for the satellites passing from the coverage region of one antenna to/from the coverage region of the other is generally set at $35^0$. 
The prototype LGF software automatically generates GPS data files with the files named in the following format.

File name: g<day of year><year>.xxx

where:
<day of the year> is the GPS day of year when the data were collected
<year> is the year in which the data were collected
xxx is the file number of the day when the data were collected
That is, a file named g2312000.001 would represent the raw data collected on the 231st day of the year 2000 (18 August 2000). The file number indicates the number of files created for that particular day. Here it is one, indicating that only one file was created. Normally one file is created for each day, unless the data collection process was stopped for some reason and restarted, in which case multiple files would be created for the same day. The data files contain binary records in the following format.

\[ \text{<ID><low counter><high counter><data>} \]

where:

<ID> is an integer indicating the serial port number from which the data were obtained;

<low counter> is the low byte of the counter indicating the number of data bytes;

<high counter> is the high byte of the counter indicating the number of data bytes;

<data> counter bytes of data

The data bytes are identical to the data output by the NovAtel receivers. The following messages are included in the data: RGEB and REPB.

5.2 Data Collection at the Stocker Center

Dual frequency GPS data, at 5-second intervals, are collected on a continuous basis at the Ohio University GPS base station located at the Stocker Center. The data are collected by a 12-channel Ashtech Z-12 survey-grade GPS receiver using a patch antenna. Figure 5.2 shows a photograph of the patch antenna located above the Stocker Center at the Ohio University GPS base station.
Figure 5.2 Patch antenna at Stocker Center

The data from the receiver are sent to a PC where files containing one hour’s worth of data are created using the GPS BASE™ software package. These files are posted on the web and can be downloaded from the following location.

http://webeecs.ent.ohiou.edu/avn/gpsbase.html

Figure 5.3 shows the Ashtech Z-12 receiver and the PC that are used in creating these files. The GPS BASE software is seen on the screen of the PC. This reference station is a
part of the Continuously Operating Reference Stations (CORS) network, which is coordinated by the National Geodetic Survey (NGS). [28]

![Data collection setup at the Stocker Center](image)

**Figure 5.3 Data collection set up at the Stocker Center**

The files obtained from the receiver are

1. B-file or the Binary measurement files which contain the pseudorange and Doppler phase measurements.
2. E-file or the Ephemeris file which contains the ephemeris data.
3. ALM-file which contains the Almanac data

All files are referenced to GPS time and are named in the following format.

1. BSTKR<hour><pyear>.<day> for the B-files
2. ESTKR<hour><pyear>.<day> for the E-files
where:

- `<hour>` is the hour indication ranging from A to X where A indicates the 1st hour and X indicates the 24th hour of the day;
- `<pyear>` are the last two digits of the year (00 indicated the year 2000 and so on)
- `<day>` is the GPS day of year

For example: A file formed of the data collected during the 19th hour of the 231st day of the year 2000 would be named as BSTKRT00.231.

The dual frequency data are used for post-processing analysis of the LGF data to observe multipath error and other potential signal anomalies.

### 5.3 Dual Frequency Data Post Processing

The GPS data provided by the Ashtech receiver must be decoded for post processing. This is accomplished with an executable that is created by a FORTRAN program. Before running the program, it is initialized with the following information the first Ashtech file to be read; the output file name; flag for the output format; and the parameter for the minimum smoothing count. Depending on the output option, the output files may contain either of the following two formats.

1. `<time><svprn><iono><elevation><azimuth>`
2. `<time><svprn><pr_CAL1><pr_PL1><pr_PL2><ad_CAL1><ad_PL1><ad_PL2>`
   `<elevation><azimuth><SNR_CAL1><SNR_PL1><SNR_PL2>`

where
<time> is the GPS time of week in seconds;

<svprn> is the satellite pseudorandom noise number;

<iono> is the difference between the L1 and L2 carrier phase in meters;

<pr_CAL1> is the pseudorange measurement on the CA code at the L1 frequency;

<pr_PL1> is the pseudorange measurement on the P-code at the L1 frequency;

<pr_PL2> is the pseudorange measurement on the P-code at the L2 frequency;

<ad_CAL1> is the accumulated Doppler measurement on the C/A-code at L1 frequency

<ad_PL1> is the accumulated Doppler measurement on the P-code at L1 frequency

<ad_PL2> is the accumulated Doppler measurement on the P-code at L2 frequency

<elevation> is the satellite elevation angle, truncated to 0.1 degree;

<azimuth> is the satellite azimuth angle, truncated to 0.1 degree.

<SNR_CAL1> is the signal to noise ratio of the C/A-code measurements on L1 frequency

<SNR_PL1> is the signal to noise ratio on the P-code measurements on L1 frequency

<SNR_PL2> is the signal to noise ratio on the P-code measurements on L2 frequency

The output file is named iono.dat. A file splitter (which is a MATLAB program) is used to split this output file according to the satellite data contained in the file. The resulting files are named sv *.mat where ‘*’ represents the svid of the satellite whose iono data are contained in the file.
5.4 LGF Data Processing

The single frequency data collected at the LGF are processed using the LGF software on a QNX operating system. The output files are named based on the satellite whose data was processed and the antenna that was used in collecting the data as follows:

\[ \text{a<antenna>s<svid>.dat} \]

where:

- \( \text{<antenna>} \) is the antenna number (1 through 8)
- \( \text{<svid>} \) is the satellite prn (1 through 31).

The output files contain the following records:

\[ \text{<time><pr><ad><cno><lock count><elevation><azimuth>} \]

where:

- \( \text{<time>} \) is the GPS time of week in seconds;
- \( \text{<pr>} \) is the pseudorange in meters;
- \( \text{<ad>} \) is the accumulated Doppler shift in wavelengths;
- \( \text{<cno>} \) is the carrier-to-noise ratio in dB-Hz;
- \( \text{<elevation>} \) is the elevation angle in degrees (high resolution);
- \( \text{<azimuth>} \) is the azimuth angle in degrees (high resolution)
The sv*.mat files and the a<antenna>s<svid>.dat files are then copied onto a PC for MATLAB™ multipath processing. A schematic is presented in Figure 5.4, which provides a pictorial description of the entire data collection process explained in the earlier paragraphs.

Figure 5.4 Post processing of GPS data for multipath studies
6 RESULTS

All the carrier phase measurement anomalies identified in this thesis were artificially introduced into the data sets of satellites that were randomly selected from the September 7, 2001 data. The anomaly detection and correction algorithm was then tested using these data sets.

6.1 Corrupted Measurement Data

A single zero-valued corrupted measurement was introduced into the L1 and L2 carrier phase measurements of satellite 3 at the GPS time of 432095 seconds.

![Graph showing L1 and L2 carrier phase measurements for satellite 3 with a single zero-valued corrupted data measurement](image)

Figure 6.1 L1 and L2 carrier phase measurements for satellite 3 with a single zero-valued corrupted data measurement
Figure 6.2 L1 and L2 carrier phase measurements for satellite 3 after the corrupted data measurement correction

The resulting L1 and L2 carrier phase histories are shown in Figure 6.1. The anomalies were successfully detected by the L1 and L2 detectors, respectively and subsequently replaced by their respective estimated measurement values. The corrected L1 and L2 carrier phase histories are depicted in Figure 6.2.

Similarly, a single corrupted carrier phase measurement of an arbitrary value was introduced in the L1 and L2 carrier phase measurements of satellite 13 at GPS time of 432105 seconds. The resulting single and dual frequency residuals are depicted in Figure 6.3. The algorithm detected these anomalies and corrected them accordingly. Figure 6.4 illustrates the single and dual frequency residuals, obtained by using the corrected carrier phase measurements.
Figure 6.3 Single and dual frequency residuals of satellite 13 with a single arbitrary valued corrupted data measurement

Figure 6.4 Single and dual frequency residuals of satellite 13 after the corrupted data measurement correction
6.2 Missing Measurement Data

Three data gaps were introduced into the L1 and L2 carrier phase measurements for satellite 13 at GPS times 432100, 432145 and 432195, respectively. The resulting single frequency carrier phase measurement histories are shown in Figure 6.5. Each of them was successfully detected and the missing measurement value was filled in with its corresponding estimated measurement value. Figure 6.6 shows the corrected L1 and L2 carrier phase measurement histories.

Figure 6.5 L1 and L2 carrier phase measurements with data gaps for satellite 13
6.3 Integer Cycle Slips

The comprehensive anomaly detection and correction algorithm was tested with integer cycle slips occurring in different permutations and combinations on the L1 and/or L2 carrier phase measurements on single and/or multiple satellites. Results pertaining to the most significant of these tests are presented in this document.

First, a whole carrier cycle was introduced into the L1 and L2 measurements of an arbitrarily chosen non-reference satellite (satellite 25). These slips were successfully detected by the single and dual frequency detectors and suitably fixed. Figure 6.7 shows the single and dual frequency residuals for satellite 25 with the uncorrected integer cycle slips present in its measurements. The corrected residuals are shown in Figure 6.8.
Figure 6.7 Single and dual frequency residuals for non-reference satellite 25 with uncorrected integer cycle slips in its measurements

Figure 6.8 Single and dual frequency residuals for non-reference satellite 25 after the cycle slip correction
The same experiment was repeated with the slips being introduced into the L1 and L2 measurements of a reference satellite (satellite 1). Figures 6.9 through 6.12 show the resulting single frequency residuals. It is seen in these plots that all of the single frequency residuals are affected by the slips present in the reference satellite’s measurements since these data are involved in the formation of all of the single frequency residuals. Hence, the single frequency detectors flag every residual formed for that instant with these measurements. On the other hand, since only the measurements of each individual satellite are utilized in the dual frequency residual formation, the dual frequency detector detects the slip only in the residual of satellite 1. The dual frequency residuals for all the satellites (reference and non-reference) tracked during this period are shown in figures 6.13 and 6.14. The cycle slips in the reference satellite’s measurements were subsequently corrected for using the previous outlined correctional procedure. Figures 6.15 through 6.18 show the corrected single frequency residuals. The slip-corrected dual frequency residuals for the reference satellite are shown in Figure 6.19.
Figure 6.9 Single frequency (L1) residuals for all satellite pairs due to an uncorrected integer cycle slip in the reference satellite measurements

Figure 6.10 Single frequency (L1) residuals for all satellite pairs due to an uncorrected integer cycle slip in the reference satellite measurements (continued)
Figure 6.11 Single frequency (L2) residuals for all satellite pairs due to an uncorrected integer cycle slip in the reference satellite measurements.

Figure 6.12 Single frequency (L2) residuals for all satellite pairs due to an uncorrected integer cycle slip in the reference satellite measurements (continued).
Figure 6.13 Dual frequency residuals for all satellites with an uncorrected integer cycle slip in the reference satellite measurements

Figure 6.14 Dual frequency residuals for all satellites with an uncorrected integer cycle slip in the reference satellite measurement (continued)
Figure 6.15 Single frequency (L1) residuals of all satellite pairs after the correction of the cycle slips in the reference satellite measurements

Figure 6.16 Single frequency (L1) residuals of all satellite pairs after the correction of the cycle slips in the reference satellite measurements (continued)
Figure 6.17 Single frequency (L2) residuals of all satellite pairs after the correction of the cycle slips in the reference satellite measurements

Figure 6.18 Single frequency (L2) residuals of all satellite pairs after the correction of the cycle slips in the reference satellite measurements (continued)
Figure 6.19 Dual frequency residuals of reference satellite 1 after the correction of the cycle slips on its measurements.

Next, the comprehensive detector was tested with slips occurring in certain unique combinations on the L1 and L2 frequencies that would go undetected by the dual frequency detector.

One combination of cycle slips that could potentially escape detection by the dual frequency detector is when the L1 measurement slips by 9 carrier cycles and the L2 measurement slips by 7 carrier cycles. This combination was introduced into the measurements of a non-reference satellite (satellite 25). Figure 6.20 shows the resulting single and dual frequency residuals. It is seen in this plot that the combination of carrier phase noise and the cycle slips remain well below the corresponding dual frequency pre-detection threshold. The single frequency detectors, on the other hand, detect the slips on their respective frequencies. These slips were corrected using the correctional procedure
described earlier. Figure 6.21 shows the single and dual frequency detector outputs after the slip correction.

Next the comprehensive detector was tested with cycle slips combinations that could potentially evade detection from the single frequency detectors. One such combination is obtained by introducing a whole carrier cycle slip into the L1 measurements of both the reference satellite (satellite 1) as well as the non-reference satellite (satellite 25). Figures 6.22 and 6.23 show the resulting single frequency (L1) detector output. It is seen here that the slip in the reference satellite is detected in the residuals formed for all the single frequency satellite pairs except for the satellite pair 1-25 as expected. The dual frequency detector, on the other hand, detects the cycle slips on both these satellites as shown in figures 6.24 and 6.25. These slips were corrected by the algorithm and the resulting corrected single frequency residuals are shown in figures 6.26 and 6.27. Similarly Figure 6.28 shows the dual frequency residuals for both the reference and non-reference satellites after the slip correction.
Figure 6.20 Single and dual frequency residuals for non-reference satellite 25 with a unique combination of integer cycle slips in the measurements.

Figure 6.21 Single and dual frequency residuals for the non-reference satellite 25 after the cycle slip correction.
Figure 6.22 Single frequency (L1) residual for all satellite pairs with a unique cycle slip combination in the measurements of reference and one non-reference satellite

Figure 6.23 Single frequency (L1) residual for all satellite pairs with a unique cycle slip combination in the measurements of reference and one non-reference satellite (continued)
Figure 6.24 Dual frequency residuals for all satellites with a unique cycle slip combination in the measurements of reference and one non-reference satellite

Figure 6.25 Dual frequency residuals for all satellites with a unique cycle slip combination in the measurements of reference and one non-reference satellite (continued)
Figure 6.26 Single frequency (L1) residuals for all satellite pairs after the correction of cycle slips on the reference and non-reference satellite measurement

Figure 6.27 Single frequency (L1) residuals for all satellite pairs after the correction of cycle slips on the reference and non-reference satellite measurement (Continued)
6.4 Slow Cycle Slips

To verify the claim made earlier that the integer cycle slip detectors are sensitive enough to detect the occurrence of slow cycle slips a slow cycle slip was introduced into the data set of satellite 27. The rate of the slip was set at 0.1 cycles per measurement epoch which roughly translates to 0.02 cycles per second. Slips below this rate were not considered for the current work due to their low probability of occurrence. The slip was introduced at the 1000th measurement and was allowed to ramp up to a whole integer cycle over ten measurement epochs (1009th measurement) and held constant for the remaining duration of the satellite pass (3844 measurement epochs). The slow cycle slip was introduced into the L1 and L2 measurements of satellite 27 such that at any given time measurements on only one frequency were affected by it. The resulting single and dual frequency detector...
statistics are plotted in Figures 6.29 – 6.32. It is to be noted that the samples numbers at which the slow cycle slip becomes visible in the single frequency residual plots do not match with that of the dual frequency plots. This is because measurements from two different satellite data sets are used in forming the single frequency test statistic, while the dual frequency statistics are derived from individual satellite data sets. Hence, an anomaly introduced at the 1000\(^{th}\) sample in the satellite data set would manifest itself at the same instant (1000\(^{th}\) sample) for the dual frequency plots, while for the single frequency statistics the manifestation will appear at a different sample, depending on when the satellite measurement was combined with the measurement of the other satellite in forming the statistic.

It is seen here that of all the three detectors, only the dual frequency detector was able to detect the slow cycle slip. In the case of single frequency detectors the effects of the slow cycle slip of this rate is seen to be masked by the residual noise and hence remains undetected. For the dual frequency detector the detection depends on the number of successive measurements used in the prediction fit. In this case, 4 successive measurements were used in predicting the next measurement value. Hence, the detection occurs at the 997\(^{th}\) and 1006\(^{th}\) time instants. For the intermediate epochs, it is seen that the dual frequency detector does an excellent job of predicting the next measurement value and hence, the slow cycle slip ramp remains undetected.
Figure 6.29 Dual frequency residuals for satellite 27 with a slow cycle slip in its L1 frequency measurements

Figure 6.30 Dual frequency residuals for satellite 27 with a slow cycle slip in its L2 frequency measurements
Figure 6.31 Single frequency residuals (L1) for satellite pair 31-27 with a slow cycle slip of 0.1 cycles/epoch present in the L1 measurements of satellite 27

Figure 6.32 Single frequency residuals (L2) for satellite pair 31-27 with a slow cycle slip of 0.1 cycles/epoch present in the L2 measurements of satellite 27
The experiment was repeated several times with increasing rates of the slow cycle slip by 0.5 cycles/measurement epoch each time. This was done to establish the minimum detectable rate of the slow cycle slips by the single frequency detectors. For the L1 detector, the minimum detectable rate was found to be 0.30 cycles/measurement epoch while for L2 detector this value was found to be 0.20 cycles/measurement epoch. The wavelength corresponding to the L2 frequency is greater than that of L1 frequency. Hence, the slow cycle slip impacts the L2 measurements more than the L1 measurements. Therefore, the minimum detectable slip rate for the L2 is smaller than that of the L1 detector. Figures 6.33 and 6.34 show the L1 and L2 residuals with the slow cycle slips in their corresponding measurements.

It is seen again that the slow cycle slip is detected at two separate instants. The first detection occurs right at the instant where the slip is introduced into the data set. The second detection occurs a couple of epochs after the slow cycle slip ramps up to a whole cycle slip, after which it stops growing. Since the single frequency detector statistics are formed by triple differencing, at least two of the three successive measurements involved should have no cycle slip increase in order to detect the slip. For all intermediate time epochs, the gradual increase in the slip size in successive measurements is masked by the triple differencing.
Figure 6.33 Single frequency residuals (L1) for satellite pair 31-27 with a slow cycle slip of 0.3 cycles/epoch in the L1 measurements of satellite 27

Figure 6.34 Single frequency residuals (L2) for satellite pair 31-27 with a slow cycle slip of 0.20 cycles/epoch in the L2 measurements of satellite 27
7 SUMMARY AND CONCLUSIONS

Various possible anomalies that degrade the integrity and accuracy of the carrier phase measurements were identified as a part of this research. These are listed below.

1. Cycle slips including whole cycles, half cycles, and slow cycle slips
2. Fractional or slow cycle slips
3. Loss of lock
4. Missing measurement data
5. Corrupted or bad data measurement data

A set of algorithms was developed in order to detect and, if possible, correct each type of anomaly identified above. Both single and dual frequency detectors were developed. Pre-detection and post-detection threshold values were derived for detectors based on the assumption that the test statistics exhibit Gaussian properties. This assumption was found to be valid in the subsequent analysis. When operated individually each of the detectors exhibit inherent weaknesses in detecting certain unique combinations of integer cycle slips. Further investigation revealed that the detectors compensate for each other’s weaknesses when operated simultaneously. Thus the individual detectors were combined to form a comprehensive carrier phase anomaly detector. Logic was developed to combine the outputs of the individual detectors to determine the identity of the satellite and the frequency in which the anomaly occurred. All of the above identified anomalies were artificially introduced into a 24-hour satellite data set and tested against the comprehensive detector. The comprehensive detector was found to successfully detect all
the listed anomalies. Table 7.1 lists the corresponding corrective action initiated by the
algorithm for each of the anomalies.

<table>
<thead>
<tr>
<th>Type Of Anomaly</th>
<th>Initiated Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single missing measurement data</td>
<td>Fill in the data</td>
</tr>
<tr>
<td>Multiple missing measurement data</td>
<td>Flag the satellite</td>
</tr>
<tr>
<td>Brief loss of lock</td>
<td>Flag the satellite</td>
</tr>
<tr>
<td>Single corrupted measurement data</td>
<td>Fill in the data</td>
</tr>
<tr>
<td>Multiple corrupted measurement data</td>
<td>Flag the satellite</td>
</tr>
<tr>
<td>Integer cycle slip</td>
<td>Fix the cycle slip</td>
</tr>
<tr>
<td>Slow Cycle Slip</td>
<td>Flag the satellite</td>
</tr>
</tbody>
</table>

In situations where a corrective action was not feasible or the initiated action failed to
correct the anomaly, the corresponding satellite was no longer used.


8 RECOMMENDATIONS FOR FURTHER WORK

Throughout this effort, several items were identified for further research. These items include:

1. Increasing the logic to handle corrupted data by recognizing that the subsequent measurements are consistent with the measurement phase history before the corrupted measurement data.

2. Research into characterization of the effects of Radio Frequency Interference and its impact on the assumptions made for the slow cycle slip detector.

3. Developing methods to accommodate multiple consecutive anomalies.

4. Investigating the use of RAIM for slow cycle slips when a redundant set of measurements is available.
REFERENCES


[28] http://www.ngs.noaa.gov/CORS (Date visited: 05/02/04)
The Ashtech GPS receiver does not make measurements at precisely 5-second intervals because of the bias in its reference clock. Figure 10.1 shows the receiver clock offset recorded in the data set for satellite 27 on September 7, 2001. It is observed here that the receiver clock jumps occur approximately every 43 minutes.

![Figure 10.1 Receiver clock offset for satellite 27 (September 7, 2001)](image)

The effect of the receiver clock jumps on the single frequency residuals is shown in figures 10.2 and 10.3, respectively. The single frequency residuals are plotted for the satellite pair 31-27 using the September 7, 2001 data. As seen from these figures receiver clock jumps, when left uncorrected, introduce large biases in the test statistics of the single frequency detectors. These biases could easily be misdiagnosed as cycle slips resulting in an inappropriate corrective action.
Figure 10.2 Effect of the receiver clock jumps on the single frequency residuals (L1) for satellite pair 31-27 (September 7, 2001)

Figure 10.3 Effect of the receiver clock jumps on the single frequency residuals (L2) for satellite pair 31-27 (September 7, 2001)
The effects of the receiver clock bias can be removed by using time–normalized carrier phase triple differenced measurements instead of the absolute differenced values. The time–normalized carrier phase measurements are obtained by computing the per-second value of the accumulated Doppler difference using the precise time difference between successive measurement epochs. Receiver clock jumps have also been observed and documented in some of the earlier work done in the detection and correction of cycle slips. [3]