



**SIGNAL DEFORMATION ANALYSIS OF THE
GLONASS CONSTELLATION USING CHIP
SHAPE PROCESSING**

THESIS

Mark J. Wireman, Capt, USAF
AFIT-ENG-MS-17-M-082

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Abstract

The objective of this thesis is to use advanced chip shape correlation processing techniques to characterize the Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) system and provide confidence for potentially using GLONASS to increase resiliency and signal diversity in the event of Global Positioning System (GPS) denial. Authenticated use of GLONASS would also provide additional Global Navigation Satellite Systems (GNSS) resources for improving accuracy and redundancy to our current GPS satellite constellation in the event of GPS outages as well as increasing the available number of satellites for robust positioning and timing. Software algorithms that could authenticate the Russian GLONASS C/A code may allow for the safe integration of foreign GNSS signals into certain Air Force systems.

AFITs chip shape processing-based software receiver was modified to compute measurements and observables vital for signal characterization for GLONASS. Live-sky data was then collected using AFITs existing Transform-Domain Instrumentation GNSS Receiver (TRIGR) SDR data collection equipment. Characterization of the GLONASS constellation was then completed after the data was analyzed utilizing the newly developed algorithms. Signal deformations using chip shape were analyzed and conclusions drawn to determine whether observed characteristics were due to front-end, multipath or satellite-borne natural signal deformation.

Utilizing chip transition eye diagrams, the data was analyzed and interpreted for uniqueness and consistency. Data from every satellite in the GLONASS constellation was gathered and examined. Each satellite's natural signal deformations were determined and cataloged for interpretation and conclusions. Each satellite provides visible deformations capable of being used for authentication with further development.

Table of Contents

	Page
Abstract	iv
List of Figures	vi
List of Tables	xi
I. Introduction	1
1.1 Background	1
II. Theory and Background	6
2.1 Satellite Navigation Fundamentals	6
2.1.1 Pseudorange Measurement and PNT Solutions	6
2.1.2 Clock Corrections	9
2.1.3 GNSS Errors	11
2.2 GLONASS Theory	14
2.2.1 GLONASS Specifications	16
2.2.2 GLONASS Ground Segment	19
2.2.3 GLONASS Signal Structure	20
2.2.4 Receiver Signal Processing	34
2.3 Correlation Functions	36
III. Methodology	45
3.1 Universal GNSS Toolbox	45
IV. Results	55
4.1 Data	55
4.1.1 Simulation	57
4.1.2 Live-Sky	64
V. Conclusion	79
Bibliography	82
Appendix A	85
0.1 Chip Shape Plots	85

List of Figures

Figure	Page
1. SBAS Regions [1]	3
2. Pseudorange Measurements	8
3. GLONASS Overview [2]	9
4. Signal Transmit Correction [3]	10
5. Positioning Algorithm	11
6. Group Delay Overview	14
7. GLONASS Constellation [4]	17
8. GLONASS Frequency Band of GLONASS L1 [5]	20
9. GLONASS Frequency Band of L2 and L3 [5]	21
10. GLONASS Shift Register [6]	25
11. Correlation Peak Development	27
12. Spectral Lines [7]	28
13. Satellite Acquisition [8]	31
14. Satellite Navigation Bands [5]	32
15. In-Phase Correlation	33
16. Inverted Correlation	33
17. System Front-End	35
18. Group Delay Response of a SAW filter	36
19. Group Delay Response of a L1 Ceramic Filter	36
20. Optimal Correlation Function	37
21. Satellite Tracking [8]	38
22. Digital Distortion	39

Figure	Page
23. Analog Distortion	39
24. "Universal" ChipShape Correlator [9]	41
25. Eight Orthogonal ChipShape Correlator Functions [9]	42
26. Chip Shape Eye Diagram	43
27. NovAtel GNSS-750 Antenna	46
28. System Front-End	47
29. Normalized Chip Shape Function for GPS Observed Through a SAW Filter [10]	48
30. Signal Acquisition Data	50
31. Acquired Signal	50
32. GLONASS Satellite Elevations for 6-8 November 2016	51
33. GLONASS NPN Masked Chip Shape	56
34. GLONASS NNN Masked Chip Shape	56
35. Simulated Normalized $R'(\tau)$ Component for the SAW Filter	57
36. Simulated Normalized $R'(\tau)$ Component for the RF Ceramic Dielectric Resonator Filter	58
37. SAW Filter Correlation Triangle	59
38. RF Ceramic Dielectric Resonator Filter Correlation Triangle	59
39. Simulated early minus late (EmL) Discriminator Function for SAW Filter	60
40. Simulated EmL discriminator function for L1 Ceramic Filter	61
41. Simulated Estimated pseudorange (PR) Natural Biases with Respect to 0.1 Correlator Spacing for SAW Filter	62

Figure	Page
42.	Simulated Estimated Pseudorange Natural Biases with Respect to 0.1 Correlator Spacing for L1 Ceramic Filter.....63
43.	Chip Shape Components for Cosmos 2516; PRN 0 on 6 November 2016, first orbit 65
44.	Chip Shape Components for Cosmos 2516; PRN 0 on 6 November 2016, second orbit 65
45.	Chip Shape Components for Cosmos 2516; PRN 0 on 7 November 2016 66
46.	Chip Shape Components for Cosmos 2516; PRN 0 on 8 November 2016 66
47.	Chip Shape Components for Cosmos 2475; PRN 6 67
48.	Normalized $R'(\tau)$ Components of GLONASS Constellation Observed on 7 November 68
49.	Normalized $R'(\tau)$ Functions for GLONASS Constellation Observed on 7 November 2016: Falling Edge 69
50.	Normalized $R'(\tau)$ Quadrature Functions for GLONASS Constellation Observed on 7 November 2016: Rising Edge 69
51.	Correlation Functions for GLONASS Constellation Observed on 7 November 2016 70
52.	Early minus Late Code Discriminator Function 71
53.	Estimated Pseudorange Natural Biases with Respect to 0.1 Correlator sSpacing for GLONASS on 7 November 2016 72
54.	SV Chip Shape Metric Variation Across Testing Period 76
55.	Cosmos 2434; PRN 13 Natural Biases 77
56.	Cosmos 2434; PRN 13 Correlator Functions 78
57.	Chip Shape Components for Cosmos 2492; PRN -3 85
58.	Chip Shape Components for Cosmos 2433; PRN 3 86

Figure		Page
59.	Chip Shape Components for Cosmos 2424; PRN -7	86
60.	Chip Shape Components for Cosmos 2516; PRN 0	87
61.	Chip Shape Components for Cosmos 2500; PRN 4	87
62.	Chip Shape Components for Cosmos 2465; PRN -1	88
63.	Chip Shape Components for Cosmos 2457; PRN -4	88
64.	Chip Shape Components for Cosmos 2434; PRN -2	89
65.	Chip Shape Components for Cosmos 2459; PRN -3	89
66.	Chip Shape Components for Cosmos 2477; PRN 5	90
67.	Chip Shape Components for Cosmos 2475; PRN 6	90
68.	Chip Shape Components for Cosmos 2460; PRN 3	91
69.	Chip Shape Components for Cosmos 2456; PRN 1	91
70.	Chip Shape Components for Cosmos 2461; PRN 2	92
71.	Chip Shape Components for Cosmos 2514; PRN 4	92
72.	Chip Shape Components for Cosmos 2485; PRN -4	93
73.	Chip Shape Components for Cosmos 2492; PRN -3	93
74.	Chip Shape Components for Cosmos 2465; PRN -1	94
75.	Chip Shape Components for Cosmos 2433; PRN 3	94
76.	Chip Shape Components for Cosmos 2476; PRN 5	95
77.	Chip Shape Components for Cosmos 2434; PRN -2	95
78.	Chip Shape Components for Cosmos 2424; PRN -7	96
79.	Chip Shape Components for Cosmos 2474; PRN 6	96
80.	Chip Shape Components for Cosmos 2425; PRN 0	97
81.	Chip Shape Components for Cosmos 2458; PRN 1	97
82.	Chip Shape Components for Cosmos 2457; PRN -4	98

Figure		Page
83.	Chip Shape Components for Cosmos 2477; PRN 5	98

List of Tables

Table	Page
1	GLONASS Constellation Status as of 8 Dec 16 [11] 18
2	GLONASS L1 Specifications 22
3	GLONASS L2 Specifications 23
4	GPS Link Budget [12] 24
5	GLONASS System Characteristics [13] 24
6	GLONASS carrier frequencies 30
7	Universal GNSS Software Receiver Toolbox settings 52
8	Cosmos 2516; PRN 0 Elevation Data 67
9	PR Error Results (m) observed at 0.2 correlator spacing 73
10	Chip Shape Differentials for 7 Nov 16 74
11	Chip Shape Differentials for GLONASS Constellation..... 75

SIGNAL DEFORMATION ANALYSIS OF THE GLONASS CONSTELLATION USING CHIP SHAPE PROCESSING

I. Introduction

1.1 Background

Navigation has always played a pivotal role in human development and expansion of influence. Those able to bring their influence to bear on allies and enemies alike dominate the world's political realm. To this end, in 1973 the United States developed the GPS to enable influence projection around the world. In response to this, the Soviet Union launched its own system called GLONASS. As with GPS, GLONASS was designed for military applications but included civilian signals. Both GNSS systems also included a constellation of 24 satellites. The first operational satellite was launched in 1982, but complete deployment did not occur until 1995. In contrast to GPS and GLONASS, the European system of Galileo was primarily intended for civilian use. Intended as a neutral technology, the European Union is making the Galileo full precision, which is normally reserved for only military application, available to both military and civilian users. In 2014, the first two IOV satellites were launched with the system scheduled to be fully operational by 2020. Finally, China has been building its own GNSS system called BeiDou Navigation Satellite System (BDS), also known as BeiDou-2. BeiDou, translated as Great Bear or Big Dipper, first launched in 2000 consisting of 3 satellites. This initial launch was intended to be an experimental, limited test system. The fully operational system of BeiDou-2, formally known as COMPASS, will consist of 35 satellites and is planned for full

global coverage by 2020. This constellation will include 5 geostationary satellites, 27 satellites in Medium Earth Orbit (MEO) and 3 satellites in inclined geosynchronous orbit. Most navigation satellites utilize MEO for a variety of reasons. This precise orbit ensures biases are kept to a minimum by providing a constant altitude and velocity. It is also easier to transmit information to MEO satellites from low-power transmitters and relatively small antenna due to their close proximity to the Earth. Finally, it also allows for a greater coverage of the Earth, requiring fewer satellites than a Low Earth Orbit (LEO) [14].

In order to improve quality, GNSSs can be augmented by supplementary systems. Satellite-Based Augmentation System (SBAS) improves overall positioning accuracy by providing error corrections. These corrections are transmitted through geostationary satellites in the same band as the core GNSS constellation. Using this information, the GNSS system increases accuracy, reliability, and availability of positioning [1]. There are currently four SBAS in use as seen in Figure 1. The Wide Area Augmentation System (WAAS) is used by the United States, the European Geostationary Navigation Overlay Service (EGNOS) is used by Europe, the GPS Aided GEO Augmented Navigation (GAGAN) is used by India and finally the Multi-functional Transport Satellite (MTSAT) Satellite Augmentation System (MSAS) used by Japan.



Figure 1. SBAS Regions [1]

Ground Based Augmentation System (GBAS) are also used to improve GNSS positioning, navigation and timing (PNT) performance. These systems provide differential corrections to pseudorange (PR) measurements in order to remove errors incurred during transmission. PR measurements will be discussed later in this thesis. GBAS systems are in use throughout the world and broadcast corrections to a localized area.

In addition to GNSS, there are regional systems that can provide supplementary signals from satellites operating over a specific geographical area. One such system, developed by Japan, is the Quasi-Zenith Satellite System (QZSS). QZSS works in conjunction with GPS and consists of three satellites in inclined geostationary orbit operating over Japan. With unique areas such as Tokyo, Japan's urban sprawl creates challenges for GNSS systems. QZSS helps mitigate these challenges and enables accurate positioning, in spite of the large surrounding structures.

Another regional system, the Indian Regional Navigation Satellite System (IRNSS),

includes three geostationary satellites and four satellites in geosynchronous orbit. This system was developed for a plethora of reasons including disaster management, mobile phone integration, marine navigation and to facilitate research and development. [15].

Many other world powers are moving away from utilizing GPS as their primary GNSS system and have begun designing and building their own. The launch rate of new GNSS satellites is increasing around the globe, providing exploitation opportunities for these new constellations. In the event of degradation or denial, this will provide additional resources for improved accuracy and redundancy to our current GPS satellite constellation. However, incorporating the signals from these foreign constellations will require confidence in the integrity of the system. Signals generated from a foreign system could be manipulated or altered by the controlling governments or institutions of said systems. Ensuring the signals fidelity is paramount to a secure and trustworthy integration of these foreign systems. The first step in this process is monitoring and characterization of these systems at all possible layers of abstraction such as signals, navigation data message, ephemeris, clock correction model or other correction model terms. Monitoring of signals, data messages, orbits, outages and any anomalies are key to understanding the subtle nuances of these systems. GLONASS is one of the oldest and most complete systems available. It is also the only other fully operational GNSS, the other being GPS. Examining these signals, using high fidelity signal processing techniques, will provide critical insight into GLONASS. Chip-shape analysis methods, which are capable of discerning anomalies for GNSS signals, have never been previously applied to GLONASS and represents a significant undertaking. The distortions and other anomalies of the satellite become apparent while utilizing the chip-shape analysis method. By using this technique, we can see distortions due to the satellite's payload electronics transfer function, the receiver electronics transfer

function and the 'channel' transfer function. By characterizing our own equipment and isolating the distortion of only the satellite, we can effectively differentiate the hardware of the satellite, which will provide insight into its architecture [16]. This will ensure the signal is genuine and unaltered, therefore providing the trust needed to confidently utilize the system safely. Successfully trusting and integrating these systems into the Air Force systems may provide needed robustness and frequency diversity. GNSS denial will be more complicated, requiring additional power and size to deny not only the GPS frequency bands, but GLONASS as well. This will make opposition systems easier to detect and counter.

II. Theory and Background

2.1 Satellite Navigation Fundamentals

2.1.1 Pseudorange Measurement and PNT Solutions.

GNSS is a form of navigation utilizing radio signals transmitted from a group of satellites (constellation) which are used to calculate precise time and a three-dimensional location anywhere on Earth. These radio signals are passive and include navigation data messages of the satellite, as well as the precise time the signal was transmitted. The precise time is determined using an on-board cesium or rubidium atomic clock. These atomic clocks measure frequency with an accuracy of 3×10^{-14} , or 2 nanoseconds of drift per day. In order to generate a three-dimensional location on Earth, PR measurements are required. The PR measurements are range calculations made by utilizing time-of-arrival (TOA) of the satellite's radio signals to determine the difference between transmit and receive time. This describes the time it takes for a satellite's signal to reach a receiver, which is then multiplied by the speed of light. The satellite and receiver clocks are not synchronized resulting in range errors. The measured range contains further errors accumulated between transmission and receipt. Because of these range errors, the prefix "pseudo" is given to range. We use these pseudorange calculations for all GNSS position fixes. The general equation for these calculations can be seen in Equation 1.

$$\begin{aligned}\rho_1 &= \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} + c\delta t_u \\ \rho_2 &= \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} + c\delta t_u \\ \rho_3 &= \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} + c\delta t_u \\ &\vdots \\ \rho_n &= \sqrt{(x_n - x_u)^2 + (y_n - y_u)^2 + (z_n - z_u)^2} + c\delta t_u\end{aligned}\tag{1}$$

The PR measurement denoted as ρ_n indicate the measurements made by the receiver for n number of satellites. x_n , y_n and z_n are the Earth Centered Earth Fixed (ECEF) coordinates of satellite n while x_u , y_u and z_u are the ECEF coordinates of the user; c is the speed of light and δt_u is the users' clock bias. The users' clock has a bias as it cannot be completely calibrated to the satellite. The difference between the receiver's clock and the satellite therefore contains an unknown clock bias. Each satellite variable in Equation 1 requires a separate satellite to broadcast a message for triangulation. Since there are four unknowns (x_u , y_u , z_u and δt_u), four equations are required to solve for range. However, a much larger constellation is required for global coverage or improved performance. More satellites in view of the receiver produce additional measurements that improve the accuracy of the position estimates.

Solving for these PR equations is well known with GNSS systems and is beyond the scope of this thesis. For full explanation on solving for these equations, refer to [17].

PR measurements between transmission and receipt can be simplified and expressed as Eq. 2.

$$PR = c (ToR - ToT) \quad (2)$$

In this equation, PR is pseudorange, c is the speed of light, Time of Receipt (ToR) is the time at which the receiver receives the signal, and finally the time of satellite signal broadcast is the Time of Transmission (ToT). When the satellite transmits PRN code, the receiver generates an exact replica of the code. The signal will travel through the atmosphere and be seen by the receiver. After comparing the transmitted code to its replica and accounting for the user's clock bias, the receiver can calculate the signals travel time. By multiplying that signal by the speed of light, this will give the range between the satellite and the receiver. This general process can be seen in

Fig. 2.

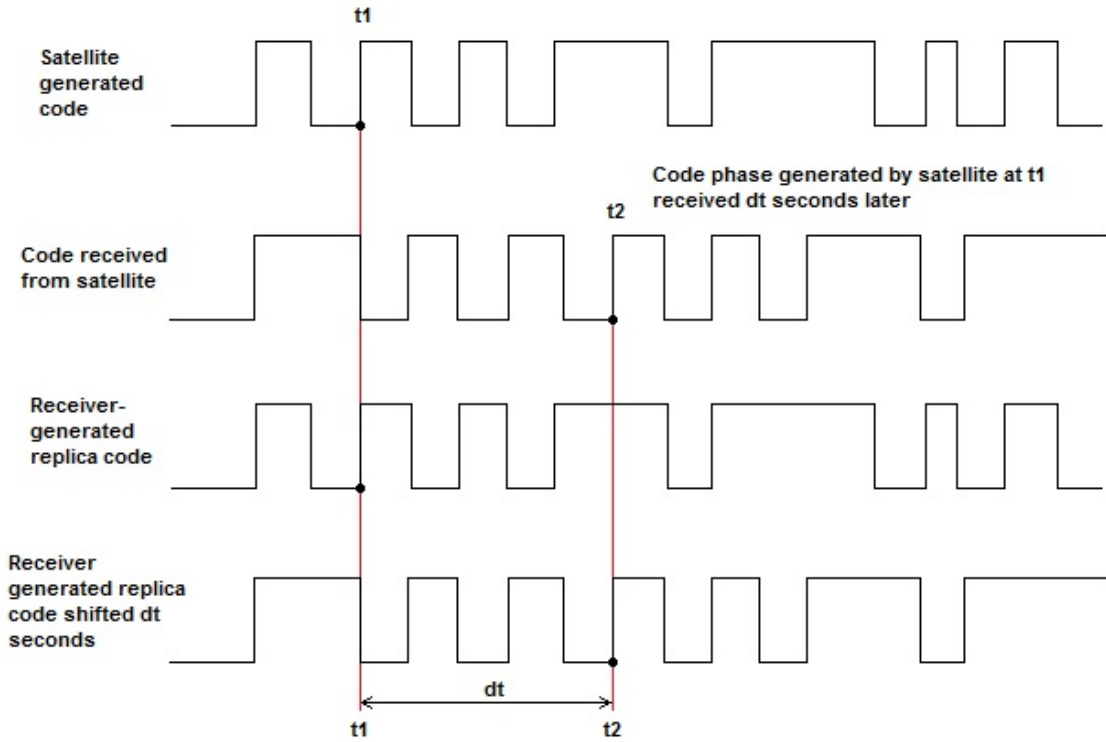


Figure 2. Pseudorange Measurements

The receiver continuously aligns its locally-generated replica carrier and code to the incoming signal in a process known as tracking. This continuous process is known as the code and carrier tracking loops. The PR calculations are then computed once the carrier and code tracking loops converge and achieve a steady-state. The code tracking loop continuously repeats this process to ensure the code arriving from the satellite continues to match the receiver replica code.

Ground control segments monitor GNSS satellites and make determinations on the health of the constellation. The ground control segment computes orbital parameters that are uploaded to the satellites in order to rebroadcast in the nav messages so the users can compute the satellites position for PNT solutions. Fig. 3 is a diagram of the

functionality of the GLONASS system with a civilian system accompanying it. Each transmission seen in Fig. 3 potentially adds PR errors that must be corrected. In this figure, “Gonets” monitors and transmits GLONASS data to track the movements of mobile assets such as commercial vehicles, trains or aircraft. This data is then transferred to ground stations where it is uploaded to the internet for users to track. The GLONASS system does not need “Gonets” and this plot is for identification purposes of the various points of error introduction.

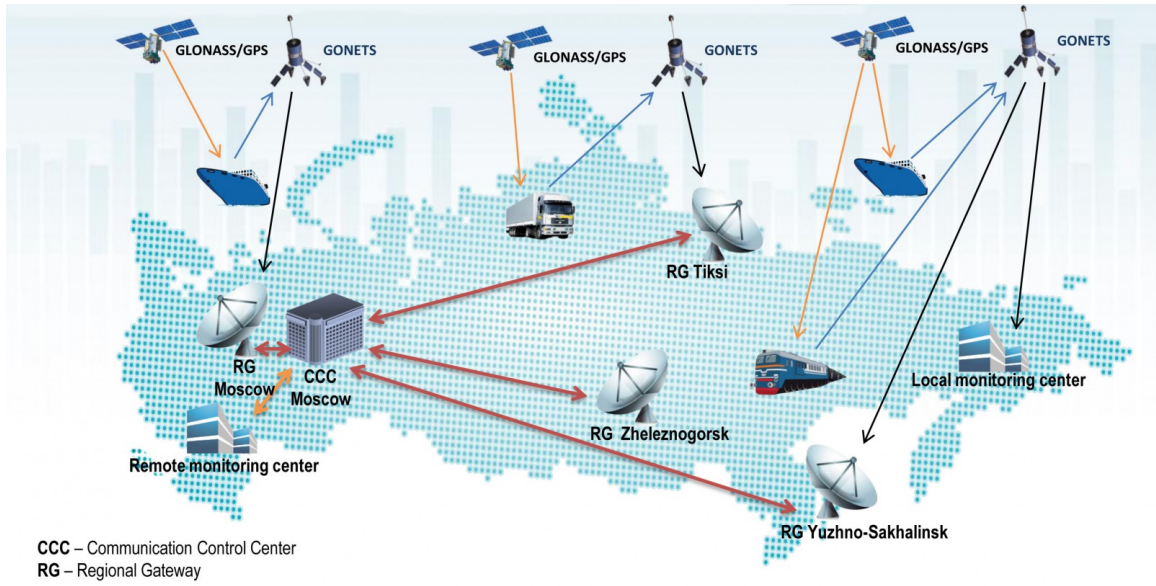


Figure 3. GLONASS Overview [2]

2.1.2 Clock Corrections.

Even though navigation satellites use extremely accurate clocks that are synchronized to its GNSS system time, these clocks drift slightly over long intervals. Hence it is necessary to measure and model these clock errors and send the model to the user so that the errors can be removed from the measured pseudoranges. Unlike GPS, which uses a second order polynomial for clock corrections, GLONASS only considers the first order polynomial.

These clock correction equations can be seen in Eq. 3:

$$c \cdot \Delta \cdot t_{SV} = t + \tau_c + \tau_n(t_b) - \gamma_n(t_b)(t - t_b) \quad (3)$$

where t is the GLONASS satellite time, τ_c and $\tau_n(t_b)$ are satellite broadcast clock offset correction factors, $\gamma_n(t_b)$ is a relativistic frequency correction and Δ is a constant time scale factor to the UTC standard [18]. The arrival time of the code is represented in receiver time and is computed by utilizing the code tracking loop. Eq. 3 is then used to correct for satellite clock error.

We can now determine the satellites position through signal transmission time.

$$T_u + \delta t_{rcvr} - \frac{\rho}{c} = T_s + \Delta t_{SV} \quad (4)$$

$T_u + \delta t_{rcvr}$ is the receiver time, T_s is the true GNSS transmit time and ρ is the pseudorange measurement. Fig. 4 illustrates the equations functionality in a simple diagram.

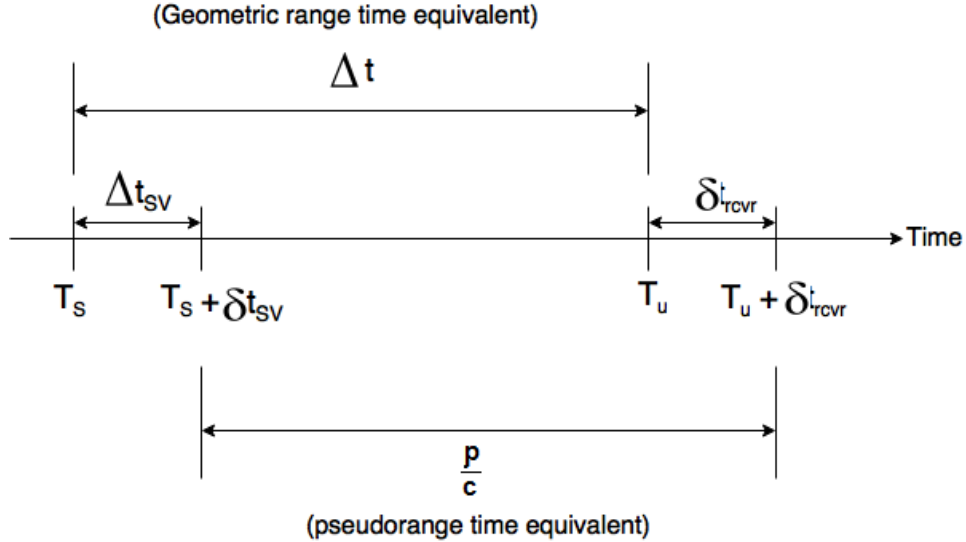


Figure 4. Signal Transmit Correction [3]

2.1.3 GNSS Errors.

Errors can be introduced at several points in the process. These range errors translate into corresponding positioning and timing errors. When determining position solution, the block diagram is displayed in Fig. 5.

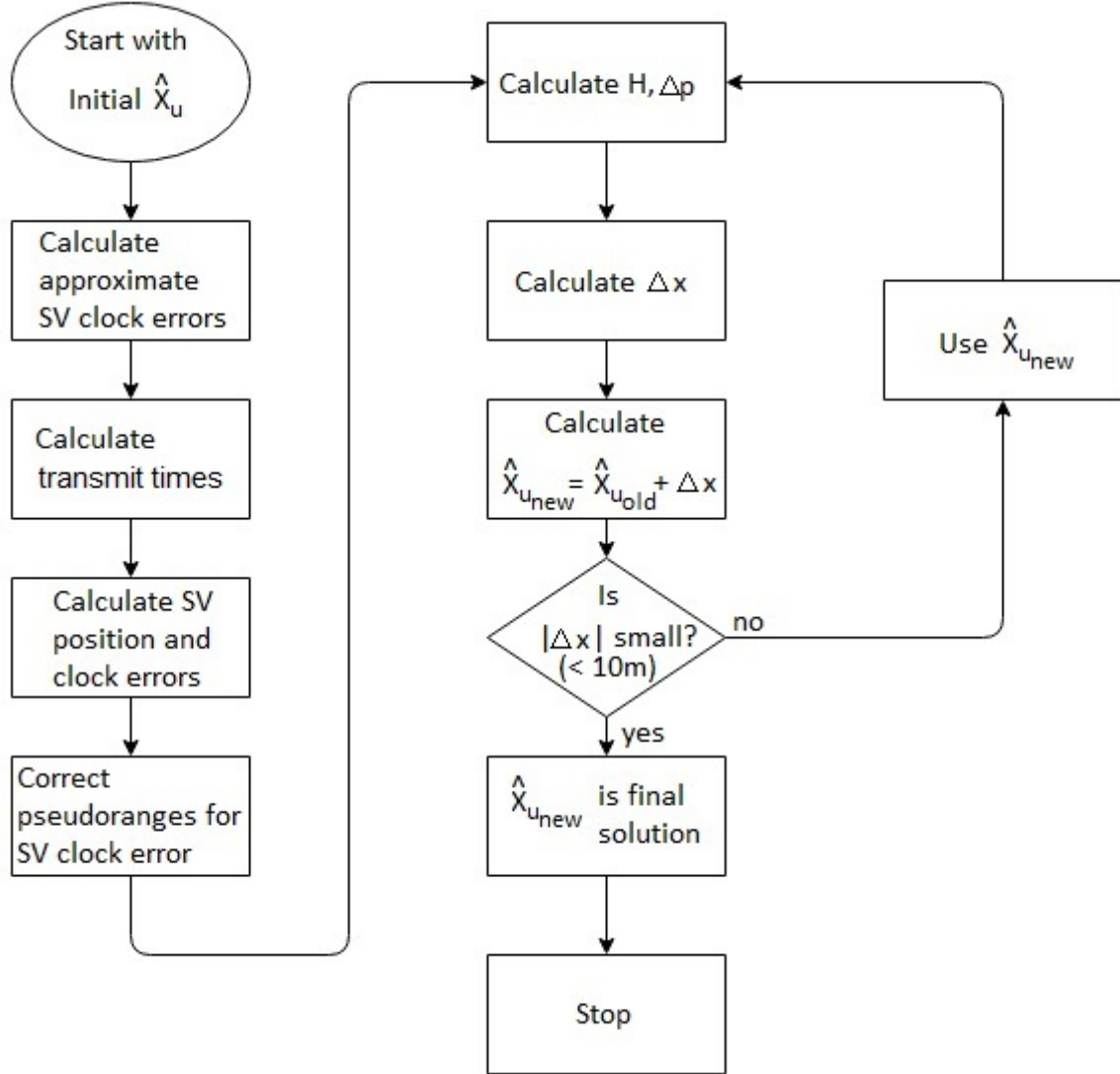


Figure 5. Positioning Algorithm

Here, $\hat{x}_u$ is the "nominal solution" chosen, Δp are the linearized equations, H are simplified pseudorange equations and Δx are the basic least-squares solution.

A nominal solution is chosen and approximate pseudorange calculations are made. The relationship between the true and approximate position are then determined. Using these equations we can calculate the simplified pseudorange equations and the linearized equations. Throughout this process, errors are being introduced and must be corrected for.

Errors are constantly present in any GNSS system and they must be mitigated or corrected. Various methods are employed to correct these errors including error models, improved receiver processing algorithms, use of externally generated data or differential GPS. At times, a combination of correction techniques is needed as some methods are only effective against specific errors. However, these correction techniques are beyond the scope of this thesis and will not be discussed. All non-clock errors are combined and contribute to a drift in the solution as seen in Eq. 5.

$$\delta t_D = \delta t_{iono} + \delta t_{trop} + \delta t_{noise} + \delta t_{mp} + \delta t_{hw} \quad (5)$$

δt_D is the total timing error, δt_{iono} is ionospheric delay, δt_{trop} is tropospheric delay, δt_{noise} is receiver noise, δt_{mp} is multipath error and finally δt_{hw} is hardware errors.

Ionospheric errors are caused by weakly ionized plasma in the atmosphere that can affect GNSS signals. These errors are caused by ultraviolet radiation from the sun that can manifest charged particles in the form of free floating "bubbles" in the atmosphere. These "bubbles" vary in size and location. Due to these variations, ionospheric errors vary by time of day, location and solar activity.

Tropospheric errors can be defined as simple atmospheric errors. These variables can be described in the Eq. 6. These include refraction of the signal which is denoted as $\frac{c_v}{c_m}$, velocity of a signal in a medium c_v , velocity of a signal in a vacuum c_m , and error due to the path curvature δ_g . The atmospheric errors vary with humidity levels

and are more unpredictable in wet areas.

$$\delta t_{trop} = \int_{path} \left(\frac{c_v}{c_m} - 1 \right) ds + \delta_g \quad (6)$$

Hardware errors consist of inter-frequency bias or inter-channel bias. GLONASS currently utilizes the Frequency Division Multiple Access (FDMA) method to distinguish different signals from individual satellites in the constellation. These biases can be modeled as a linear function of a frequency number and are consistent for all receivers of a given type [19]. This bias can be interpreted as a group delay offset between the channels used by GLONASS and will be different based on the frequency of the device. Fig. 6 outlines the group delay response of the system with two GLONASS signals and the differences based on frequency. The group delay response of the system is displayed here in dark blue and represents the different delays experienced by signals at different frequencies. The first GLONASS signal will have a different group delay response than GLONASS signal 2. Because of the FDMA method used by GLONASS, this variation will compound the problem as the signals will not be delayed by the same amount of time throughout the front-end. This will incur errors on Eq. 3 as seen in Eq. 7. This will in turn produce errors on the PR equations.

$$\delta t_{SV_{L1}} = \delta t_{SV} - T_{GD} \quad (7)$$

Here, T_{GD} is group delayed differential parameter and $\delta t_{SV_{L1}}$ is the clock correction for L1 [20].

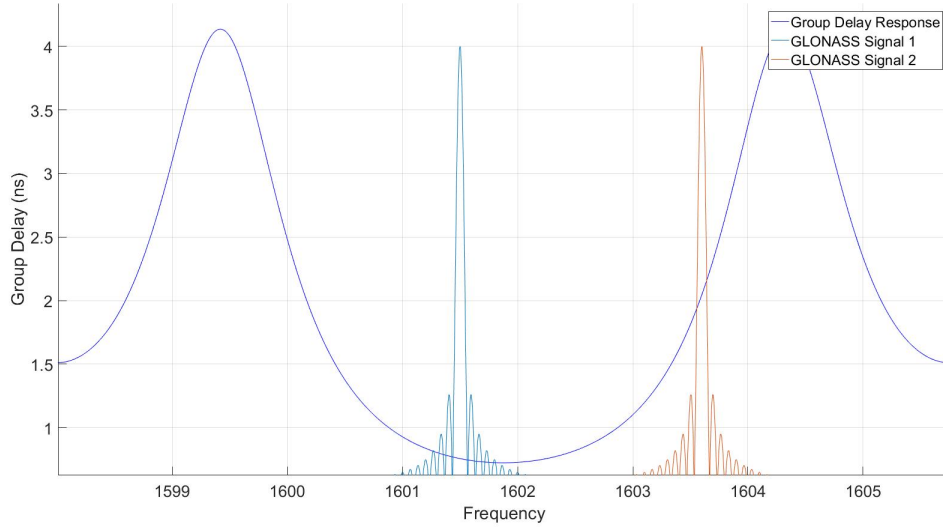


Figure 6. Group Delay Overview

Another significant error source is multipath which are caused by reflected signals bouncing off geographic features of the terrain at the receiver's location. Since terrain features are always present, multipath error is always attributing some kind of bias on each code range measurement. Multipath bias is one of the most difficult errors to remove. Instead, it must be mitigated through ground planes, advanced signal processing techniques or a choking-antenna. This antenna is enclosed in concentric rings that block signal ground reflections and other low elevation signals.

2.2 GLONASS Theory

GLONASS uses ephemeris and almanac data, provided in the navigation message, to calculate the velocity and the coordinates of the satellites. In order to accomplish this calculation, the satellites velocity and initial position, at time t_b , are required. Also required for the calculations are the acceleration, satellite clock offset and Doppler corrections. The technique used by GLONASS to make its calculations

involves numerical integration of these differential equations to describe the motion. These calculations include the lunar and solar perturbations due to various gravitational forces acting on the satellite. Once the parameters are identified and obtained from the satellite via the navigation message, they are used to solve for the satellites position at time t_b . The differential equations used by GLONASS are:

$$\frac{dx_o}{dt} = Vx_o \quad (8)$$

$$\frac{dy_o}{dt} = Vy_o \quad (9)$$

$$\frac{dz_o}{dt} = Vz_o \quad (10)$$

$$\frac{dVx_o}{dt} = -\bar{\mu}\bar{x}_o + \frac{3}{2}C_{20}\bar{\mu}\bar{x}_o\rho^2(1 - 5\bar{z}_o^2) + j_{x_{os}} + j_{x_{om}} \quad (11)$$

$$\frac{dVy_o}{dt} = -\bar{\mu}\bar{y}_o + \frac{3}{2}C_{20}\bar{\mu}\bar{y}_o\rho^2(1 - 5\bar{z}_o^2) + j_{y_{os}} + j_{y_{om}} \quad (12)$$

$$\frac{dVz_o}{dt} = -\bar{\mu}\bar{z}_o + \frac{3}{2}C_{20}\bar{\mu}\bar{z}_o\rho^2(1 - 5\bar{z}_o^2) + j_{z_{os}} + j_{z_{om}} \quad (13)$$

$$r_o = \sqrt{(x_o^2 + y_o^2 + z_o^2)} \quad (14)$$

$$\mu = \frac{\mu}{r^2}, \bar{x}_o = \frac{x_o}{r}, \bar{y}_o = \frac{y_o}{r}, \bar{z}_o = \frac{z_o}{r}, \rho = \frac{a_e}{r}$$

where κ is the index for a perturbing body; values of κ vary from m which indicates "lunar" and s which indicates "solar". Here, $j_{x_{os}}, j_{y_{os}}, j_{z_{os}}$ are accelerations due to solar gravitational perturbations, $j_{x_{om}}, j_{y_{om}}, j_{z_{om}}$ are accelerations due to lunar

gravitational perturbations, a_e is the equatorial radius of the Earth, μ is the gravitational constant, C_{20} is the second zonal coefficient of a spherical harmonic expansion, (x_o, y_o, z_o) is the satellites initial position, $(\frac{dx_o}{dt}, \frac{dy_o}{dt}, \frac{dz_o}{dt})$ is the initial satellite velocity and finally $(\frac{dVx_o}{dt}, \frac{dVy_o}{dt}, \frac{dVz_o}{dt})$ is the satellites initial acceleration [6].

Accelerations due to lunar and solar perturbations are calculated using:

$$j_{x_o\kappa} = \bar{\mu}_\kappa [(\zeta_{o_{\kappa\ominus}} - \bar{x}_{o_\kappa})\Delta_{o_\kappa}^{-3} - \zeta_{o_{\kappa\ominus}}] \quad (15)$$

$$j_{y_o\kappa} = \bar{\mu}_\kappa [(\eta_{o_{\kappa\ominus}} - \bar{y}_{o_\kappa})\Delta_{o_\kappa}^{-3} - \eta_{o_{\kappa\ominus}}] \quad (16)$$

$$j_{z_o\kappa} = \bar{\mu}_\kappa [(\mathfrak{S}_{o_{\kappa\ominus}} - \bar{z}_{o_\kappa})\Delta_{o_\kappa}^{-3} - \mathfrak{S}_{o_{\kappa\ominus}}] \quad (17)$$

$$\bar{\mu}_\kappa = \frac{\mu_\kappa}{r_{o_{\kappa\ominus}}^2}, \quad \bar{x}_{o_\kappa} = \frac{x_o}{r_{o_{\kappa\ominus}}}, \quad \bar{y}_{o_\kappa} = \frac{y_o}{r_{o_{\kappa\ominus}}}, \quad \bar{z}_{o_\kappa} = \frac{z_o}{r_{o_{\kappa\ominus}}} \quad (18)$$

$$\Delta_{o_\kappa}^2 = (\zeta_{o_{\kappa\ominus}} - \bar{x}_{o_\kappa})^2 + (\eta_{o_{\kappa\ominus}} - \bar{y}_{o_\kappa})^2 + (\mathfrak{S}_{o_{\kappa\ominus}} - \bar{z}_{o_\kappa})^2 \quad (19)$$

where κ is the index for a perturbing body.

$\zeta_{o_{\kappa\ominus}}, \eta_{o_{\kappa\ominus}}, \mathfrak{S}_{o_{\kappa\ominus}}, r_{o_{\kappa\ominus}}$ are the directive cosines and radius vectors of perturbing bodies in Cartesian coordinates at instant t_e [6].

The lunar gravitational constant, $\mu_\pi = 4902.835 \text{ km/s}^2$;

The solar gravitational constant, $\mu_c = 0.1325263 \times 10^{12} \text{ km/s}^2$.

2.2.1 GLONASS Specifications.

The GLONASS constellation consists of a ground, space and user segment. Fig 3 illustrates this relationship and the different components involved in a functioning

GLONASS system. The space segment consists of 24 satellites in three orbital planes with 8 satellites in each plane. Longitudes of ascending nodes of the orbital planes are disseminated on 120° with the orbital planes having an order of 1, 2 and 3 counting towards the Earth rotation [6]. This is illustrated along with simulated coverage areas of each satellite in Fig. 7.

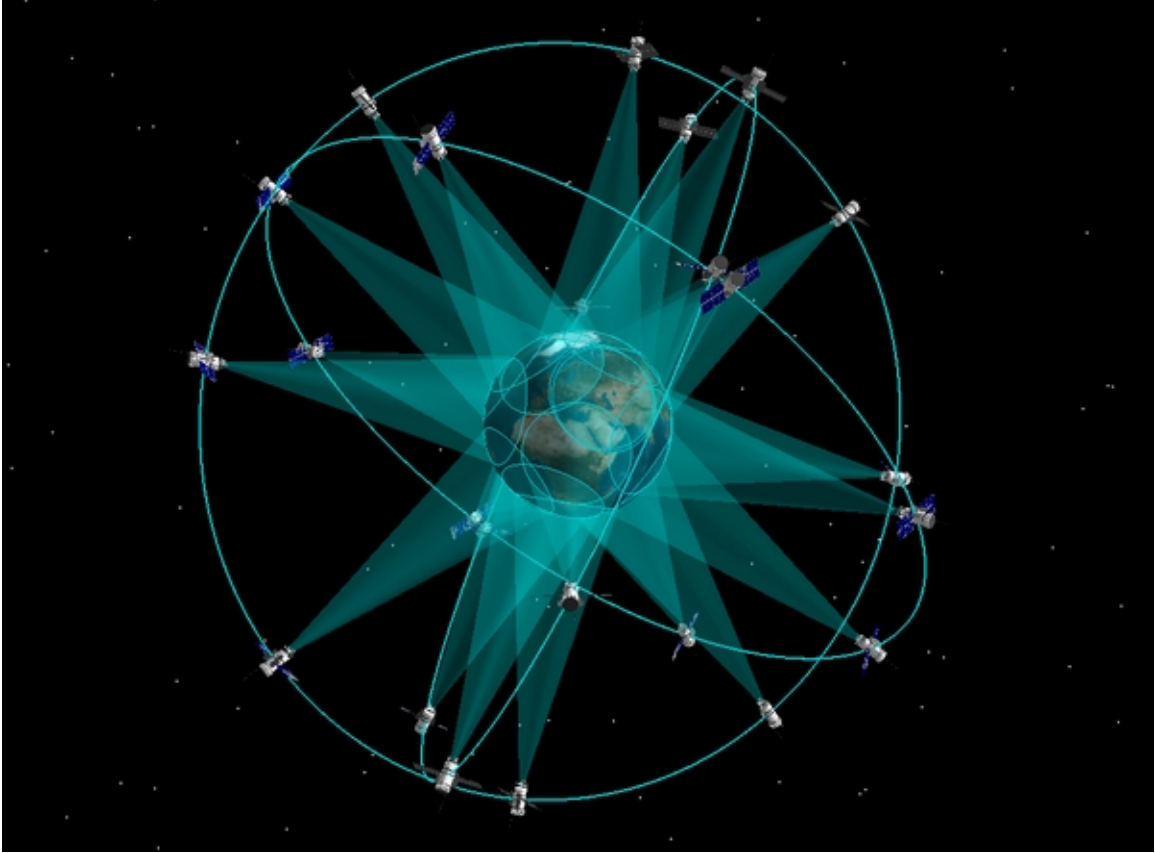


Figure 7. GLONASS Constellation [4]

The first orbital plane contains slot numbers 1 through 8, the second has 9 through 16 and the third has 17 through 24. Table 1 contains information on the current status of the GLONASS constellation as of 8 December 2016 [11].

Table 1: GLONASS Constellation Status as of 8 Dec 16 [11]

Orb. Slot	Orb. Pl.	RF Channel	# GC	Launched	Operation begins	Life-time (months)	Comments
1	1	01	730	14.12.09	30.01.10	83.9	In operation
2	1	-4	747	26.04.13	04.07.13	43.5	In operation
3	1	05	744	04.11.11	08.12.11	61.2	In operation
4	1	06	742	02.10.11	25.10.11	62.3	In operation
5	1	01	734	14.12.09	10.01.10	83.9	In operation
6	1	-4	733	14.12.09	24.01.10	83.9	In operation
7	1	05	745	04.11.11	18.12.11	61.2	In operation
8	1	06	743	04.11.11	20.09.12	61.2	In operation
9	2	-2	702	01.12.14	15.02.16	24.3	In operation
10	2	-7	717	25.12.06	03.04.07	119.5	In operation
11	2	00	753	29.05.16	27.06.16	6.3	In operation
12	2	-1	737	02.09.10	12.10.10	75.3	Maintenance
13	2	-2	721	25.12.07	08.02.08	107.5	In operation
14	2	-7	715	25.12.06	03.04.07	119.5	In operation
15	2	00	716	25.12.06	12.10.07	119.5	In operation
16	2	-1	736	02.09.10	04.10.10	75.3	In operation
17	3	04	751	07.02.16	28.02.16	10.0	In operation
18	3	-3	754	24.03.14	14.04.14	32.5	In operation
19	3	03	720	26.10.07	25.11.07	109.5	In operation
20	3	02	719	26.10.07	27.11.07	109.5	In operation
21	3	04	755	14.06.14	03.08.14	29.9	In operation
22	3	-3	731	02.03.10	28.03.10	81.3	In operation
23	3	03	732	02.03.10	28.03.10	81.3	In operation
24	3	02	735	02.03.10	28.03.10	81.3	In operation
11	2	-	723	25.12.07	22.01.08	107.5	Spares
17	3	-	714	25.12.05	31.08.06	131.5	Spares
20	3	-5	701	26.02.11	-	69.4	Flight Tests

Nominal values of the absolute longitudes of ascending nodes is fixed at 00 hours 00 minutes 00 seconds Moscow Standard Time (MSK) which translates to UTC plus 3 hours. The time is calculated in Eq. 20:

$$251^{\circ}15'00'' + 120^{\circ}(i - 1) \quad (20)$$

where "i" is the individual orbital plane number.

The nominal orbital altitude of each satellite is 19,100 km with an inclination of 64.8° and eccentricity of 0° . Each satellite is in a circular orbit with a period of 11 hours 15 minutes 44 seconds. Each satellite's nominal spacing is 45° to adjacent satellites within a single orbital plane. The mean rate of orbital plane precession is approximately -0.59251×10^{-3} radians per day. The maximum deviation of each satellite relative to its nominal position does not exceed $\pm 5^{\circ}$ over its projected lifetime.

2.2.2 GLONASS Ground Segment.

The GLONASS ground control segment has been expanded to meet the resurgence in popularity and the increased number of satellites in orbit. The systems control center, located at Krasnoznamensk in western Russia, is responsible for satellite constellation control and managing each GLONASS satellite. It provides telemetry as well as command and control, and it coordinates all functions and operations. It also processes the information gathered from the command and tracking stations in order to update the navigation messages and to determine each satellite's clock and over-all health.

The command and tracking stations are distributed throughout Russia and are composed of five telemetry, tracking and command centers. These stations track GLONASS satellites and accumulate ranging data and telemetry from each. These accumulated data are transmitted to one of three upload stations.

Two laser ranging stations are in operation at Schelkovo and Komsomoisk. These stations provide system correction used for the calibration of GLONASS ephemeris.

The central clock is located at Schelkovo and utilizes a highly precise hydrogen atomic clock to implement the GLONASS time scale. This information is then relayed to the state Etalon in Mendeleevo which then synchronizes the GLONASS cesium atomic clocks on each satellite.

In the near future, Russia is using the newly funded program to expand their monitoring and measuring stations. There are currently 10 stations around that region that are either under construction or slated for construction [5].

2.2.3 GLONASS Signal Structure.

Similar to the GPS signal structure, GLONASS utilizes a dual sub-band carrier frequency structure, L1 and L2. The navigational signal types of GLONASS sub-bands are separated into two different types. The first signal is in standard (ST) code, used for general navigation and is accessible to any user in the world. The second signal, more-precise W code, is reserved for military or special purposes and is accessible to military users and users of the L2 sub-band [6]. L3 is a new band for future updates to the GLONASS system. The frequency bands for L1, L2 and L3 are seen in Fig. 25 and Fig. 26.

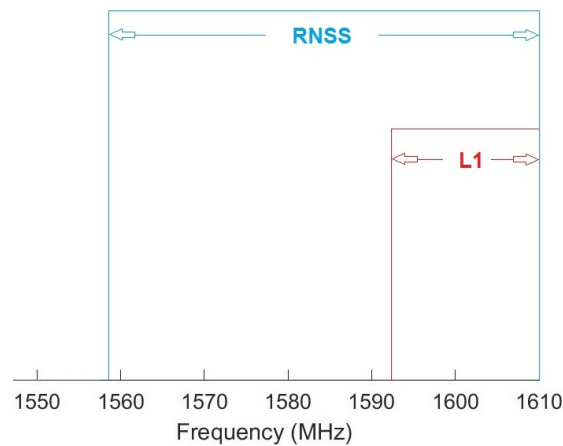


Figure 8. GLONASS Frequency Band of GLONASS L1 [5]

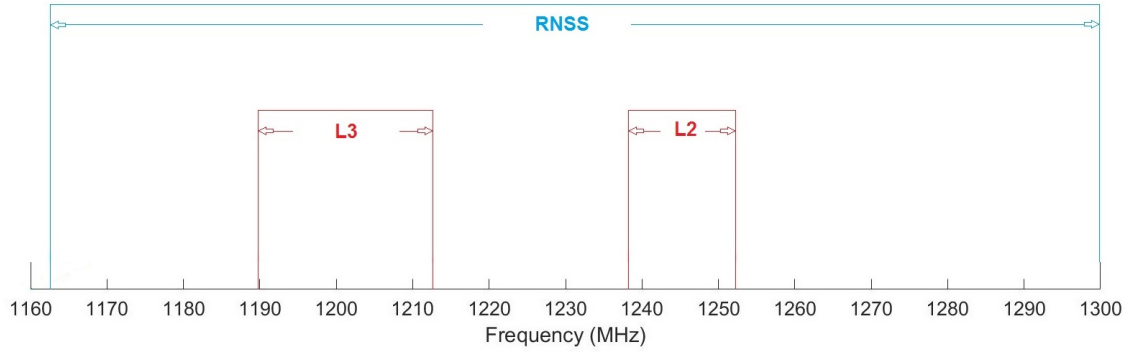


Figure 9. GLONASS Frequency Band of L2 and L3 [5]

The L1 band ranges from 1598.0625MHz to 1605.375Mhz. The upgraded GLONASS-M comes equipped with filters that diminish unwanted, out-of-band emissions in the frequency ranges of 1610.6 MHz to 1613.8 MHz and 1660.0 MHz to 1670.0 MHz. The L2 band ranges from 1242.9375 to 1248.625 MHz. The L3 band will center on 1201 MHz with an approximate bandwidth of 15 MHz.

Table 2: GLONASS L1 Specifications

GNSS System	GLONASS	GLONASS
Service Name	ST Code	W Code
Center Frequency	(1598.0625 - 1605.375)MHz $\pm$ 0.511MHz	
Frequency Band	L1	L1
Access Technique	FDMA	FDMA
Spreading Modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Data
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander Sequence	100 Hz	N/A
Data Rate	50 bps	N/A
Minimum Receiver Power[dBW]	-161 dBW	N/A
Elevation	5°	N/A

Table 3: GLONASS L2 Specifications

GNSS System	GLONASS	GLONASS
Service Name	ST Code	W Code
Center Frequency	(1242.9345 - 1248.625)MHz $\pm$ 0.511MHz	
Frequency Band	L2	L2
Access Technique	FDMA	FDMA
Spreading Modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier Frequency	-	-
Code Frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Data
Primary PRN Code Length	511	N/A
Code Family	M-sequences	N/A
Meander Sequence	100 Hz	N/A
Data Rate	50 bps	N/A
Minimum Receiver Power[dBW]	-167 dBW	N/A
Elevation	5°	N/A

The link budget for GLONASS will be similar to other GNSS systems. This link budget provides information on the GLONASS systems gains and losses. While this information is difficult to locate for GLONASS, it is available from for GPS as seen in Table 4. Table 5 provides data that describes typical GLONASS-M receiver characteristics and is partially relevant to its link budget.

Table 4: GPS Link Budget [12]

Minimum Transmitted Signal Power (P)	26.8 dBW
Free-Space Loss (F)	182.4 dB
Atmospheric Attenuation(A)	2.0 dB
Minimum Received Signal Power	-157.6 dBW

Table 5: GLONASS System Characteristics [13]

Receiver power	-155.2 dBW
Transmitted power	11.6 dBW
Undetected bit-error rate	1×10^{-5}
Minimum received power level (L1)	-161 dBW
Minimum received power level (L2)	-167 dBW
Elevation	5°
Preamplifier limiting level	-80 dBW
Preamplifier burnout level	-1 dBW, average
Overload recovery time	1s
RF 3 dB filter bandwidth	± 20 MHz
RF 30 dB filter bandwidth	± 45 MHz
Permissible Interference/Signal (I/S) margin (L1, ST)	15 dB (for acquisition)
Permissible I/S margin (L1, W)	25 dB (for acquisition)
Intrasystem interference	-48 dB

The ST ranging code is transmitted at a rate of 511 kilobits per second (kbps) with a period of 1 millisecond. The navigation message is transmitted at a rate of 50 bits per second (bps) with a phase-locked 100Hz auxiliary meander sequence.

This meander sequence is used as a rudimentary overlay code to reduce the cross correlation of the repeating spreading code within a data bit.

The ranging code is the same for all satellites and is generated using a polynomial in Eq. 21 and is seen in Fig. 10 [6].

$$G(X) = 1 + X^5 + X^9 \quad (21)$$

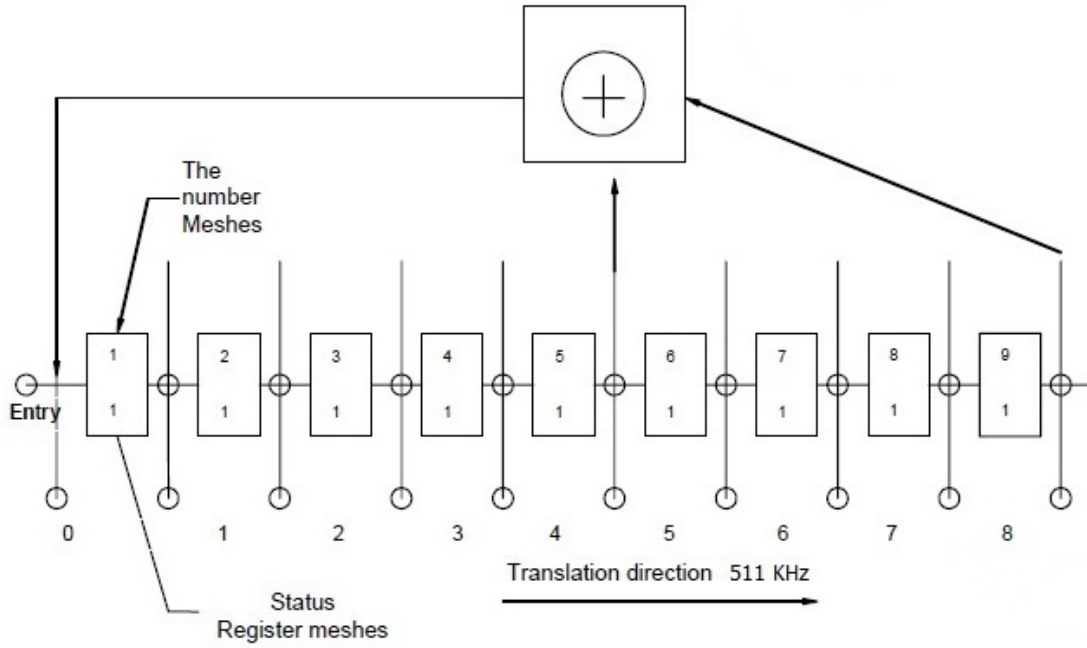


Figure 10. GLONASS Shift Register [6]

The output signal from the front-end of the receiver is a combination of signals from all visible satellites in view of the antenna. This equation can be written as:

$$y(t_n) = \sum_j A_j D_{jk} M_{jk} C[0.001 \frac{t_n - \tau_{jk}}{\tau_{jk+1} - \tau_{jk}}] [\cos(\omega_{IFj} t_n + \Theta_j(t_n)) + \sin(\omega_{IFj} t_n + \Theta_j(t_n))] + n_j \quad (22)$$

where t_n is the sample time, j is the channel number, A_j is the amplitude, M_{jk} is

the meander code, D_{jk} is the navigation data bit, $C[t]$ is the periodic PR ranging code, τ_{jk} and τ_{jk+1} is the initial received code periods, ω_{IFj} is the intermediate frequency, $\Theta_j(t_n)$ is the carrier phase perturbation and n_j is noise [18].

The navigation signal structure transmitted in particular carrier frequencies of L1 and L2 sub-bands is a binary phase-shift key (BPSK) modulated pseudorandom noise sequence. A BPSK is generated by using a modulated binary bit stream to modulate a sinusoidal carrier wave. As the bit stream changes polarity, the sinusoidal carrier waves polarity will be reversed. The information of the bit stream is contained in the transmitted signals phase changes. The Power Spectral Density (PSD) is a measure of the distribution of power with respect to frequency and can be described in Eq. 23.

$$S(f) = \frac{PT}{2} [\text{sinc}^2((f - f_c)T) + \text{sinc}^2((f + f_c)T)] \quad (23)$$

where P is signal power, T is the duration, f is the frequency and f_c is the center frequency [21].

The bandwidth of BPSK between the first and second null is called null to null bandwidth. These nulls on the power spectrum are observed at $f - f_c = \pm \frac{1}{T}$ and $f - f_c = \pm \frac{2}{T}$. This bandwidth is the width of the main spectral lobe of the PSD bounded by the spectral nulls. The majority of the baseband signal power is contained within these first two nulls. The amount of spectrum width needed to contain a certain percentage of signal power can be defined by Eq. 24.

$$\int_{-B}^B S(f)df = \alpha \int_{-\infty}^{\infty} S(f)df \quad (24)$$

where 2B is the power containment bandwidth and α is the decimal equivalent power ratio [22].

The correlation triangle is developed from the autocorrelation of GNSS signal code and replica code in order to form triangular correlation peaks as seen in Fig. 11.

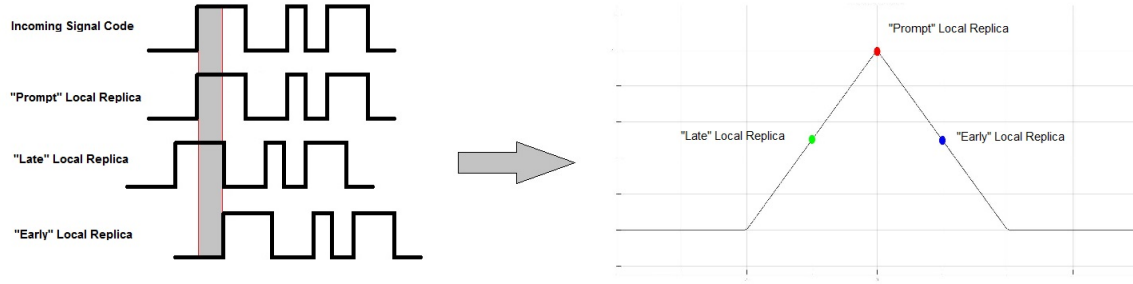


Figure 11. Correlation Peak Development

GNSS error sources affect correlation peaks in different ways and provide insight into various anomalies in the system. By increasing front-end bandwidth, the correlation peak becomes more defined resulting in more accurate PR measurements. Increasing the bandwidth beyond null-to-null increases over-all accuracy of the PR measurements, but requires additional power in consumption. Lower signal resolution is a result of lower bandwidth which begins to "round off" the correlation triangle. Correlation peaks will be discussed more in depth later in this thesis.

The PSD is not a continuous function but rather a cluster of spectral lines. The signal occupies a bandwidth which is spread across what is called the spread spectrum through use of the code. This code is independent of the data and synchronized with the receiver to despread and recover the data. There are $2n$ distinct lines in the main lobe of the spectrum, where n is the number of chips in the modulating code. Fig. 12 displays generic spectral lines of a GNSS signal.

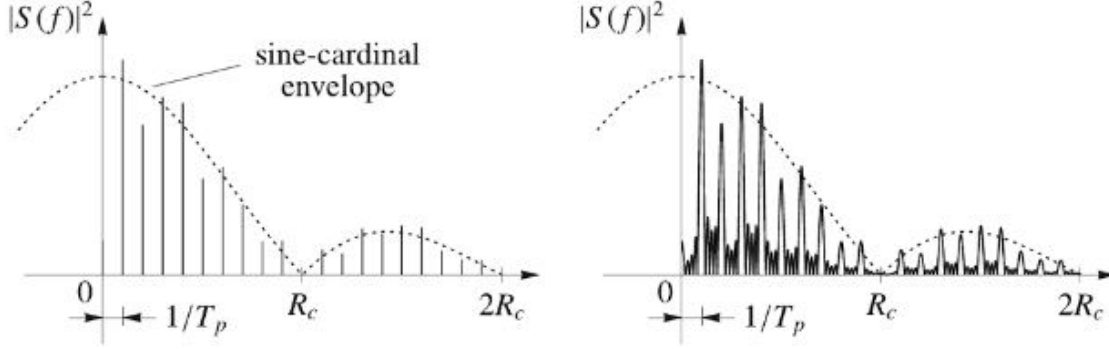


Figure 12. Spectral Lines [7]

T_p is the length of the ranging code sequence, R_c is the nulls and $S(f)$ is the signal. Here, the power spectral density is on the left and a PRN code that is modulated by the data is on the right [7]. The signal power is divided among these spectral lines by the spreading factor. The spreading factor is a ratio of the chip rate and the symbol rate which is the number of sign changes of the code. This technique decreases interference, signal interception and is resistant to narrow-band interference making it ideal for GNSS systems [23].

Code Division Multiple Access (CDMA) is a method of utilizing a single transmission channel with a plethora of signals occupying it. This form of multiple access or band sharing by multiple users optimizes the available bandwidth and is used in all GNSS, with the exception of GLONASS. CDMA is the primary method used by GPS and Galileo to multiplex signals.

GLONASS differs from most other GNSS systems in that it uses FDMA. This design separates the signals using multiple frequencies to designate individual satellites. This satellite frequency must be known prior to processing the GLONASS carrier phase observations where the carrier wavelength is needed to convert the phase cycles to distance measurements [24]. Compared to CDMA, the FDMA technique results in better interference rejection for narrow-band signals. An interference source af-

fecting all CDMA signals may only disrupt a single FDMA signal, providing for a much more robust system. It also avoids cross-correlation effects that affect CDMA systems. While there are many advantages to utilizing FDMA over CDMA, FDMA does introduce challenges when designing receivers to utilize the system. As stated previously in this thesis, it introduces group delay problems and inter-frequency bias. It also requires a more complex and expensive antenna and receiver design for the system.

The GLONASS FDMA method of L1 and L2 are defined by Eq. 25 and Eq. 26.

$$f_{K1} = f_{01} + K\Delta f_1 \quad (25)$$

$$f_{K2} = f_{02} + K\Delta f_2 \quad (26)$$

where K is the frequency number (satellite number) of the signal being transmitted, $f_{01} = 1602\text{MHz}$ and $\Delta f_1 = 562.5\text{KHz}$ are for sub-band L1 and $f_{02} = 1246\text{MHz}$ and $\Delta f_2 = 437.5\text{KHz}$ are for sub-band L2. These nominal values of carrier frequencies for f_{K1} and f_{K2} for channels K are shown in Table 6 [6].

All GLONASS satellites launched after 2005 are using channel numbers $K = (-7 \dots +6)$, 14 unique frequencies. The frequency number for the GLONASS constellation is embedded in the almanac and broadcast message. Each GLONASS satellite can transmit navigational signals on fundamental frequencies equal to each other on opposite points on the orbital plane (antipodal).

During acquisition, information from the carrier Doppler shift and code phase is used to compute a course of the visible satellites. GLONASS receivers perform a Doppler shift for each channels center frequency at each code phase offset. This form of acquisition is primarily due to FDMA method used by GLONASS. The algorithm

Table 6: GLONASS carrier frequencies

Channel No.	Nominal value of frequency in L1 sub-band, MHz	Nominal value of frequency in L2 sub-band, MHz
06	1605.375	1248.625
05	1604.8125	1248.1875
04	1604.25	1247.75
03	1603.6875	1247.3125
02	1603.125	1246.875
01	1602.5625	1246.4375
00	1602.0	1246.0
-01	1601.4375	1245.5625
-02	1600.8750	1245.1250
-03	1600.3125	1244.6875
-04	1599.7500	1244.2500
-05	1599.1875	1243.8125
-06	1598.6250	1243.3750
-07	1598.0625	1242.9375

selects a satellite number which in turn indicates the nominal center frequency. It then conducts a search over the range of the carrier frequencies. Once a signal has been identified and acquired, the code phase and carrier Doppler shift are passed to the code and carrier tracking loops [18]. A block diagram for signal acquisition can be seen in Fig. 13 where I and Q are the in-phase and quadrature correlation. These can be seen in Equations 29 and 30.

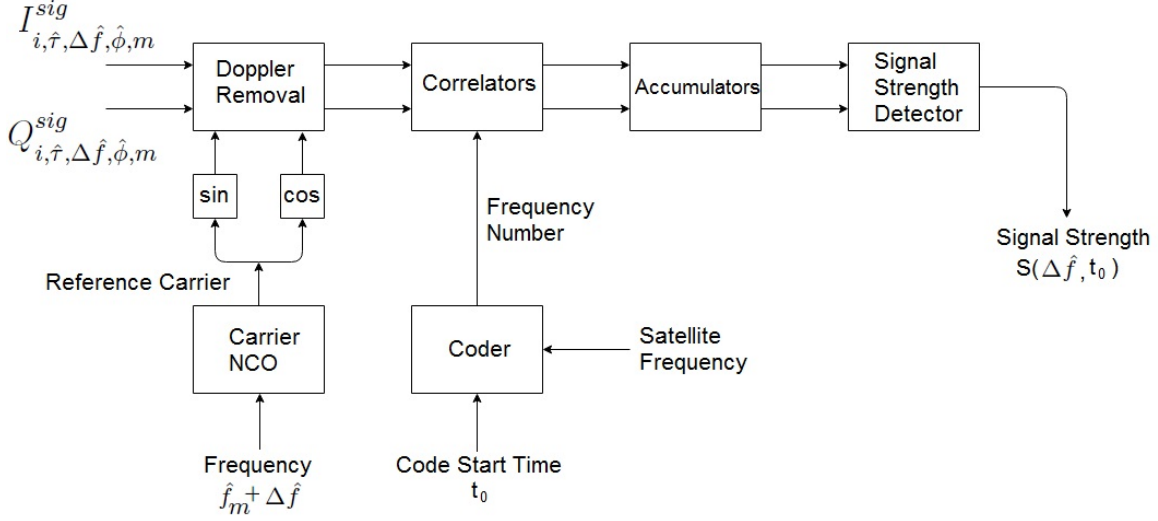


Figure 13. Satellite Acquisition [8]

Carrier frequencies of L1 and L2 sub-bands for each satellite are coherently derived from a common onboard time/frequency standard [6]. The values of the carrier frequencies are within 2×10^{-11} relative to its nominal value of f_K .

Future GLONASS satellites, GLONASS-K series, will transmit both FDMA and CDMA signals on L1 and L2 bands but with different carrier frequencies [25]. The international communities have relegated these Radio Navigation Satellite Service (RNSS) signals to 1164-1300 MHz and 1559-1610 MHz. GLONASS CDMA L3 bands will utilize a band designated on 1207.14 MHz. This is currently used by Galileo and BeiDou E5b signals for safety of life applications. GLONASS CDMA will also utilize an L1 band centered on 1575.42 MHz for military and open use, and an L2 band centered on 1242 MHz. This L2 band will be primarily for military use. A fourth band is also being planned for use in the GLONASS-KM model satellite. This satellite will transmit signals on the L5 frequency, centered at 1176.45 MHz. Current bands in use for GNSS can be seen in Fig. 14. The safety of life bands can be seen as Aviation Radio Navigation Service (ARNS) in the figure.

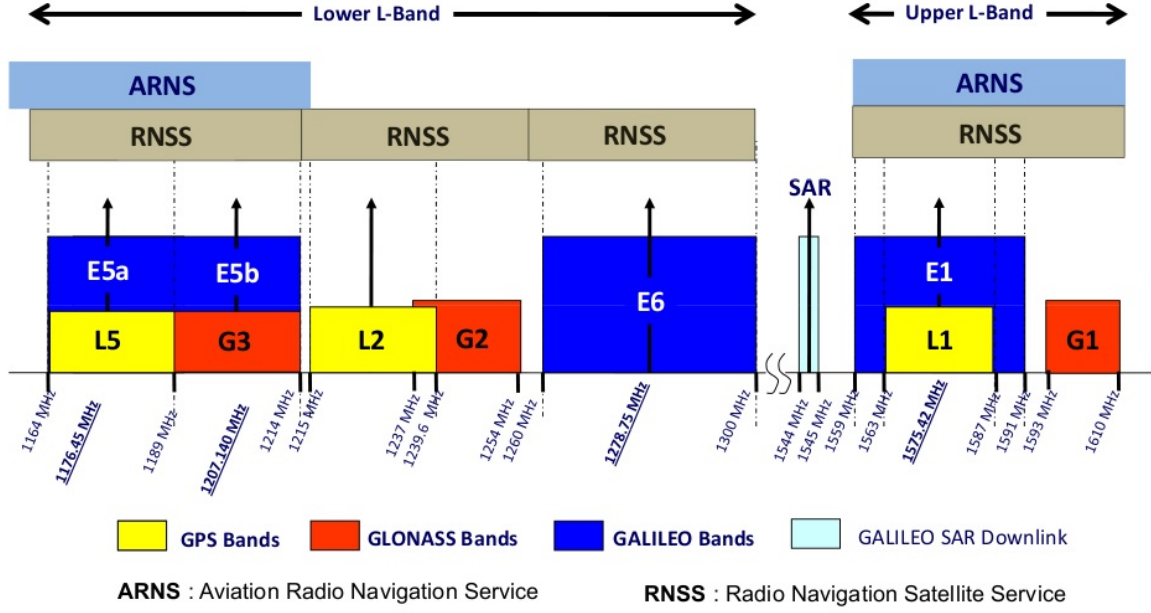


Figure 14. Satellite Navigation Bands [5]

GNSS signals are below the noise floor requiring special algorithms to detect and process them. When looking at the GPS link budget from Table 4, the value of the signal observed by the receiver is roughly -159 dBW. The thermal noise floor is -130 dBW making the signal 29 dB below the noise floor. When the Signal to Noise Ratio (SNR) is positive, demodulation is done to extract the information contained within the signal. Since the SNR of GNSS signals is negative and thus below the noise floor, demodulation will not work and correlation must be done. Using the GNSS replica code, we use correlation of the received signal to line up the replica code with the GNSS signal in order to pull it out from the noise floor. When the incoming signal is aligned in phase with the local carrier replica, “in-phase” alignment occurs and results in a large positive correlation. This is seen in Fig. 15 where the red sinusoid is the incoming signal and the blue sinusoid is the local carrier replica.

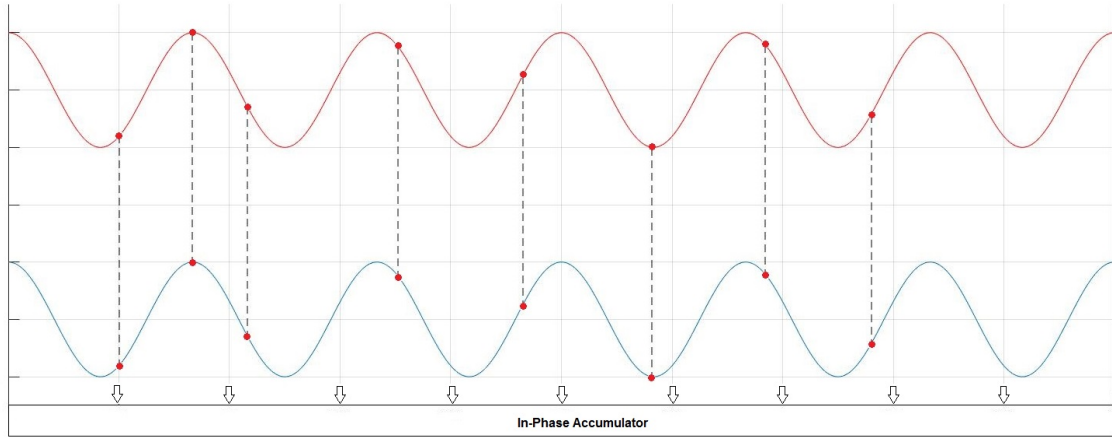


Figure 15. In-Phase Correlation

When the signal is 180° out of phase, a large negative correlation occurs. This out of phase diagram can be seen in Fig. 16.

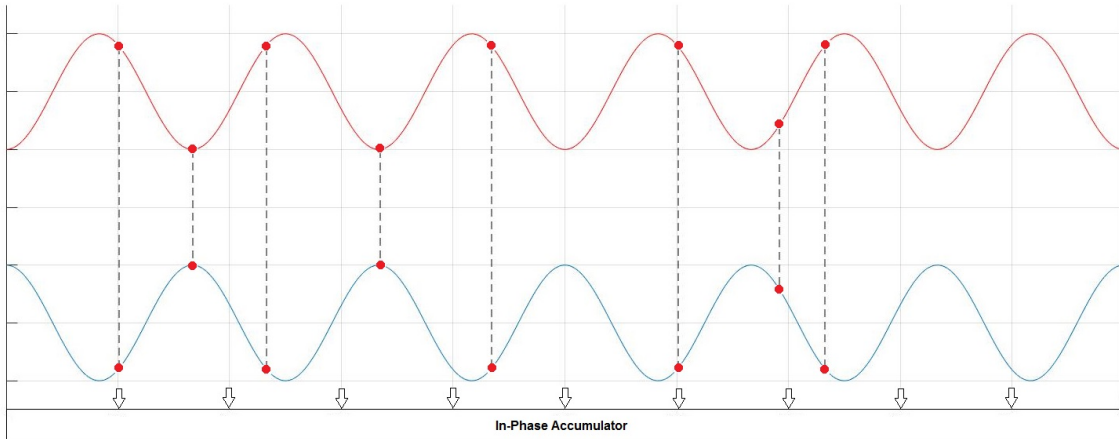


Figure 16. Inverted Correlation

In mathematical terms, correlation in continuous time can be described as

$$R(\tau) = \int_{-\infty}^{\infty} x(t) \cdot y(t + \tau) d\tau \quad (27)$$

while correlation in discrete time is

$$R(k) = \sum_{n=1}^{\infty} x_{n+k} \cdot y_n \quad (28)$$

where x and y are both signals and R is the correlation function.

To recover phase information, correlation must be accomplished in phase-quadrature.

This in-phase correlation can be simplified to:

$$I_{i,\hat{\tau},\Delta\hat{f},\hat{\phi},m}^{sig} = \frac{A_{Q,m}}{\sqrt{2}} \cdot N \cdot D_{i,m} R(\hat{\tau}) \cdot \frac{\sin(\pi(\Delta' \hat{f}_m) T_{pdi})}{(\pi(\Delta' \hat{f}_m) T_{pdi})} \cdot \cos(\Delta\hat{\phi}_m) \quad (29)$$

$$Q_{i,\hat{\tau},\Delta\hat{f},\hat{\phi},m}^{sig} = \frac{A_{Q,m}}{\sqrt{2}} \cdot N \cdot D_{i,m} R(\hat{\tau}) \cdot \frac{\sin(\pi(\Delta' \hat{f}_m) T_{pdi})}{(\pi(\Delta' \hat{f}_m) T_{pdi})} \cdot \sin(\Delta\hat{\phi}_m) \quad (30)$$

where $A_{Q,m}$ is the amplitude, N is the number of samples, $D_{i,m}$ is the data bit, $R(\hat{\tau})$ is the correlation function, T_{pdi} is the pre-detection integration time and $\Delta\hat{\phi}_m$ is the phase offset.

2.2.4 Receiver Signal Processing.

GNSS signals are received and processed through the front-end of a user's receiver. The front-end includes the antenna used by the system and hardware needed for filtering and amplification of the acquired signal, and digitization of the signal for processing. The front-end digitizes the analog GNSS signals to an Intermediate Frequency (IF) and then to a baseband signal of in-phase (I) and quadrature (Q) components by taking the sine and cosine. A block diagram of this can be seen in Fig. 17.

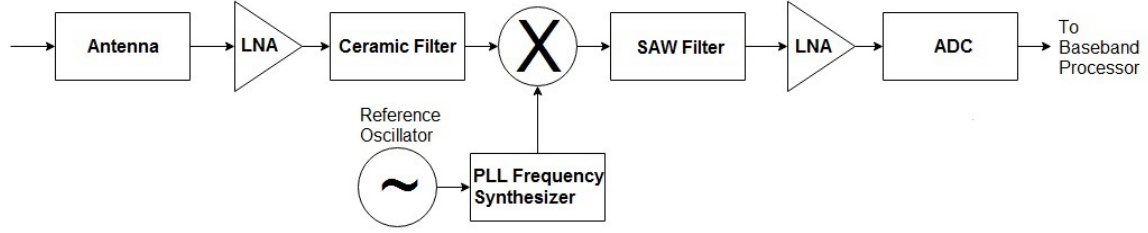


Figure 17. System Front-End

Previous research has shown that components used in the design of receiver front-ends can have a significant impact on measured natural biases [10]. GNSS signals undergo group delays when a signal is passed through the analog components of a user's antenna and receiver. This delay is frequency dependent and incurs these delays at each component within the front-end which makes it particularly problematic on the GLONASS system. Different GLONASS receivers may be of unique design requiring testing of individual receiver versions to compensate for the front-end group delays. This is due to GLONASS utilizing FDMA which will incur an additional term in the pseudorange error which can be interpreted as group delay differences between the GLONASS channels when a signal is traveling through the front end of a receiver.

The filter utilized by the front-end also effects the signals received by the antenna. Different filters will have different effects on the chip shapes by inducing biases on the system. Characterizing these filters is necessary to in turn, characterize GLONASS. Fig. 18 and Fig. 19 display the different group delays incurred in the front-end by two different filters. The front-end used for GLONASS signal analysis results presented in this thesis used a transversal SAW IF filter and a ceramic dielectric RF filter.

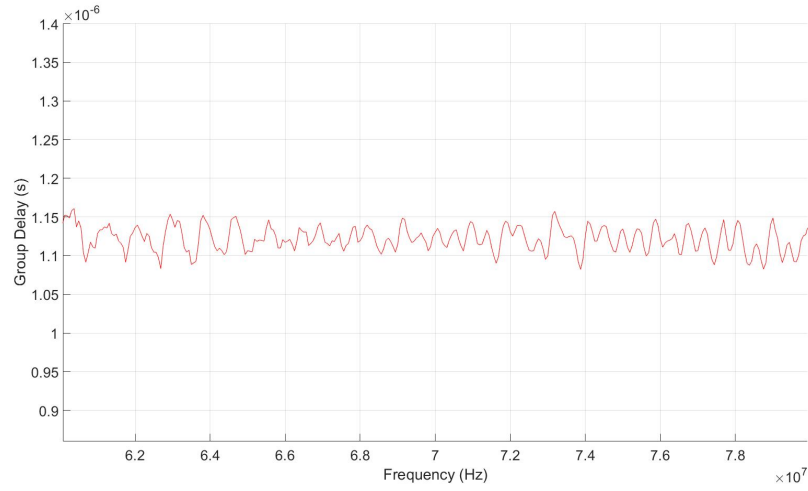


Figure 18. Group Delay Response of a SAW filter

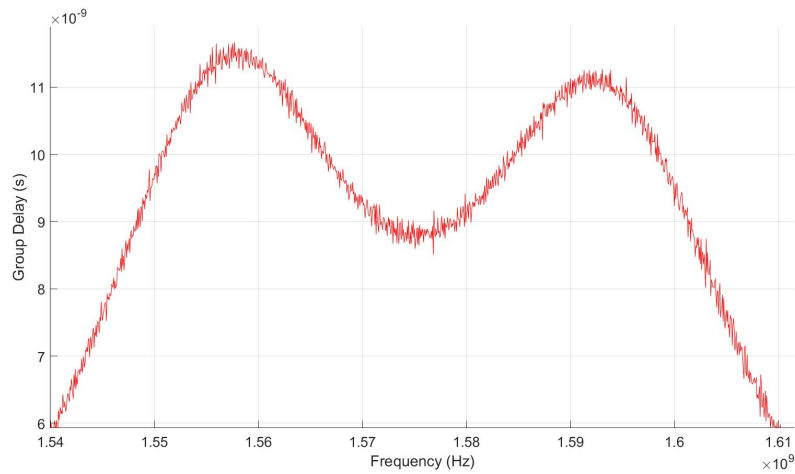


Figure 19. Group Delay Response of a L1 Ceramic Filter

2.3 Correlation Functions

A correlation function is produced using the incoming signal and code replicas. An optimal correlation function produces a perfect triangle indicating biases are not present within the incoming signal. This perfect signal is impossible in practice but a

nominal correlation function can be attained. Fig. 20 outlines the optimal correlation function with the actual function we wish to obtain.

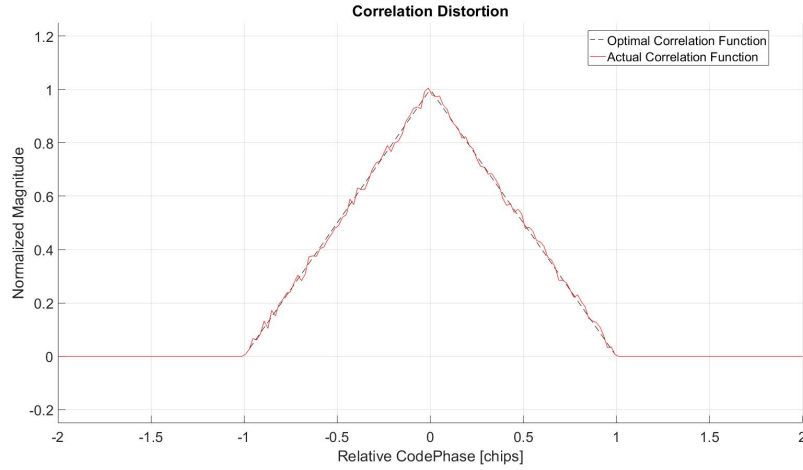


Figure 20. Optimal Correlation Function

Anomalies and distortions in the GNSS signal cause the correlation function to become asymmetric leading to range errors. These asymmetries can occur from multiple error sources including multipath, atmospheric anomalies, satellite architecture and/or group delay. Some error sources may affect position while another may affect timing. These error sources can be dependent on location, time of year or receiver/emitter hardware. Some errors vary with time or atmospheric conditions while other errors will be constantly present in all measurements.

A receiver aligns the incoming code and the local replica by looking at the code phase discriminator detailed Equation 31 [5]. Once the incoming code and local replica have been aligned, the receiver uses a delay lock loop (DLL) to track the signal from each satellite. The satellite tracking performed by the receiver can be seen in Fig. 21 where I and Q can be seen in Equations 29 and 30.

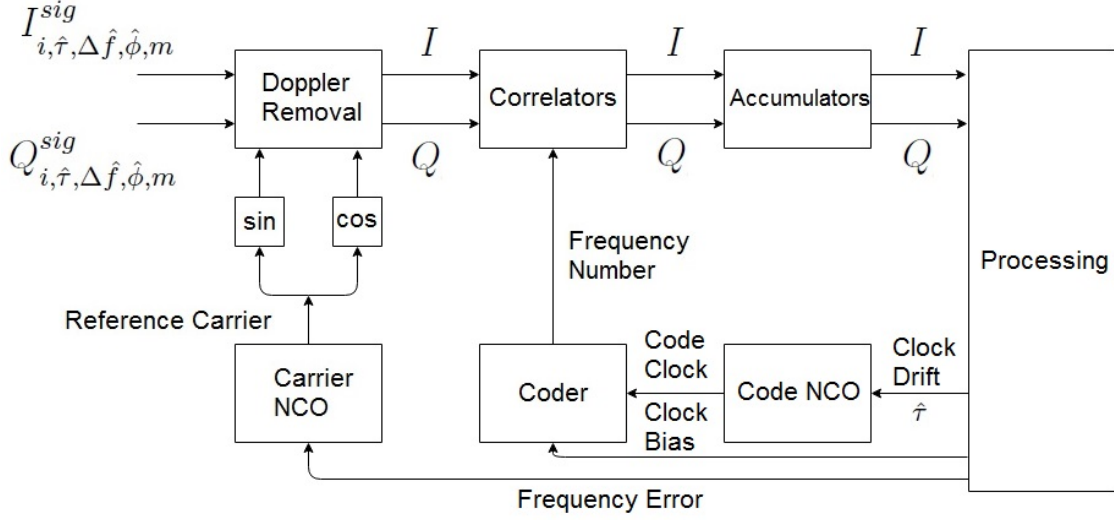


Figure 21. Satellite Tracking [8]

The DLL correlates the received signal with a slightly early and late replica of the signal. This spacing in the DLL is known as the correlator spacing. Distortions in the correlator function will produce different zero crossings in the early minus late code phase. These correlation function distortions are then used to produce PR biases.

$$Z = \frac{Q_E - Q_L}{Q_P} \quad (31)$$

Errors generally cause two types of deformations, digital and analog. Digital deformations occur when timing of the transmitted codes begin varying from the ideal chip. They can be seen as either leading or lagging the ideal code chip and can create a "dead zone" or plateaus atop the correlation peak [26]. An example of this can be seen in Fig. 22.

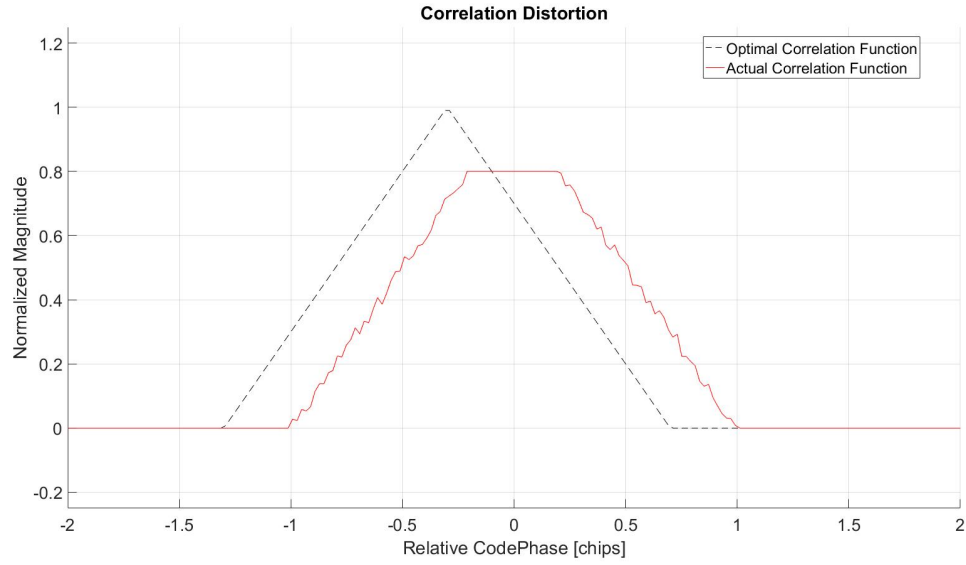


Figure 22. Digital Distortion

Analog deformations are resultant from filter limitations or signal path errors in the receiver hardware. These errors can create oscillations in the chip shape that results in asymmetries as seen in Fig. 23.

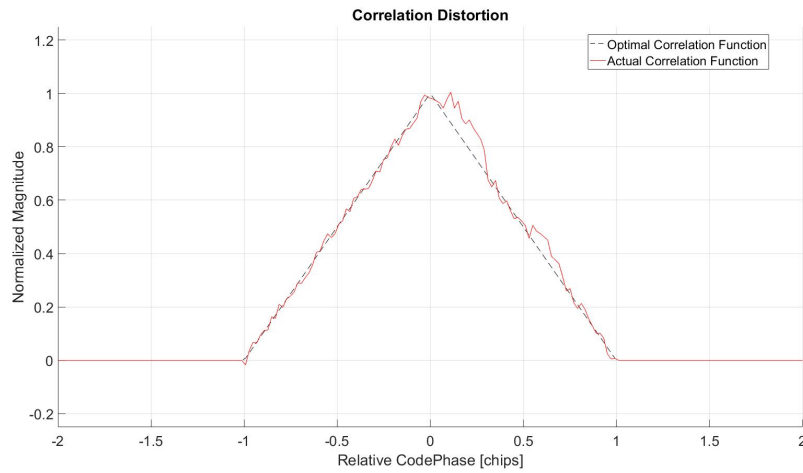


Figure 23. Analog Distortion

Digital deformations alone would produce minimal range errors. However, these

digital abnormalities combine with analog deformations to produce more substantial range errors. The receiver would process this combined distortion and output a range error based on signal deformations determined by the tracking error on any individual signal relative to the others [26]. Because these errors are satellite dependent, the signal deformations and range errors will vary from satellite to satellite.

A difficulty in analyzing these correlation functions is identifying asymmetries from nominal signal deformations. While there are signal deformation monitors currently in place that can detect and exclude range sources that differ from other satellites, the assumptions made about nominal signal deformations have other implications to system performance [26]. Position errors, range errors and correlation peak distortions are some of the effects we see from these asymmetries. While position measurements are easiest to obtain and process, these distortions are most difficult to observe in the position domain. Inversely, correlation peak measurements are the most difficult to obtain but the biases are easiest to identify in the correlation domain [27].

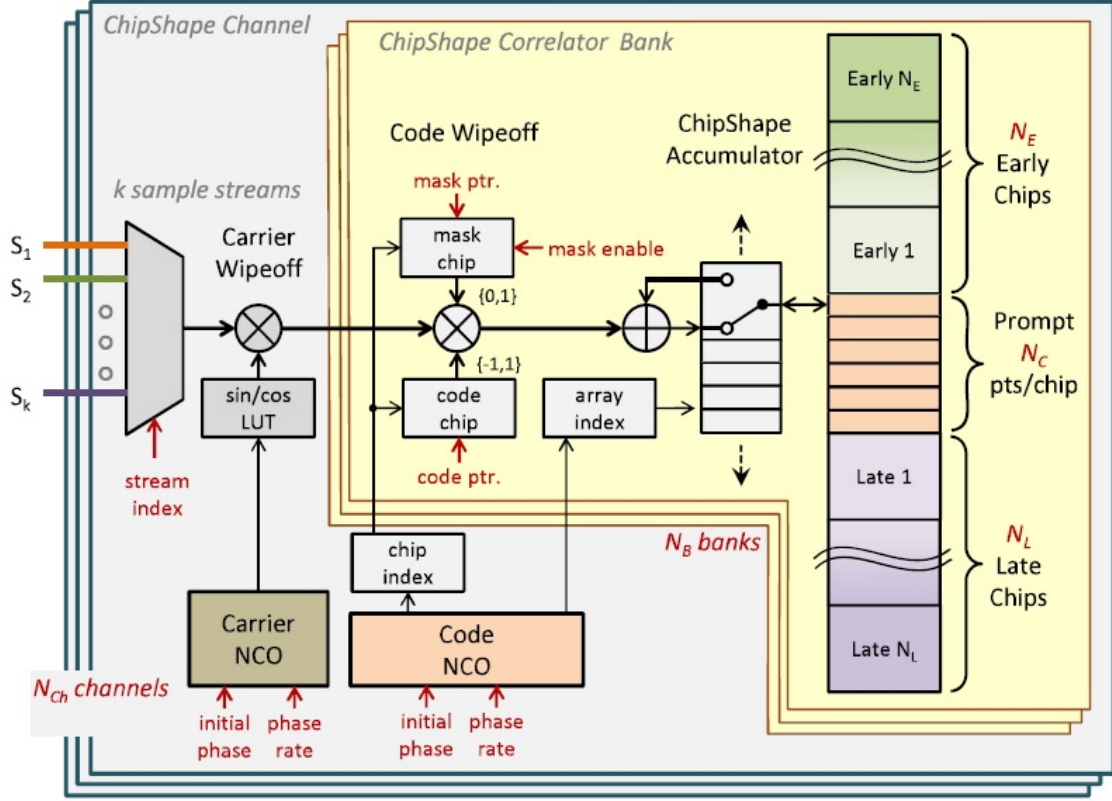


Figure 24. "Universal" ChipShape Correlator [9]

By utilizing a "universal" chip shape correlator such as the one seen in Fig. 24, we can observe the average shape of a spreading code chip shape with respect to the code phase and produce a code sequence masking pattern to observe the rising and falling edges and stationary chip responses [9].

The stream index selects the digitized sample streams from a front-end to be processed. Once selected, a carrier wipeoff is performed using replica carrier from the carrier Numerically Controlled Oscillator (NCO). The carrier-wiped sample stream is then sent to N_B independent banks of correlators that perform chipshape correlation and are used to form the indices to N_c partial correlation accumulators. This code stream can be incremented or decremented to produce early or late partial correlations [9]. With these correlations, we can observe the signal PR ranging code chip transition

edges of individual GLONASS satellites.

Eight orthogonal ChipShape correlation functions can be used. These correspond to masking codes in which the positive (P) and negative (N) chip events are isolated from the original GLONASS spreading code. These functions are then used to increase the processing gain for the chip-transition events being observed [10]. Chipshape functions have the indicated sign of the masking codes only when the underlying signal is non-inverted. Thus, the navigation databit sign must be determined and correctly ascertained when combining these correlator functions. The individual masking functions can be seen in Fig. 25.

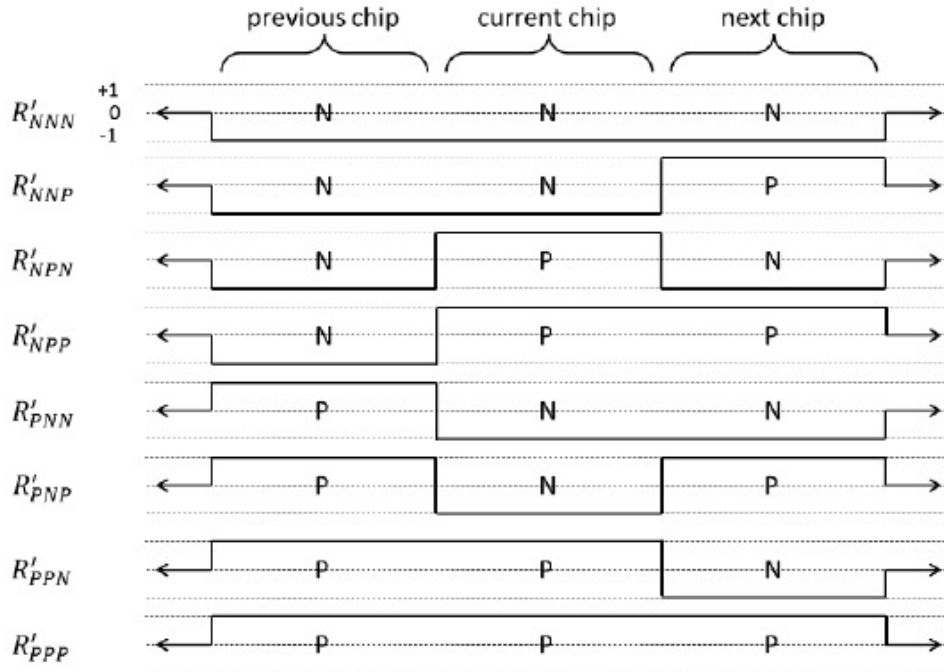


Figure 25. Eight Orthogonal ChipShape Correlator Functions [9]

The chip transition eye diagram from a GLONASS signal is seen in Fig. 26. The pattern allows us to perform a more complete characterization of each satellite and what is happening with the signals being produced. The chip shape correlation output can be transformed into the typical early, prompt and late complex correlation points

used for traditional signal tracking.

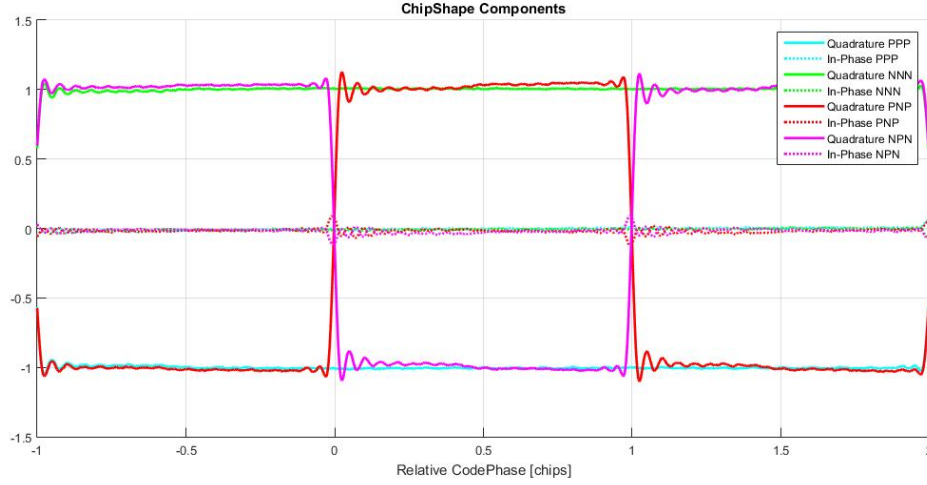


Figure 26. Chip Shape Eye Diagram

Normally, these chip shape distortions are not visible using standard GNSS receiver processing. However the effects of chip shape distortion translate into pseudorange errors or biases. It is only in recent years that research has been conducted into chip shape characterization. Increasing the bandwidth of the front-end will increase the higher frequency transients seen in the chip shape correlation output and allow for better discrimination of satellite biases.

Each satellite produces unique and observable distortions in GLONASS chip shape correlator eye diagrams which enables characterization of said satellites. These distortions are the product of satellite hardware and signal generation. When outside interference such as multipath, ionospheric effects and receiver front end bias are identified, distinguishing individual satellites for authentication becomes possible [28].

Previous research has been conducted into the area of GNSS signal authentication. Many of this research focused on characterization of natural signal deformation and inter-PRN biases for GPS-SPS and Galileo signals. These efforts conclude that several types of signal deformations can be revealed when nuisance effects such as multipath

are mitigated and the receiver front-end transfer function is properly characterized. While inter-PRN bias is not a critical error source for GLONASS, inter-channel and inter-frequency bias are due to the FDMA method utilized. Modern receiver design effectively neutralizes inter-channel bias through a method of sending a signal to the front-end from within the receiver and measuring group delays dynamically. The duration the receiver measures is then corrected and the process repeated [29].

III. Methodology

3.1 Universal GNSS Toolbox

This thesis utilizes both hardware and software to gather data and process data, respectively. The hardware is of particular importance as it can introduce biases into the final results. Location of the antenna for gathering GLONASS signals was considered during planning due to multipath and the sensitivity of chip shape correlation functions to this particular error. Software can be used to determine these biases and account for them in the final data results. We must account for these biases due to the deformation analysis of GLONASS systems requiring high fidelity data collection techniques. Natural environmental effects such as ionosphere and troposphere will also incur errors on the signal which become apparent during signal analysis. Previous research into signal deformation of GPS and Galileo reveal a high sensitivity to multipath and other error sources making “clean” data critical for GLONASS analysis. After data collection occurs, the software component utilizes the Universal GNSS Software Receiver Toolbox to generate the visible chip shape components for analysis.

Multipath has been identified as particularly invasive to data collection and analysis by previous research conducted on GNSS systems. This error source is pervasive in data if not mitigated properly. In reaction to this, special precautions were taken to mitigate these errors. Data were collected on a roof to reduce reflective multipath and ground clutter. The primary data utilized was also collected at the apex of each satellite’s elevation, which eliminated most multipath and ionospheric errors seen from lower elevations. A NovAtel GNSS-750 Wideband Choke Ring Antenna, as seen in Fig. 27, is also utilized.



Figure 27. NovAtel GNSS-750 Antenna

The “choking” antenna is a specially designed antenna to reduce multipath from the environment. The NovAtel GNSS-750 Choke Ring Antenna provides the robust, high performance necessary for chipshape analysis. This antenna provides for increased signal observations by improving multipath rejection and features a built-in low noise LNA resulting in a lower noise figure compared to other active antennas.

The signal is received by the antenna and then passed to the system’s front-end. A modified Ohio University TRIGR data collection system is used to capture GLONASS signals in a manner consistent with previous deformation analysis experiments from GPS and Galileo [30]. This equipment samples and records GLONASS data on L1 and L2 bands at an approximate 3 dB bandwidth of 26 MHz. The signal is sampled at 56.32 MSPS with 4bits/sample and streamed at ~ 113 MB/sec to a 32 TB RAID storage system. The front-end channels utilize a 70 MHz IF surface acoustic wave (SAW) filter and RF ceramic dielectric resonator filter. An analog to digital converter (ADC) is used and are referenced to a low phase-noise (< -130 dBc/Hz @10Hz) external Rubidium oscillator with a short term frequency stability specified

at $< 2 \times 10^{-11}$ per 100 second. Fig. 28 displays the system front-end utilized.

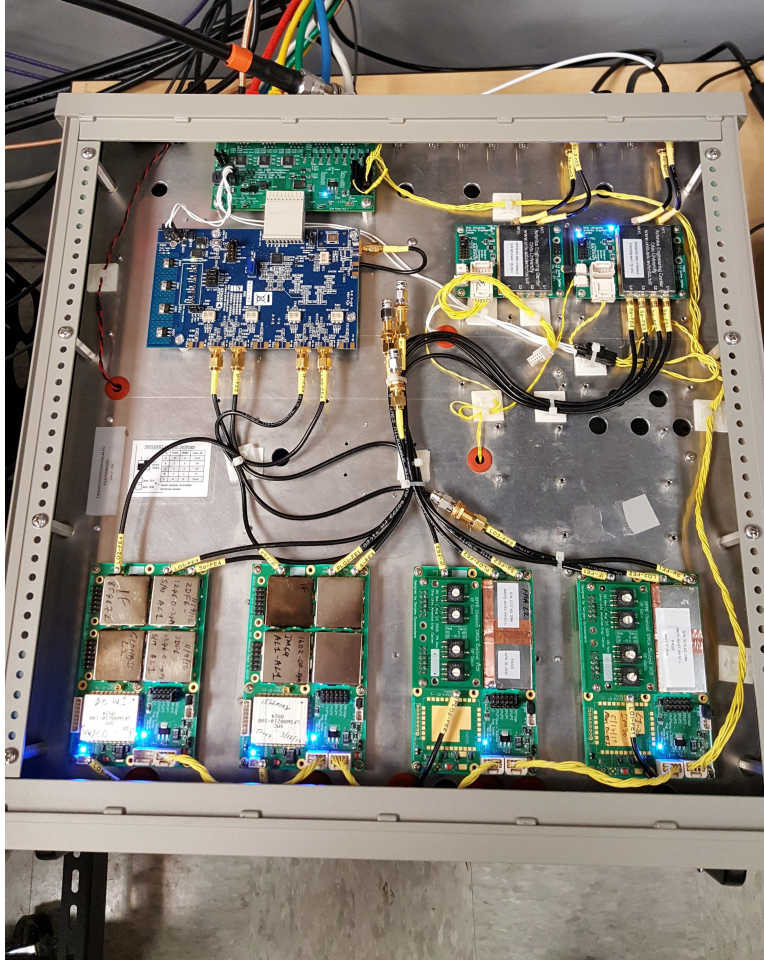


Figure 28. System Front-End

As previously discussed in this thesis, components used in the design of receiver front-ends can have a significant impact on measured natural biases. The use of transversal SAW IF filters can impose additional signal deformations in the form of oscillations on the chipshape diagram. Looking at Fig. 29, we can see variations in the combined chipshape which could influence the observations [10].

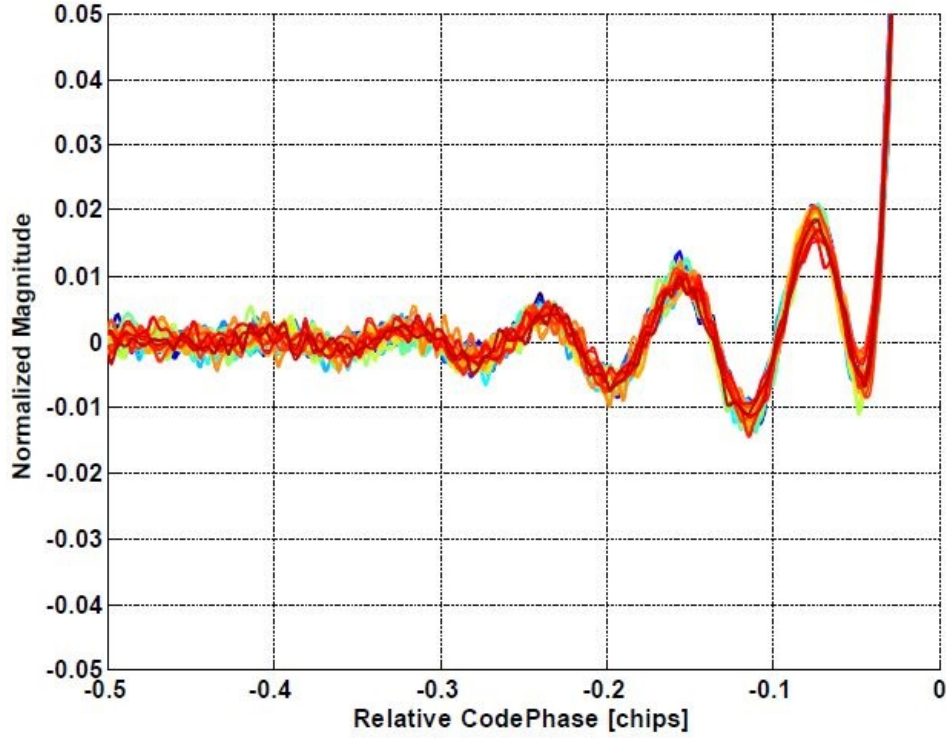


Figure 29. Normalized Chip Shape Function for GPS Observed Through a SAW Filter [10]

The RF ceramic dielectric resonator filter also induces perturbations on the signal but to a very minimal degree. Understanding and accounting for these variations in data is critical to accurately characterizing GLONASS signals.

Simulations were conducted in order to determine the amount of inter-channel bias introduced by the filters utilized in the front-end. Perfect GLONASS signals are introduced into a simulated front-end utilizing a SAW filter and an RF ceramic dielectric resonator filter. Simulations are intended to show filter bias upper bound due to front-end filtering and compensate accordingly. With multipath mitigated and front-end biases considered, analysis of the remaining biases will include only the satellite hardware and atmosphere. Development of the chip shape will display only the natural signal deformations and variations of the satellite constellation itself. Ex-

tended data collection should provide atmospheric biases which can be then removed from the satellite bias. This will allow us to characterize these variations in the chip shape as differences in satellite architecture alone.

A SAW filter converts an electrical input signal to an acoustic wave by transducers on a substrate such as quartz. The filter does this conversion in order to slow down the signal and induce delays. The transducers consist of metal electrodes which are used to launch and receive the waves. This is so that an electrical signal can be converted to an acoustic wave and then back to an electrical signal. These SAW filters have several benefits that make them ideal for GNSS systems. These benefits include a reduction in size, weight and cost. They also do not require tuning or adjustment and they are mass producible. A negative of the SAW filter is they tend to have high insertion loss on the order of several dB.

The RF ceramic dielectric resonator filter is a ceramic filter that offers very low insertion loss, reasonable Q and decent group delay. Each filter is custom designed for exact specifications of the user in order to receive optimum performance and best selectivity available. Since each filter is custom designed, they are too expensive for wide commercial use.

During live-sky collection, the TRIGR Data Collection System (DCS) creates two files with the GLONASS signal data, one in the format of .tgd and the other in .tgx. The amount of data gathered during testing is considerable. A rate of one 538 MB file is created every 5 seconds over the test period of three days. As such a 32 TB RAID storage system is required to save the information for analysis. The .tgx is the meta-data of the file set. Contained in this file is the file creation time, location of data gathered, name of data collection engineer, file name, carrier frequencies and channel numbers. The second file is in the format of .tgd and contains the actual live-sky data captured by the antenna. This live-sky data is then inserted into a

signal acquisition program capable of correlating GNSS signals out of the noise floor. Fig. 30 displays the data necessary to continue evaluating the signals. This software acquisition program displays signal strength, satellite number, code phase, C/N_0 and Doppler shift relative to each frequency found. Fig. 31 displays the signal itself relative to code phase and the correlation envelope.

```

----- RESULTS -----
Found 7 Signals!
Ch#      HitBlk      Pdi Adi df[Hz]      codephase[Chips]      Est_C/N0[dB-Hz]
-7       00000001      2  1  -666.67      +297.42      +46.7
-3       00000001      2  1   +00.00      +160.29      +44.7
-2       00000001      2  1  -3666.67      +406.80      +45.7
00       00000001      2  1  +2333.33      +258.29      +50.8
01       00000001      2  1  +3333.33      +499.82      +46.6
05       00000001      2  1  -3666.67      +125.35      +49.3
06       00000001      2  1   +00.00      +488.64      +54.1

```

Figure 30. Signal Acquisition Data

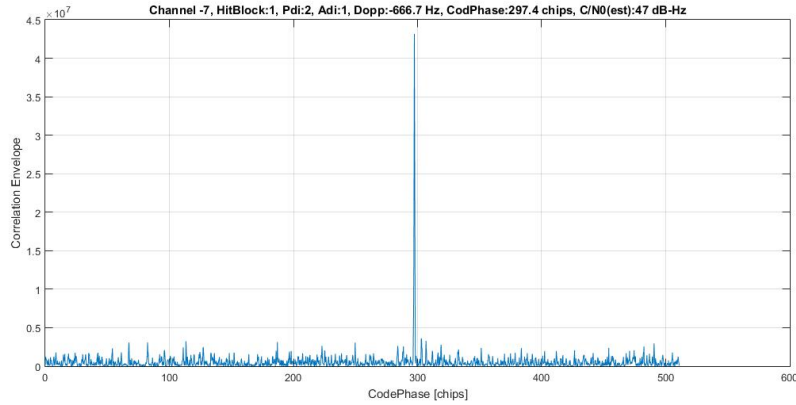


Figure 31. Acquired Signal

The nominal range of carrier frequencies has been tuned to 5000 Hz from the ICD specified L1 and L2 bands. Minimum detection threshold for signal acquisition is set to 40 dB-Hz. The minimum satellite elevation and declination threshold was set at 20° to avoid processing signals with potential ground multipath.

When determining which signal to process, outside information sources are required. The satellites position relative to any location on Earth was calculated using "www.GNSS-radar.com" or ephemeris data. With the antenna's exact coordinates already determined from previous experiments, retrieval of the satellite data for this area was possible. Fig. 32 displays the GLONASS constellation over the testing area for the testing time period. The time of each apex is determined and the corresponding .tgd file is found and loaded. The signals are cross referenced with Table 1 to determine the satellite of signal origin and ensure accuracy of the results.

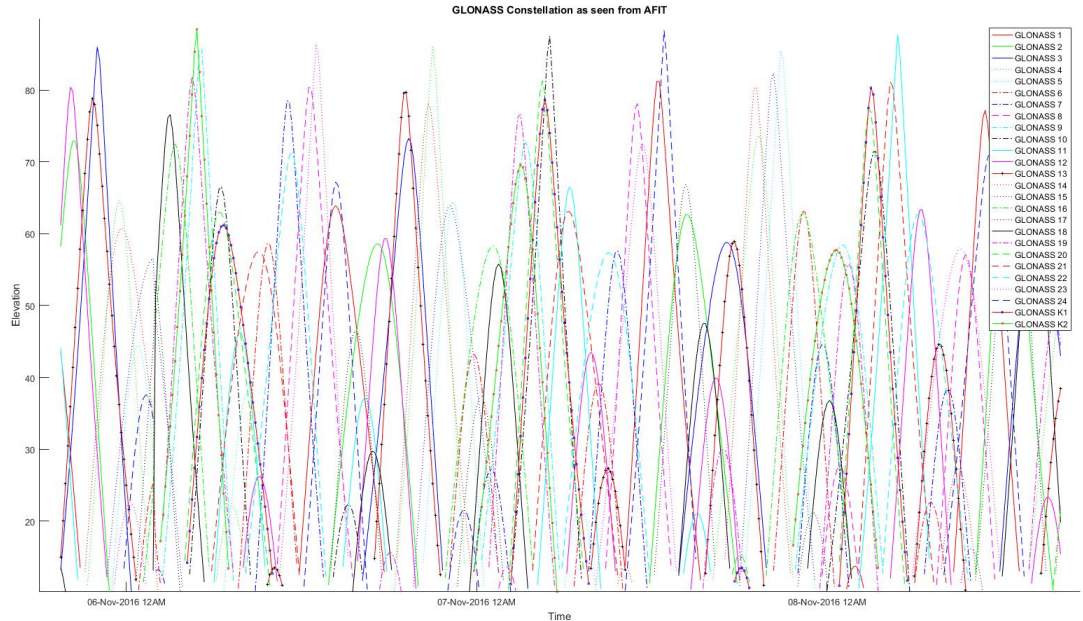


Figure 32. GLONASS Satellite Elevations for 6-8 November 2016

When the correct satellite is determined, the .tgd file root path is inserted into the Universal GNSS Software Receiver Toolbox. In order for the software to distinguish between signals, the channel number, code phase and doppler from Figure 30 is also uploaded to the software.

The Universal GNSS Software Receiver Toolbox can accommodate several GNSS

systems including GPS and Galileo. These GNSS system settings were incompatible with GLONASS requiring extensive modification to the software and system parameters. Table 7 outline the software parameters used.

Table 7: Universal GNSS Software Receiver Toolbox settings

Points per chip (N_c)	240
$N_E = N_L$	1 chips
Delay Locked-Loop (DLL)	2 Hz
Phase Locked-Loop (PLL)	18 Hz
Carrier Loop Type	Costas PLL
Carrier Loop Order	2^{nd} order
Pre-Detection Integration Time	1ms
Post-Detection Integration Time	1ms
Code Discriminator Type	Non-coherent
Correlator Spacing	0.0167 chips (early-late)
Fundamental Time Frame (FTF)	10 blocks in a databit/overlay-code-chip
Code Rate	0.511×10^6
Coherent Integration Time	5 min
Auxiliary Meander Sequence	100 Hz

N_E is defined as early chips, N_L is the late chips and based on chip shape integration, $N_E = N_L = 1$ will produce 720 correlation points spanning 3 spreading code chips. In addition, while a coherent integration time of 5 minutes is unusually long, this integration time was used in an effort to reduce the effective noise allowing for chip shapes to be observed clearly in the results. Finally, the fundamental time frame of 10 indicates the number of 1-millisecond blocks in a databit per overlay-code-chip interval.

The Universal GNSS Software Receiver Toolbox has been configured to include the carrier offset of 562.5 KHz outlined by the GLONASS ICD. Satellite numbers identified by the GLONASS ICD are used to configure the carrier offset frequency and are inserted into the code for signal acquisition. Eight masking functions seen in Fig. 25 are applied to the GLONASS code and saved off in individual banks. These masking functions use Equation 32 to generate the chip shape functions.

$$R'(\tau) = \frac{d(R)}{d(\tau)} = R'_{PPP} + R'_{PNP} - R'_{NPN} - R'_{NNN} \quad (32)$$

$R(\tau)$ is the correlation function for a zero-mean chipping sequence and is computed by integrating $R'(\tau)$. This high resolution correlation triangle is then used to compute the EmL code discriminator as a function of early to late correlator spacing. This is computed for each satellite's maximum elevation angles within the given test period and contains the signal deformations of each satellite due to hardware of signal formation and transmission.

General variables, whose values are consistent across all GNSS systems are then applied to the code. These variables range from speed-of-light to cycles-per-radian. Next, a transformation is applied to convert the chip shape points to the Early Prompt and Late correlation points of the traditional triangular correlation function. This transformation involves integrating the chip shape points spanning a codephase range of one chip. For example, integrating the mid 120 points of the 360 point chipshape output yields the traditional Prompt correlator output. The loop integrators are initialized and then, using the Doppler estimates from the acquisition software, the NCOs are likewise initialized. This will be the first commands applied to the tracking loop software routines. Using all this information, the channels are then configured for GLONASS signals. The data is then sent into the engine for processing.

Correlator values are saved along with any data necessary for analysis. This data

is applied to a secondary program which converts the .mat files produced to .CsDat. The data remains equivalent but reformatted in such a way that processing speed is increased. These .CsDat files are then run in MATLAB to produce biases needed for full GLONASS characterization. The methods used for determining those biases have been discussed previously in this thesis, in section 2.3.

Data used to develop the chip shapes are accumulated and compared to a baseline chip shape to quantify the satellite biases. This baseline chip shape used was frequency number 0 of Cosmos 2516. This was selected due to the frequency number being a median to the remaining frequency numbers. So long as the baseline remains constant, the particular satellite used as the baseline is not critical to quantification. Using this static baseline, Equation 33 is developed to determine the differences.

$$Z(k) = \frac{1}{N} \sum_{k=0}^{N-1} (R_k - R_{Ref})^2 \quad (33)$$

Here, N is the total number of chip shapes, R_{Ref} is the reference chip shape and R_k is the chip shape under analysis. This method provides the difference between the satellite and baseline. The number is squared to accentuate the differences between the two chip shapes. This equation was then applied to all three days and includes the total mean and standard deviation. $Z(k)$ was then plotted for all chip shapes across the testing period.

IV. Results

4.1 Data

The culmination of background information and methodology was used to gather data necessary to draw conclusions. Using the methodology outlined, we gathered results in chip shape to ensure accuracy and fidelity of the data. Simulations are conducted to characterize the front-end and filters. Finally live-sky data is utilized to characterize the satellites natural biases.

During evaluation, steady-state tracking of the signal is achieved and the Chip-Shape algorithm is enabled. Each satellite at the highest elevation and signal strength was chosen for the data analysis. This is intended to produce data with the highest signal strength and the least amount of multipath. For the results derived in this thesis, the differential $R'(\tau)$, with respect to code phase of the traditional triangular correlation function, was generated using Eq. 32. Cosmos 2456 was randomly selected to display masking chip shapes for a single signal respectively. R'_{NPN} and R'_{NNN} masked chip shapes were selected and the components can be seen in Fig. 33 and Fig. 34. These plots display biases in the chip shapes in-phase and quadrature components as abnormalities and oscillations in the square wave.

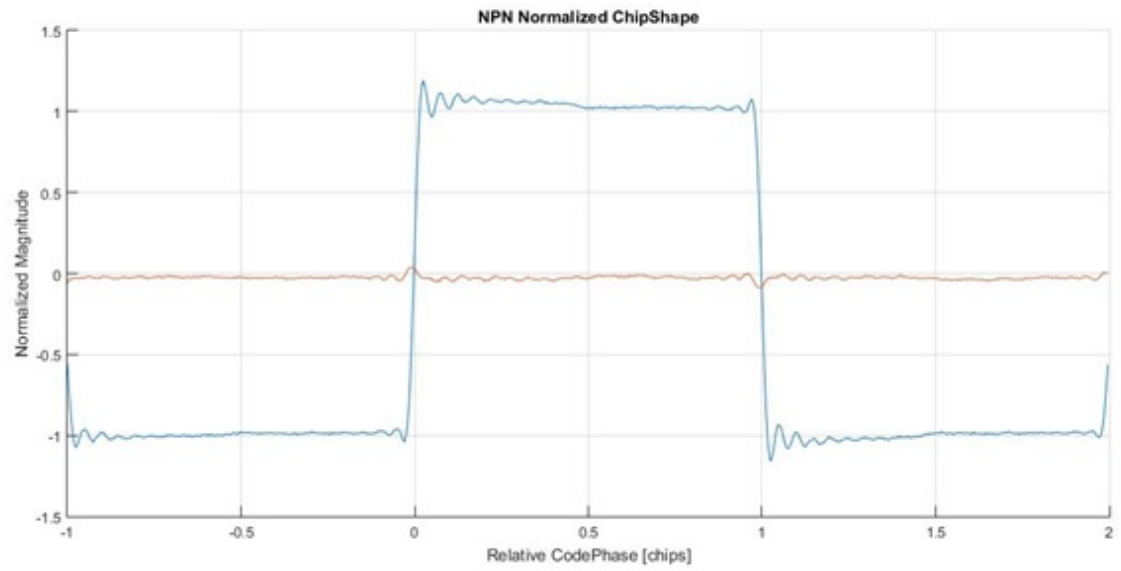


Figure 33. GLONASS NPN Masked Chip Shape

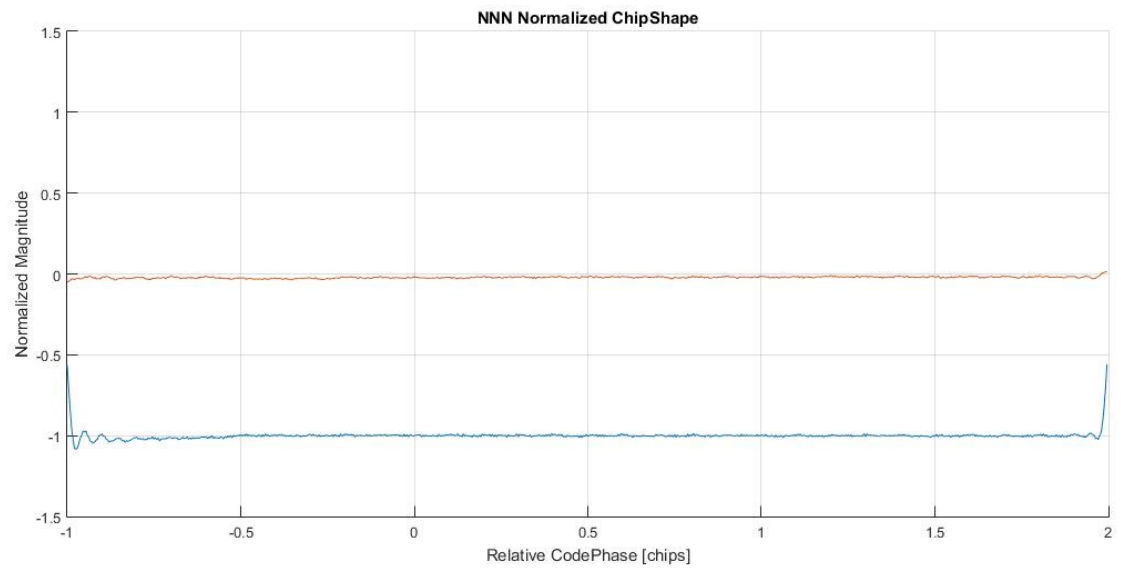


Figure 34. GLONASS NNN Masked Chip Shape

4.1.1 Simulation.

Simulation was conducted in order to determine the amount of inter-channel bias introduced by the filters utilized in the front-end. Simulated GLONASS signals are inserted into a front-end utilizing simulated SAW and RF ceramic dielectric resonator filters. The results provided in simulated figures detail the individual filters and are used to identify front-end bias from satellite component bias. Figure 35 shows the simulated in-phase and quadrature components of a GLONASS signal through a SAW filter. Since these are simulated results, the chip shape is, by definition, devoid of channel-induced multipath or atmospheric anomalies, enabling a characterization of the front-end only to be seen. There is a characteristic pre-ringing seen on SAW filters that can be observed just prior to the rising or falling edge transitions of the correlator functions [10].

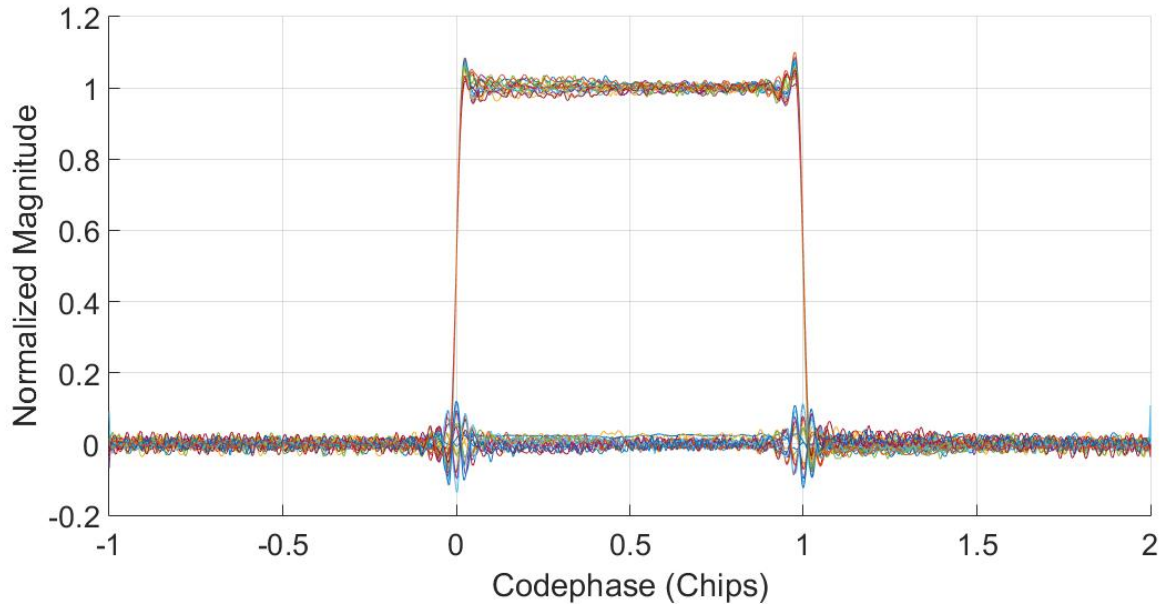


Figure 35. Simulated Normalized $R'(\tau)$ Component for the SAW Filter

In contrast, the RF ceramic dielectric resonator filter correlator function is virtu-

ally devoid of excessive transients and oscillations. This translates into very minimal correlator triangle(or correlation function) deformations and thus, biases. While the filter is not devoid of error, its performance is significantly better than the SAW filter. The simulated in-phase and quadrature components can be seen in Fig. 36.

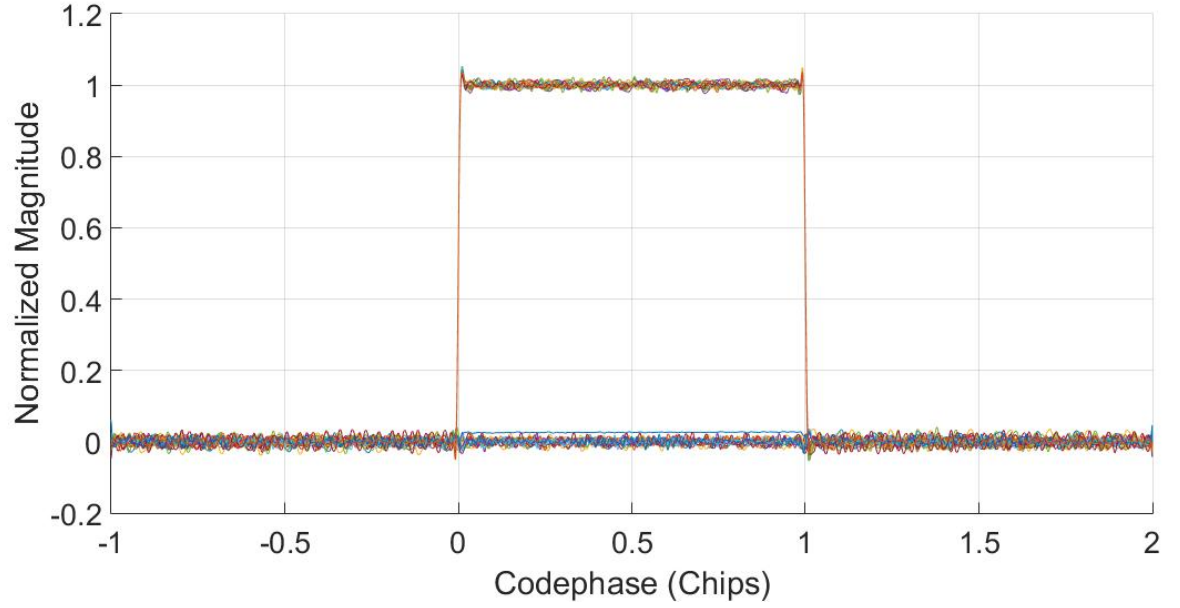


Figure 36. Simulated Normalized $R'(\tau)$ Component for the RF Ceramic Dielectric Resonator Filter

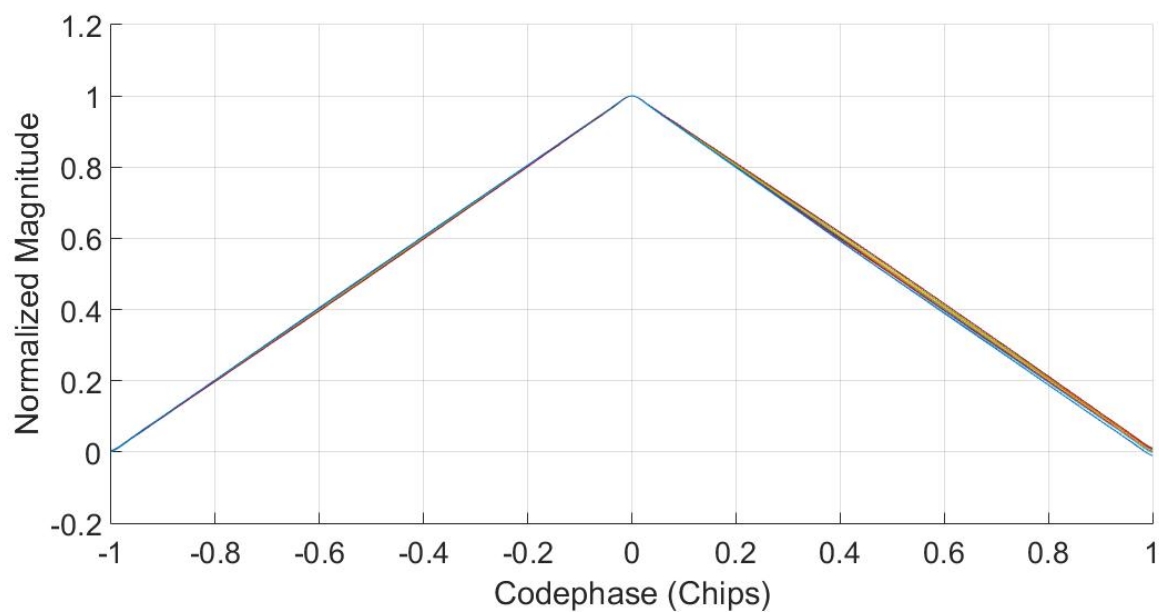


Figure 37. SAW Filter Correlation Triangle

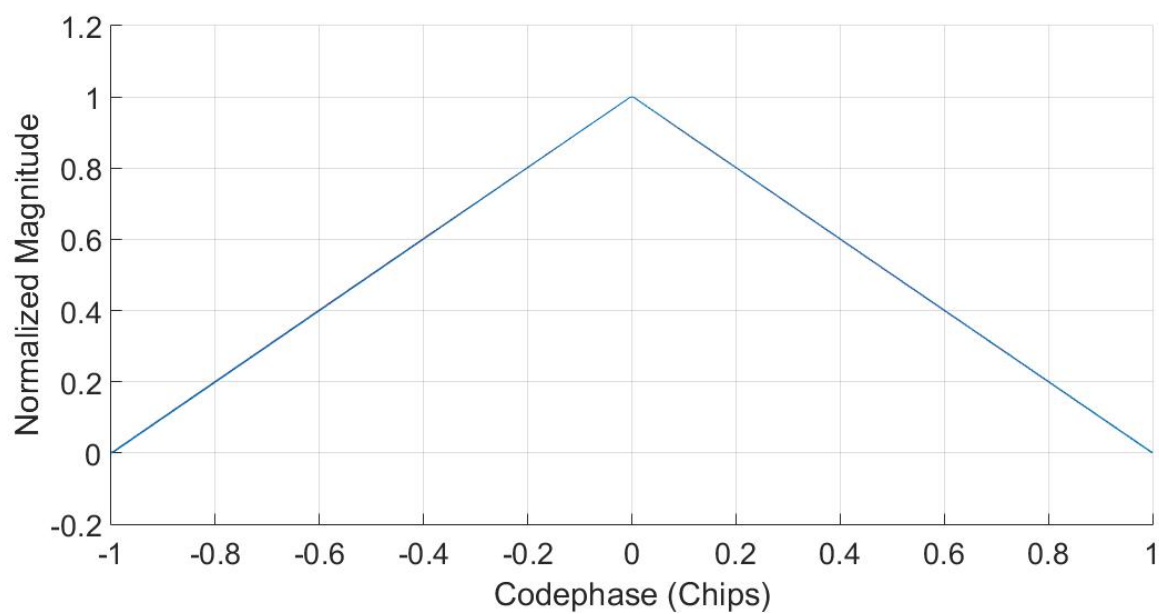


Figure 38. RF Ceramic Dielectric Resonator Filter Correlation Triangle

Fig. 37 and Fig. 38 show the simulated correlation function for the SAW and RF

ceramic dielectric resonator filters. While biases are present in both the early and late offsets of this correlation function, errors are readily apparent in the late portion of the SAW filter seen in Figure 37. While the general shape is consistent across all satellite's, unique variations in each of the satellites numbers can be seen. Taking the combined chip shape of $R'(\tau)$ and converting it into a correlation triangle will provide the early, prompt and late correlator envelopes. These outputs are then used to create the EmL code discriminator that drives the code tracking loop necessary for code synchronization. By using Equation 31, we can determine the EmL code discriminator output as a function of correlator spacing for each GLONASS FDMA channel ID. This can be seen in Fig. 39

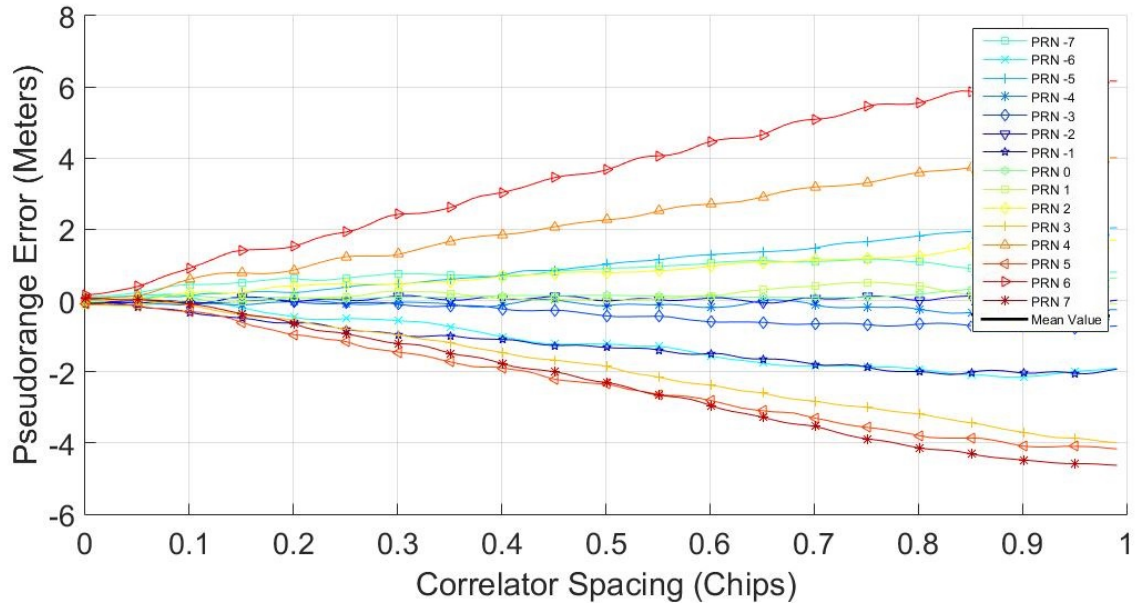


Figure 39. Simulated EmL Discriminator Function for SAW Filter

These show many biases of around ± 2 meters at $d = 0.3$ with a mean value close to 0 as shown by the solid black line. The increasing bias appears to be increasing at a constant rate with relatively high levels of PR error being accumulated as the correlator spacing is increased. A real SAW filter is used in the TRIGR DCS front-

end module and was thus chosen for analysis. By understanding the biases caused by the filter alone for ideal simulated GLONASS signals, we can establish an upper bound for the FDMA-based inter-channel biases due to the filter. Then, any biases seen above this upper bound for live sky GLONASS can be attributed to natural signal deformation from the satellites.

Using the same method to determine the simulated SAW filters EmL code discriminator, we calculate the RF dielectric resonator filter PR error. The RF ceramic dielectric resonator filter once again outperforms the SAW filter with regard to PR errors. While the SAW filter accumulated errors in the meter range, the RF ceramic dielectric resonator filter PR bias is much lower, seen in the tenths of a meter. At the same correlator spacing of the SAW filter, $d = 0.3$, the RF ceramic dielectric resonator filter sees PR bias of roughly ± 0.2 meters. This can be seen in Fig. 40.

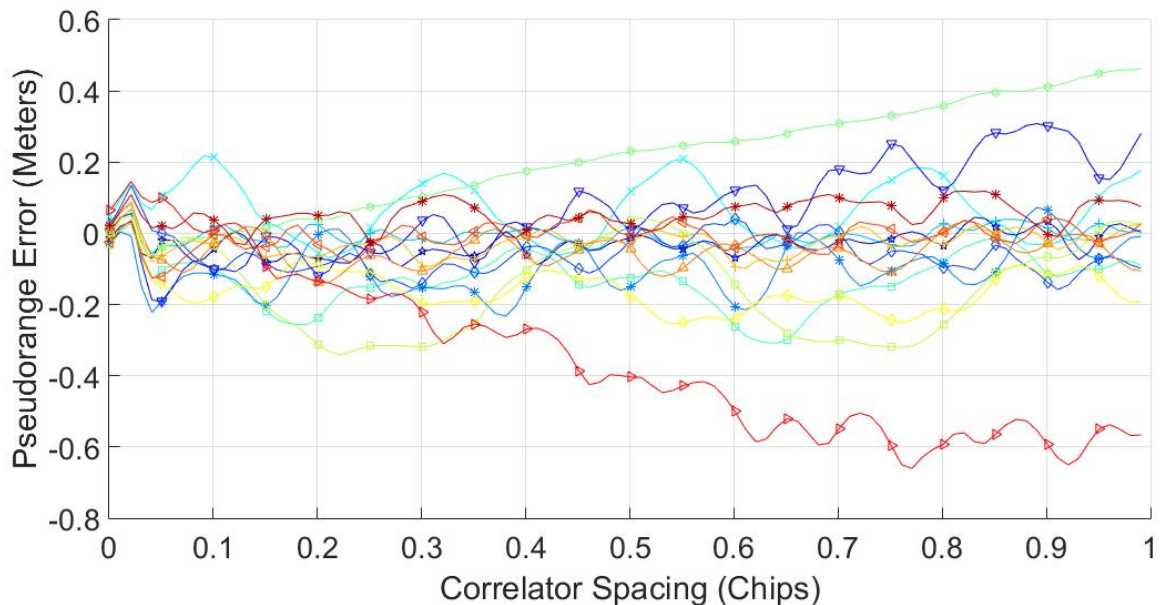


Figure 40. Simulated EmL discriminator function for L1 Ceramic Filter

The mean value is subtracted from the individual PRNs in order to de-trend the curves and remove the receiver's transfer function [31]. In so doing, we can estimate

the PR natural biases relative to each other.

The simulated results for the estimated PR biases with respect to 0.1 correlator spacing with the SAW filter is shown in Fig. 41. This figure shows that when $d=0.1$ chip is considered for reference correlator spacing, the natural biases between correlator spacing range 0.1 to 0.2 is less than ± 0.5 meters with no outliers. At $d=1$, the pseudorange biases for the most part are ± 4 meters with two satellite's falling outside that range. We produce results with respect to 0.1 correlator spacing because GBAS send corrections to the general area using correlator spacing of 0.1. If the receiver is utilizing a different spacing, the corrections will induce additional errors into the system.

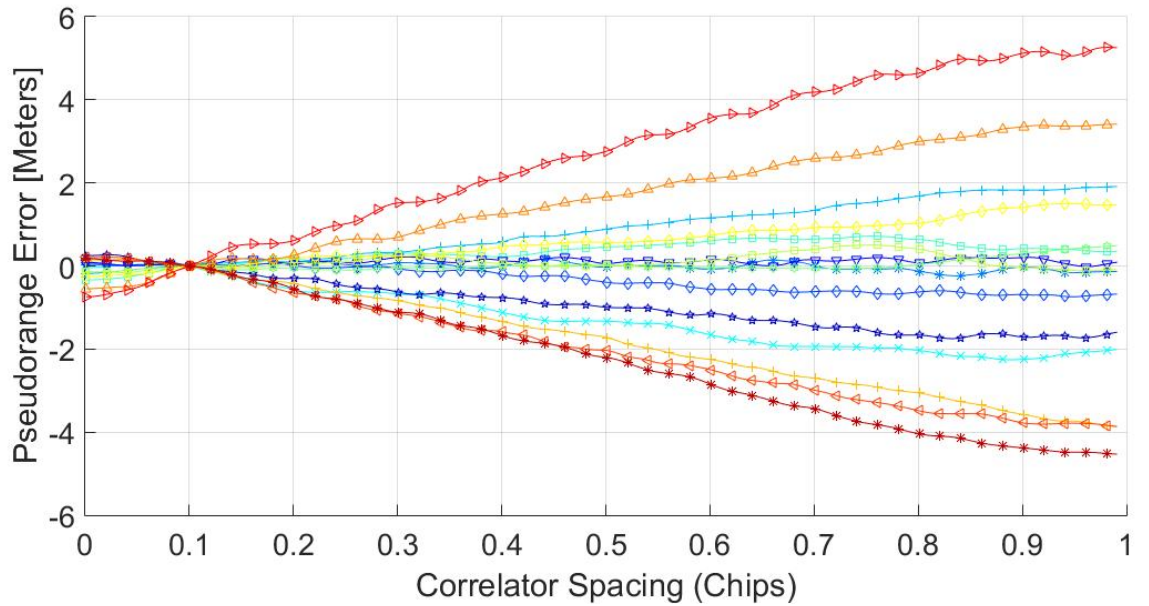


Figure 41. Simulated Estimated PR Natural Biases with Respect to 0.1 Correlator Spacing for SAW Filter

The simulated results for the estimated PR biases with respect to 0.1 correlator spacing with the RF ceramic dielectric resonator filter can be seen in Fig. 42. These results show the natural biases between the correlator spacing range of 0.1 to 0.2 to be

less than ± 0.2 meters with one outlier. At $d=1$, the pseudorange biases for the most part are between 0.5 and -0.1 meters with PRN 6 being the outlier and approaching -0.58 meters.

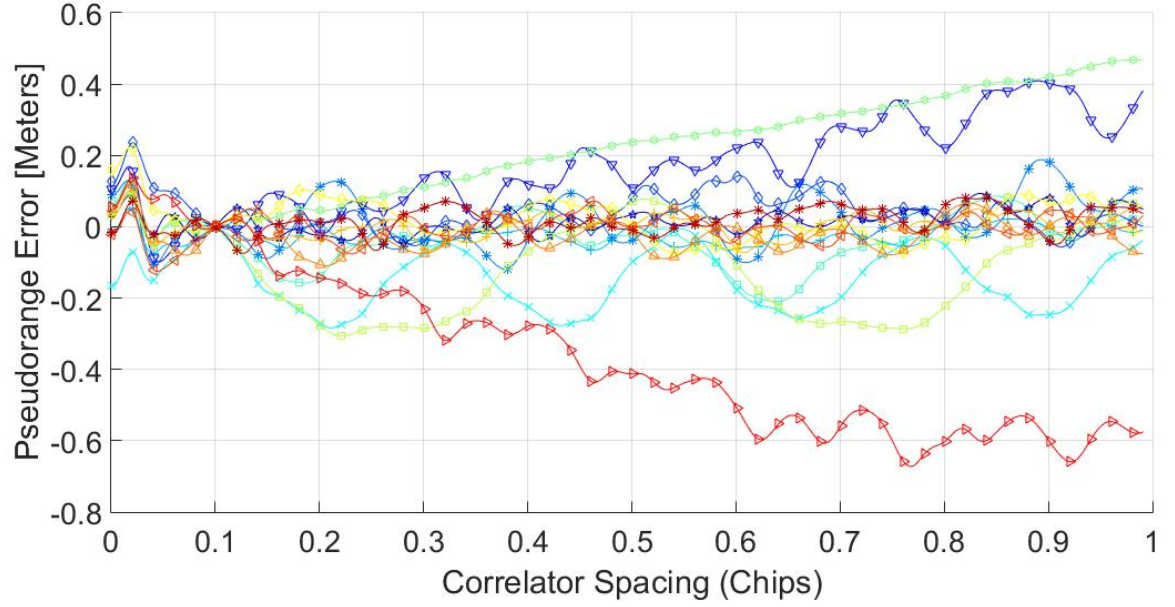


Figure 42. Simulated Estimated Pseudorange Natural Biases with Respect to 0.1 Correlator Spacing for L1 Ceramic Filter

4.1.2 Live-Sky.

With the simulations complete and the front-end biases identified, live-sky data was then uploaded to the program. Initial data processing was limited to day 2 of the three days of data gathered. This was to ensure the initial analysis would encompass the most comprehensive amount of data available. After the second day was analyzed and results processed, the other two days were then examined.

Data was gathered on each satellite, passing through the front-end with both the SAW and RF ceramic dielectric resonator filters. The signal was then processed using the Universal GNSS Software Receiver Toolbox. Upon analysis of the data, each chip shape contains unique anomalies and provides ample information to characterize each satellite. Figures 43, 44, 45 and 46 display the chip shapes for Cosmos 2516 over a three day period. This satellite's results are characteristic for the remainder of the constellation. Each figure for Cosmos 2516 can be seen with minor variations that can be explained with atmospheric anomalies or some other minor variation in the clutter observed by the antenna. Each chip shape contains the same general shape and oscillations on the components.

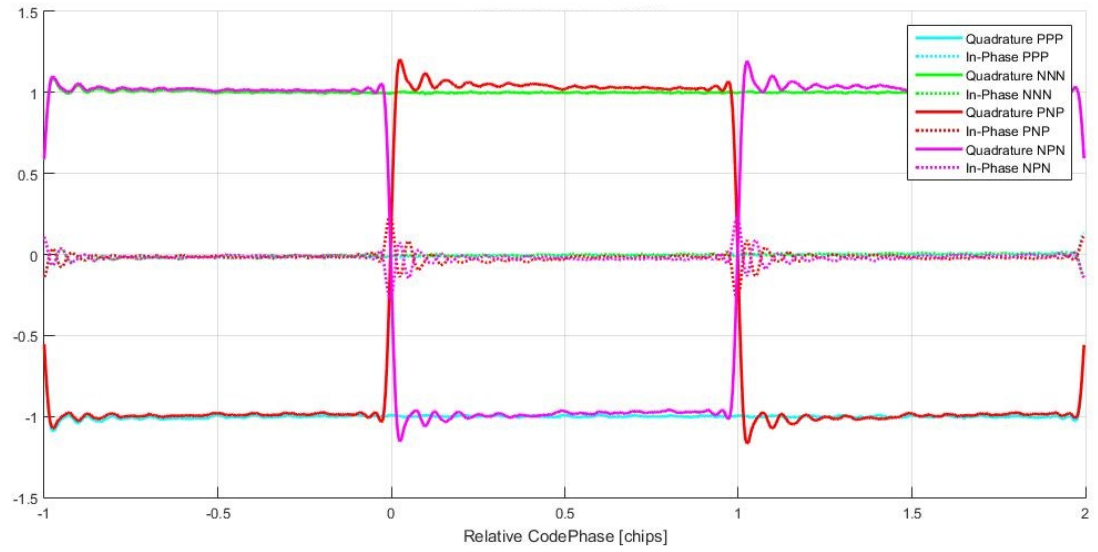


Figure 43. Chip Shape Components for Cosmos 2516; PRN 0 on 6 November 2016, first orbit

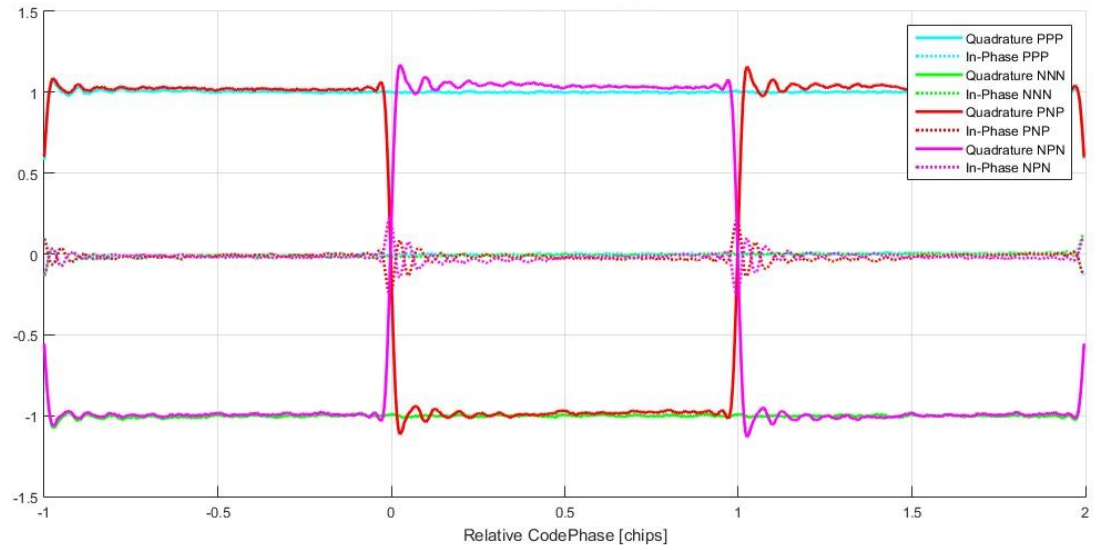


Figure 44. Chip Shape Components for Cosmos 2516; PRN 0 on 6 November 2016, second orbit

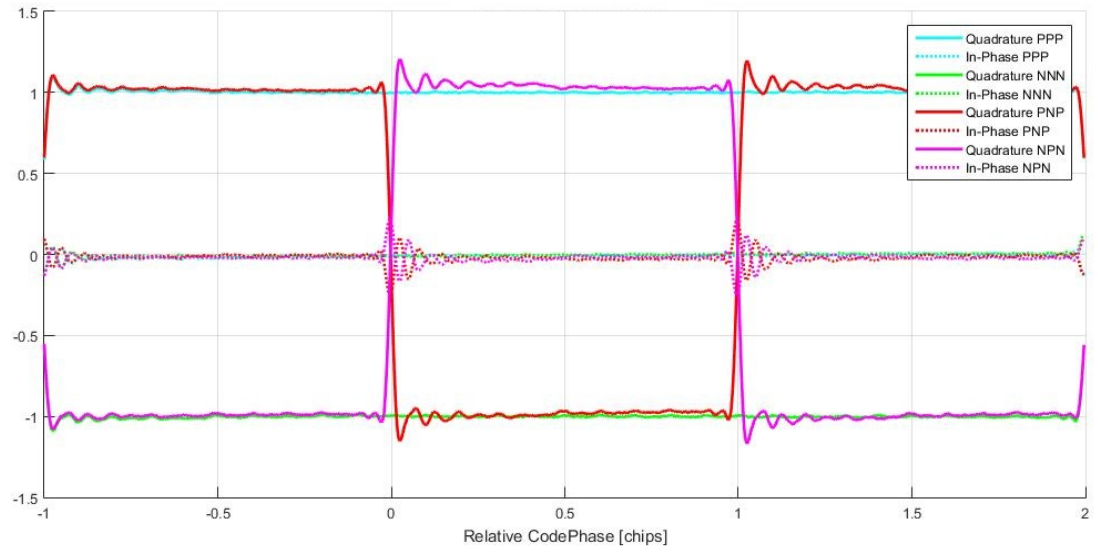


Figure 45. Chip Shape Components for Cosmos 2516; PRN 0 on 7 November 2016

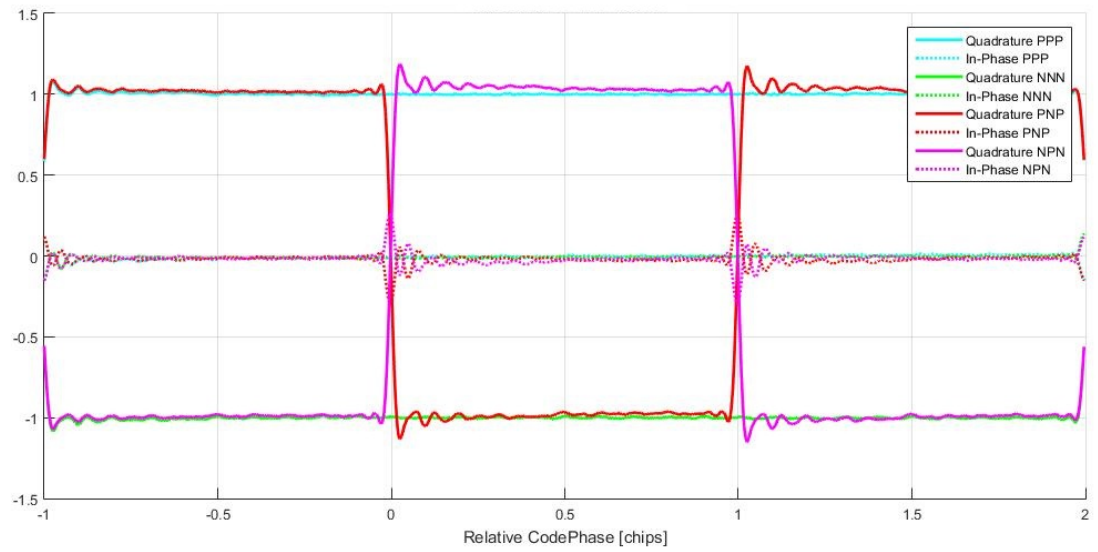


Figure 46. Chip Shape Components for Cosmos 2516; PRN 0 on 8 November 2016

Data for each of Figures 43, 44, 45 and 46 were taken while at their apex however that apex occurred when the satellite was at different maximum elevations. Despite

being at different elevations and azimuth, the chip shape components remain nearly identical. The elevation differences can be seen in Table 8.

Table 8: Cosmos 2516; PRN 0 Elevation Data

Cosmos 2516; Satellite number 0	6 Nov	6 Nov	7 Nov	8 Nov
Elevation	46.3°	37.2°	66.5°	87.7°
Azimuth	283°	67.9°	276.8°	285.6°

In comparison to Fig. 67 which is Cosmos 2475, Cosmos 2516 displays significantly different chip shape components. These results demonstrate that the characteristic natural signal deformations on each satellite do not change with time. This observation has also been confirmed for GPS using long term observations [32]. This observation is crucial for being able to use these natural signal deformation 'signatures' for authenticating open GNSS signals.

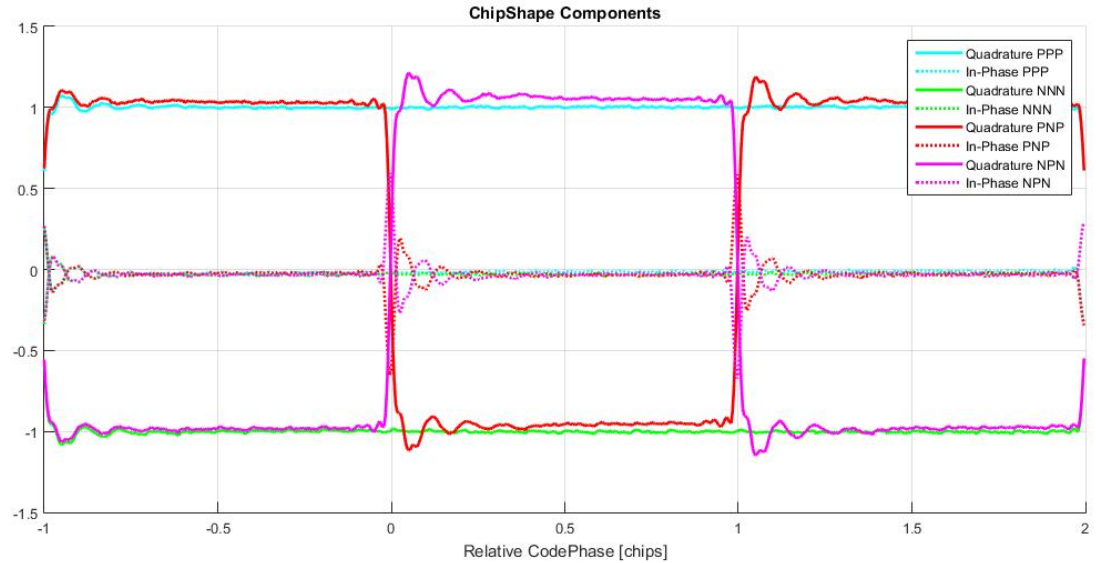


Figure 47. Chip Shape Components for Cosmos 2475; PRN 6

Each satellite of the GLONASS constellation was processed starting with satellite number -7 and continuing to satellite number 7. Processing showed no abnormal

behavior seen on the chip shape patterns with results consistent across all satellites. It is important to note that all satellites induce unique biases to the correlator function. The data for Cosmos 2516 shows variations in elevation angle inducing minimal changes on the chip shape components. Each chip shape will retain the same basic shape when outside variables, such as multipath do not corrupt the chip shape.

Fig. 48 shows the quadrature component and the in-phase components for $R'(\tau)$ for the GLONASS constellation on 7 November. These components show abnormalities in the rising and falling edges, which will carry over into the correlation function and PR natural bias plots.

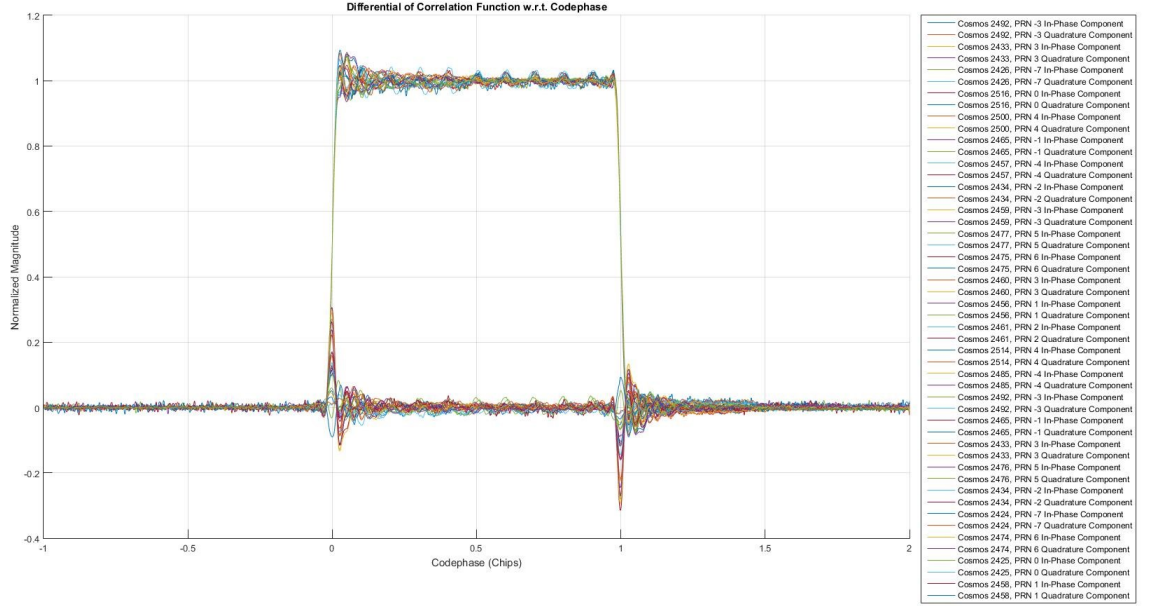


Figure 48. Normalized $R'(\tau)$ Components of GLONASS Constellation Observed on 7 November

Fig. 49 shows a ringing, which could be an artifact of SAW filters or be a result of the signal generation at the source. Fig. 50 shows a rising edge with the ringing still present however the oscillation appears more stable prior to the edge itself. These enhanced views of the rising and falling edges of the chip shape functions display

possible data points that can be used to characterize the signal errors.

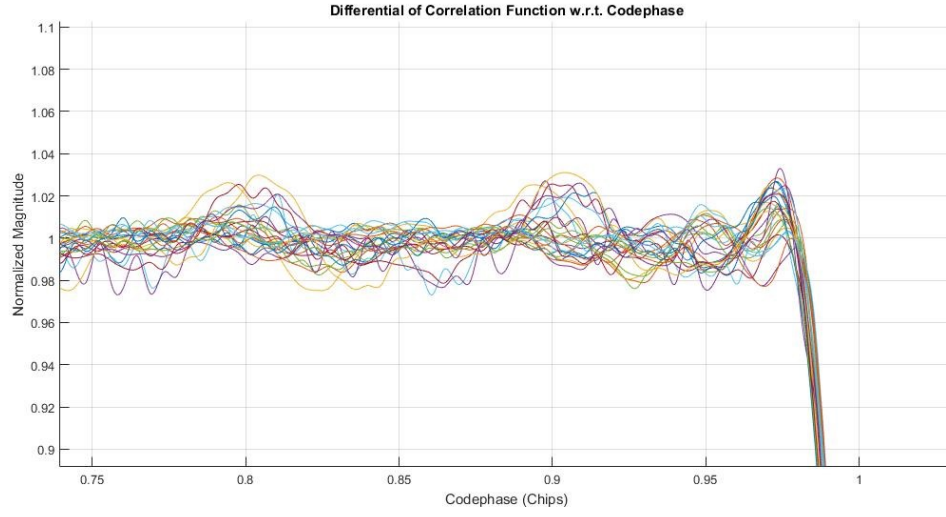


Figure 49. Normalized $R'(\tau)$ Functions for GLONASS Constellation Observed on 7 November 2016: Falling Edge

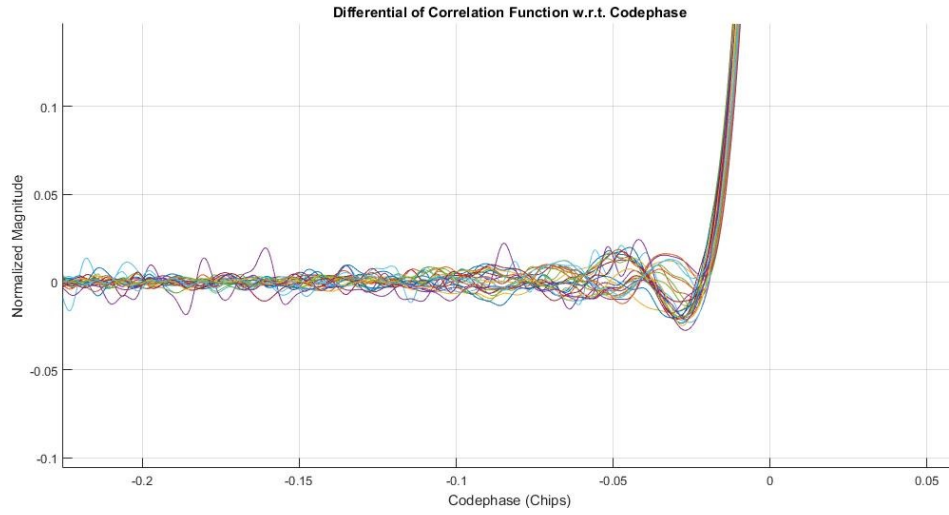


Figure 50. Normalized $R'(\tau)$ Quadrature Functions for GLONASS Constellation Observed on 7 November 2016: Rising Edge

Fig. 51 shows the correlation triangle for the GLONASS constellation as observed

at their maximum elevation on 7 November 2016.

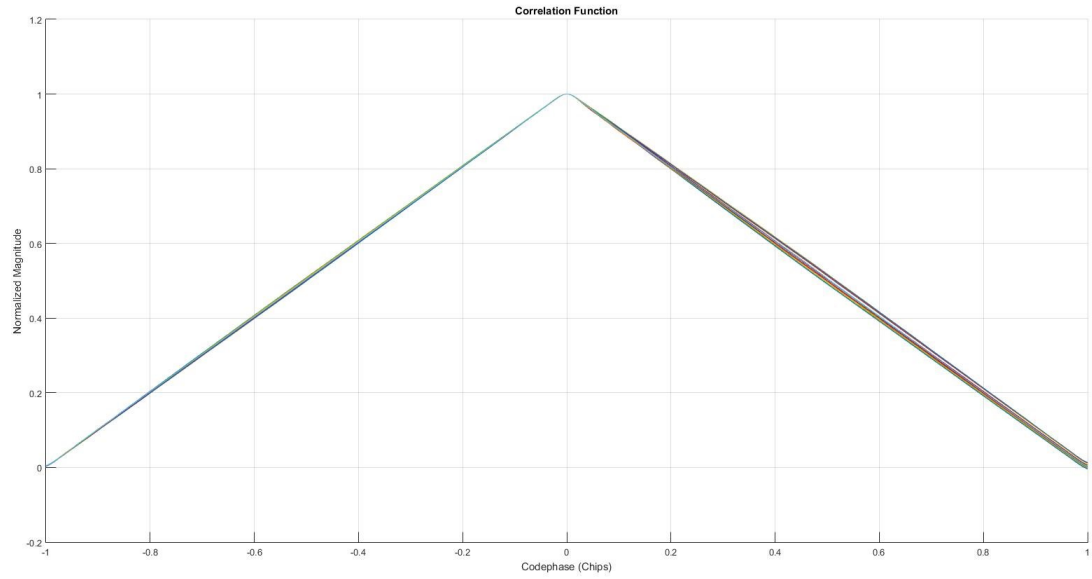


Figure 51. Correlation Functions for GLONASS Constellation Observed on 7 November 2016

Using the method described above to find the EmL function, we can derive the PR natural biases and see them in Fig. 52. The mean value for all satellites is illustrated by the solid black line. The legend will remain the same for the subsequent plots.

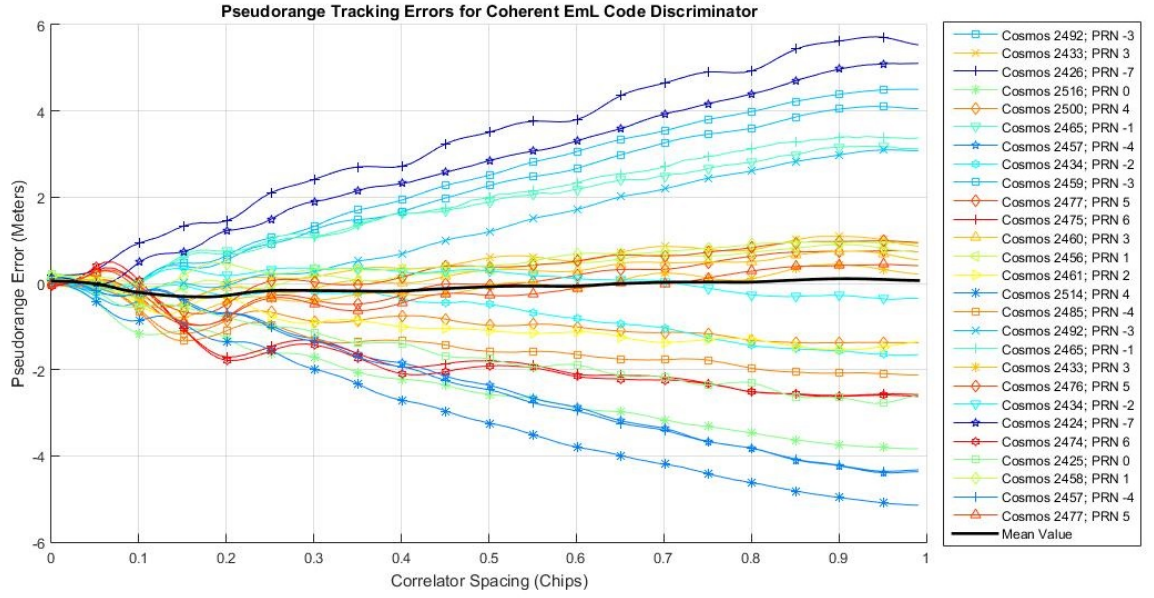


Figure 52. Early minus Late Code Discriminator Function

As correlator spacing increases in Fig. 52, pseudorange error continues to increase. At $d=0.3$, the pseudorange error is roughly 2 meters with Cosmos 2426 being an outlier of roughly 2.5 meters. In addition, several of the satellites appear to be biased in such a way that at starting at $d=0.5$, some signals appear to cluster together as correlator space is increased. This is producing four distinctive groups within the data.

In Fig. 53, when $d=0.1$ chip is considered for reference correlator spacing, the natural biases between correlator spacing range 0.1 to 0.2 is less than 1 meter. Cosmos 2474 and Cosmos 2475, both with a satellite number of 6, have their pseudorange error at the maximum of 1.7 meters.

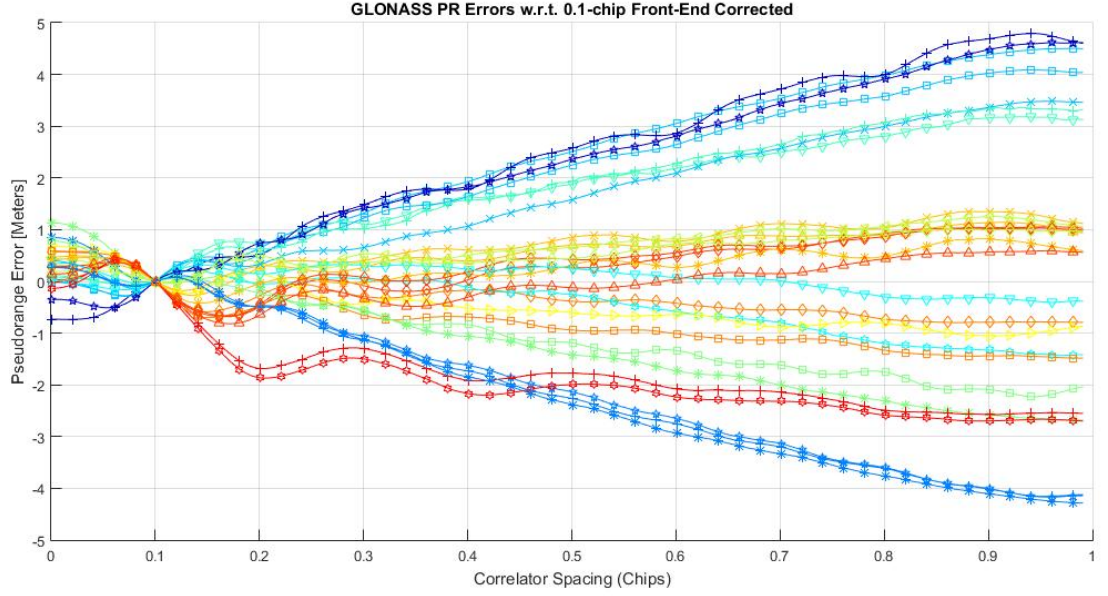


Figure 53. Estimated Pseudorange Natural Biases with Respect to 0.1 Correlator sSpacing for GLONASS on 7 November 2016

The natural biases seen from the live-sky results are ± 0.75 meters with two satellites being outliers to that range error. These two satellites are anti-podal, and utilize the same satellite frequency number. Since both satellites are exhibiting the same behavior, it's logical to assume the PR error displayed is a result of the front-end being used. Since multipath has been mitigated by means of method of data collection and by accounting for the inter-channel bias, we can see the difference to be the bias generated by the satellite itself or by atmospheric anomalies.

Pseudorange measurements from each frequency are differenced to obtain pseudorange biases as a function of correlator spacing, with respect to the 0.1-chip reference. The GLONASS constellations pseudorange natural biases are within 1 meters of each other respectively at 0.2 correlator spacing. The biases incurred by the front-end filters is detailed in Table 9. Using these results, we can characterize these front-end biases from the final results gathered, giving a proper representation of the satellite

and atmospheric bias. By knowing these biases, we can determine what effects are influencing the results and to what extent.

Table 9: PR Error Results (m) observed at 0.2 correlator spacing

	PR Tracking Errors	PR Errors w.r.t. 0.1-chip
SAW Filter	± 1	± 0.75
L1 Ceramic Filter	± 0.2	± 0.1
Live-Sky Data	± 1.75	± 0.9
Estimated biases	± 0.55	± 0.05

The estimated biases are due to the satellite's natural signal deformations and is estimated by:

$$\epsilon_N \approx \epsilon_A - (\epsilon_S + \epsilon_c) \quad (34)$$

where ϵ_N is the natural signal biases, ϵ_A is the actual live-sky bias, ϵ_S is the simulated SAW filter bias and ϵ_c is the simulated RF ceramic dielectric resonator filter bias.

Quantifying the biases using Equation 33, we develop Table 10.

Table 10: Chip Shape Differentials for 7 Nov 16

Cosmos #	Channel #	Differential Value	Cosmos #	Channel #	Differential Value
2492	-3	20.1388	2514	4	24.7773
2433	3	27.3763	2485	-4	36.9496
2426	-7	73.4089	2492	-3	20.1800
2516	0	2.0304	2465	-1	16.1509
2500	4	44.7619	2433	3	25.8873
2465	-1	11.9763	2476	5	51.1939
2457	-4	38.5681	2434	-2	16.1733
2434	-2	18.8407	2424	-7	97.8378
2459	-3	23.2879	2474	6	75.3523
2477	5	51.5840	2425	0	23.9738
2475	6	77.7059	2458	1	12.7576
2460	3	14.5498	2457	-4	33.5785
2456	1	14.0975	2477	5	43.1673
2461	2	15.4803			

Each value is based on the difference between the baseline chip shape and the chip shape under evaluation. While there are 720 points per correlator bank, using interpolation, the number of points being analyzed is roughly 1.75 million points. This approach can be seen in Equation 35.

$$y_i = y_1 + \frac{y_2 - y_1}{x_2 - x_1} \cdot (x_i - x_1) \quad (35)$$

This allows for far higher resolution per chip shape to help characterize the system biases. It also allows for the zero crossing to be exactly determined for the biases.

By taking the mean value and standard deviation of the data gathered, we arrive

with the information in Table 11.

Table 11: Chip Shape Differentials for GLONASS Constellation

Cosmos #	Channel #	Mean	Std
2456	1	10.7147	1.7426
2485	-4	10.3625	1.6087
2476	5	6.9551	0.7926
2474	6	9.785	0.3826
2457	-4	17.1781	2.5558
2458	5	28.5920	6.1440
2457	6	16.0920	0.1616
2426	-7	11.9009	0.0383
2516	0	14.6407	2.1954
2465	-1	37.9456	2.4115
2434	-2	24.0230	10.9496
2424	-7	22.3644	9.2992
2425	0	15.3982	0.9561
2464	-1	16.4485	1.0884
2514	4	19.1059	8.8302
2459	-3	13.0470	5.2066
2460	3	9.3332	3.3910
2432	2	16.0971	0.1085
2500	4	9.5939	0.4881
2492	-3	8.1081	3.3585
2433	3	22.3237	2.2490
2461	2	32.9587	9.0503

Plotting the satellites against the metric seen Equation 33 and the GLONASS satellites, we arrive with Fig. 54. We can see from this figure how most of the satellites maintain consistent values across multiple days with few exceptions.

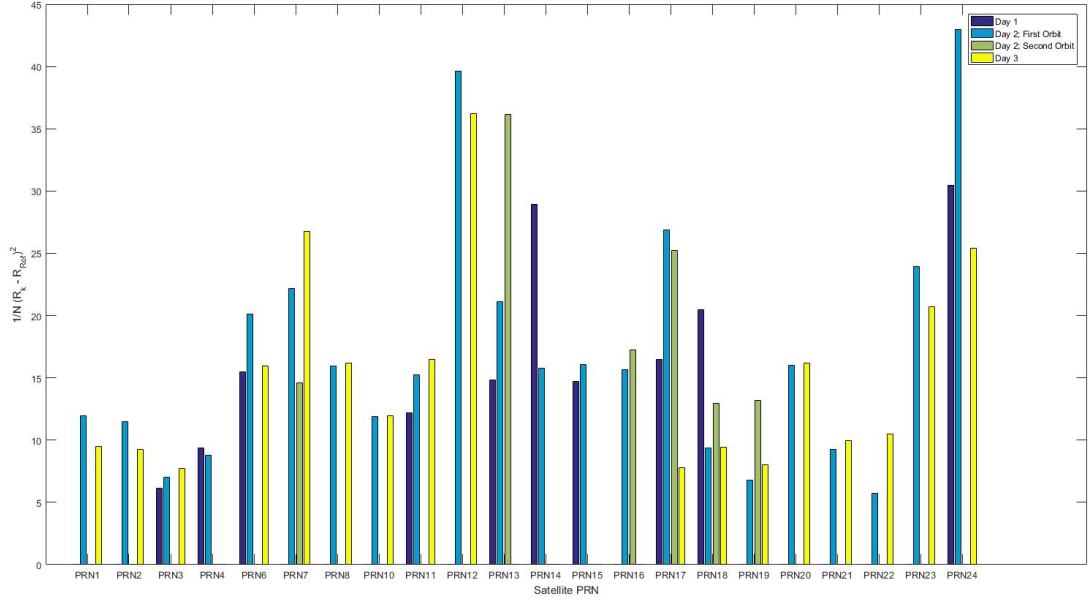


Figure 54. SV Chip Shape Metric Variation Across Testing Period

PRN 13 has the greatest disparity between the different orbits with values ranging from 15 to 36. This indicates variations in the biases and when we isolate and plot that data, we arrive with Fig. 55.

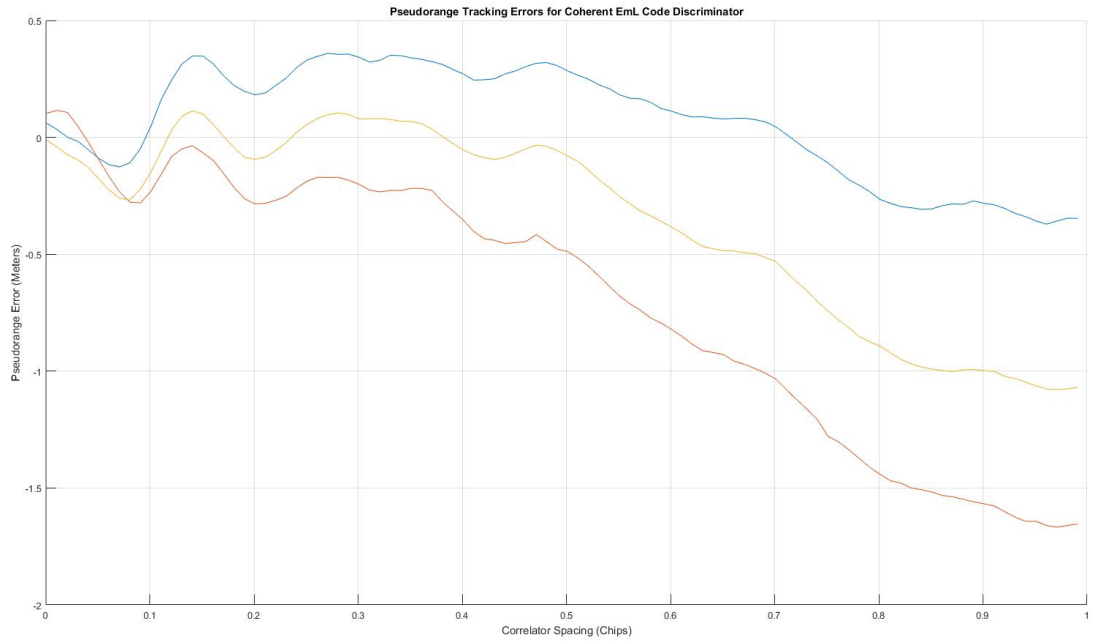


Figure 55. Cosmos 2434; PRN 13 Natural Biases

There is a large disparity between the biases between ± 1 meter seeming to indicate large deformations in the chip shape between orbits. However, when looking at the correlation function in Fig. 56, we see there is no major deformations that significantly alter the general correlation function. Additional processing is necessary to determine the cause.

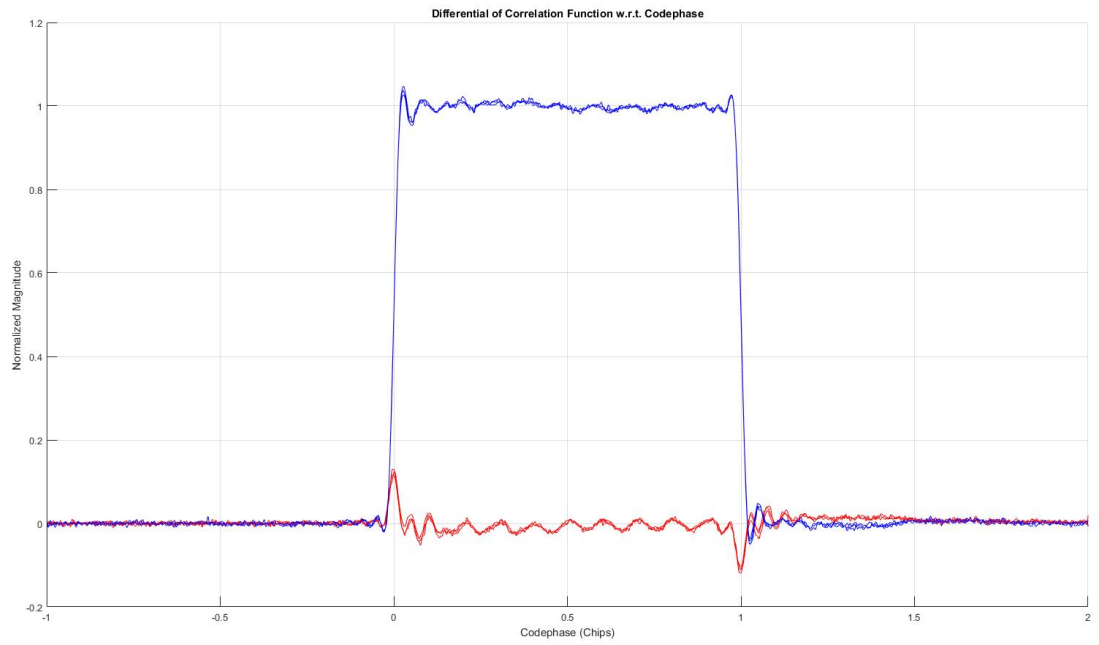


Figure 56. Cosmos 2434; PRN 13 Correlator Functions

V. Conclusion

This thesis has investigated a method to maintain global navigation superiority by utilizing advanced chip shape correlation processing techniques in order to enable signal authentication and provide confidence for potential use of GLONASS within American military applications. Utilizing the chip shape for authentication, algorithms can be constructed for receivers to utilize foreign signals with confidence in their veracity.

Between 6 November 2016 and 8 November 2016, this thesis gathered data on chip shape analysis for the GLONASS constellation over Dayton, Ohio. This analysis was performed using high-fidelity data collection techniques in order to reveal the effects of hardware signal generation, satellite transmission and receiver hardware errors. Modification of the software currently used for GPS chip shape analysis allows GLONASS signals to be accepted and provide a wide breadth of GNSS receivers to be tested for possible broad integration into American systems. To ensure accuracy and confidence in the methodology used in this thesis, a comprehensive investigation was conducted into GLONASS and its inner workings. Each GLONASS specification was scrutinized and researched to determine its functionality, impact on GLONASS signals and impact on the receiver software. When each specification was sufficiently characterized, they were integrated into the software. Simulations were conducted to ensure proper integration into the software and no errors were present in the final data. GLONASS chip shapes and biases were generated and compared to expected behaviors to ensure accurate and consistent results.

GLONASS signals were introduced into a simulated front-end utilizing a SAW filter and a RF ceramic dielectric resonator filter. These signals were free of satellite, atmospheric and multipath biases. This provided the filter bias upper-bound due to front end filtering and allowed the data to account for this bias. The filter biases

upper-bound was larger than the satellites bias but not by a large amount. Both location of the antenna and collecting data while the satellites were at their apex, mitigated the multipath errors. With these errors considered, the remaining bias on the signal is atmospheric and satellite bias. This enables precise characterization of the constellation. Chip shape analysis shows that correlator function consistency and symmetry vary across the satellite constellation, indicative of differences in satellite hardware components. However, the same satellite's chip shapes are virtually identical across the three day period, despite differences in elevation and azimuth.

Analytical analysis of the chip shapes indicate variances in the values calculated indicative of chip shape asymmetry. Analyzing the biases of satellites across the testing period seems to confirm this however, upon further inspection of the chip shape, we determine this to not be the case. Instead, chip shapes remain constant despite wide variations in the calculated mean and standard deviation. The chip shapes maintain the same configuration throughout the testing period and only incur outside biases which do not alter the basic shape. This indicates chip shape analysis may be utilized in areas that incur biases on the signal without seeing large deformations. This information provides more confidence in the methods outlined in this thesis.

Techniques used in this thesis require further research into GLONASS signal deformations to determine if the observed anomalies are permanently present on signals. GBAS monitor biases from satellites over long periods of time to ensure additional errors are not being incurred. However this must be substantiated through chip shape processing. If the variations and abnormalities are consistent across time, characterization of the GLONASS constellation could be accomplished due to the easily quantifiable anomalies observed. The same satellite's chip shapes are virtually identical across the three day period, despite differences in elevation and azimuth. This corroborates the standing theory that a comprehensive characterization of the

GLONASS constellation is not only possible, but should provide enough information to adequately allow for the authentication and confidence in the signal for use in military applications. However, chip shape processing is numerically intensive and despite having shown the method works for characterizing natural signal deformations, we cannot utilize this method using post-processing approaches. A realtime correlation engine capable of chip shape processing is desired. Multipath induced bias will remain an issue for a realtime engine and may cause false positives of satellite manipulation to occur. This is currently unavoidable and will require extensive signal processing techniques to rectify.

Currently, AFIT is conducting research into a realtime engine with a goal of deployment for field studies and tests. SatNav signals can be continuously monitored and observed and provide warning to users if expected chip shapes deviate from the established characterized norms. This will garner integrity for chipshape-based authentication techniques. Further research is required in this field to adequately characterize the GLONASS signal and conduct field tests of a realtime engine. As this thesis currently only analyzes the L1 band, further examination of the available data is also required to characterize the L2 band.

Additional research is recommended into chip shape processing for L2 bands and other GNSS constellations. Additional characterization across a more lengthy period of time is also recommended. Integration of the data gathered by this thesis and future GNSS constellation characterization into a realtime engine is also highly recommended.

In summary, this thesis provides strong evidence that GLONASS has adequate and observable natural signal deformation signatures that can be exploited for open signal authentication.

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Appendix . Appendix A

0.1 Chip Shape Plots

This appendix contains the individual satellites chip shapes in chronological order from their apex.

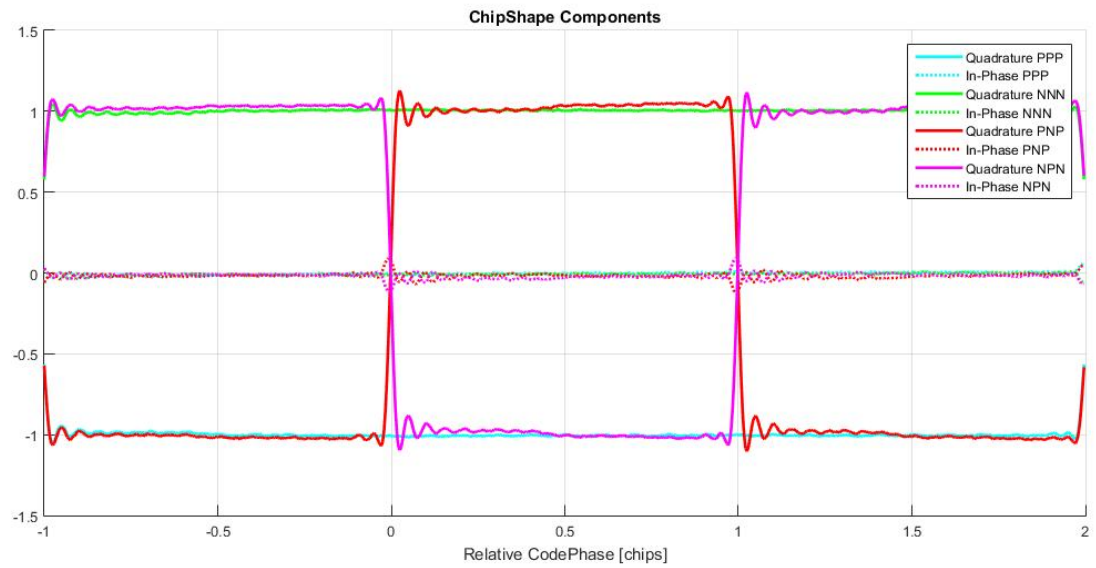


Figure 57. Chip Shape Components for Cosmos 2492; PRN -3

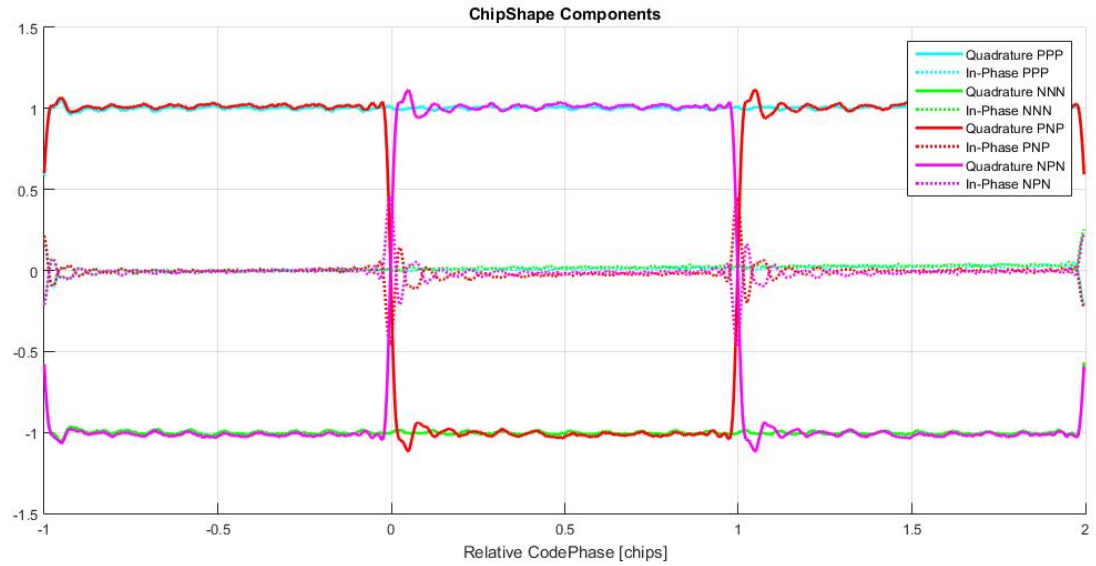


Figure 58. Chip Shape Components for Cosmos 2433; PRN 3

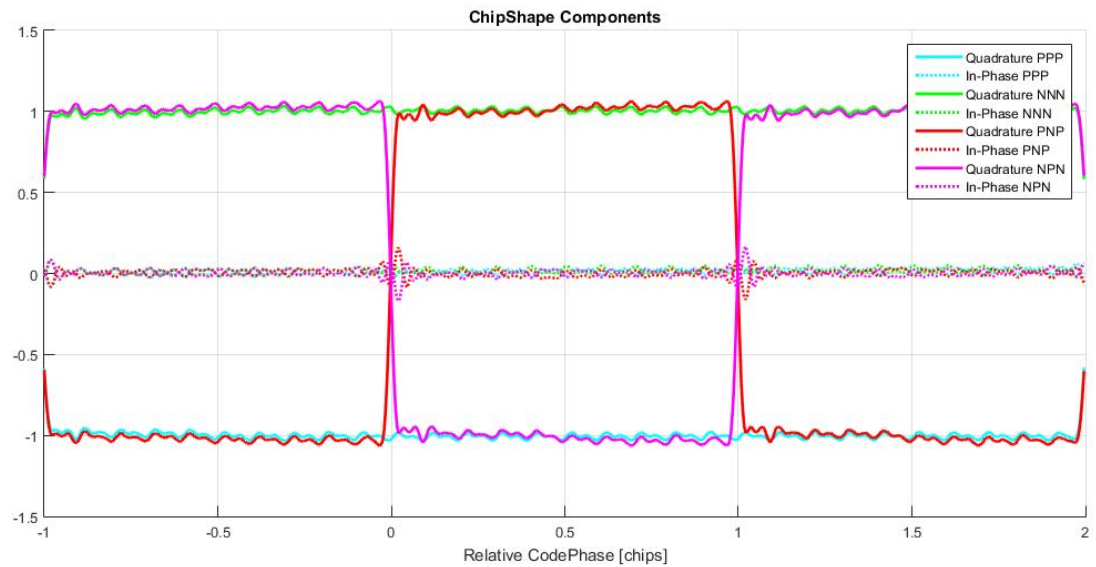


Figure 59. Chip Shape Components for Cosmos 2424; PRN -7

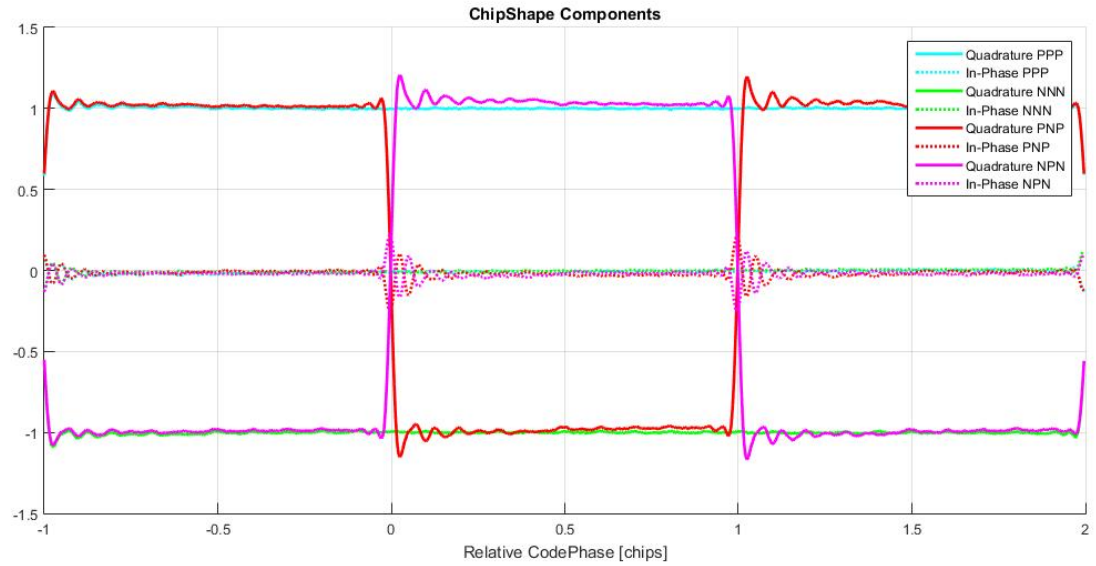


Figure 60. Chip Shape Components for Cosmos 2516; PRN 0

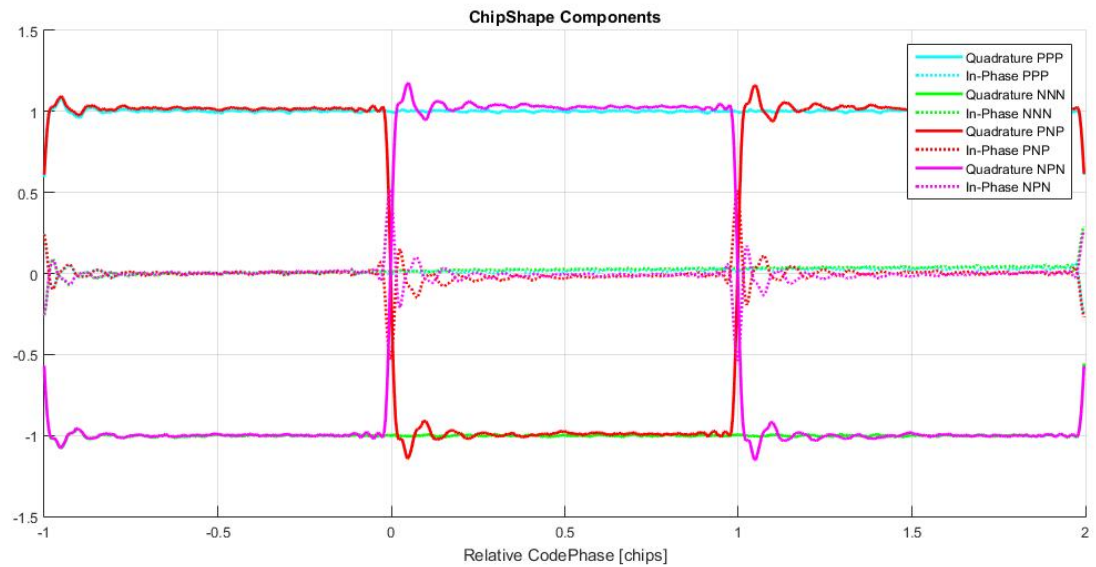


Figure 61. Chip Shape Components for Cosmos 2500; PRN 4

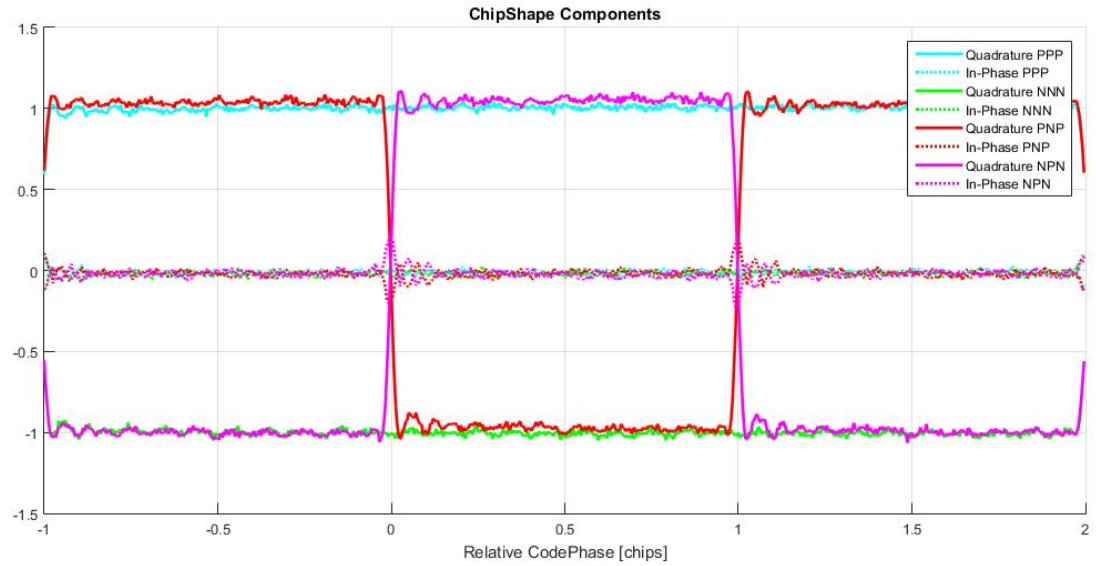


Figure 62. Chip Shape Components for Cosmos 2465; PRN -1

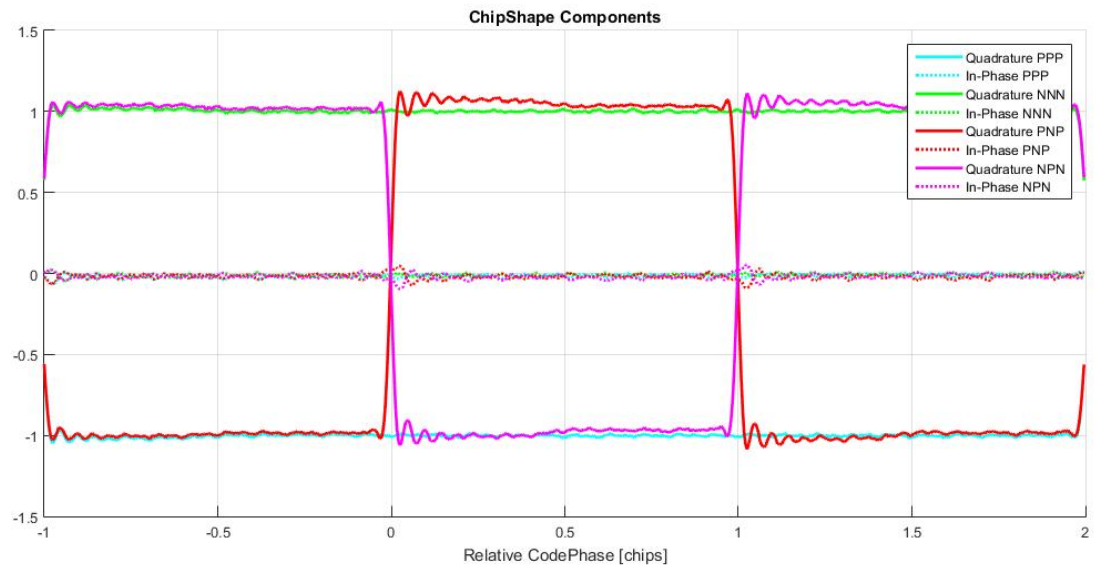


Figure 63. Chip Shape Components for Cosmos 2457; PRN -4

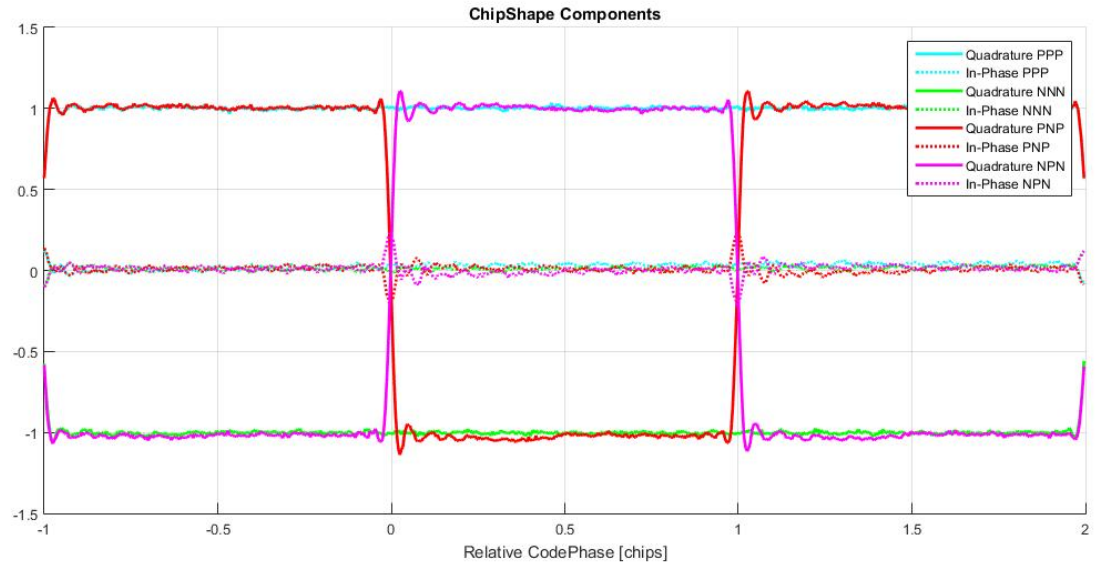


Figure 64. Chip Shape Components for Cosmos 2434; PRN -2

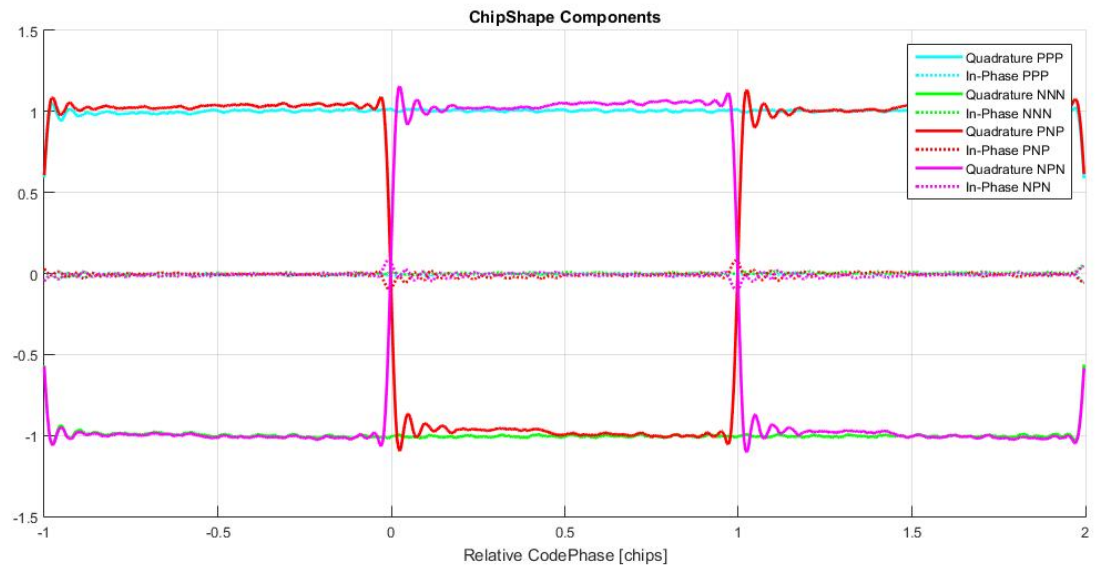


Figure 65. Chip Shape Components for Cosmos 2459; PRN -3

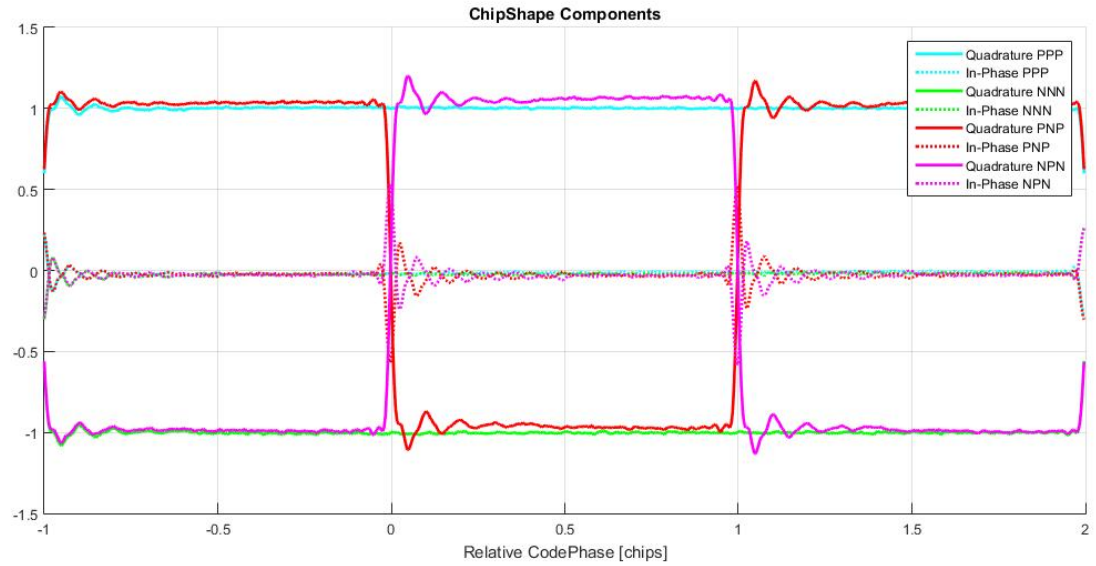


Figure 66. Chip Shape Components for Cosmos 2477; PRN 5

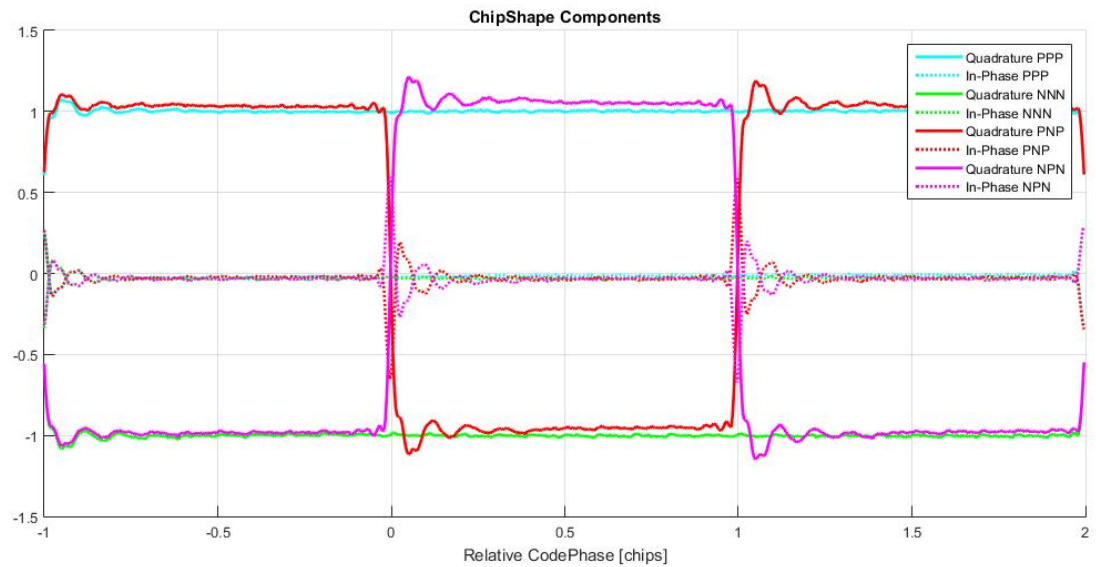


Figure 67. Chip Shape Components for Cosmos 2475; PRN 6

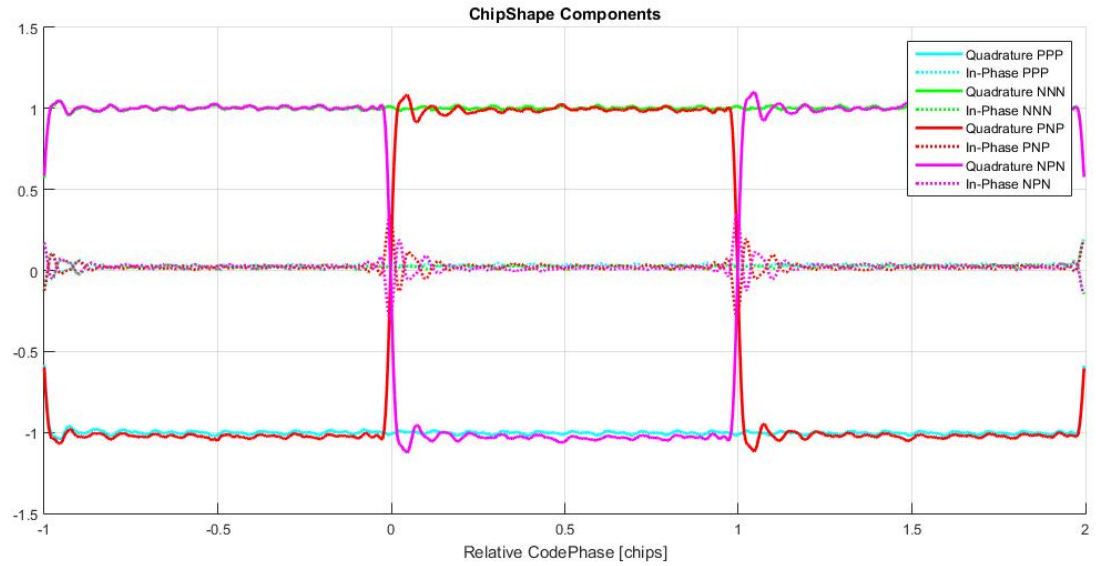


Figure 68. Chip Shape Components for Cosmos 2460; PRN 3

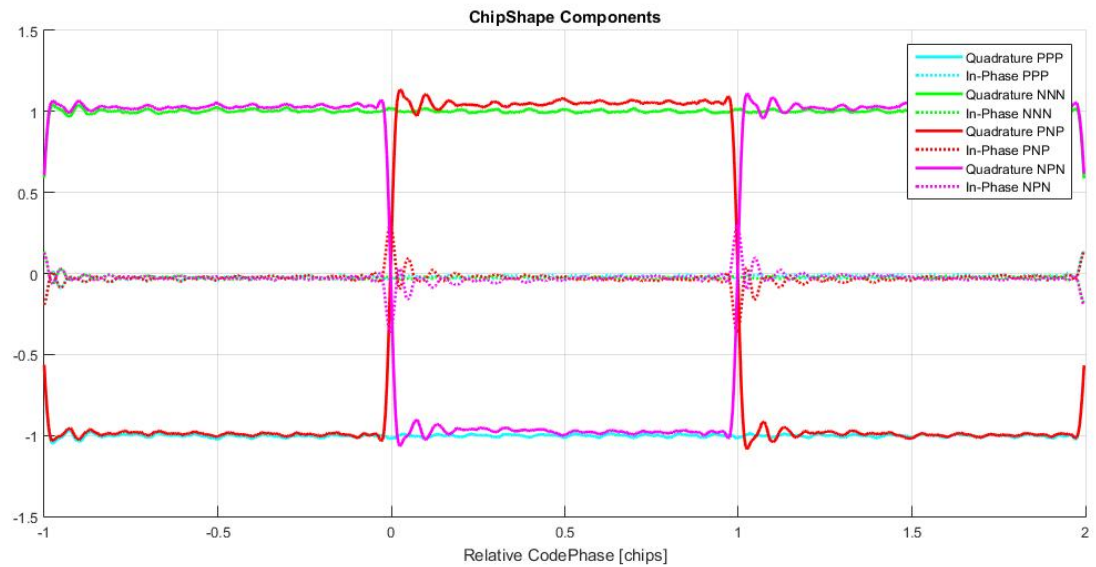


Figure 69. Chip Shape Components for Cosmos 2456; PRN 1

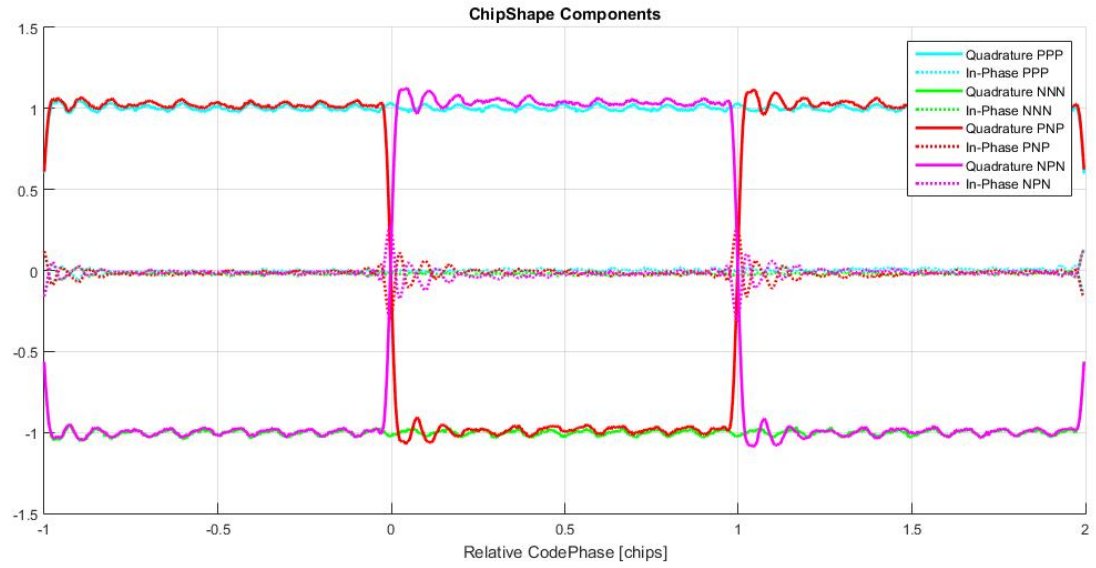


Figure 70. Chip Shape Components for Cosmos 2461; PRN 2

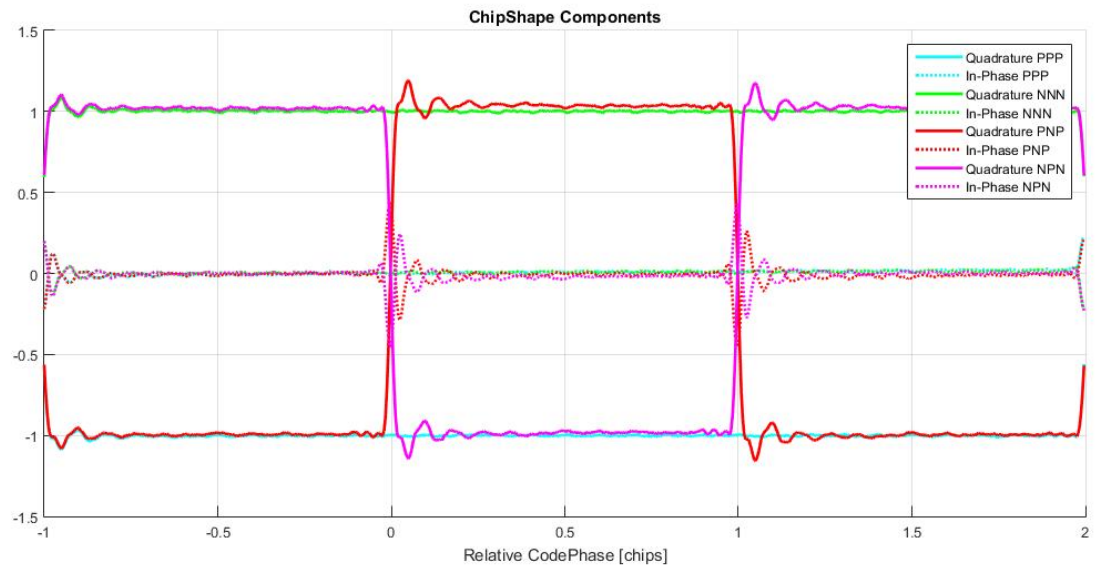


Figure 71. Chip Shape Components for Cosmos 2514; PRN 4

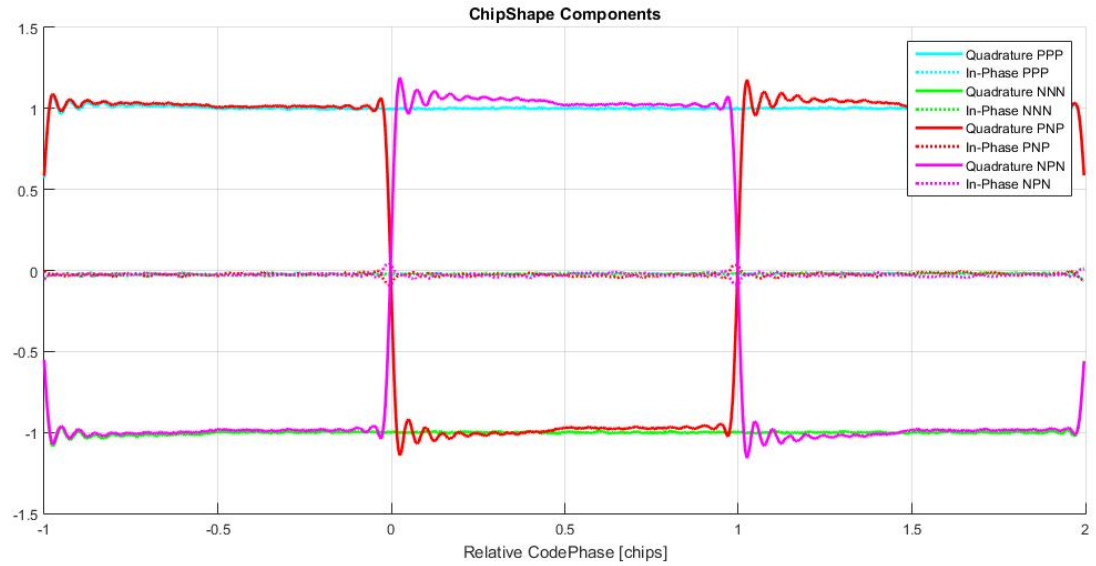


Figure 72. Chip Shape Components for Cosmos 2485; PRN -4

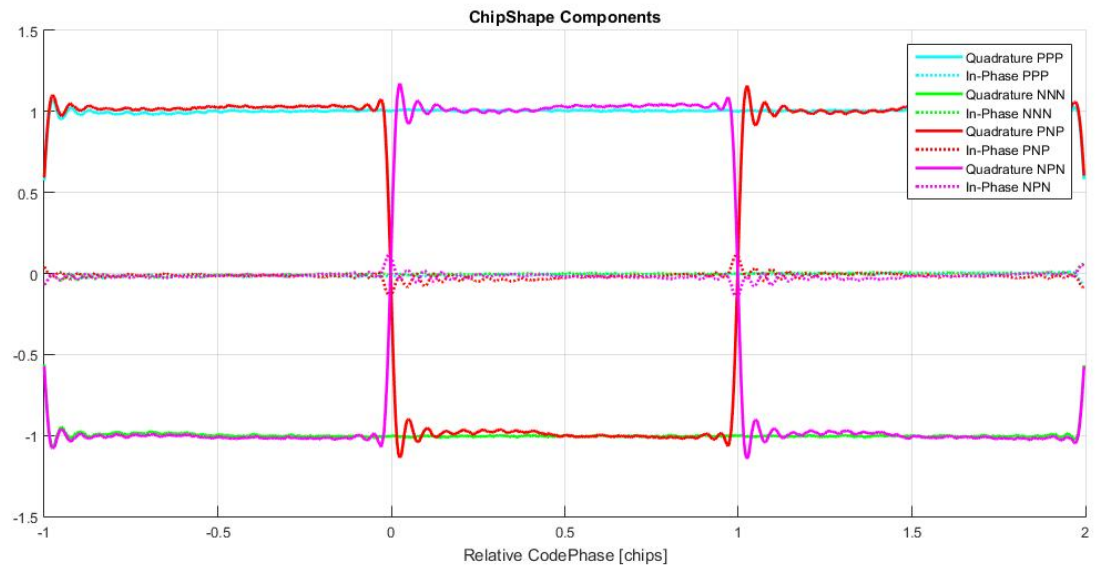


Figure 73. Chip Shape Components for Cosmos 2492; PRN -3

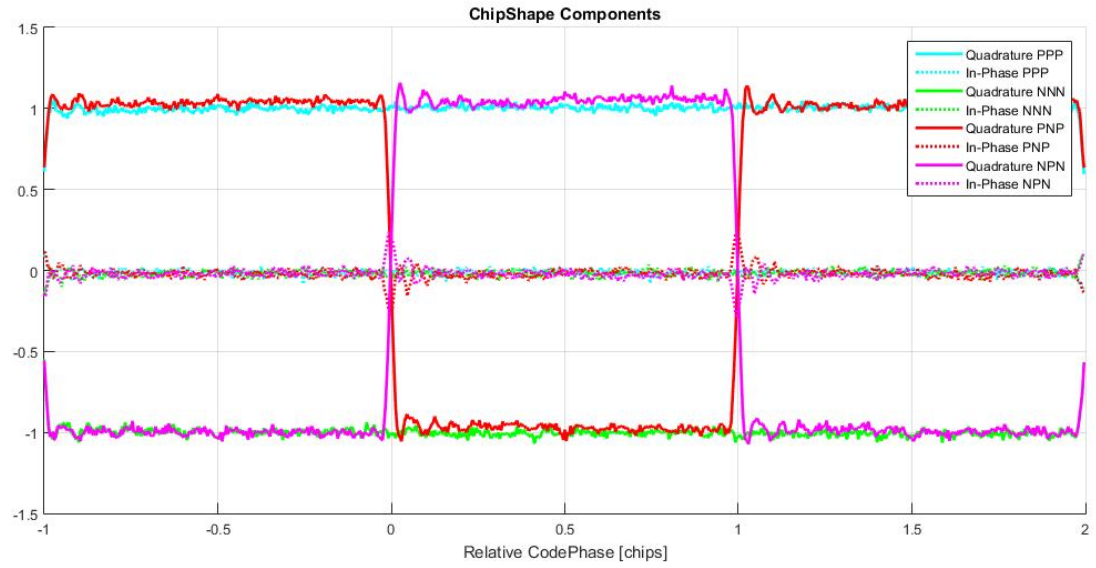


Figure 74. Chip Shape Components for Cosmos 2465; PRN -1

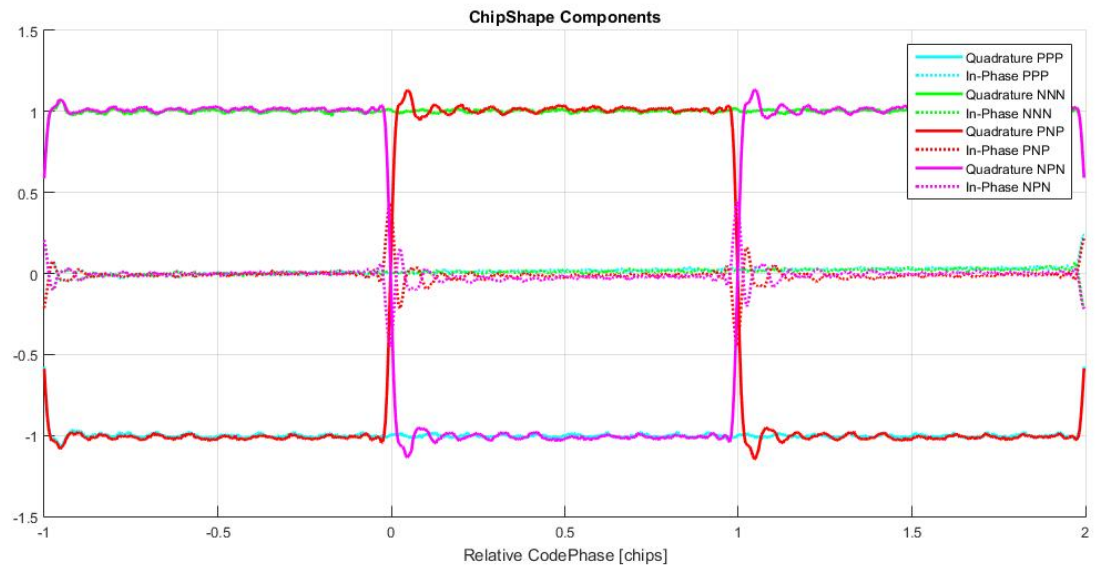


Figure 75. Chip Shape Components for Cosmos 2433; PRN 3

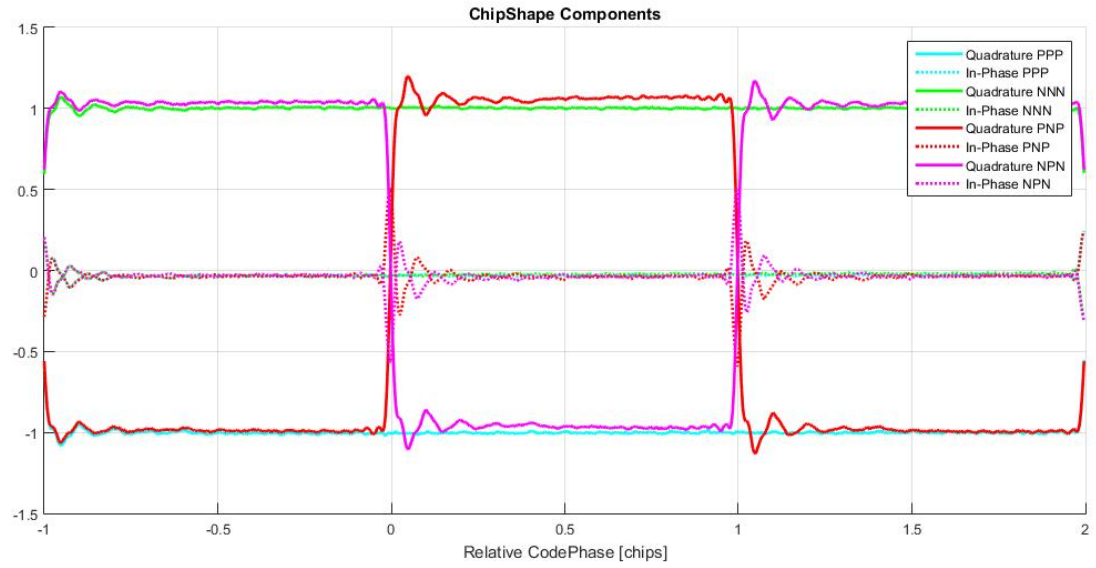


Figure 76. Chip Shape Components for Cosmos 2476; PRN 5

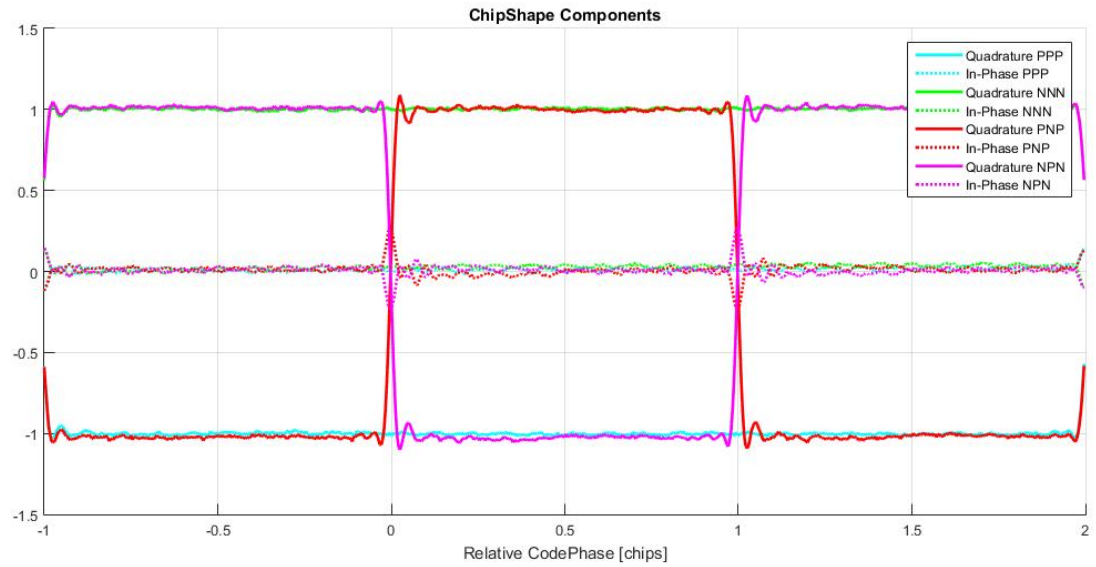


Figure 77. Chip Shape Components for Cosmos 2434; PRN -2

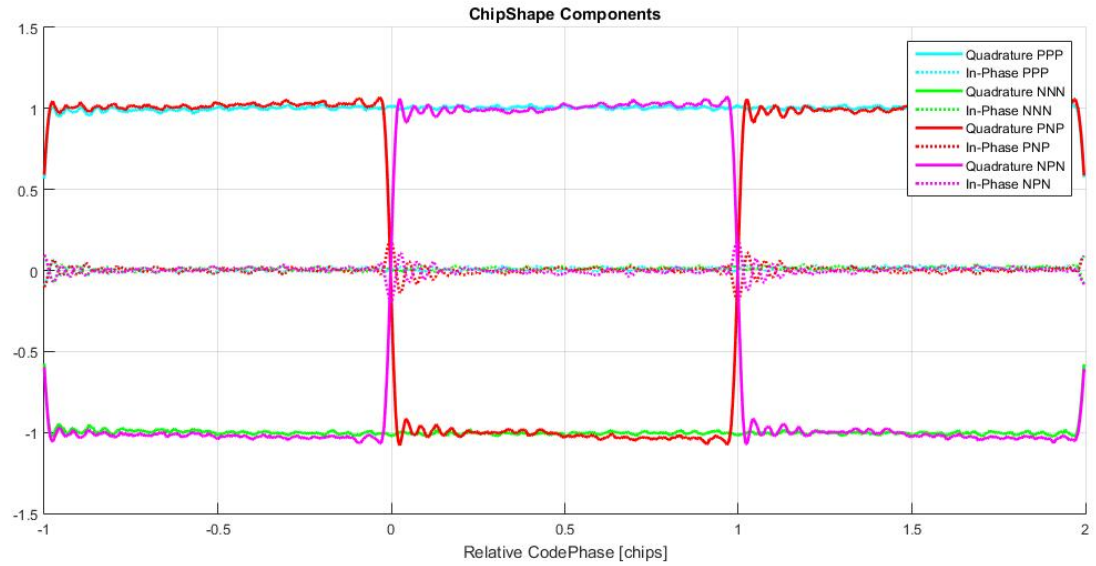


Figure 78. Chip Shape Components for Cosmos 2424; PRN -7

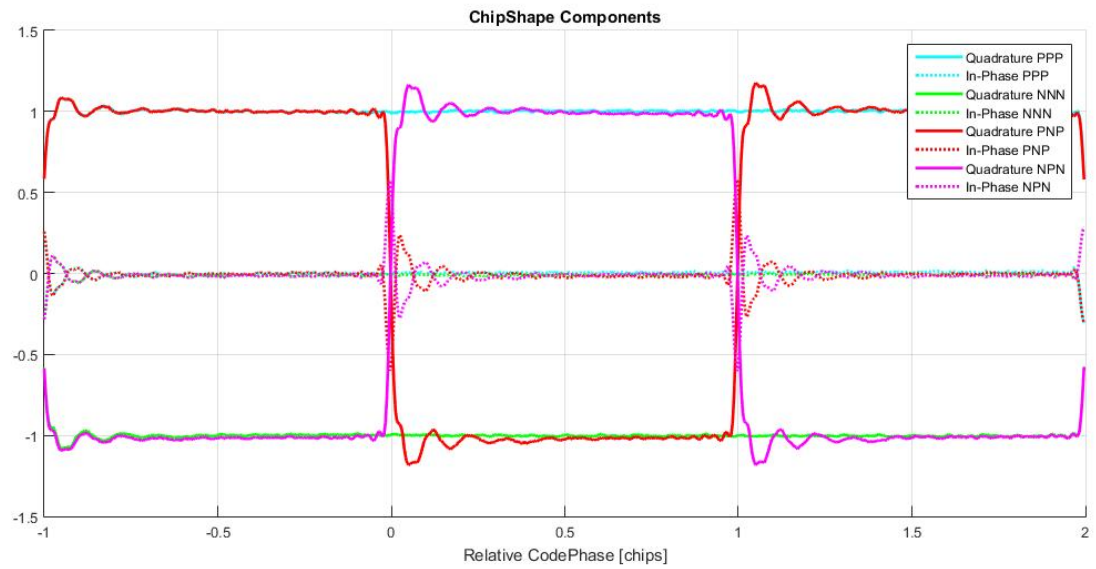


Figure 79. Chip Shape Components for Cosmos 2474; PRN 6

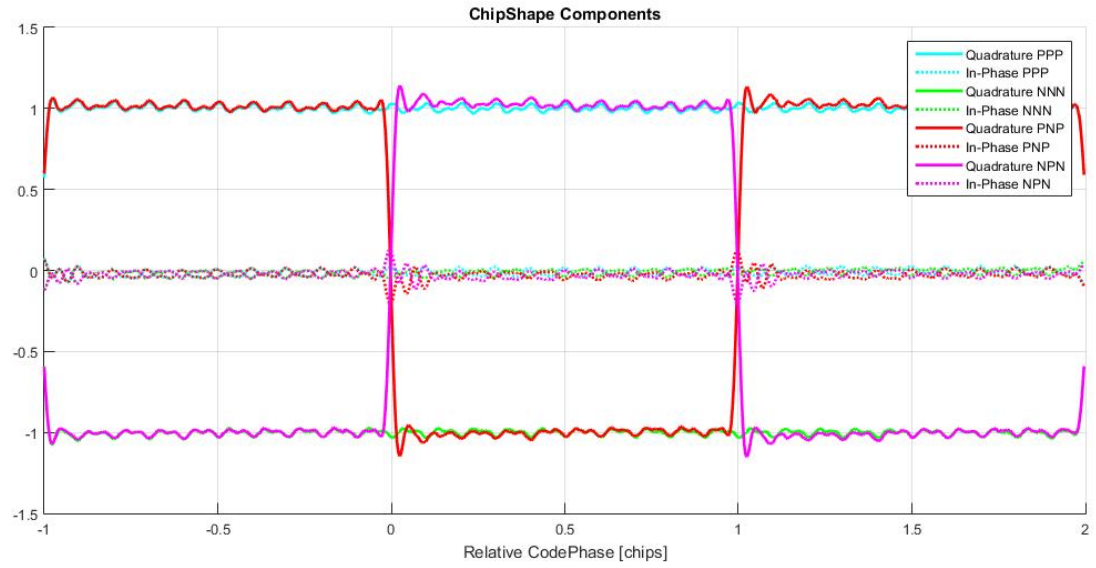


Figure 80. Chip Shape Components for Cosmos 2425; PRN 0

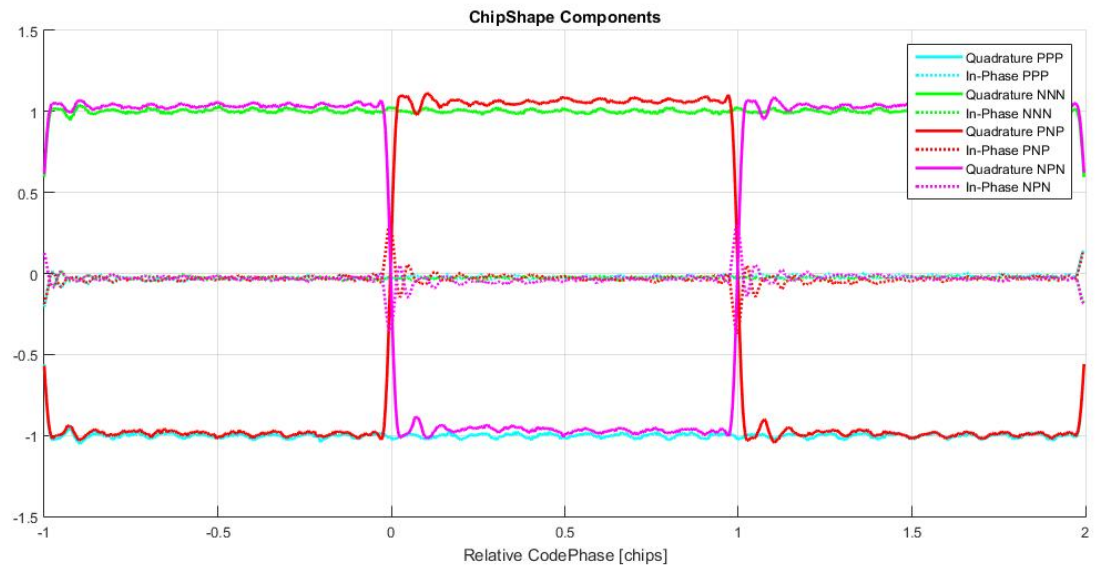


Figure 81. Chip Shape Components for Cosmos 2458; PRN 1

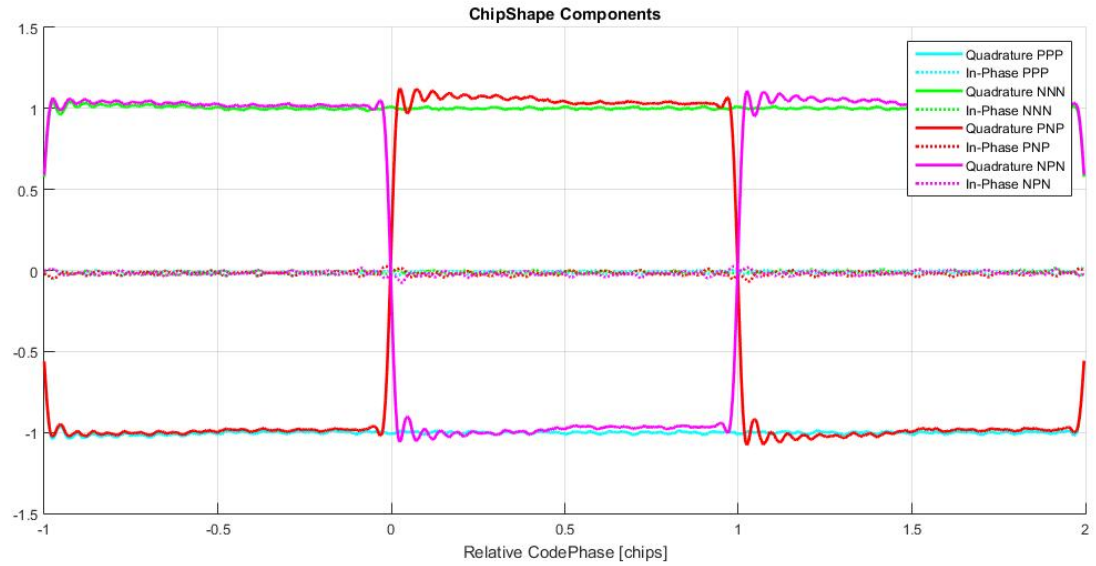


Figure 82. Chip Shape Components for Cosmos 2457; PRN -4

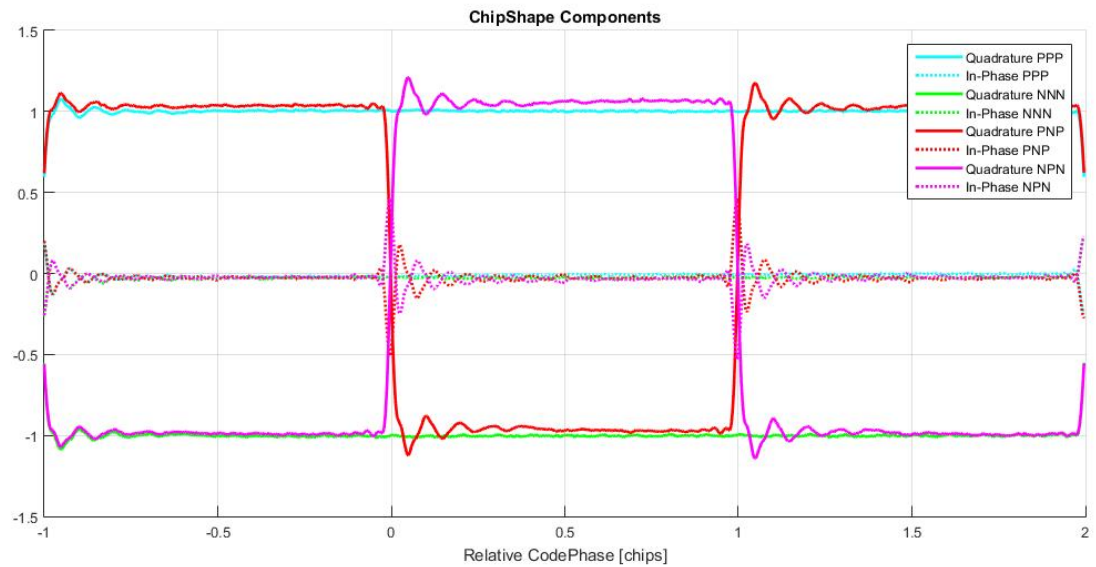


Figure 83. Chip Shape Components for Cosmos 2477; PRN 5

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14. ABSTRACT The objective of this thesis effort is to characterize the Russian Global Navigation Satellite System (GLONASS) by utilizing advanced chip shape correlation processing techniques to determine C/A code chip shape and other signal characteristics. Fully characterizing GLONASS chip shape will enable signal authentication and provide confidence for potential use of GLONASS in military applications to increase resiliency and frequency diversity in the event of GPS denial. Characterization of GLONASS will also provide additional GNSS resources for improved accuracy and redundancy to our current GPS satellite constellation in the event of GPS spoofing and augmenting the number of satellites available for positioning and timing. Development of software algorithms necessary to characterize the Russian GLONASS C/A code will allow for the potential safe integration of the foreign signals into certain Air Force systems.					
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