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Systems analysis for a navigation receiver allowing simultaneous utilization of the GLONASS and NAVSTAR GPS satellite navigation systems

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LIST OF ABBREVIATIONS

AEEC	Airlines Electronic Engineering Committee
APC	Aircraft Passenger Communications
Ausrire	All Union Scientific Research Institute of Radio Equipment
C/A	Coarse Acquisition PRN Code
CDMA	Code Division Multiple Access
dB	decibels
dBi	decibels with respect to an isotropic...
dBW	decibels with respect to one Watt
dB-Hz	decibel - Hertz
deg	degrees
DOD	Department of Defense
DOP	Dilution of Precision
ECEF	Earth Centered Earth Fixed
FAA	Federal Aviation Administration
FANS	Future Air Navigation Systems
FDMA	Frequency Division Multiple Access
GDOP	Geometric Dilution of Precision
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HOW	Handover Word
Hz	Hertz

IA	Iowa
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engin
IF	Intermediate Frequency
ION	Institute of Navigation
ITU	International Telecommunications Union
L1	Link 1
L2	Link 2
LSRRI	Leningrad Scientific Research Radiotechnical Institute
m	meters
MHz	Mega Hertz
MIPS	Million Instructions Per Second
MIT	Massachusetts Institute of Technology
msec	milliseconds
N	North
nm	nautical mile
NNSS	Navy Navigation Satellite System
NRZ	Non-Return to Zero
NTS	Navigation Technology Satellite
P	Precision PRN Code
PDI	Pre-Detection Integration
PDOP	Position Dilution of Precision
PLANS	Position Location and Navigation Symposium
P-R	Pseudo-Range
PRN	Pseudo Random Noise

RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RZ	Return to Zero
SA/AS	Selective Availability/Anti-Spoofing
satcom	satellite communications
SPS	Standard Positioning Service
SU	Soviet Union
SV	Space Vehicle
TLM	Telemetry Word
TOW	Time of Week
TDOP	Time Dilution of Precision
UK	United Kingdom
US	United States
USNO	United States Naval Observatory
USSR	Union of Soviet Socialist Republics
UTC	Coordinated Universal Time
VDOP	Vertical Dilution of Precision
W	West

ABSTRACT

A single navigation receiver allowing simultaneous utilization of the former Soviet Union's GLONASS and the United States' NAVSTAR GPS satellite navigation systems will encounter significant satellite coverage redundancy and integrity monitoring options unavailable to either separate system. A feasibility study was performed for an integrity monitoring approach simultaneously utilizing measurements from both navigation systems and using maximum solution separation among redundant solutions as the integrity check. A discussion then follows identifying system integration issues arising from the combined and simultaneous utilization of the two navigation systems.

I. INTRODUCTION

A. Statement of Problem

The United States' Global Positioning System (GPS) and the former Soviet Union's Global Navigation Satellite System (GLONASS) are two similar, world wide, satellite based, twenty-four hour, all weather, navigation systems. Each is capable of providing suitably equipped users with position accuracies down to tens of meters, velocity accuracies to hundredths of meters per second, and time accuracies under one hundred nanoseconds.

Even though each system's capabilities are similar, and their implementations are alike in many respects, the problem exists where a specific receiver designed to work with one system can not interpret the signals from the other.

Furthermore, whether a navigation solution is formed based upon measurements from the GPS or GLONASS constellation, the solution will be subject to errors in the event of a "soft" satellite failure. Safeguards within both GPS and GLONASS exist such that warnings are broadcast over the navigation data messages, notifying users of the irregular space vehicle (SV) health.

However, for the GPS, the availability of these warnings can often lag the failure anywhere from fifteen minutes to two hours [1]. For GLONASS, the anticipated lag may be even greater due to a more limited number of ground monitor stations. Although these failures are expected to be infrequent, auxiliary means for enhancing integrity monitoring are desired.

One such auxiliary means is Receiver Autonomous Integrity Monitoring (RAIM), where users of a system can monitor that system's health by forming redundant sets of navigation solutions. Unfortunately, a problem exists where limited number of SVs within each system can lead to periods where RAIM is unavailable due to poor SV geometries.

The simultaneous utilization of the two navigation systems would thus be desirable, particularly during the initial build up of the satellite constellations, when neither system possesses a full complement of SVs. Even more so, the user of a navigation receiver capable of simultaneously tracking both GPS and GLONASS SVs will have integrity monitoring options available that are unattainable for users of either separate system.

Until quite recently, little formal action has occurred towards the integration or exchange of information on these two systems. Although numerous sources exist which describe the characteristics of GPS, the information on GLONASS is sparse and has been primarily obtained through the investigative efforts of an academic team lead by Dr. Peter Daly of Leeds University, Great Britain. Only in the last couple of years have representatives from the former Soviet Union participated with official representatives of the United States of America in pursuing the availability of a combined satellite based navigation system.

This thesis examines the feasibility of utilizing seven SV measurements from the combined GPS/GLONASS constellation to form redundant navigation solutions for Receiver Autonomous Integrity Monitoring, providing not only detection of a "soft" SV failure, but also identification of the source of this failure. Then, based upon an examination of the available literature on the GLONASS navigation system, this thesis presents a discussion of integration issues confronting the user of a navigation receiver capable of allowing simultaneous utilization of the GLONASS and GPS satellite navigation systems.

B. Review of Related Work

Appendix C presents a literary survey of material regarding the GLONASS. Papers by Dr. Daly et al. are quite exhaustive with respect to GLONASS, and address many of the systems issues resulting from combined applications of GPS with GLONASS. However, to date, this team has published only one paper specifically addressing the integrity monitoring aspects [2] of GPS/GLONASS, and that publication did not address RAIM, but rather reported on stationary integrity monitoring tests comparing timing measurements between precise local time references and GPS/GLONASS system times.

Several other papers listed in Appendix C comment upon integration issues for the two systems, but only one has presented substantial information on the integrity monitoring aspects available for the combined systems [3]. That effort, being a collaboration between Honeywell, Northwest Airlines, and the Leningrad Scientific Research Radiotechnical Institute, presents, among other things, a RAIM algorithm using parity space methods for detecting and isolating SV failure. As presented, the methods call for a pseudorange measurement to be formed for all SVs in view. Alternatively, the methods presented by this thesis allow detection and isolation of an SV failure through measurements from only seven SVs. Minimizing the number of required measurements from GLONASS SVs is important for allowing rapid integrity monitoring using minimal hardware assets.

C. Scope of Thesis

This thesis is divided into three key sections. Chapter I provides the introductory material, including the problem statement and a brief discussion of related papers. Chapter II examines the feasibility of the proposed RAIM scheme which utilizes redundant measurements from the combined GPS/GLONASS constellation. Lastly, Chapter III examines the systems issues confronting the use of a hybrid receiver capable of simultaneously utilizing the GPS/GLONASS signals.

In addition, numerous appendices provide auxiliary information helpful to the consideration of the hybrid receiver, as well as being informative on the subject of satellite navigation in general. Foremost among these appendices is a summary of the RF signal characteristics for both the GLONASS and GPS systems.

D. Conclusions

This thesis presents a discussion examining the feasibility of utilizing seven measurements from the combined GPS/GLONASS constellation to form redundant solutions used in a maximum solution separation RAIM scheme. The results of this examination demonstrate that the proposed scheme is effective in detecting and identifying SV signals that contribute excessively to radial range error. Further research is warranted to establish the global coverage and integrity protection levels provided by such a scheme. Drawbacks to this scheme center upon the intensive effort required in selecting a suitable set of seven SVs for which all subsets of five SVs possess low values of Horizontal Dilution of Precision (HDOP).

This thesis also presents a discussion highlighting integration issues arising from the combined utilization of GPS and GLONASS. Foremost amongst these issues are the differences between world-wide geodetic reference systems. These difference can only be resolved through further cooperation between the United States and the Commonwealth of Independent States.

Additional issues center upon hybrid receiver construction. Differences between signal structures require additional complexity in the construction of a hybrid receiver, most notably in the areas of RF filtering and RF/IF strip construction. Although the literature has presented a systems design of unified receivers, the use of two side-by-side independent receivers providing selected measurements from each system will also permit formation of a RAIM solution based upon the combined GPS/GLONASS constellation. Further demonstration of cost and/or size savings must be warranted before the single, hybrid receiver is a certainty.

Lastly, the specter of uncertainty looms over the future of the Commonwealth of Independent States, and accompanying that specter is the apprehension that world events will out pace technological developments for a combined GPS/GLONASS system.

II. GPS/GLONASS AUTONOMOUS INTEGRITY MONITORING

This chapter examines the feasibility for utilizing the combined GPS/GLONASS SV constellation for receiver autonomous integrity monitoring. Characteristics of the combined SV constellation are presented. Formation of a single navigation solution utilizing simultaneous measurements from both systems is discussed. Integrity monitoring aspects, including both detection of excessive radial error and identification of specific error contributing SVs, are examined.

A. Summary

When the presently planned twenty-four SV constellations for the GPS and GLONASS are fully populated, each constellation will offer comparable SV visibility and Geometric Dilution of Precision (GDOP) characteristics to users of either system. Furthermore, a single navigation solution may be formed based upon both systems by using simultaneous pseudorange measurements from a combination of five GPS and GLONASS SVs. The technique proposed herein for providing such a navigation fix is solving five equations, in five unknowns, through the use of vectors and matrix algebra.

The ability to form a single solution from mixed system measurements essentially doubles the number of observable SVs previously available to users of either separate system. This expansion of available SVs allows the user to select not only one, but multiple sets of five, mixed system, geometrically sound SVs. For the purposes of the integrity monitoring scheme proposed herein, "geometrically sound" indicates that a set, or all subsets, of five, mixed system SVs possess minimal HDOP values.

A separate navigation solution may be formed for each set of five SVs. These redundant solutions provide extensive integrity monitoring capabilities, as illustrated by the following examples. Given a combination of six, geometrically sound, GPS/GLONASS SVs, the user can detect excessive radial range error caused by a single SV measurement by monitoring the maximum separation between horizontal position solutions for all combinations of five-SV solutions. With a combination of seven, geometrically sound SVs, the user can not only detect, but can also identify the specific SV responsible for the excessive radial range error. The range error levels against which detection and identification are possible are a function of the measurement noise, the presence of Selective Availability/Anti-Spoofing (SA/AS), the SV geometric configuration, and the desired probabilities of false alarm.

B. The Combined GPS/GLONASS SV Constellation

Prior to entering a detailed discussion on integrity monitoring, an examination must be made of the combined constellation SV visibility. This first requires the understanding of the orbital characteristics of each system's separate constellation.

1. <u>GPS SV orbits</u>

Under the "21 Primary Satellite Constellation" [4] concept, the GPS space segment will consist of four SVs in each of six orbital planes. This total of twenty-four SVs includes three in-orbit active spares. The orbital planes are inclined at 55 degrees, and are spaced 60 degrees apart in the equatorial plane. The four SVs in each orbital plane will be irregularly distributed, as will be their relative phasings between orbit planes, so as to optimize coverage in the case of a single SV failure.

The SVs will orbit roughly 20,200 km above the earth. As such, the constellation described will permit the observation of at least six SVs from any terrestrial point at all times [5], with as many as eleven SVs simultaneously visible.

The GPS constellation is currently in a period of system build-up, and full three dimensional global coverage is not expected until the mid-1990s.

2. <u>GLONASS SV orbits</u>

Under the fully operational configuration [6], the GLONASS space segment will consist of eight SVs in each of three orbital planes. These twenty-four total SVs include three spares. The nearly circular orbital planes are inclined at 64.8 degrees, and are separated by 120 degrees in the equatorial plane. Within each orbital plane the SVs are separated from each other by 45 degrees. Furthermore, the satellites between planes are offset in phase by +/-30 degrees.

The SVs will orbit at an altitude of 19,100 km. The GLONASS SV constellation will permit the viewing of at least six SVs from any terrestrial location at all times, and as many as eleven SVs may be simultaneously observable [7].

The GLONASS constellation is currently in a period of system build-up, and full operational status was originally planned to be achieved during the period 1991-1995.

3. GPS/GLONASS SV visibility

The following paragraphs present examples of GPS/GLONASS SV visibility under their respective twenty-four SV constellations, as described in the preceding sections. Three graphs are provided for each system, presenting each system's SV visibility from low, medium, and high terrestrial latitudes, in each case assuming a 5 degree mask angle. Finally, information is presented for both systems' visibility from a medium latitude location, but with an irregular mask angle pattern as suited to that location's topography.

Figure II-1 presents the GPS SV visibility as computed based upon a user location in Cedar Rapids, IA, at N42 1' 56.8", W91 38' 27.1", and at an altitude of 232 m, for the

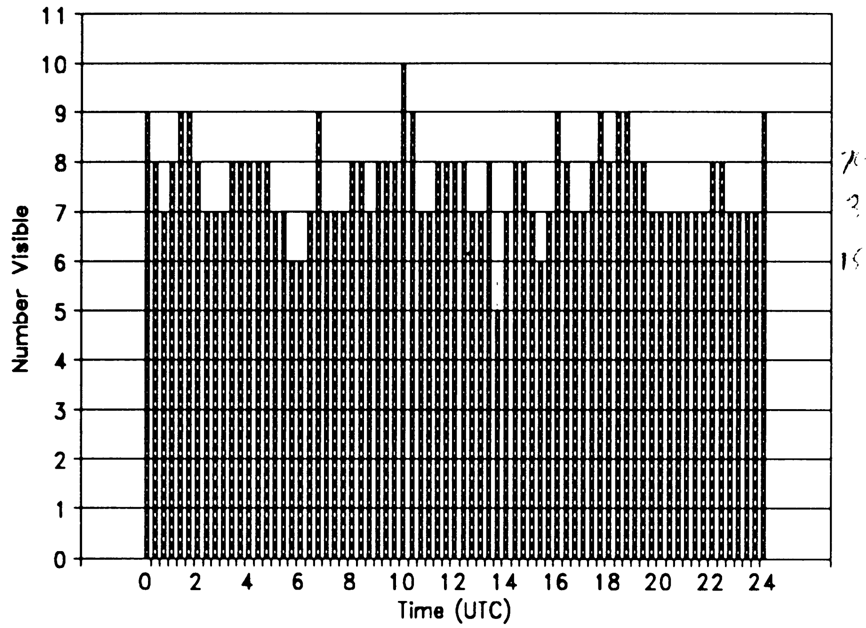


Figure II-1. GPS SV visibility at Cedar Rapids, IA

complete "21 Primary" GPS constellation. The minimum acceptable SV elevation is 5 degrees, thus rendering un-usable any SV lower than 5 degrees in elevation. Contrary to the statement made in reference [5], there is one instance where less than six SVs are visible. Otherwise, six SVs are always visible, with seven SVs visible most of the time. Observability of eight, nine, and ten SVs occurs only during limited times.

Figure II-2 presents the SV visibility from the same location, and with the same mask angle, but for the GLONASS constellation. As reported in reference [7], at least six SVs are visible at all times. Significant periods exist where both seven and eight SVs are also visible, and periods of nine

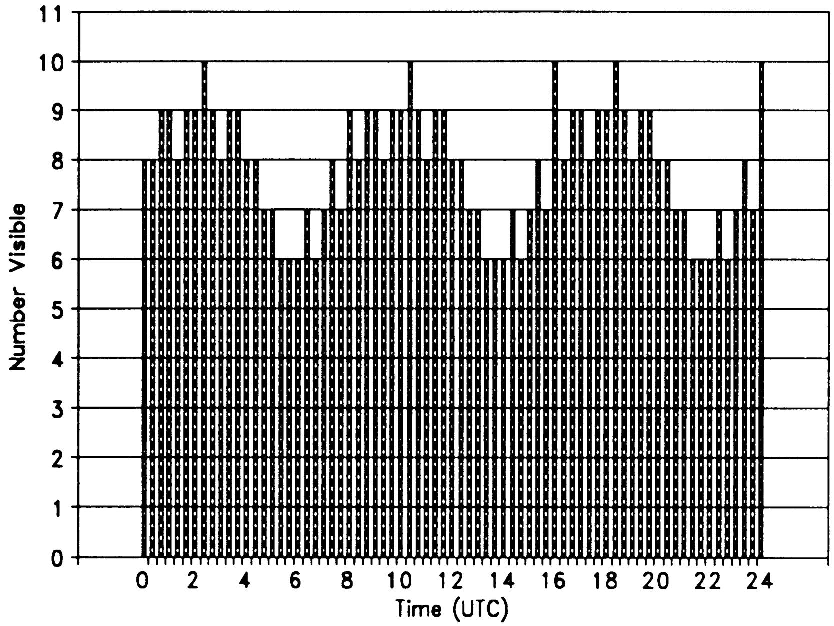


Figure II-2. GLONASS SV visibility at Cedar Rapids, IA

SV visibility occur more than twice as often as in the GPS case.

Figures II-3 and II-4 present the SV visibility based upon a user location just above the Arctic Circle, at N65, W91, and at an altitude of 0 m, with a 5 degree mask angle. Comparing these two figures reveals that the GLONASS constellation provides a consistently higher number of visible SVs at this high latitude location, which can be explained by the larger angle of inclination for the GLONASS orbits.

The converse situation is revealed by Figures II-5 and II-6, which present the SV visibility based upon a user location on the Equator, at N0, W91, and at an altitude of 0 m, again with a 5 degree mask angle. The GPS constellation

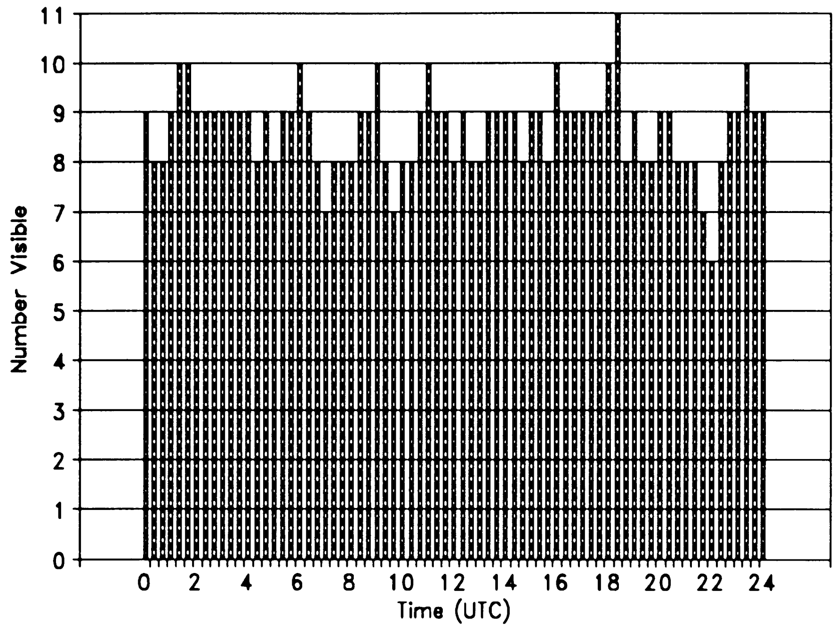


Figure II-3. GPS SV visibility near the Arctic Circle

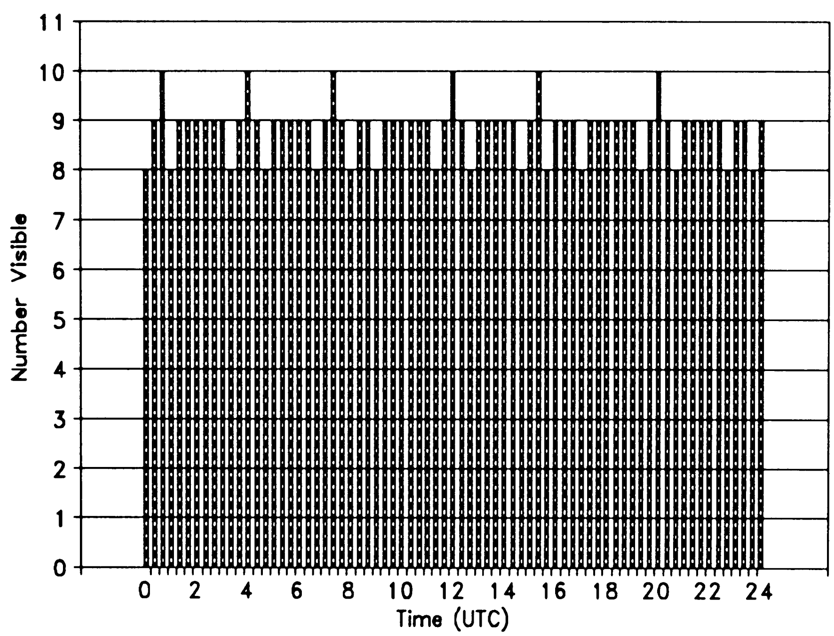


Figure II-4. GLONASS SV visibility near the Arctic Circle

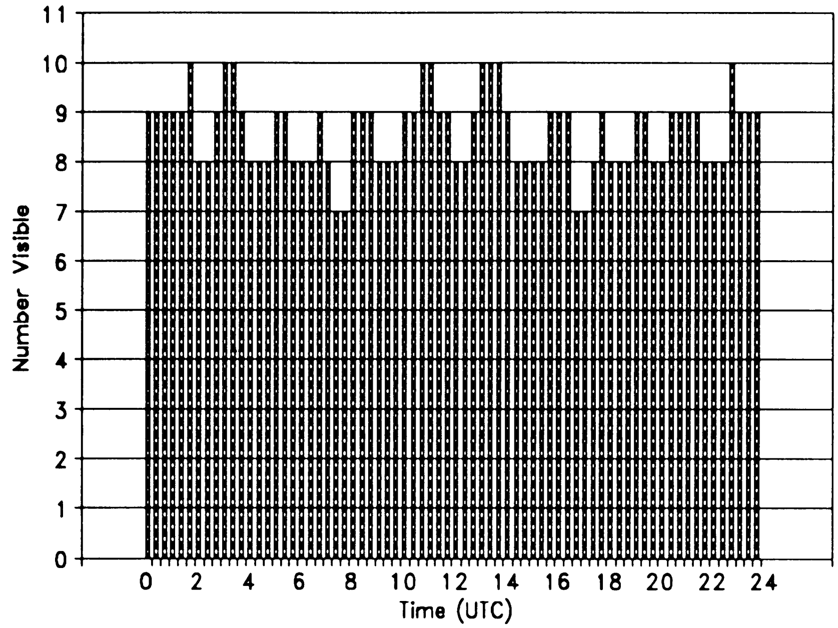


Figure II-5. GPS SV visibility at the Equator

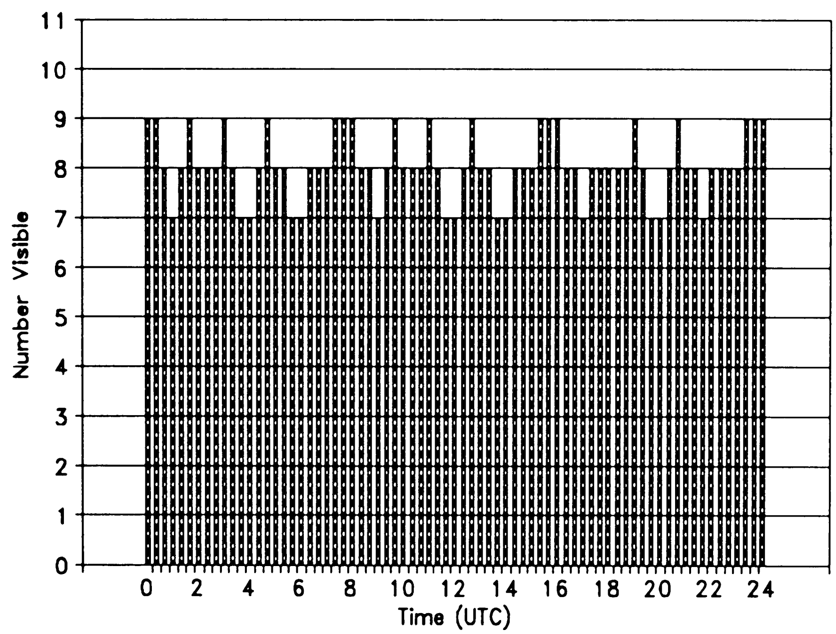


Figure II-6. GLONASS SV visibility at the Equator provides longer periods with higher numbers of visible SVs for this low latitude location. Again, this is consistent with the differences in orbital inclination angles for the two systems.

Each of the plots discussed to this point have involved a 5 degree mask angle. This represents a nominal margin accounting for distant ground clutter (i.e., trees, buildings) which may obscure SVs that are low on the horizon. However, it assumes that the surrounding terrain is relatively flat, which may not be true in all cases.

To pursue this point further, a location was chosen for study which would experience definite terrain masking of low elevation SVs. This location is Kamiah, Idaho, located at at N46 13′ 42.7", W116 1′ 34.4", at an altitude of 371 meters. Since it is at a latitude similar to that of Cedar Rapids, IA, one would expect SV visibility results from Kamiah to be similar to those obtained at Cedar Rapids. However, taking into account the irregular terrain masking experienced at Kamiah, then Kamiah's SV visibility numbers will be somewhat reduced.

Figure II-7 presents a terrain masking pattern for Kamiah, Idaho, as determined from the United States Department of the Interior Geological Survey Kamiah Quadrangle topographic map (7.5 minute series). The presence of irregular terrain varies the elevation mask angle from five

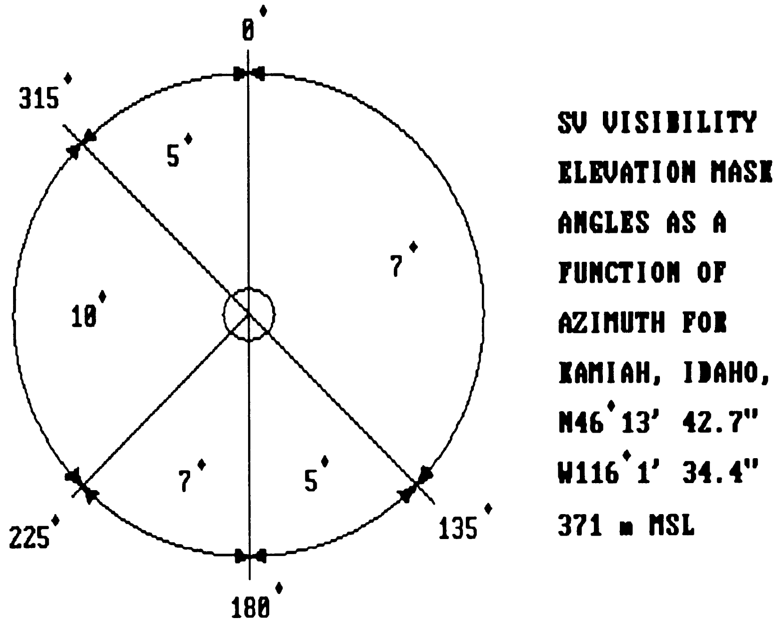


Figure II-7. SV masking elevations at Kamiah, Idaho

through ten degrees, as a function of azimuth. The mask function depicted by Figure II-7 was used for all subsequent SV visibility and integrity monitoring analyses performed for the Kamiah location.

Figure II-8 presents both the GPS and GLONASS SV visibility at Kamiah, as effected by this irregular mask pattern. At all times both systems have at least six SVs visible. Being a "stacked bar" graph, the total height of both graphed bars represents the total number of SVs visible to a receiver capable of utilizing both the GPS and GLONASS signals.

The figures discussed above have depicted the total number of available SVs for a specific time and location.

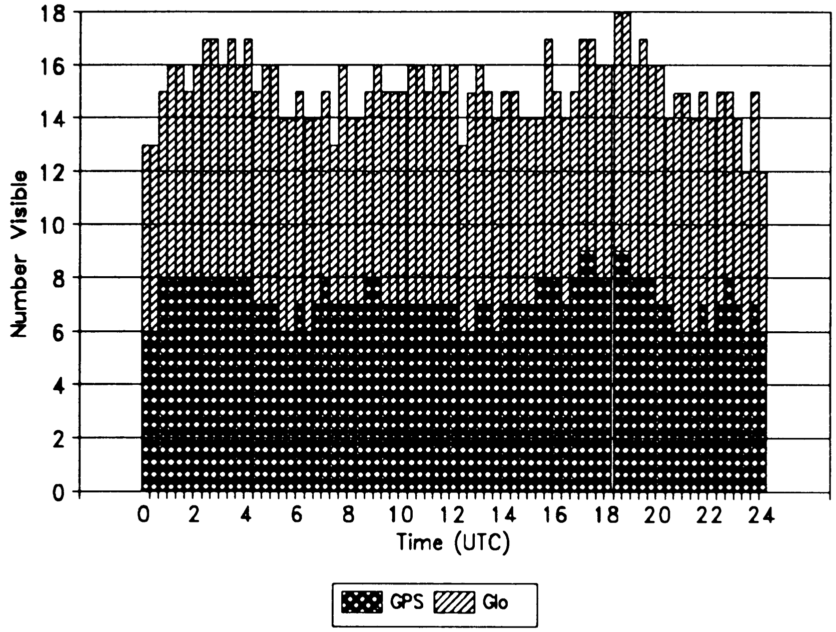


Figure II-8. SV visibility of GPS and GLONASS at Kamiah, Idaho

They often reveal that the GLONASS system presents more visible SVs than does the GPS system. However, this does not mean that the GLONASS systems is "better" than the GPS system. A parameter equally important to the number of visible SVs is the relative geometries of the visible SVs.

Figure II-9 presents a computation of the best four SV GDOP over a 24 hour period for the Cedar Rapids, IA, location, with a mask angle of 5 degrees. Whereas the GPS GDOP rarely exceeds 3.5, the GLONASS GDOP exhibits numerous GDOP spikes reaching or exceeding 4.0. Thus, even though the GPS system may present fewer SVs, the relative geometries available from

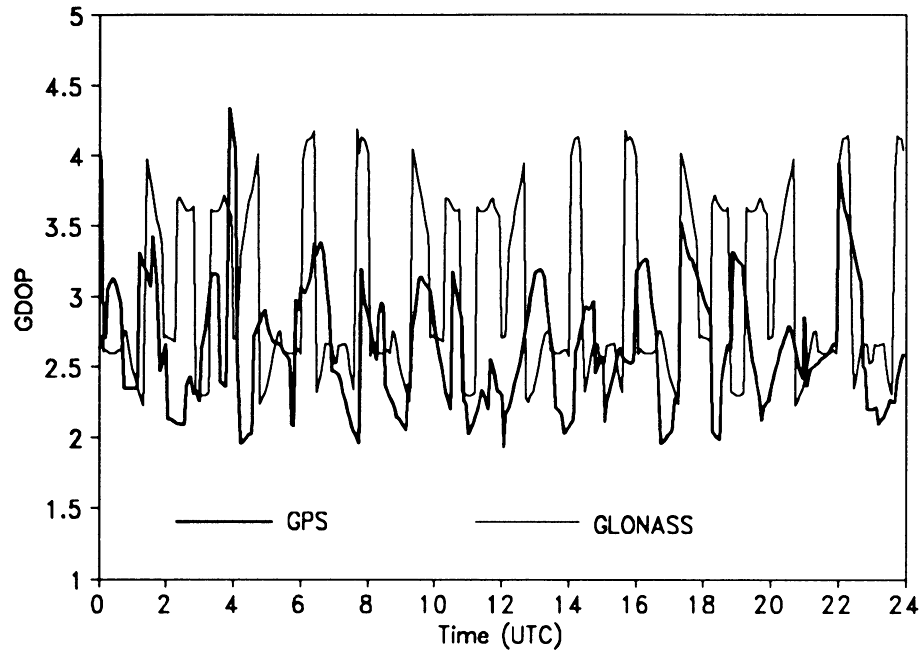


Figure II-9. Best GDOP of GPS and GLONASS at Cedar Rapids, IA

its SVs are better than those available from GLONASS, at least for this example.

C. The Combined GPS/GLONASS Five SV Position Solution

The formation of a combined GPS/GLONASS navigation solution can be achieved through solution of a set of five equations in terms of five unknowns: user X, Y, and Z position; user clock bias with respect to GPS system time; and user clock bias with respect to GLONASS system time.

Milliken & Zoller [8] provide a discussion on the formation of the GPS navigation solution for a set of four (or more) equations in four unknowns. Paralleling their discussion, the following paragraphs present the proposed methodology for the formation of a combined GPS/GLONASS navigation solution. But first, a review of pertinent notation is in order.

A vector quantity shall be denoted by a lower case letter accompanied by a super bar, such as: $\bar{r}$. A subscript may also accompany the vector to indicate a specific quantity: $\bar{r}_u$, where "u" indicates "user", or "i" indicates "*i-th* SV". Vectors may also be identified by an ordered set of their components:

$$\bar{r}_u = r_{u1}\bar{i} + r_{u2}\bar{j} + r_{u3}\bar{k}$$
$$= \langle r_{u1}, r_{u2}, r_{u3} \rangle$$

Magnitude of a vector is denoted by vertical bars: $|\bar{r}_u|$. Column vectors and matrices are denoted by an upper case letter accompanied by a super bar: $\bar{X}$. Subscripts may also be used, as may notation indicating size of the column vector or matrix: $\bar{X}_{u(5\times1)}$. Utilizing this notation, and assuming an Earth Centered Earth Fixed (ECEF) coordinate system, the following equations present the formation of a combined GPS/GLONASS navigation solution.

For a geometry as indicated by Figure II-10, the initial set of range equations is depicted by equation (1),

$$\bar{r}_u = \bar{r}_i - \bar{d}_i \qquad (1)$$

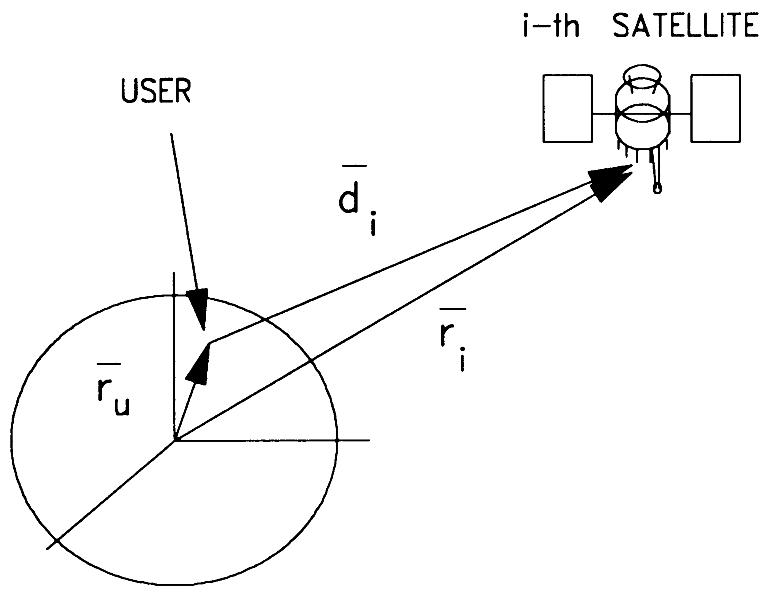


Figure II-10. Solution geometry

where:

$\overline{r}_u = \langle r_{u1}, r_{u2}, r_{u3} \rangle$ the vector from the center of the earth to the user;
$\overline{d}_i = \langle d_{i1}, d_{i2}, d_{i3} \rangle$ the vector from the user to the *i-th* SV;
$\overline{r}_i = \langle r_{i1}, r_{i2}, r_{i3} \rangle$ the vector from the center of the earth to the *i-th* SV;

and where: i = 1 to 5 SVs. More than five measurements may be utilized in the formation of a mixed-constellation navigation solution, but for the purposes of this thesis, no more than five shall be used for a single solution.

Three of the desired five unknowns, the user's X, Y, and Z components of position, are obtained by solving for the vector $\overline{r}_u$ in equation (1). To do this, one must first obtain information on both vectors $\overline{r}_i$ and $\overline{d}_i$. Vector $\overline{r}_i$ is known based upon ephemeris data gathered from the SVs. Vector $\vec{d}_i$ is not known, but its magnitude, $|\vec{d}_i|$, may be obtained via the receiver's pseudorange measurements, after taking into account user and SV clock biases.

Equation (1) may be rewritten in terms of $|\vec{d}_i|$ through use of $\bar{e}_i = \langle e_{i1}, e_{i2}, e_{i3} \rangle$, which is the unit vector from the user to the *i-th* SV. Since $\bar{e}_i$ and $\vec{d}_i$ are co-linear, the dot product of the two vectors is simply the magnitude of $\vec{d}_i$, that is, $\bar{e}_i \cdot \vec{d}_i = |\vec{d}_i|$, or the range from the user to the SV. Thus, (1) becomes:

$$\bar{e}_i \cdot \bar{r}_u = \bar{e}_i \cdot \bar{r}_i - |\vec{d}_i| \qquad (2)$$

The range $|\vec{d}_i|$ can be represented as follows:

$$|\vec{d}_i| = \rho_i - B_u - B_i \qquad (3)$$

where ρ_i is the measured pseudorange. B_i is the range equivalent of the SV clock bias for the *i-th* SV. SV clock bias parameters are available from the navigation data message broadcast by the satellite. B_u is the range equivalent of the user's clock bias, and is unique for each user platform with respect to each system. That is, two separate forms of equation (3) exist:

$$|\overline{d}_i| = \rho_i - B_{u,GPS} - B_i \tag{3a}$$

$$|\overline{d}_i| = \rho_i - B_{u,GLO} - B_i \tag{3b}$$

with equation (3a) corresponding to pseudorange measurements from GPS SVs, and equation (3b) for pseudorange measurements from GLONASS SVs. Note that $|\overline{d}_i|$, ρ_i, and B_i are unique to the *i-th* SV, regardless of system.

Equations (3a) and (3b) may be combined with (2) to give:

$$\overline{e}_i \cdot \overline{r}_u - B_{u,GPS} = \overline{e}_i \cdot \overline{r}_i - \rho_i + B_i \tag{4a}$$

$$\overline{e}_i \cdot \overline{r}_u - B_{u,GLO} = \overline{e}_i \cdot \overline{r}_i - \rho_i + B_i \tag{4b}$$

Vector equations (4a) and (4b) are the basic range equations, containing the five previously discussed unknowns, r_{u1}, r_{u2}, r_{u3}, $-B_{u,GPS}$, $-B_{u,GLO}$, which are the three components of the user's position, along with the range equivalents of the two clock bias. Five equations and at least five pseudorange measurements are needed for a unique solution.

Using matrix definitions from Milliken and Zoller [8], we now demonstrate how a solution is obtained.

Let $\overline{X}_u$ represent a column vector of the five unknowns:

$$\overline{X}_{u(5\times1)} = [\ r_{u1},\ r_{u2},\ r_{u3},\ -B_{u,GPS},\ -B_{u,GLO}\ ]^T$$

Let $\bar{\tau}_i$ be the observation vector to the *i-th* SV. For measurements from a GPS SV, $\bar{\tau}_i$ equals:

$$\bar{\tau}_i = (e_{i1}, e_{i2}, e_{i3}, 1, 0)$$

and for measurements from a GLONASS SV, $\bar{\tau}_i$ equals:

$$\bar{\tau}_i = (e_{i1}, e_{i2}, e_{i3}, 0, 1)$$

Note that the observation vector $\bar{\tau}_i$ contains the components of the unit vector $\bar{e}_i$, which are a function of the user's position.

Let $\bar{G}_u$ and $\bar{A}_u$, matrices formed from the five unique measurement vectors, be defined as:

$$\bar{G}_{u\,(5\times5)} = \begin{bmatrix} \bar{\tau}_1 \\ \bar{\tau}_2 \\ \bar{\tau}_3 \\ \bar{\tau}_4 \\ \bar{\tau}_5 \end{bmatrix}$$

$$\bar{A}_{u\,(5\times25)} = \begin{bmatrix} \bar{\tau}_1, & \bar{0}, & \bar{0}, & \bar{0}, & \bar{0} \\ \bar{0}, & \bar{\tau}_2, & \bar{0}, & \bar{0}, & \bar{0} \\ \bar{0}, & \bar{0}, & \bar{\tau}_3, & \bar{0}, & \bar{0} \\ \bar{0}, & \bar{0}, & \bar{0}, & \bar{\tau}_4, & \bar{0} \\ \bar{0}, & \bar{0}, & \bar{0}, & \bar{0}, & \bar{\tau}_5 \end{bmatrix}$$

where, $\overline{O}$ is the null matrix defined as:

$$\overline{O} = [\ 0,\ 0,\ 0,\ 0,\ 0\ ]$$

Let $\overline{S}$ and $\overline{\rho}$ be:

$$\overline{S}_{(25\times1)} = [\ r_{11},\ r_{12},\ r_{13},\ B_1,\ B_1,\ \ldots\ ,\ r_{51},\ r_{52},\ r_{53},\ B_5,\ B_5\ ]^T$$

$$\overline{\rho}_{(5\times1)} = [\ \rho_1,\ \rho_2,\ \rho_3,\ \rho_4,\ \rho_5\ ]^T$$

$\overline{S}$ contains the SV position vector components and SV clock bias values for the five *i-th* SVs. $\overline{\rho}$ contains the five pseudorange measurements for the five SVs.

Utilizing these matrix definitions, equations (4a) and (4b) may be rewritten to aid in the solution of $\overline{X}_u$:

$$\overline{G}_u\ \overline{X}_u = \overline{A}_u\ \overline{S} - \overline{\rho} \tag{5}$$

Premultiplying by $\overline{G}_u^{-1}$, equation (5) becomes:

$$\hat{X}_u = \overline{G}_u^{-1}[\overline{A}_u\ \overline{S} - \overline{\rho}] \tag{6}$$

which provides the solution to our five unknowns, $\overline{X}_u$. Since this expression contains components of the unit vectors from the user to each *i-th* SV, e_{i1}, e_{i2}, and e_{i3}, which are functions of the user's unknown position, Milliken and Zoller note that the solution requires an iterative process based upon an initial, independent estimate of user position.

Milliken and Zoller also present an expression for the covariance of the navigation estimate, valid when the measurement error statistics are accurately known. $\delta\overline{X}_u$ denotes the error in the estimate of $\overline{X}_u$:

$$Cov\delta\overline{X}_u = (\overline{G}_u^T \overline{G}_u)^{-1} = \begin{bmatrix} \sigma^2{}_{xx} & \sigma^2{}_{xy} & \sigma^2{}_{xz} & \sigma^2{}_{xt_{GPS}} & \sigma^2{}_{xt_{GLO}} \\ \sigma^2{}_{yx} & \sigma^2{}_{yy} & \sigma^2{}_{yz} & \sigma^2{}_{yt_{GPS}} & \sigma^2{}_{yt_{GLO}} \\ \sigma^2{}_{zx} & \sigma^2{}_{zy} & \sigma^2{}_{zz} & \sigma^2{}_{zt_{GPS}} & \sigma^2{}_{zt_{GLO}} \\ \sigma^2{}_{t_{GPS}x} & \sigma^2{}_{t_{GPS}y} & \sigma^2{}_{t_{GPS}z} & \sigma^2{}_{t_{GPS}t_{GPS}} & \sigma^2{}_{t_{GPS}t_{GLO}} \\ \sigma^2{}_{t_{GLO}x} & \sigma^2{}_{t_{GLO}y} & \sigma^2{}_{t_{GLO}z} & \sigma^2{}_{t_{GLO}t_{GPS}} & \sigma^2{}_{t_{GLO}t_{GLO}} \end{bmatrix} \qquad (7)$$

The diagonal values of this matrix are the variances of the user position estimates, for each coordinate axis, and the variances of the user time offset, for both GPS and GLONASS. Since $\overline{G}_u$ is a function of only the system geometry, this covariance expression relates the effects of SV geometry to the errors in computed user position and user time.

As such, this expression is used to develop formula for the various components of Dilution of Precision. The Geometric Dilution of Precision (GDOP), an overall measure of the geometric effects on navigation performance, is simply the square root of the sum of the diagonal elements from this covariance matrix. The remaining DOP values, Horizontal Dilution of Precision (HDOP), Vertical Dilution of Precision (VDOP), Position Dilution of Precision (PDOP), and Time Dilution of Precision (TDOP), are similarly formed from their respective terms, as indicated by the following equations. Prior to the computation of these DOP values, a matrix transformation will be performed, transforming the covariance values from error components along the system coordinate axis to error components along the horizontal and vertical axis at the user's position.

$$HDOP = \sqrt{\sigma^2_{xx} + \sigma^2_{yy}}$$
$$VDOP = \sigma_{zz}$$
$$PDOP = \sqrt{\sigma^2_{xx} + \sigma^2_{yy} + \sigma^2_{zz}}$$
$$TDOP_{GPS} = \sigma_{t_{GPS}t_{GPS}}$$
$$TDOP_{GLO} = \sigma_{t_{GLO}t_{GLO}}$$

$$GDOP = \sqrt{\sigma^2_{xx} + \sigma^2_{yy} + \sigma^2_{zz} + \sigma^2_{t_{GPS}t_{GPS}} + \sigma^2_{t_{GLO}t_{GLO}}}$$

D. Error Detection with Six GPS/GLONASS SVs

This section describes a RAIM methodology utilizing the combined GPS/GLONASS SV constellation for detection of extreme solution radial error, even under the presence of Denial of Accuracy (Selective Availability, (SA)). When no Denial of Accuracy is present, this methodology will, more specifically, determine the presence of a single SV failure.

Monitoring the maximum solution separation between redundant navigation solutions for all five SV combinations from six SVs provides the means to detect extreme radial error/single SV failure. The following pages develop this concept of error detection and provide examples utilizing this technique. A subsequent section will further build upon these ideals to provide not only detection, but identification of an extreme radial error source/single SV failure.

1. <u>The concept of error detection</u>

The concepts behind most RAIM schemes involve the formation of redundant navigation solutions to monitor the integrity of the SVs involved. Use of the maximum solution separation [9] is but one of many suggested RAIM methods.

For GPS, the idea of maximum solution separation checking is as follows. At a particular instant in time, five GPS SVs are identified, and all possible combinations of four SV navigation solutions are formed from these five SVs, resulting in a total of five position solutions. Because of differences in pseudorange errors and SV geometries, the resultant solutions will differ from each other. The maximum separation between solutions, as measured in the horizontal plane, is identified, becoming the test statistic.

This statistic is compared against a predefined threshold. If all of the SVs are healthy, then it is expected that the five solutions will be closely grouped, producing a test statistic of small numerical value. If the test statistic is less than the threshold, all is declared well. However, if one of the SVs is "bad", four of the five solutions will be corrupted, and driven away from both truth and the one solution which was formed without the failed SV. Thus, the solutions are more separated, and will produce a larger test statistic. When the test statistic exceeds the threshold, an error condition is declared, indicating the presence of extreme radial error, caused perhaps by either Denial of Accuracy, or by the failure of a single SV.

The concepts of this previous GPS-only discussion may be equally applied to a combined GPS/GLONASS integrity monitoring scheme, where the use of maximum solution separation checking remains as discussed above. However, since five SVs are required for a single, mixed-constellation solution, a total of six SVs are necessary for the integrity monitoring check. Six combinations of five SV solutions are formed, and the maximum separation between these solutions is compared against a predefined test threshold. A factor important to the success of this mixed system integrity monitoring scheme is the greater number of SVs available from the combined constellation.

In particular, complications arise as stated in reference [9] when RAIM is performed with just GPS. Due to occasionally low numbers of visible SVs, the formation of redundant solutions may involve solutions formed with poor SV geometries. Poor geometry will amplify pseudorange errors, making the detection of radial error/SV failure more difficult. Similarly, Denial of Accuracy (Selective Availability) can compound the detection problem, since it introduces errors into the pseudorange measurement, making it difficult to distinguish between SVs which have failed and normal Denial of Accuracy conditions.

As a result of these complicating factors, Brown and McBurney have put forward two suggestions. The first, in response to Denial of Accuracy, is that the problem itself be re-thought with respect to the normal treatment. That is, refrain from considering the problem as the detection of a single SV failure. Rather, they suggest focusing on whether the radial position error is less than or greater than a preset bound. Their point is that a user desires to know when a position solution possesses large error. Knowing whether an SV has failed becomes incidental. Having redefined the problem, the effects of Denial of Accuracy no longer obscure the process but become part of the event being detected.

Secondly, they suggest use of six GPS SVs for the formation of the maximum solution separation check. This suggestion stems from the combination of poor geometries and Denial of Accuracy, and is intended to reduce the effects of "unhappy coincidence" in geometries and errors that mask the detection process. They do comment, however, that additional SVs will mitigate, but not eliminate, the problem.

These two suggestions take on a new light when considered with respect to the combined GPS/GLONASS integrity solution. First, their suggestion to redefine the problem remains valid for the combined GPS/GLONASS case, and, as such, the integrity monitoring scheme described herein will indicate when the radial error exceeds a specific bound. Note, that GLONASS does not possess Denial of Accuracy. This is a phenomenon limited only to GPS. When one considers the absence of Denial of Accuracy from GPS, the problem collapses to the traditional treatment of identifying a single SV failure.

In response to their second suggestion, if one were to increase the number of necessary SVs, the combined system integrity monitoring check would require seven, and not six, SVs. Happily, with the resources of the combined constellations, the seven SVs will readily be available, but rarely needed.

2. Error detection examples

This section provides a series of examples depicting the error detection process through use of six GPS/GLONASS SVs. The location of Kamiah, Idaho, was chosen, and the full GPS and GLONASS constellations were simulated. At the specific time of the following examples, with the predefined terrain masking profile, seventeen SVs were available, eight GPS SVs and nine GLONASS SVs. From these, six SVs were chosen, such that all combinations of five SVs possessed HDOP less than 3.0.

Table II-i presents the Elevation, Azimuth, and simulated pseudorange errors for the six SVs. The pseudorange errors were picked from a N(0,198.81) distribution corresponding to the "no Selective Availability" case of Brown and McBurney.

Table II-i. 6-SV integrity monitoring SVs

SV	Elevation	Azimuth	P-R Error
1	30 deg	141 deg	8 m
24	12 deg	50 deg	6 m
39	21 deg	185 deg	10 m
43	25 deg	263 deg	23 m
44	68 deg	323 deg	4 m
45	36 deg	52 deg	27 m

The SV numbering convention used throughout this thesis is that SVs one through twenty-four are considered GPS SVs, and SVs twenty-five through forty-eight are considered as GLONASS SVs. As such, two GPS SVs and four GLONASS SVs were picked for this example.

Table II-ii presents the SV combinations, and their HDOP, as utilized for the maximum solution separation checks. Note that the HDOPs for combinations 24,39,43,44,45 and 1,39,43,44,45 are identical. This results because four of the five SVs for each combination come from the same system, i.e., 39,43,44, and 45 are all GLONASS SVs. In each case, GPS SVs 1 and 24 contribute only to the evaluation of the user clock bias with respect to GPS system time, and do not contribute to the position aspect of the navigation solution. As such, the horizontal projections of the navigation solution for these two combinations will be identical.

Table II-ii. 5-SV combinations and their HDOP

5 SV Combinations	HDOP
1, 24, 39, 44, 45	2.2
1, 24, 39, 43, 45	1.3
1, 24, 39, 43, 44	1.8
1, 24, 43, 44, 45	1.7
24, 39, 43, 44, 45	1.6
1, 39, 43, 44, 45	1.6

The identical nature of solutions for these two cases is revealed by Figure II-11, which presents the horizontal projections of the six solutions for each of these previously mentioned five-SV combinations. The horizontal position solutions, indicted by the "+" marks, are labeled with their corresponding five SVs. The point near (0, -20) is actually two points, both corresponding to the two combinations of four-GLONASS SVs, as discussed above. All indicated solutions were formed with the "nominal" pseudorange errors as listed in

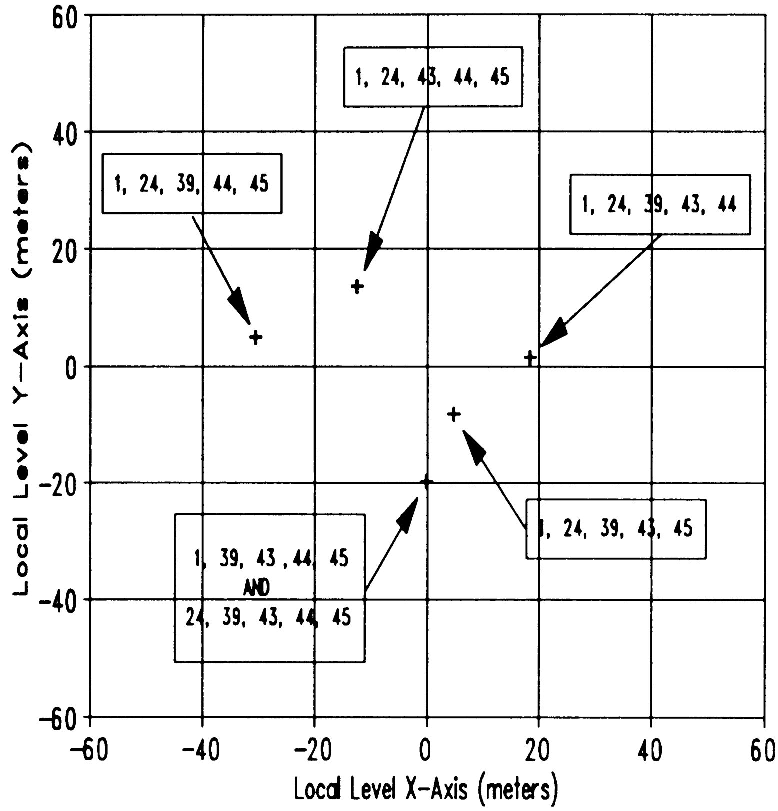


Figure II-11. 6-SV horizontal solutions - nominal pseudorange error

Table II-ii. Since the origin of Figure II-11 represents truth, the radial error of each solution is indicated by the distance of that solution from the origin.

Brown and McBurney suggest that for the non-Denial of Accuracy condition, a maximum solution separation threshold of 85 meters can be used to protect against radial range errors in the range of 100 to 125 meters. This threshold of 85 meters was empirically derived based upon the desired unconditional alarm rate, a function of the test threshold and the interaction of noise and geometric conditions associated with the SV constellation. Although the new constellation formed by the combined GPS and GLONASS SVs would require a recomputation of test thresholds for optimal use, the original thresholds suggested by Brown and McBurney will be used herein.

The maximal separation of solutions in Figure II-11 is approximately 50 meters. Since this is less than our prescribed threshold, a "no failure" case would be declared. In truth, the maximum radial range error is about 30 meters, so the decision was correctly made. Under these conditions, having detected no failures, the user would then form a single navigation solution based on all six SVs as the navigation solution for use.

Figure II-12 presents a similar six SV solution case, but for the conditions of a 100 meter bias added to SV 1. As depicted here, the maximum solution separation is roughly 150 meters, which exceeds the test threshold of 85 meters, indicating a "failure" condition possessing extreme radial range error. In fact, the maximum radial range error is on the order of 110 meters, within the target detection range of 100 to 125 meters, and so the correct decision was made.

As a result of this integrity check, the user would know one of these six SVs was contributing extreme range error, either because of Denial of Accuracy errors, or due to an

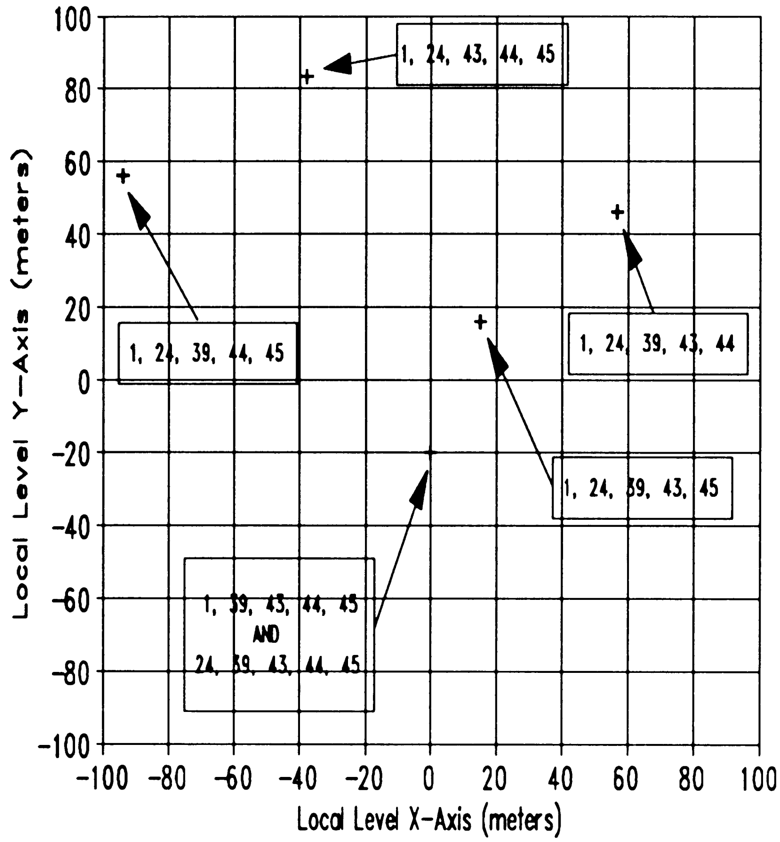


Figure II-12. 6-SV solutions; SV1 with 100 m error

actual SV failure. However, the user would not know which SV was the culprit, and as such, could form no navigation solution without risk.

E. Error Identification via the GPS/GLONASS Seven SV Solution

The previous example depicts a situation where the user has detected a "failure" condition, but because no information is available as to the cause of the failure, the user can form no navigation solution without risk of unacceptable and unknown range error. In response, this section discusses how additional redundant solutions may be used to determine the cause of the failure condition, allowing for the failed SV to be removed, and a "good" solution to be formed. These additional redundant solutions are formed through the addition of a seventh SV.

1. <u>The concept of error identification</u>

The ability to identify the failed SV comes from adding a seventh SV to the integrity monitoring scheme. With seven SVs, there exist seven sets of six SVs such that each set of six can perform the previously described failure detection process. If six of the seven sets indicate a failure, but the remaining seventh set indicates no failure, then the single SV excluded from the seventh set of six SVs will be the SV responsible for the extreme radial range error. Of course, if less than six sets detect an error, then no specific error identification is possible, but detection of the failure has been successful nonetheless.

The GPS/GLONASS seven SV solution failure identification scheme requires that three SVs be chosen from one system, and four SVs chosen from the other system. Furthermore, for these seven chosen SVs, all twenty-one sub-combinations of five SVs must contain a minimal HDOP. The following two examples will illustrate the error identification technique, and further discuss this topic of SV selection for integrity monitoring purposes.

2. <u>Error identification examples</u>

Continuing with the example begun in the previous section, let there be added a seventh SV, number 9 (Elevation = 14 degrees, Azimuth = 320 degrees, pseudorange error = 19 m). SV 9 was not chosen arbitrarily, but rather all seven SVs were picked based upon their resulting combinations of HDOP. In general, there is nothing mysterious about picking SVs to provide acceptable navigation geometry. The trick here is to pick several SVs such that all subsets possess acceptable geometry.

For the time of this example, seventeen SVs are visible from the mixed-constellation. Two straight-forward techniques exist to aid in selecting from among these seventeen SVs the desired set of seven. The first technique is a ground-up approach, where the seventeen SVs are taken five at a time, and their 5-SV HDOPs computed. A thinning filter can be used to throw out cases of large HDOP (i.e., > 8.0). After performing this calculation upon all combinations of five out of the seventeen SVs, the resulting list of 5-SV groups and their associated HDOPs is searched to determine the single set of seven SVs which possesses the lowest, average 5-SV HDOP value for its twenty-one sub-combinations of five SVs.

The second technique is a top-down approach, where the seventeen SVs are taken seven at a time, and the 5-SV HDOPs are computed for all twenty-one sub-combinations of five SVs.

Again, a filter can be used to throw out cases of large HDOP, with the test advancing to the next set of seven. With each new group of seven SVs, the twenty-one values of 5-SV HDOP are averaged, and the particular set of seven SVs providing the lowest average 5-SV HDOPs is identified and maintained. After performing this calculation on all sets of seven, the best set of seven will have been identified.

This second technique is less efficient than the first, since many 5-SV HDOPs will be common to several groups of seven SVs, and thus re-computed many times. However, this second technique requires no complicated search algorithm to search and determine the set of seven SVs with the lowest average 5-SV HDOP, and therefore this second technique was the one utilized herein.

Out of the seventeen visible SVs for this example, there exist 19448 combinations of seven SVs. 203 sets of seven exist such that all twenty-one sub-combinations of five SVs possess an HDOP less than 8.0. The specific set of seven that was chosen for this example possesses the lowest average five-SV HDOP, equal to 1.97. The maximum HDOP for a set of five from these seven is 4.4, being only one of three times (out of twenty-one chances) that the HDOP level exceeds 3.0.

Although selection of the best set of seven SVs proved tedious, the selected seven SVs turned out to contain the four lowest elevation SVs and the highest SV from among the seventeen visible SVs. The remaining two SVs were among the next lowest four visible SVs. This would indicate that a simple method may exist to thin out or easily select a set of seven suitable SVs. Otherwise, the process presented for choosing the best seven may prove too time consuming for high rate use (1 Hz). For example, assume you can compute the 5-SV HDOP for a group of five SVs in as little as 500 instructions. If you perform this computation at a 1 Hz rate for all twenty-one 5-SV combinations, for all 19448 sets of seven SVs, approximately 200 MIPS of processing power would be required.

Figure II-13 depicts the twenty-one five-SV horizontal solutions for the chosen seven SVs. Two interesting items may be noted. First, only nineteen unique solutions would seem to be indicated.

Actually, three of the horizontal projections are identical, resulting from three cases where four SVs from one system are involved in the solution, i.e., cases 1,39,43,44,45; 9,39,43,44,45; and 24,39,43,44,45. Similar to the cases discussed in the previous section, these three will each produce the same horizontal position solution, since in each the lone SV from one system only contributes to an estimate of clock bias with respect to its system, and not to the position solution.

The second item of interest is that the position solutions can be noted to form series of lines containing

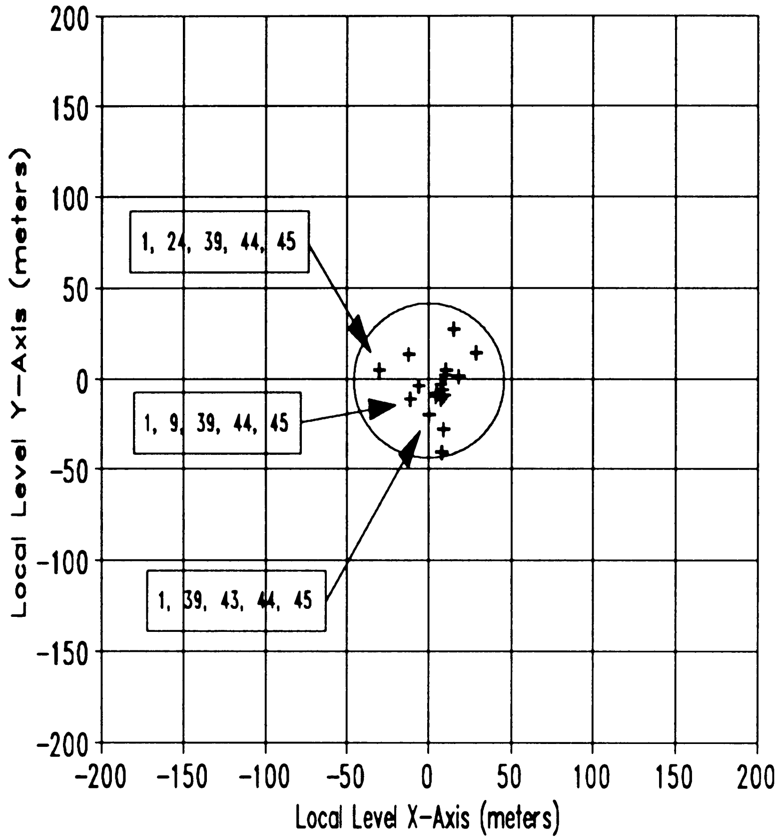


Figure II-13. 7-SV horizontal solutions - nominal pseudorange error

three and/or four solutions. This phenomena is caused by a series of solutions each differing by only one associated SV, such as 1,24,39,44,45; 1,9,39,44,45; and 1,39,43,44,45, as indicated by Figure II-13.

From among the twenty-one five-SV solutions depicted by Figure II-13, the nominal pseudorange errors and geometries produce a maximum radial range error of about 41 meters. As such, the expectation is that a "no failure" condition will be indicated by the maximum solution separation test.

This is exactly what results, as each of the seven, six-SV integrity checks produces a maximum separation under the 85 meter threshold. Table II-iii presents the maximum solution separations for each of the six-SV cases for this nominal case. In addition, the maximum solution separations are displayed for cases of 50, 100, and 150 meters of error on SV 1. Note that the case which excludes SV 1 maintains a constant maximum solution separation.

Figure II-14 depicts the twenty-one seven SV solutions for the case of SV 1 containing 150 meters of pseudorange

Table II-iii. Maximum solution separations (meters)

Excluded SV	Error Conditions			
	Nominal	SV 1 @ 50	SV 1 @ 100	SV 1 @ 150
1	38.0	38.0	38.0	38.0
9	49.1	95.7	151.2	206.7
24	47.3	110.3	185.3	260.3
39	67.9	107.6	154.9	202.3
43	54.4	94.1	141.4	188.7
44	8.5	8.7	29.3	49.8
45	29.8	89.4	160.3	231.2

error. The maximum radial range error exceeds 200 meters, but not all of the expected six, six-SV cases exceed the 85 meter maximum separation threshold. As expected, the case which excludes SV 1 maintains relatively low maximum separation values. However, the case which excludes SV 44 has only 49.8 meter maximum solution separation for an SV 1 error of 150 meters, and the maximum solution separation for this combination does not exceed 85 meters until an error of nearly 250 meters exists.

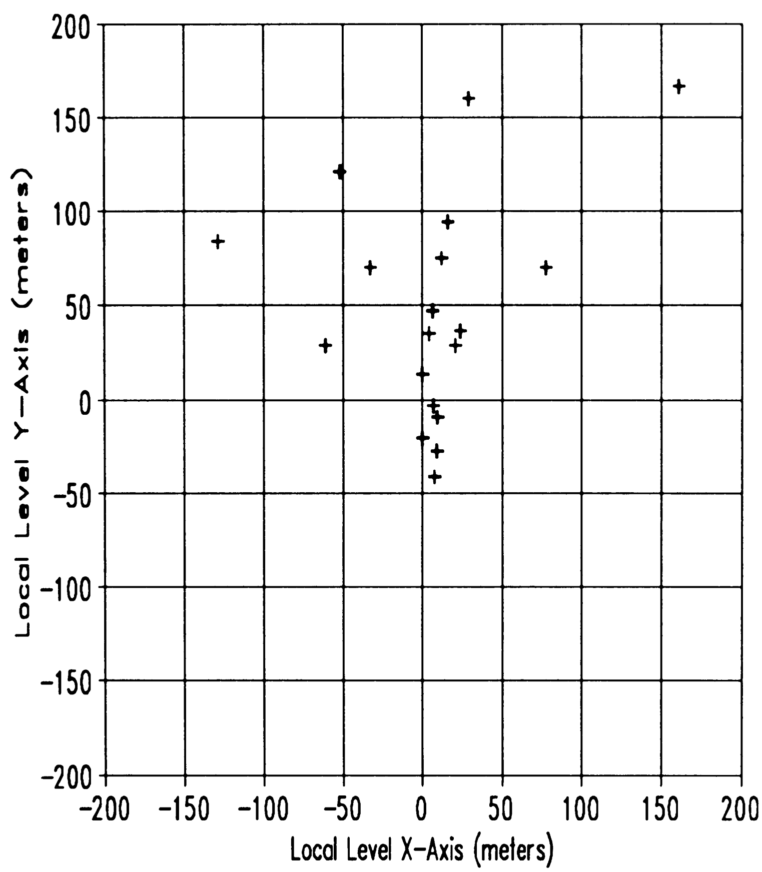


Figure II-14. 7-SV solutions; SV1 with 150 m error

As it turns out, the six-SV case which excludes SV 44 does contain rather large position errors in each of it sub-combinations of five SV. However, these errors are predominately in the vertical direction, and as such, they do not show up in the projection of horizontal error. Thus, the ability to identify the specific failed SV is not available for the target errors of 100 to 125 meters. However, the user would still be able to detect the presence of a failure from the other six-SV combinations. This points out that with the combination of the GPS/GLONASS SVs, new sets of target errors/detection thresholds must be computed. Such a venture would be a logical follow-on effort to this thesis. A second example follows.

At the beginning of the simulated day for the Kamiah location, thirteen SVs are visible, six GPS SVs and seven GLONASS SVs. Out of the 1716 combinations of seven SVs, twenty exist such that all sub-combinations of five have an HDOP less than 8.0. The set of seven with the minimum average HDOP (2.53) includes SVs 13, 17, 23, 31, 39, 40,and 44. These represent the three lowest GPS SVs, three out of the four lowest GLONASS SVs, and the highest elevation GLONASS SV.

Table II-iv presents the maximum solution separations for the case of 50, 150, and 250 meters of pseudorange error on SV 31. The other pseudoranges all contains errors from the N(0, 198.81) distribution.

Table II-iv. Maximum solution separations - start of day

Excluded SV	Error Conditions (meters)		
	SV 31 @ 50	SV 31 @ 150	SV 31 @ 250
13	121.7	432.3	742.9
17	33.2	154.0	274.8
23	29.4	85.0	140.7
31	13.0	13.0	13.0
39	118.0	442.6	767.1
40	130.9	475.0	787.2
44	82.4	324.9	640.7

Figure II-15 presents the twenty-one seven-SV solutions for the case of 150 meters error on SV 31. As indicated, the maximum radial range error is nearly 400 meters. For this case all but one set of six-SV maximum solution separations meet or exceed the test threshold of 85 meters. Since the set that excludes SV 31 does not exceed the threshold, one would correctly deduce that SV 31 is the failed SV, and exclude SV 31 from the navigation solution.

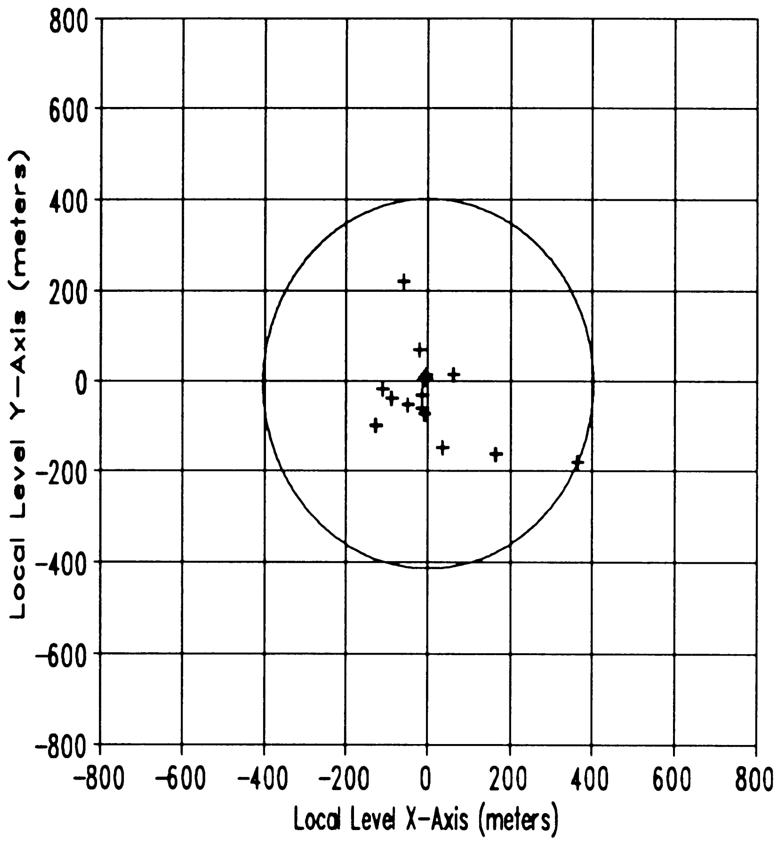


Figure II-15. 7-SV solutions at beginning of day

III. SYSTEM INTEGRATION ISSUES

A. Summary

Utilization of a single navigation receiver capable of simultaneously forming measurements from GPS and GLONASS SVs will provide integrity monitoring opportunities unavailable to users of either separate system. However, several issues confront the user of a single receiver integrating both navigation systems.

Foremost among the Space Segment issues are SV coverage concerns, caused especially by noted GLONASS SV reliability problems [34]. User Segment issues focus upon receiver front end architectures, additionally complex due to the CDMA nature of GPS and FDMA nature of GLONASS. Control Segment issues are highlighted by the noted differences between each system's geodetic references, producing different navigation solutions for the same location. Cooperation between the United States and the Commonwealth of Independent States will be required to determine the proper conversion between reference frames.

The following sections examine in greater detail each of these, and related, issues.

B. Space Segment Issues

1. Coverage issues

The constellation definition for each system, as discussed in the previous chapter, determines, for each terrestrial location, the specific number, geometry, and times for which satellites of a system are visible. These definitions also determine when gaps in the system coverage will occur. Such gaps will cause degraded operation due to poor SV geometries. For extreme cases, when SVs have failed, periods of temporary system unavailability may occur.

For the GPS constellation of 24 satellites, users in only few points of the world will experience periodic gaps in coverage, or times when poor geometries degrade the navigation solution [4]. If satellites should fail, these gaps or degradations will increase in length. GLONASS, with its higher inclination angles for the orbital planes, will allow for increased visibility in the northern and southern regions, but overall its constellation will not be as robust as that for GPS.

The ability to launch satellites impacts the speed at which the initial navigation constellation can be built, as well as determines the rate at which failed satellites can be replaced. One advantage enjoyed by GLONASS over GPS is its system's ability to launch three SVs at a time from the Tyuratam space center. GPS launches carry only one SV.

2. SV reliability

Coverage concerns become more of an issue with GLONASS, because past observations have shown that the GLONASS SVs demonstrate a marked lack of reliability [34]. Although over forty-five GLONASS SVs have been launched since 1982, only ten were currently working as of December of 1991. In comparison, through August of 1991, twenty-two GPS SVs have been launched, with sixteen still in service.

The observed average life of a GLONASS SV seems to be only a couple of years. This compares unfavorably to the GPS NAVSTAR satellites, which have an expected life of over seven years, with many having worked even longer. As of August of 1991, GPS PRN 06 was still in service, even though this Block I SV had been launched in October of 1978. Although the Soviets have reportedly solved their SV reliability problems [41], further time and observations are warranted to verify their claim.

Perhaps the main component subject to failure aboard the SVs of either system are the precision time standards. The GPS Space Segment satellites employ three types of frequency oscillators; crystal oscillators, higher accuracy Rubidium oscillators, and even higher accuracy Cesium oscillators. Oscillator redundancy allows for the continued use of the GPS satellites even after one or more of their on board standards fail. As of August of 1991, for the six operating Block I SVs, three were utilizing Rubidium standards and three were utilizing Cesium standards. PRN 8, which had its L band transmissions turned off October 14, 1989, had operated for almost three years on its crystal oscillator.

As far as the GLONASS SVs are concerned, reports [10] have indicated that since 1986, the GLONASS satellites have utilized frequency oscillators which exhibit the quality of Rubidium atomic oscillators. Since that time, the satellites have demonstrated a continued improvement in the quality of their on board frequency standards. Thus, some current GLONASS satellites are demonstrating performance equivalent to that from the Cesium beam standards utilized on GPS satellites launched during the mid 1980's.

SV reliability can effect the selection of SVs for formation of the navigation solution. Typically, the choice as to which satellite is to be used is primarily a factor of geometry. A common practice is to compute the GDOP or PDOP for all possible combinations of visible satellites, and then to make use of the constellation of four satellites which possesses the lowest DOP.

Assuming the user of a combined GPS/GLONASS receiver needed measurements from five satellites, the user could follow this typical scheme and select the five satellites which provide the best PDOP. However, one may want to consider augmenting the geometry factors of the satellite selection process. Possibilities would include weighting the PDOP computations by factors which describe the satellite's clock accuracy, or which account for the presence of Selective Availability on the GPS signals. This weighting would have the effect of allowing constellations of slightly poorer geometry to be chosen with the advantage of obtaining satellites with slightly better range accuracy, the net effect would be a better navigation solution.

C. User Segment Issues

When considering a single, integrated, hybrid receiver capable of simultaneously utilizing signals from both GPS and GLONASS SVs, several User Segment issues result. These issues are explored by the following sections. As a reference, Appendix A provides a detailed discussion of the RF signal structures for both GPS and GLONASS.

1. FDMA vs. CDMA

The first issue confronted in integrating the two systems revolves around the differences between the Frequency Division Multiple Access (FDMA) characteristics of GLONASS and the Code Division Multiple Access (CDMA) nature of GPS.

Users of GPS acquire and track specific SVs, all which are transmitting at the nominal L1 and/or L2 frequency, through a correlation process utilizing a pseudorandom code unique to the desired SV. In contrast, users of GLONASS select specific SVs, all which are transmitting a signal modulated by the same pseudorandom code, through a correlation process utilizing a single frequency unique to the desired SV.

The practical result is that to track "n" GPS SVs at one time, the GPS receiver need utilize only a single Intermediate Frequency (IF) strip, fanning-out to "n" numbers of correlator channels for tracking "n" numbers of SVs. In comparison, the GLONASS receiver must have "n" numbers of IF strips, each down converting the received signals, for tracking "n" SVs.

This need then precludes the hybrid receiver from having a simple, single IF strip design. The feeling may exist that the creation of a hybrid receiver really doesn't buy anything for the user. In fact, two separate receivers (one GPS and the other GLONASS) could be used side by side, and the independent measurements from each could be integrated in a single nav computer for integrity checking.

2. Filtering issues

A second line of issues develops for RF filtering of the GLONASS signals. Interfering, out of band signals will be found in applications involving civilian aircraft [11]. A proposed system for passenger/ground communication is Aircraft Passenger Communications (APC). Ground to air links are proposed at 1593 to 1594 MHz, and the aircraft to ground link at 1625.5 to 1625.6 MHz. These frequencies closely bracket the GLONASS L1 signals, requiring that very sharp filtering be performed to reduce the potential interference. Although additional help will be gained by physical separation of the

GLONASS antenna and the APC antenna, the necessary filtering will add unwelcomed cost and size.

In addition, the higher GLONASS frequencies are near the satellite communications (satcom) channels, causing even further filtering constraints. One option under investigation involves the reallocation of GLONASS frequencies [12]. Under this proposal, the GLONASS system would discontinue use of the presently assigned twelve higher GLONASS SV frequencies, and would then assign signal frequency pairs to SVs directly opposite from each other in an orbital plane. Thus, no user would see two SVs transmitting the same frequency pair at the same time, and an additional 7 MHz separation would be gained between the highest GLONASS signals and the satcom "interference".

3. Signal tracking and downlink data issues

Once the received signals have been digitized, the remaining correlation, tracking, and data demodulation can be performed in dedicated digital signal processing hardware, and for the most part, the requirements for GPS and GLONASS processing will be identical.

Of course, the generation of the local pseudorandom codes will need to be appropriate for each system. And it will be desirable to form all internally generated frequencies for both systems from a single receiver clock.

The maximum pre-detection integration (PDI) interval, a function of the downlink navigation data bit rate, will be different for the two systems. GPS utilizes 50 Hz nav data, and so each data bit is 20 msec long. Therefore, for GPS the PDI can not exceed 20 msec or possible bit transitions will cause destructive interference in the integrated signals. Since GLONASS utilizes 100 Hz data, the maximum PDI can not exceed 10 msec. This would suggest that GPS, with PDI intervals up to twice as long as those available for GLONASS, will enjoy 3 dB better performance against noise.

Not only is the bit structure of the downlink data different, but the actual content of the data differs in a couple of ways. While the GPS user calculates the satellite's location from the Keplerian parameters of the ephemeris data, the GLONASS user has to extrapolate SV position from a set of cartesian coordinates provided in the data.

Furthermore, the GPS user has access to a few terms not available to the GLONASS user. The terms missing for the GLONASS system are the second order satellite clock drift correction term and the ionospheric delay correction term [13]. The lack of the ionospheric delay correction terms becomes no issue if the user has access both the L1 and L2 frequencies. However, the availability of the L2 GLONASS signals is uncertain.

D. Control Segment Issues

1. Time bias determination

As part of the formulation of the mixed-constellation navigation solution, it is necessary to determine the user's time bias with respect to each of the GPS and GLONASS systems. One method, as discussed in the previous chapter, consists of taking measurements from a total of five satellites to solve for the five unknowns, X,Y,Z position, and the two system time biases. This is not necessarily the best approach, because now all mixed-constellation solutions require five measurements, with three contributed from one system, and two from the other.

Other potential solutions have been suggested [31]. One is to form the navigation solution for each system independently, and then for times when reduced coverage or integrity failures force combined use of the systems, the pre-calculated clock bias and drift values would be used. This ability to "ride the clock" would not be usable indefinitely, but would rather be a function of the particular receiver's clock stability.

Another suggestion is to have the precise relationship between the two system times broadcast, either in the downlink data messages for each system, or from another satellite source, such as from an INMARSAT geostationary satellite overlay. For example, each system currently broadcasts its offset from UTC(USNO) and UTC(SU). If each system were to broadcast their precise offsets from the UTC in Paris, then there would be essentially only one clock bias value to solve, and measurements from only four SVs would be required.

Yet another suggestion calls for the Soviets to reference their system time to UTC(USNO), or to reference it to GPS system time via a GPS receiver at a known location. Again, this would result in only one time bias to solve. Thus four measurements from any four satellites would be sufficient to provide the navigation solution. This ideal leads to a related suggestion for localized users. A hybrid receiver placed at a known location could monitor the differences between the two system times, and could then broadcast these data in a manner similar to that used by differential GPS.

One particularly interesting note is that as the system time scales are now defined, a definite problem exists in the area of how the two systems handle the relations between their own system time and UTC. GPS system time is a free running time scale, referenced back to midnight on the night of January 5, 1980/morning of January 6, 1980. As leap seconds are introduced into UTC, an offset of an integer number of seconds grows between UTC and GPS. This offset is known and transmitted as part of the navigation data message. However, as UTC introduces leap seconds, GLONASS also introduces leap seconds into its system time. This would cause great havoc with the combined GPS/GLONASS system. For example, a jump in time by one second is equivalent to a range change of 3e+08 meters. To circumvent this problem, it was observed on December 31, 1989, that the GLONASS system stopped transmitting 15 minutes prior to midnight, at which time a leap second was introduced in UTC. The GLONASS satellites did not begin transmission again until January 3, 1990, after their system time had been adjusted. Alternatives to this manner of operation need to be pursued.

2. Coordinate system references

In the process of formulating a mixed-constellation navigation solution, the user will have to account for the differences between the coordinate reference frames of the two systems. It is presently unclear what the relationship is between WGS-84 and SGS-85, although it is reported that the Soviet "Shkipper" receiver utilizes both systems. If this is so, then some relationship may already have been identified by the Soviets. If not, then it may be necessary to survey a multitude of locations over the globe using both systems in order to gain an understanding of the differences between the two. The differences could be as simple as an offset, or it could entail both an offset and rotation of the reference axis. Reports from Hartman et al. [3] indicate that differences between the two systems are less than twenty meters for mid-latitude locations.

3. Control Segment coordination

Many of the issues discussed herein fall outside the control of the user. If a truly combined approach were to be effective for both systems, coordination on the system control levels would be essential. This would allow for the relationships between system times and coordinate references to handled in the most efficient manner possible.

For either system the Control Segment must consist of the facilities required to; 1) monitor the satellites, and 2) upload control signals and the navigation data to be transmitted by the satellites. It is reported that the Soviets have a master control station capable of these monitoring and uploading tasks located in the western portion of what was the Soviet Union. It is unclear what other monitor or upload stations exist for GLONASS, although suggestions have been put forward monitor stations exist throughout the former USSR.

In a recent article by the Soviets [7], it was stated that the GLONASS Control Segment will consist of "monitoring stations located for appropriate coverage, a master control station, and an upload station." If the GLONASS system does in fact possess only one upload station, this could be a point of concern for the hybrid system, since rapid alteration of the satellite's transmitted data will not be possible until the satellite comes into view over the upload station. This could result in a failed GLONASS satellite continuing to transmit for several hours before it can be marked as "bad" in the navigation data. Unless the GLONASS satellites have some sort of cross-linking communication capabilities previously unmentioned, this will present a problem for the hybrid system.

In comparison, the GPS Control Segment is, by design, spread around the world. The master control station for GPS is located in Colorado, and four monitor/uplink stations are in Diego Garcia, Kwajalein, Ascension, and Hawaii. This permits the GPS system to have communication capabilities with all GPS satellites at any given instant.

This raises the question that if the GPS system were to share its monitor and uplink stations with the Soviets, possible improvements to the GLONASS health warning capability would be possible. This is extremely important since the observed reliability of the GLONASS satellites is quite low in comparison to those of GPS.

E. Other Issues

Because the two systems are not identical, there will exist performance differences. One difference will be in the area of acquisition time for the C/A signals. Since the GLONASS C/A signal has only half the number of chips as the GPS C/A signal, it can be acquired in half the time on the average. For example, assuming a search rate of 50 chips per second, it takes approximately 21 seconds to find the GPS C/A signal. For the same search rate, it takes about 11 seconds to acquire the GLONASS C/A signal.

Another performance difference is the time required to demodulate the entire navigation message. For GPS this time is 12.5 minutes, while for GLONASS only 2.5 minutes is required.

The navigation accuracy of GLONASS will be slightly less than what is available with GPS. This results in part from the fact that the GLONASS chips are roughly twice a long as their GPS counterparts. Even so, it has been reported that navigation accuracies utilizing the GLONASS C/A were on the order of 30 meters, which is actually better than what will be available from GPS C/A when Selective Availability is invoked.

The two systems will each have their own distinct advantages against potential jamming sources. Due to the spread spectrum nature of the signals, there is a processing gain against narrowband jammers (intentional or otherwise) which is a function of the chipping rate of the signal. Since the GPS P code chipping rate is 10.23 MHz, the P code signal exhibits approximately 70 dB of processing gain against a CW jammer [15]. Since the GLONASS P code chipping rate is 5.11 MHz, it will exhibit 3 dB less gain against a narrowband jammer, providing only 67 dB of resistance.

This rejection of narrowband interference does not apply to the C/A code signals, for either GPS or GLONASS. Both signals exhibit power spectral densities with the characteristic spread spectrum sinc squared envelope. But due to the short, 1 msec periods of both systems' C/A codes, both spectrum contain discrete signal components spaced at 1 KHz intervals, making them vulnerable to narrowband interference.

In GLONASS' favor, since each of the transmitted signals are at different frequencies, interference which would effect one satellite may not effect other satellites. However, this last advantage will only be realized if the receiver's filters attenuate the jammer power in the particular L-Band frequency range where both the interference and GLONASS signals fall. This is not the case for GLONASS designs presented in the literature.

Lastly, the users of an integrated system must contend with political aspects of the systems. The GPS, primarily developed for military purposes, provides the Standard Positioning Service (SPS) for civilians at an accuracy reduced from that warranted by the capabilities of the system. To date, lobbying has failed to lift or limit the application of these signal degradations.

The GLONASS signals are not purposely degraded in accuracy, but even so users are now wary of becoming dependent upon GLONASS, for with the dissolution of the USSR, the entire future of GLONASS seems in jeopardy as the newly formed Commonwealth of Independent States struggles to provide the barest of essential services for its people. Dr. Daly has suggested that perhaps Japan, which has plenty of national wealth but no national satellite navigation system, should purchase GLONASS from the former USSR.

BIBLIOGRAPHY

1. R. Kalafus. "GPS Integrity Channel RTCA Working Group Recommendations." Navigation: Journal of The Institute of Navigation 36 No. 1 (Spring 1989): 24-44.

2. P. Raby, P. Daly, and S. Riley. "Integrity Monitoring Tests Conducted on GPS/GLONASS." Proceedings of ION GPS-91 Held in Albuquerque, New Mexico 11-13 September 1991 (1991) 1063-1069.

3. R. Hartman, M. Brenner, and N. Kant. "GPS/GLONASS Flight Test, Lab Test, and Coverage Analysis Tests." Proceedings of ION GPS-91 Held in Albuquerque, New Mexico 11-13 September 1991 (1991) 333-344.

4. G. Green, P. Massatt, and N. Rhodus. "The GPS 21 Primary Satellite Constellation." Navigation: Journal of the Institute of Navigation 36 No. 1 (Spring 1989): 9-24.

5. R. Langley. "Innovation: The Orbits of GPS Satellites." GPS World 2 No. 3 (March 1991): 50-53.

6. T. Anodina. "The GLONASS System Technical Characteristics and Performance." Paper presented at the Special Committee on Future Air Navigation Systems (FANS) meeting of the International Civil Aviation Organization (ICAO), Montreal, 2-20 May 1988.

7. G. Moskvin, and V. Sorochinsky. "Navigational Aspects of GLONASS." GPS World 1 No. 1 (January/February 1990): 50-54.

8. R. Milliken, and C. Zoller. "Principle of Operation of NAVSTAR and System Characteristics." Global Positioning System: Papers published in Navigation 1 (1980): 3-14.

9. R. Grover Brown, and P. W. McBurney. "Self-Contained GPS Integrity Check Using Maximum Solution Separation." Navigation: Journal of The Institute of Navigation 35 No. 1 (Spring 1988): 41-53.

10. P. Daly, and I. Kitching. "Characterization of NAVSTAR GPS and GLONASS On-Board Clocks." IEEE AES Magazine 5 No. 7 (July 1990): 3-9.

11. R. Johannessen, S. Gale, and M. Asbury. "Potential Interference Sources to GPS and Solutions Appropriate for Applications to Civil Aviation." IEEE AES Magazine 5 No. 1 (January 1990): 3-9.

12. "GPS/GLONASS Talks Accelerate Momentum toward Global Air Plan" GPS World 2 No. 1 (January 1991): 16.

13. S. Dale, and P. Daly. "Developments in Interpretation of the GLONASS Navigation Satellite Data Structure." Proceedings of the IEEE 1988 National Aerospace and Electronics Conference Held in Dayton, Ohio 23-27 May 1988 (1988) Vol. 1 292-297.

14. NAVSTAR GPS Space Segment/Navigation User Interfaces (ICD-GPS-200) Rockwell Internationsl Corporation, Satellite Systems Division, 1984.

15. J. Spilker. "GPS Signal Structure and Performance Characteristics." Global Positioning System: Papers published in Navigation 1 (1980): 29-54.

16. G. Kremer, R. Kalafus, P. Loomis, and J. Reynolds. "The Effect of Selective Availability on Differential GPS Corrections." Navigation: Journal of The Institute of Navigation 37 No. 1 (Spring 1990): 39-52.

17. "GPS Status Information, GPS Time Transfer Performance." U.S. Naval Observatory On-Line Information Service. 15 September 1989.

18. P. Daly. "Aspects of the Soviet Union's GLONASS Satellite Navigation System." The Journal of Navigation 41 No. 2 (May 1988): 186-198.

19. G. Lennen. "The USSR's GLONASS P-Code - Determination and Initial Results." Proceedings of The Institute of Navigation Satellite Division Meeting, GPS-89 Held in Colorado Springs, Colorado 27-29 September 1989 (1989) 77-83.

20. S. Dale, P. Daly, and I. Kitching. "Understanding Signals from GLONASS Navigation Satellites." International Journal for Satellite Communication 7 (January-March 1989): 11-22.

21. N. Bowditch, ed. American Practical Navigator: An Epitome of Navigation Washington, D.C.: Defense Mapping Agency Hydrographic Center, 1977.

22. M. Quigley, "Airlines Electronic Engineering Committee letter 89-093/GPS-18." Letter presented to the AECC members concerning GLONASS, August 1, 1989.

23. T. Anodina, and M. Prelepin. "The GLONASS System." Contained in AEEC letter 89-093/GPS-18, August 1, 1989.

24. "Indicateur-Recepteur 'ASN'." Handout provided at the Soviet Pavilion at the 1989 Paris Air Show, Contained in AEEC letter 89-093/GPS-18, August 1, 1989.

25. V. Bogdanov. "GLONASS Satellite Navigation System: Overview, Future Developments." Contained in AEEC letter 89-093/GPS-18, August 1, 1989.

26. N. Ivanov, and V. Salistchev. "GLONASS and GPS: Prospects for a Partnership." GPS World 2 No. 4 (April 1991): 36-40.

27. N. Ivanov, V. Salischev, A. Vinogradov, V. Hovanskov, and A. Kuprijanov. "A Study in Support of the Monitoring Required for a Global Integrity Monitoring Network for GPS and GLONASS." Proceedings of ION GPS-91 Held in Albuquerque, New Mexico 11-13 September 1991 (1991) 801-811.

28. S. Dale, and P. Daly. "Recent Observations with the Soviet Union's GLONASS Navigation Satellites." Proceedings of IEEE PLANS '86: Position, Location and Navigation Symposium Held in Las Vegas, Nevada 4-8 November 1986 (1986) 20-25.

29. S. Dale, and P. Daly. "An early comparison of the pre-operational NAVSTAR GPS (USA) and GLONASS (USSR) satellite navigaiton systems." Proceedings of MELCON '87: Mediterranean Electrotechnical Conference and 34th Congress on Electronics Joint Conference Held in Rome, Italy 24-26 March 1987 (1987) 711-714.

30. S. Dale. "The Soviet Union's GLONASS Navigation Satellites." IEEE AES Magazine 2 No. 5 (May 1987): 13-17.

31. I. Kitching, S. Dale, and P. Daly. "Potential for a Unified GLONASS/NAVSTAR Civil Navigation System." Proceedings from the Fourth International Conference on Satellite Systems for Mobile Communications and Navigation Held in London, United Kingdom 17-19 October 1988 (1988) 181-185.

32. I. Kitching, S. Dale, and P. Daly. "Time Transfer with GLONASS Navigation Satellites." Contained in AEEC letter 89-093/GPS-18, August 1, 1989.

33. S. Dale, I. Kitching, and P. Daly. "Position-Fixing Using the USSR's GLONASS C/A Code." IEEE AES Magazine 4 No. 2 (February 1989): 3-10.

34. P. Daly. "Progress Towards the Operational Phase of GLONASS." Navigation: Journal of The Institute of Navigation 38 No. 1 (Spring 1991): 37-51.

35. P. Daly, G. Cherenkov, N. Koshelyaevski, and S. Pushkin. "Satellite Time Transfer Between UTC(USNO) and UTC(SU) Using Navstar GPS and GLONASS." Proceedings of ION GPS-91 Held in Albuquerque, New Mexico 11-13 September 1991 (1991) 199-206.

36. J. Carter. Letter to Massachusetts Institute of Technology, Haystack Observatory, 11 August 1986, Contained in AEEC letter 89-093/GPS-18, August 1, 1989.

37. J. Ponsonby. "Spectrum Management and the Impact of the GLONASS and GPS Satellite Systems on Radioastronomy." Paper presented at the West German-Soviet Workshop on Scientific and Industrial Cooperation in the use of GLONASS, Held in Leningrad, USSR, September 1990.

38. S. Chenard. "GLONASS Twin to GPS?" Interavia Space Markets 5 No. 3 (August 1989): 170-175.

39. A. Kleusberg. "Comparing GPS and GLONASS." GPS World 1 No. 6 (November/December 1990): 52-54.

40. R. Eastwood. "An Integrated GPS/GLONASS Receiver." Navigation: Journal of the Institute of Navigation 37 No. 2 (Summer 1990): 141-151

41. P. Misra, E. Bayliss, R. Lafrey, M. Pratt, and R. Hogaboom. "Integrated Use of GPS and GLONASS in Civil Aviation Navigation II: Experience with GLONASS." Proceedings of ION GPS-91 Held in Albuquerque, New Mexico 11-13 September 1991 (1991) 321-332.

42. B. Nordwall. "Flight Tests Highlight New GPS Uses, Emphasize Need for GPS/GLONASS System." Aviation Week & Space Technology 135 No. 22 (December 2, 1991): 71-73.

43. "Ashtech Targets December 1991 for GPS/GLONASS Unit." GPS World 2 No. 1 (January 1991): 18-19.

4. G. Kinal, and J. Singh. "An International Geostationary Overlay for GPS and GLONASS" Navigation: Journal of The Institute of Navigation 37 No. 1 (Spring 1990): 81-93.

5. R. G. Brown. Introduction to Random Signal Analysis and Kalman Filtering New York: John Wiley and Sons, 1983.

6. J. A. Rajan. "Adaptive Acquisition of Multiple Access Codes." Presented at the IEEE International Conference on Communications in Philadelphia, Pennsylvania, 13-17 June 1982.

APPENDIX A: GPS/GLONASS SIGNAL CHARACTERISTICS

The previous chapters have discussed the applications and issues revolving around a single navigation receiver capable of simultaneously tracking signals from GPS and GLONASS satellites. To facilitate these discussions, the following sections provide a summary of the signal attributes for these two satellite navigation systems.

A. GPS Signal Characteristics

Each space vehicle (SV) of the GPS system transmits two L-Band direct sequence spread spectrum signals. These signals, Link 1 (L1) at 1575.42 MHz, and Link 2 (L2) at 1226.6 MHz, each consist of a sinusoidal L-band carrier which is phase modulated by one or more pseudorandom noise (PRN) codes, denoted as C/A or P code. It is this action of modulating the carrier with an PRN sequence which creates the spread spectrum signal. The PRN codes themselves are modulated by 50 Hz downlink navigation data, providing the user with precise information describing the SV's orbit.

Since the PRN codes are unique to each satellite, GPS is characterized as a Code Division Multiple Access (CDMA) system, where the user's choice of PRN code specifies which SV is to be tracked. Figure A-1 presents the conceptual signal flow within a GPS SV. Note that L1, which is 154 times the base frequency of 10.23 MHz (f_o), contains two components, one

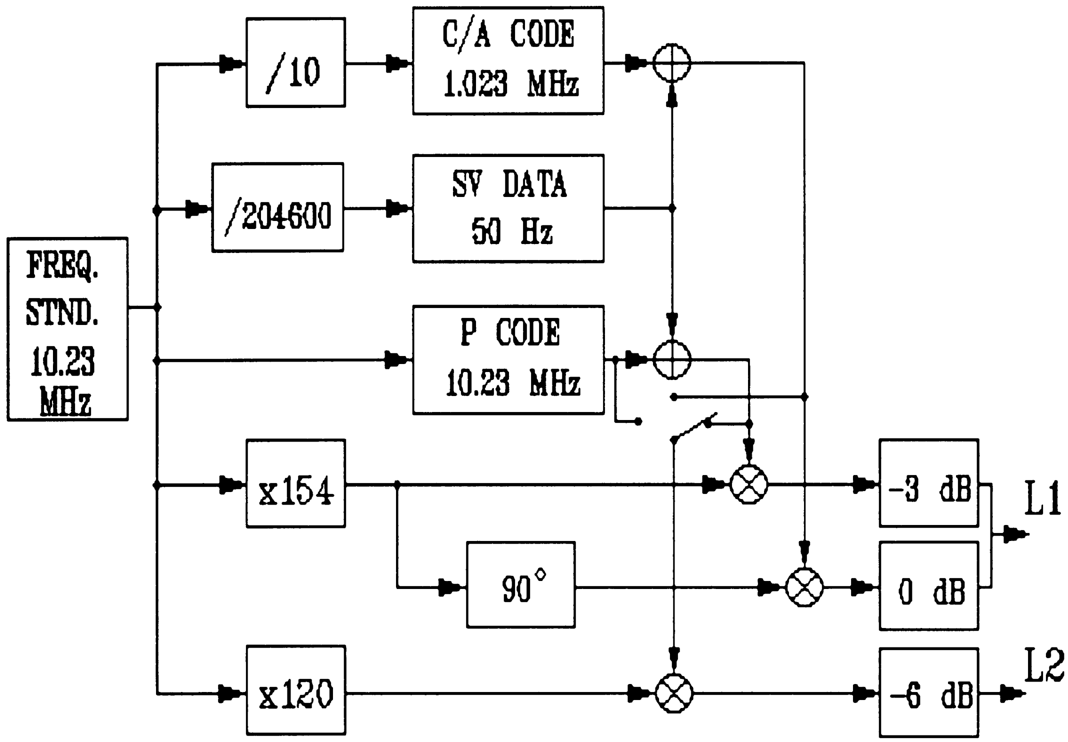


Figure A-1. Signal flow within a GPS satellite

modulated by C/A, and the other modulated by P code. L2, which is 120 times f_o, contains only P code or C/A, but not both. Typically, L2 transmits a P code signal.

Figure A-2 depicts the relationships between the GPS carrier, PRN code, navigation data, transmitted signal, and received/correlated signal. This figure is for illustration purposes only, and as such is not drawn to scale.

The digital PRN code and the 50 Hz nav data are exclusively ORed together (XOR), and then used to modulate the GPS carrier. This process results in the 180 degree phase reversals depicted in the carrier. The signal is transmitted,

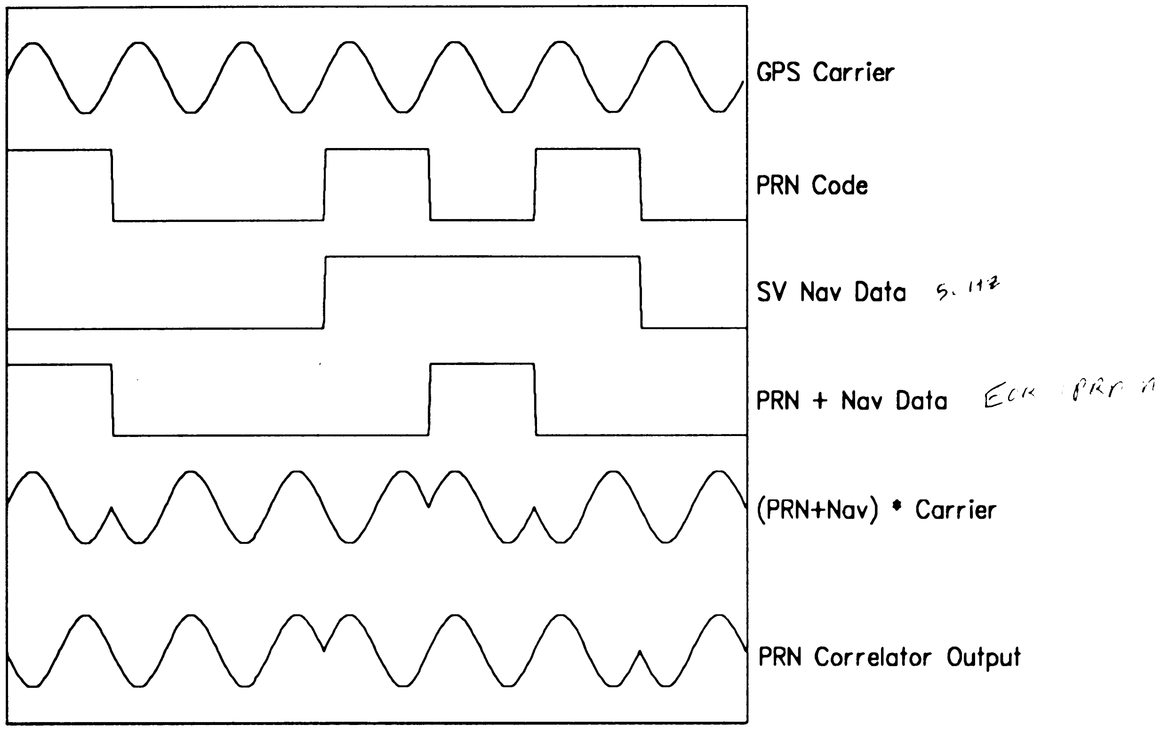


Figure A-2. GPS signal structure

and then, in the receiver, the correlation process effectively adds back on the PRN code, leaving the carrier modulated by only the 50 Hz nav data.

The pictorial representation provided by Figure A-2 may be reenforced by a mathematical description of these two GPS signals.

The L1 signals may be represented as follows:

$$L1 = A_1[D_i(t) \oplus P_i(t)]\cos(2\pi 154 f_o t + \theta) + A_2[D_i(t) \oplus C/A_i(t)]\sin(2\pi 154 f_o t + \theta)$$

while the L2 signals may be represented by any one of three representations:

$$L2 = A_3\,[D_i(t) \oplus P_i(t)]\cos(\,2\pi 120 f_0 t + \theta\,)$$

or

$$L2 = A_3 P_i(t)\cos(\,2\pi 120 f_0 t + \theta\,)$$

or

$$L2 = A_3\,[D_i(t) \oplus C/A_i(t)]\cos(\,2\pi 120 f_0 t + \theta\,)$$

where these terms are as defined as follows:

A_1, A_2, A_3 = *Relative amplitudes*
$D_i(t)$ = *Downlink navigation data for* SV_i
$P_i(t)$ = *P code PRN for* SV_i
$C/A_i(t)$ = *C/A code PRN for* SV_i
f_o = 10.23 *MHz*
θ = *Phase error*
t = *Time*
$\oplus$ = *Modulo* 2 *addition*

Thus, the L1 signal, at a nominal carrier frequency of 1575.42 MHz (154 times 10.23 MHz), contains a P code modulated component in phase quadrature with a C/A code modulated component, with each PRN code modulated by the SV's downlink navigation data. The relative amplitudes of the L1 signal are set such that the C/A component will be 3 dB higher than that of the P code component. The minimum received RF signal strength at the output of a 3 dBi linearly polarized antenna (or a 0 dBi circularly polarized antenna) is specified for L1 C/A to be -160.0 dBW, and -163.0 dBW for L1 P [14].

The L2 signal, utilizing a nominal carrier frequency of 1227.60 MHz (120 times 10.23 MHz), contains one of three possible PRN modulation patterns as determined by the GPS Control Segment. Typically, L2 uses P code to modulate the carrier, with the P code itself modulated by the SV's downlink navigation data. However, the system also allows for the use of C/A code to modulate the carrier, with the C/A code similarly modulated by the SV's downlink navigation data, or for the P code to modulate the carrier without the presence of the downlink navigation data. The minimum received RF signal strength at the antenna outputs for the antennas described above is specified to be -166.0 dBW for either C/A or P on L2.

The existence of these two separate links allows for the GPS receiver to estimate the ionospheric delay of the received signals since the propagation delay through the ionosphere is inversely proportional to the square of the signals' frequency. For the remainder of this section it will be assumed that the GPS L2 signal contains P code modulated by the downlink navigation data.

1. PRN codes

Two classes of PRN codes are utilized within GPS, the Coarse Acquisition (C/A) codes, and the Precision (P) codes. These C/A and P codes are unique to each GPS SV.

a. C/A codes The C/A codes are Gold codes [15] 1023 chips in length. With a chipping rate of one tenth f_o (1.023 MHz), the C/A codes repeat every 1 msec. Thus, each chip has a duration of roughly 0.9775 microseconds, which is equivalent to a wave length of about 293 meters per chip. This short length of only 1023 chips makes the C/A code ideal for use in the initial acquisition of the GPS signals, i.e., for a search routine which scans 50 chips/sec, only 21 seconds need be spent searching for a visible SV's signal.

The choice of utilizing Gold codes for the C/A code was based in part upon the need for codes with excellent cross-correlation characteristics.

The C/A codes are formed by the modulo-2 addition of two code sequences, each 1023 chips long. Figure A-3 depicts the generation of the C/A code by use of tapped feedback shift registers.

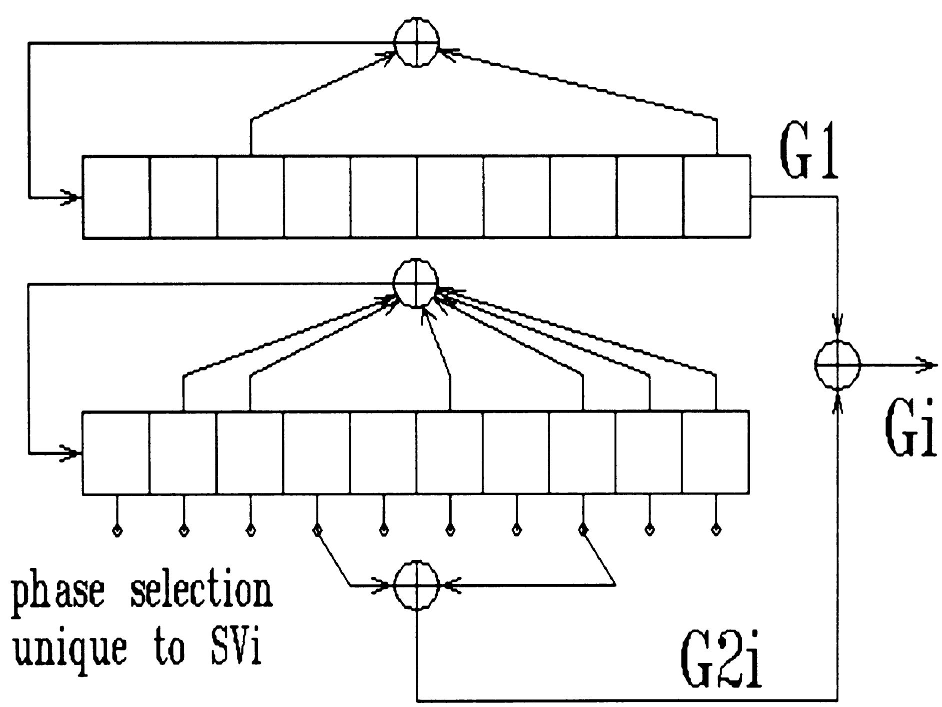


Figure A-3. GPS C/A code generation

The selected code phase of the G2 register serves to create thirty-six unique C/A codes. Thirty-two of these codes are assigned for use by the GPS satellites, and the remaining four are reserved for other uses, such as ground transmitters.

As an alternative mode of C/A code generation, table look-up can be used.

b. <u>P codes</u> The P codes are much longer than the C/A codes, with a length of 7 days at a chipping rate of f_o (10.23 MHz). Each chip has a duration of roughly 0.09775 microseconds, which is equivalent to a length of about 29.3 meters per chip. The smaller wavelength of the P code chip allows it to provide more accurate measurements than the C/A code, but its length prohibits its use during initial acquisition, that is, unless a precise time source is available.

The P codes are formed by the modulo-2 addition of two code sequences, X1 and X2i, each formed by the modulo-2 addition of the output from two twelve stage tapped feedback shift registers. A variable delay in the X2i sequence is used to create the thirty-seven unique P code sequences.

Thirty-two of these codes are assigned for use by the GPS satellites, with the remaining five reserved for other uses. Figure A-4 provides a top level depiction of the P code generation.

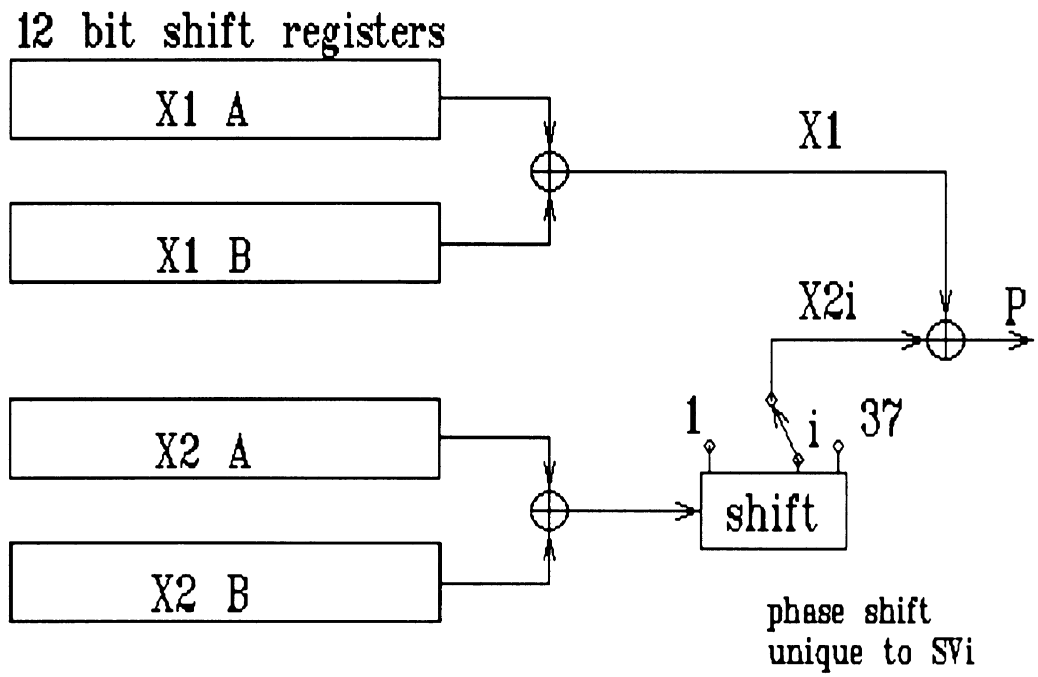


Figure A-4. GPS P code generation

2. Power spectral densities

The characteristic power spectral density for a direct sequence spread spectrum signal is in the shape of the squared sinc function [15]:

$$\left(\frac{\sin(x)}{(x)}\right)^2$$

While these signals have infinite bandwidth, it is common to consider the bandwidth between the first nulls of the signal, which is a function of the chipping rate of the modulating PRN code. For P code signals this double-sided first null-to-first null bandwidth is 20.46 MHz (centered at

L1 and L2, respectively), while for C/A code signals this bandwidth is 2.046 MHz (centered at L1).

The power spectral density for the L1 signal is depicted in Figure A-5. Note the narrower "spike" formed by the C/A component. The L2 power spectral density is similar in shape to that depicted for L1 in Figure A-5, but without the C/A component.

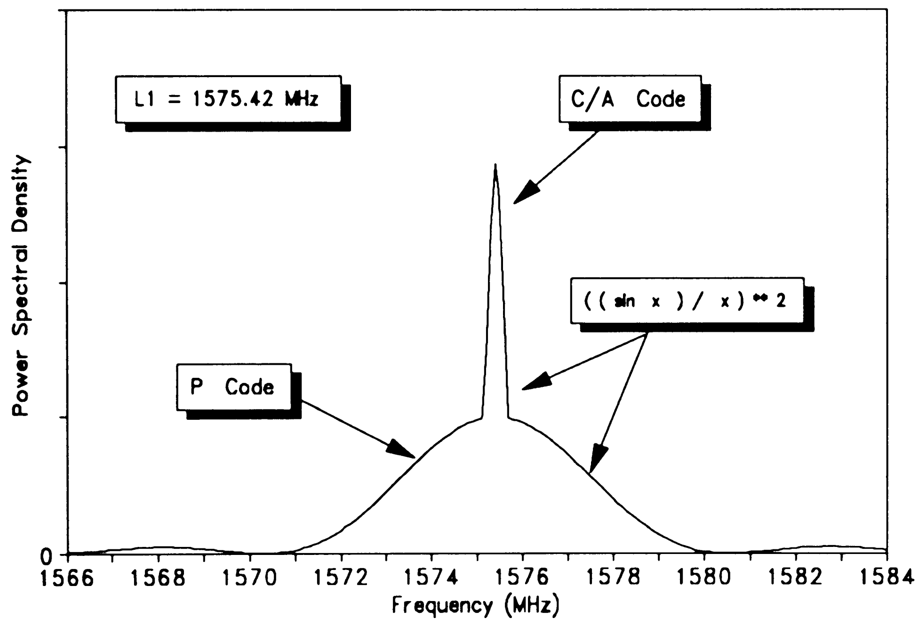


Figure A-5. GPS L1 power spectral density

3. Downlink navigation data

Modulating the PRN codes is the 50 Hz non-return to zero (NRZ) downlink navigation data. This data contains the ephemeris and clock correction parameters for the transmitting

SV, as well as almanac and health summary data for each SV in the constellation.

The 20 msec data bits are organized into words of thirty bits, twenty-four information bearing bits followed by six parity bits. The parity algorithm utilizes a (32.26) Hamming Code. Ten data words form a subframe, which is 6 seconds in duration. Five subframes make up an entire frame, which is 30 seconds in duration.

Subframe 1 contains the transmitting SV's clock correction parameters, and subframes 2 and 3 contain the transmitting SV's ephemeris parameters. The data in subframes 1 through 3 is typically updated by the control segment on an hourly basis. Subframes 4 and 5 consist of twenty-five unique pages, and contain almanac data, health summary data, ionospheric correction data, UTC data, and other special interest data. The almanac data is typically updated once every 6 days.

Figure A-6 depicts the broadcast order of the subframes, showing subframes 1, 2, 3, subframe 4 page 1, subframe 5 page 1. Next would follow subframes 1, 2, 3, subframe 4 page 2, subframe 5 page 2, etc. Broadcast in this manner, it takes a receiver 12.5 minutes to collect the entire twenty-five frame message.

Each data subframe begins with the same two words, the Telemetry (TLM) Word and the Handover Word (HOW). The TLM

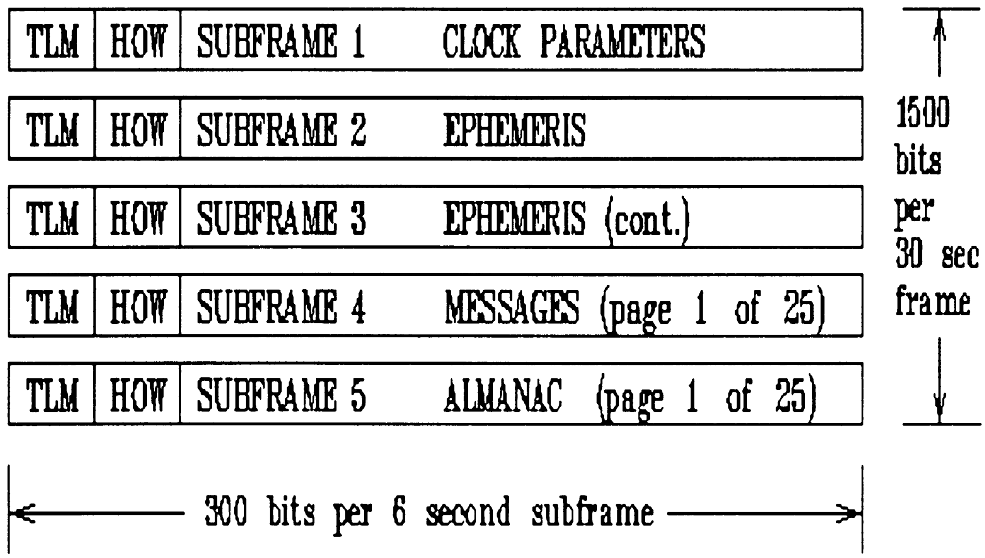


Figure A-6. GPS data subframes

word begins with the same eight bit preamble, 8B hex. Each HOW contains the subframe ID, and a GPS Time-of-Week (TOW) count. This TOW count corresponds to the P code X1 epoch to occur at the start of the following subframe. Thus by utilizing the information contained in the HOW, a receiver tracking the C/A code of a certain SV can anticipate the P code position at the beginning of a following subframe, which thus allows for easy handover from C/A to P code.

4. Selective Availability/Anti-Spoofing

The basic GPS signal formats described in the sections above may be altered by what are known as the Selective Availability/Anti-Spoofing techniques. These cryptographic techniques were developed by the DOD to prevent unauthorized users access to full navigation accuracies and from use of the P code signal.

In the beginning days of GPS it was believed that unauthorized use of the GPS system would be limited to the C/A code signals, and would provide only 400 meters accuracy. But after early testing proved the C/A signals could provide accuracies in the 30 to 50 meter range, the technique of "Denial of Accuracy" was created, which is now known as Selective Availability. Under this technique [16] the signal and data are manipulated such that unauthorized users cannot obtain full navigation accuracy. Access to the P code signal is denied unauthorized users by altering the P code in a cryptographic manner, so as to create the Y code. Not only does this technique deny the P (Y) code from being used by an unauthorized user, but it also serves to prevent intentional spoofing of the P code signal by bogus transmitters, thus giving this process the name Anti-Spoofing.

Lobbying of the DOD to do away with the SA/AS techniques has not proven successful. However, there is hope that at least one SV will be left in the unSA/ASed mode of operation [17]. This will allow stationary users to obtain precise time transfers from the one unSA/ASed satellite, while still preventing unauthorized, dynamic users from obtaining full navigation accuracies.

B. GLONASS Signal Characteristics

Similar to the GPS, two L-Band direct sequence spread spectrum signals are transmitted from each SV in the GLONASS system [18]. These signals, which shall be denoted as L1 and L2, are formed with a sinusoidal carrier that is phase modulated by one or more PRN codes. GLONASS, being a frequency division multiple access (FDMA) system, uses a unique nominal carrier frequency for each SV, with the system using the identical PRN codes for each of its SVs. Thus, the user would choose a specific SV for track by dialing up the carrier frequency unique to that SV. This implementation is notably different from the GPS CDMA implementation. However, as with GPS, the PRN codes of GLONASS are modulated by downlink navigation data.

A mathematical representation of the GLONASS signals will further reveal the similarities and differences with respect to the GPS signals. Looking first to the L1 signal, it can be seen to contain both components of C/A and P signals [19]:

$$L1_{C/A} = [D_{iC/A}(t) \oplus C/A(t)]\ \sin(2\pi[f_1+0.5625(i-1)]t+\theta)$$

$$L1_{P} = [D_{iP}(t) \oplus P(t)]\ \cos(2\pi[f_1+0.5625(i-1)]t+\theta)$$

while the L2 signal is represented by:

$$L2 = [D_{iP} \oplus P(t)]\ \cos(2\pi[f_2+0.4375(i-1)]t+\theta)$$

where:

$D_{iC/A}(t)$ = *Downlink navigation data from* SV_i *for C/A*
$D_{iP}(t)$ = *Downlink navigation data from* SV_i *for P*
$P(t)$ = *P code PRN for all SV*
$C/A(t)$ = *C/A code PRN for all SV*
$f_1 = 1602.5625\,MHz$
$f_2 = 1246.4375\,MHz$
θ = *Phase error*
t = *Time*
$\oplus$ = *Modulo 2 addition*
$i = i^{th}$ *SV*

Thus, unlike GPS, the L1 signals for GLONASS are not a single frequency, but rather a frequency band which forms a "picket fence" of carrier frequencies ranging from 1602.5625 to 1615.5 MHz, with a unique carrier assigned to each of the twenty-four GLONASS SVs. These L1 signals each contain a P code modulated component and a C/A code modulated component, again noting that the same P code and C/A code are used for each SV. It seems reasonable to assume that these components are in phase quadrature with each other. The PRN codes are modulated with the SV navigation data, but unlike GPS, the downlink message formats are unique to the PRN code types.

The L2 signals, similar to the L1 signals, are a "picket fence" of frequencies ranging from 1246.4375 to 1256.5 MHz, with a unique carrier assigned to each of the twenty-four GLONASS SVs. The L2 signals contain P code modulation, which is itself modulated with the downlink SV navigation data.

The GLONASS L-Band frequency ranges start about 20 to 30 MHz higher in frequency than their corresponding L-Band GPS signals. But as with GPS, the dual frequency nature of the

GLONASS signals allows the user to estimate the ionospheric delay of each SVs signals.

1. <u>PRN Codes</u>

Two classes of PRN codes are utilized within GLONASS, the Coarse Acquisition (C/A) code, and the Precise (P) code. The same C/A and P code is used by each GLONASS SV.

a. <u>C/A code</u> The GLONASS C/A code is a maximal length code 511 chips in length. With a chipping rate of 0.511 MHz, the C/A code repeats every 1 msec. Thus, each chip has a duration of roughly 1.957 microseconds, which is equivalent to a length of about 587 meters per chip.

The C/A code is formed using a maximal length 9 bit shift register. The PRN is taken from the 7th stage of the register, and the 5th stage and 9th stage are modulo-2 added and fed back into the 1st stage. This can be represented by the following generating polynomial [6]:

$$g(x) = 1 + x^5 + x^9$$

The code sequence length for a maximal nine-bit shift register is:

$$\textit{code length} = 2^9 - 1$$

for the total of 511 chips. Figure A-7 depicts the generation of the GLONASS C/A code via a tapped feedback shift register. Since GLONASS C/A is a maximal length code, its false correlation levels in autocorrelation will be lower than those for GPS C/A. This is expanded upon further by Appendix D.

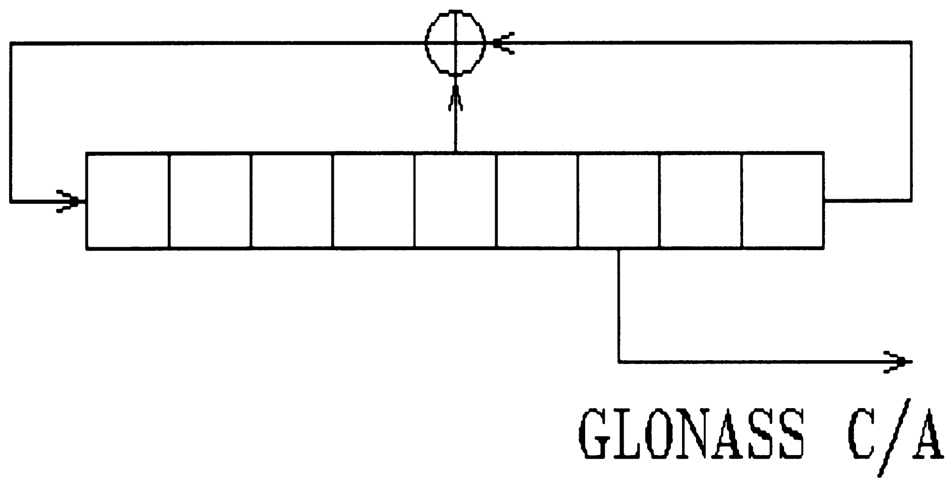


Figure A-7. GLONASS C/A code generation

b. P Code The P code is much longer than the C/A code, with a length of 1 second at a chipping rate of 5.11 MHz. Each chip has a duration of roughly 0.1957 microseconds, which is equivalent to a length of about 58.7 meters per chip.

The GLONASS P code sequence is produced by a twenty-five bit maximal length shift register. The PRN is taken from the 25th stage of the register, with the 3rd and 25th stage modulo-2 added and fed back into the 1st stage. This can be represented by the following generating polynomial:

$$f(x) = 1 + x^3 + x^{25}$$

The code sequence produced by this register is short cycled at the 1 second epoch by resetting the register to the all 1's state. In comparison to the GPS P code, the production of the GLONASS P code is a much simpler task. Figure A-8 depicts the generation of the GLONASS P code.

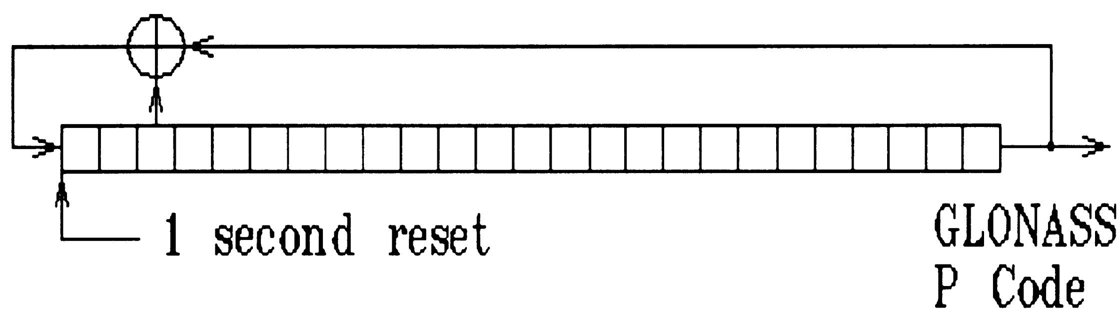


Figure A-8. GLONASS P code generation

2. Power spectral densities

The power spectral densities for the GLONASS C/A and P code signals have the same characteristic sinc squared shape as was seen in the GPS signals. The notable difference is that instead of having just one sinc squared shape for both L1 and L2, there are now 24 copies for both L1 and L2, one centered at each SV's transmitting frequency. For the C/A code signals the bandwidth between the first nulls of the signal is 1.022 MHz, while for P code it is 10.22 MHz.

3. Downlink navigation data

As with GPS, the GLONASS downlink navigation data is modulo-2 added with the PRN code sequences to produce the modulating binary sequence applied to the carrier. The navigation data bitstream occurs at a rate of 100 bits per second [20]. The specific navigation data bitstream used to modulate the GLONASS P code has been observed to differ from that used on their C/A code. Since only the navigation data applied to the C/A code has been described in the open literature, only this data will be considered in the following descriptions.

The GLONASS data format is based on a 3000-bit frame, each with 15 subframes of 200 return-to-zero (RZ) bits. Transmitted at 100 bit/second, each subframe lasts 2 seconds, and so the entire 3000 bit frame has a duration of 30 seconds. Within each frame are four predominant fields, with the first thirty-two bits providing a preamble. The remaining 168 bits are differentially encoded RZ bits, which are reduced to eighty-four NRZ bits. The first four of these bits give the subframe number. Next, seventy-two bits provide the data message, and are followed by eight bits for parity.

Subframes 1 through 4 provide the ephemeris, status flags, and clock corrections for the transmitting SV. Subframe 5 contains a UTC correction parameter and an almanac day number. Subframes 6 through 15 provide almanac data for five satellites, with two subframes per satellite. This requires five complete frames to be collected so that the user can gather almanac data for an entire 24 SV system. This would then take 150 seconds to gather the entire data set, which is notably shorter than the equivalent 12.5 minutes for GPS. Figure A-9 presents a pictorial representation of the GLONASS subframe structure.

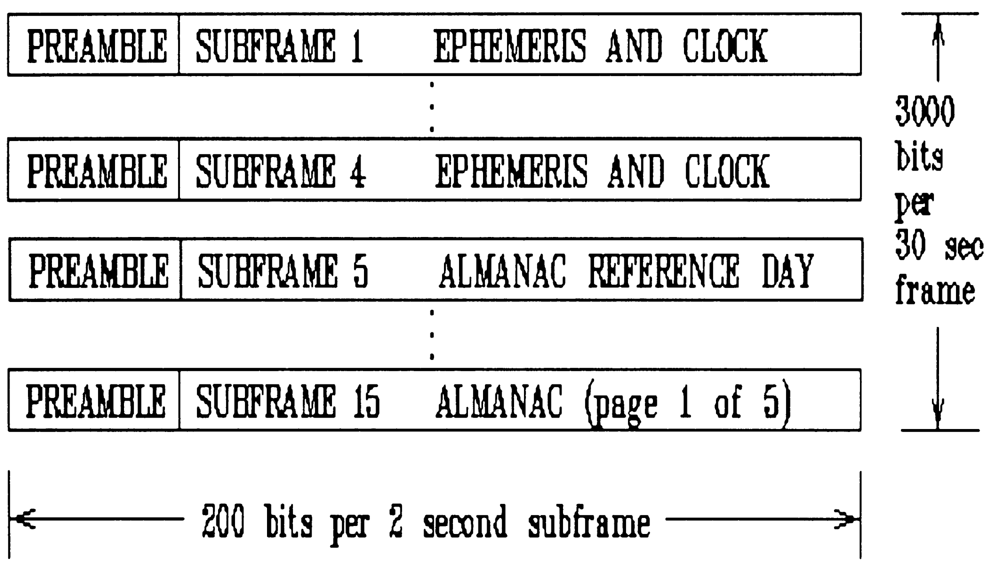


Figure A-9. GLONASS navigation data subframe structure

The ephemeris data, typically updated every half-hour, is a set of position, velocity, and acceleration values for a Cartesian earth-centered earth fixed (ECEF) coordinate system. These values are valid at the mid point of the current half hour interval, and from these the user must extrapolate the current SV values. In contrast, the almanac data is a set of

Keplerian ellipse elements, and is updated on a daily basis. The satellite clock correction values consist of a time and a frequency offset.

4. Selective Availability/Anti-Spoofing

No information has been published to suggest that GLONASS has anything analogous to the GPS SA/AS. However, the official releases from the former Soviet Union have stated that only the C/A signal is intended for civilian use. Furthermore, since GLONASS is remarkably parallel in its system design to GPS, and since its role includes a military nature, its not difficult to imagine that some form of SA/AS does exist for GLONASS. One suggestion has been made that GLONASS might utilize a form of Anti-Spoofing that is based on a frequency hopping algorithm. This was suggested in part by the FDMA nature of GLONASS.

APPENDIX B: HISTORY OF SATELLITE NAVIGATION

A. U.S. Satellite Navigation Systems

Satellite navigation systems can trace their origins back to observations made of the Soviet's Sputnik satellite. It was from these observations that American scientists realized measurements of the doppler in the satellite's signal could be combined with knowledge of the satellite's orbit to provide very precise navigational information. These observations led to the development of the United States' Transit satellite navigation system [21].

1. Transit

The Navy Navigation Satellite System (NAVSAT, or NNSS), also known as Transit, is a world-wide satellite navigation system with accuracies better than 0.1 nautical miles (nm). Measurements of the doppler, or the rate of change of range to the orbiting satellites, is combined with orbital information broadcast by the satellites to allow computation of the receiving station's location. Positioning is not instantaneous, and many measurements must be made to improve the navigation fix. Knowledge of the user's velocity is also required.

The Transit satellites are in nominal circular polar orbits ranging in altitudes of from 450 to 700 nm. The satellite system, which first became operational in 1964, transmits phase-modulated data on two carriers, one at 150 MHz and the other at 400 MHz. These two signals allow the user to compensate for propagation delay introduced by the ionosphere, using the fact that the delay is inversely proportional to the square of the signal frequency. Presidential orders in 1967 led to the system's availability to users of all nationalities.

If the system was operating as intended, Transit position fixes could be made every couple of hours. However, the Transit satellites have no on-board thrusters, and so orbital corrections can not be made for the precession of the orbits. Thus, with the Transit orbits precessing at uneven rates, the satellites tend to "bunch" up, and there are longer time periods between fixes than were originally planned. This interval may be up to 12 hours. System complementing Nova satellites have been launched to aid the constellation and offset the occasional "bunching" effect of the Transit satellites. Altogether, seven Transit or Nova satellites have been launched since 1967, and of those seven, five Transit and one Nova satellite are still in operation.

2. NAVSTAR GPS

Subsequent to Transit, alternative satellite navigation systems were pursued by the various branches of the American military. The U.S. Navy was pursuing the Timation system, while the U.S. Air Force was pursuing the 621B system. However, by 1973, the Navy and the Air Force had combined efforts to create the Navigation Technology Satellite (NTS) system, now known as the NAVSTAR Global Positioning System (GPS).

The first NTS satellite was launched in 1974. As the system now stands, a constellation of twenty-four GPS satellites in 12 hour orbits will transmit signals to provide military users all-weather, world-wide navigation accuracies of 15 meters. Civilian users will have access to signals which will permit accuracies of 100 meters. The system's primary navigation technique is via range measurements between four satellites and the user. The signal's format, and additional system characteristics are discussed in detail in Appendix A.

B. Soviet Satellite Navigation Systems

Just as the United States has developed satellite navigation systems, the Soviet Union has followed suit, with both Tsikada (or Cicada) and the Global Navigation Satellite System (GLONASS).

1. Tsikada

The Tsikada system is remarkably similar to the United States' Transit system. In Tsikada a set of satellites are in near circular orbits, at altitudes of 1000 km and inclined at

83 degrees to the equator. Each satellite transmits a signal at 150 and 400 MHz. The system operates off of doppler ranging principles similar to Transit. Tsikada also suffers from the same disadvantages as Transit, in that the position fixes are not continuously available, and that the user's velocity must be known.

2. GLONASS

In a manner similar to how the United States recognized the shortcomings of Transit and thus developed GPS, the Soviet Union identified disadvantages with Tsikada, and thus developed GLONASS. GLONASS, as the system now stands, will consist of a constellation of twenty-four satellites in 11 hour, 15 minute orbits, and will transmit ranging signals to provide users continuous, all-weather, world-wide navigation accuracies of at least 100 meters. Further descriptions of GLONASS may be found in Appendix A.

APPENDIX C: LITERARY SURVEY ON GLONASS

This discussion examines the available literature on the Global Navigation Satellite System (GLONASS), a satellite navigation system belonging to the Commonwealth of Independent States, formerly known as the Soviet Union.

The subject of GLONASS has received greater attention over the past several months, and if one were to pick up a handful of technical magazines dealing with aviation, navigation, or satellites, there would be a good chance of finding articles explaining, commenting, or discussing GLONASS. As an example, the maiden issue of the magazine GPS WORLD prominently discusses GLONASS in over five of its articles and editorials. Yet, this attention to GLONASS has not always been so developed, particularly since relatively few sources could authoritatively comment upon GLONASS.

Amidst this lack of substantial data, two main sources of information on GLONASS do exist. The first source, but not necessarily the best source, is the former Soviet Union. Breaking with past practices of silence on their own technical developments, the Soviet's have released small amounts of information on GLONASS.

The second, and perhaps best source is an academic research team from Leeds University, Great Britain. This team has significantly contributed to the knowledge on GLONASS, exceeding even the former Soviet Union in the depth and extent of information published.

In addition to these two primary sources, a third source concerning GLONASS exits, and shall be considered as "auxiliary publications." This third category presents mostly speculative or application-based discussions related to GLONASS. Only recently have the former Soviets worked closely with outsiders to allow for a far greater mass of "auxiliary publications" matter.

Articles and papers originating from all three of these categories are discussed in the following paragraphs, as a summary is presented of a literature survey on GLONASS.

A. Soviet publications

One of the earliest references to GLONASS made by the Soviets in the Western world seems to be via the information lodged officially with the International Telecommunications Union (ITU) in Geneva in 1982. Little more was said until May of 1988, when the Soviet Union surprised the world by presenting a working paper on the civilian portion of GLONASS [6]. Written by T. Anodina, this paper was presented at the fourth meeting of the Special Committee on Future Air Navigation Systems (FANS), held in Montreal.

The working paper presents GLONASS characteristics on such items as the navigation measurement concept, the space segment, navigation signal structure, navigation measurement structure, and general system characteristics. However, several areas are not touched upon at all, such as the system coordinate references or on the system time. And no mention is made of the P code signals from the GLONASS satellites. Even though these shortcomings exist, this working paper still represented a major source of information.

Three subsequent Soviet releases are contained in a compilation of GLONASS papers gathered in a letter by the Airlines Electronic Engineering Committee (AEEC) [22]. The first of these is a short information paper again written by Anodina [23], which in its entirety is an extraction of information from his previously released working paper from the '88 FANS meeting. The second of these releases is a handout provided by the Soviet Pavilion at the 1989 Paris Air Show [24]. The handout seems to be a marketing brochure for a single channel GLONASS receiver intended for commercial aviation uses, and the handout is very similar to what might be released from a manufacturer of GPS equipment. This brochure describes the general characteristics of the receiver, and from the photograph the receiver looks to be quite large.

The third release by the Soviets included in the AEEC letter is a paper by Valery Bogdanov [25]. It presents an overview of GLONASS and then discusses future developments. Within the overview section he describes their work on the shipborne equipment "Shkipper", intended for navigation use at sea. He then proceeds to discuss possibilities for combining GPS and GLONASS.

More recently, the maiden issue of GPS WORLD contains a well polished article written by G.I. Moskvin and V.A. Sorochinsky [7], which further presents the basic material of Andonia's original working paper. It also provides further information on the "Shkipper" receiver. As an interesting note, the Soviets claim that Shkipper testing resulted in positional accuracies of 2.5 meters (1 sigma). This is a claim that can be met by GPS only under the best of conditions, and it is so remarkable that one would like to learn more about the conditions under which the testing was performed.

An even later issue of GPS WORLD contains another Soviet authored article [26], by N. Ivanov and V. Salistchev. This article contrasts the similarities and differences between the two systems, and discusses the potential for their combined use. The authors state, starting with a baseline of either a GPS or GLONASS receiver, that only an additional 10% of hardware complexity must be added to achieve a combined GPS/GLONASS receiver.

These two authors have also participated with several other Soviet scientists in reporting on work (performed in participation with INMARSAT) that examined use of ground monitoring stations and geosynchronous satellites to determine and distribute system time scale and health information [27]. Their presented methods would allow users to form combined GPS/GLONASS solutions based on only four measurements, rather than requiring the five used herein.

In addition to publishing articles and papers, during 1988 and 1989 the Soviets began to participate in combined GPS/GLONASS talks with the United States. In these talks the U.S. was represented by the Federal Aviation Administration (FAA) and the Airlines Electronic Engineering Committee (AEEC). At these discussions the Soviets were provided with official GPS system specifications, and the Soviets have since reciprocated in kind, providing to U.S. officials a GLONASS Interface Control Document.

B. Leeds University, U.K. (Daly et al.)

Well before the 1988 disclosure made by the Soviets on the civilian side of their system, a series of investigations at Leeds University in Great Britain were uncovering the secrets of GLONASS. Since 1986, a team lead by Dr. Peter Daly has published over a dozen articles describing the progress of their findings. Starting with no prior information, and through meticulous study of the Soviet signals, they have created a receiver which is capable of producing a navigation solution from the civilian GLONASS signals.

A short summary of the articles chronicling their developments follows. In 1986 members of the team published an article [28] describing the orbits of the GLONASS satellites, the radio-frequency signal structure, and the observed radio frequency channelization of the system. Within this article they also contrasted the GLONASS system with the United States' GPS navigation system. Two subsequent articles appearing in 1987 echoed the contents of their first publication [29,30].

Several new articles were published by the team in 1988. The first provides a rather extensive discussion on the characteristics of the GLONASS satellite orbits, and for the first time, presented speculative interpretation of the downlink data transmitted by the satellites [18]. It was not stated, but may be inferred, that the team had successfully cracked the pseudorandom noise (PRN) code of the civilian transmissions from the GLONASS satellites.

In the same time frame, another article [13] was published with similar information on the satellite orbits, and the article provides a few more tidbits on the interpretation of the GLONASS data messages. It also compared the data's structure with that of GPS.

In the last half on 1988, three more articles were delivered or published [31,32,33]. They dealt with applying the GLONASS signals to time transfer, the obstacles for combining the GPS and GLONASS systems, and reported the first results of formulating a navigation solution based on the GLONASS civilian signals. Accuracies obtained from these civilian signals were between 10 and 30 meters.

A paper published in early 1989 updated the status of the GLONASS satellite constellation, as well as presented an even more thorough description of the downlink satellite data messages for GLONASS [20]. Similarly, a paper published in late 1989 further updated the constellation status and then considered the benefits and obstacles to a combined GPS/GLONASS system.

In late 1989 a rather remarkable bit of investigative research was reported showing how the research team had unraveled the Soviet Union's GLONASS P code [19]. Thus, from a starting point of no information, the team has progressed over a period of three or so years to the point where the civilian C/A code can be used to produce a navigation solution, and the P code has been successfully cracked.

More recently, papers published by Dr. Daly have examined the characteristics and stability of the on-board oscillators of the GLONASS space segment [10,34]. Papers have also dealt further with time transfer capabilities of the two systems [35], even leading to potential ideas for integrity monitoring tests [2].

These articles have also indicated that the team from Leeds University is currently pursuing new goals in their work with GLONASS. Additional information on the GLONASS P code signal may be forthcoming, and word on the development of a combined GPS/GLONASS receiver can also be expected.

C. Auxiliary articles

While many of the articles published by the Soviets or the research team at Leeds University have revealed new aspects of the GLONASS system, benefits have also come from articles written by interested third parties.

In 1986, J. C. Carter of MIT reported [36] on his observations of the GLONASS transmissions and on how they caused interference in the radio astronomy band of 1610.6-1613.8 MHz. His letter indicated he had been observing the GLONASS transmissions from as early as December of 1984. Similar reports have been issued by other astronomers [37].

Technical reports also serve to keep the general reader informed on GLONASS. For example, Aviation Week and Space Technology has continued to report on the progress of the GLONASS studies by P. Daly and his team, and on the progress of the Soviet's position on GLONASS. As yet another example of third party participation, writers often speculate on the combined benefits and obstacles to a hybrid GPS and GLONASS approach [38,39].

As part of a study of an integrated GPS/GLONASS system, Magnavox has built for the MIT Lincoln Labs a combined GPS/GLONASS receiver. Magnavox has published an article describing their own testing with that system [40]. Lincoln Labs has, in turn, reported on their work, performed for the FAA, describing the performance of the hybrid system [41].

Several Western companies are currently pursuing the commercial GPS/GLONASS market. As noted above, Magnavox has already performed extensive testing of combined receivers. Aviation Week and Space Technology has reported that the Canadian Marconi Company is also developing a combined GPS/GLONASS receiver, to be available in the summer of 1993 [42].

The same article describes how Honeywell and Northwest Airlines have been working with the Leningrad Scientific Research Radiotechnical Institute (LSRRI) and All Union Scientific Research Institute of Radio Equipment (Ausrire) of the former Soviet Union on GPS/GLONASS flight tests. A report by Honeywell at the ION-91 conference described their success in this combined venture [3].

Ashtech, who has also worked with the Soviets, is planning a combined GPS/GLONASS receiver whose initial target date was December of 1991 [43]. Billed as an eight to twelve channel receiver, the receiver may also have the capability to utilize the GLONASS P code signals.

Yet another company in this market is 3S Navigation. They are offering a full line of GPS, GPS/GLONASS, and GLONASS chip sets, prototyping boards, antenna and RF/IF subsystems, and signal generators.

In a support role, INMARSAT has proposed a system of geostationary satellites which will augment both the GPS and GLONASS systems, providing not only signals for navigation use, but also providing integrity information for both systems [44].

And lastly, one could expect Trimble Navigation to enter into the activity, since G. Lennen left Leeds University to work with Trimble, after he and Daly had cracked the GLONASS P code.

APPENDIX D: C/A CODE AUTOCORRELATION STUDY

A. Introduction

This discussion examines the autocorrelation properties possessed by the C/A codes for both GPS and GLONASS. It will demonstrate that the GLONASS C/A code is less susceptible to false correlations during correlation of the locally generated replica with the desired SV's signal.

A fundamental characteristic of both the GPS and GLONASS navigation systems is their determination of pseudorange via correlation detection of a received signal using a locally generated replica. This correlation detection is possible because the pseudorandom codes utilized by these systems possess unique autocorrelation properties. During periods of high signal power, false correlations can occur during the acquisition attempts on the desired C/A codes. In effort to better understand this phenomena, the autocorrelation characteristics possessed by the C/A codes for both GPS and GLONASS are examined.

B. A Review of the Autocorrelation Function

The autocorrelation function, defined as:

$$R_X(\tau) = E[X(t)X(t+\tau)]$$

is a measure of similarity existing between two separate instances for a stationary, random process X(t). Since this involves the expected value E[ ], it is, in fact, an ensemble average [45]. For processes which are not ergodic (such that the time average is not equivalent to the ensemble average), a further "time autocorrelation function" must be pursued:

$$R_{X_A}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_0^T X_A(t)\,X_A(t+\tau)\,dt$$

where $X_A(t)$ is a sample realization of the X(t) process.

Figure D-1 presents the time autocorrelation function for a typical random signal.

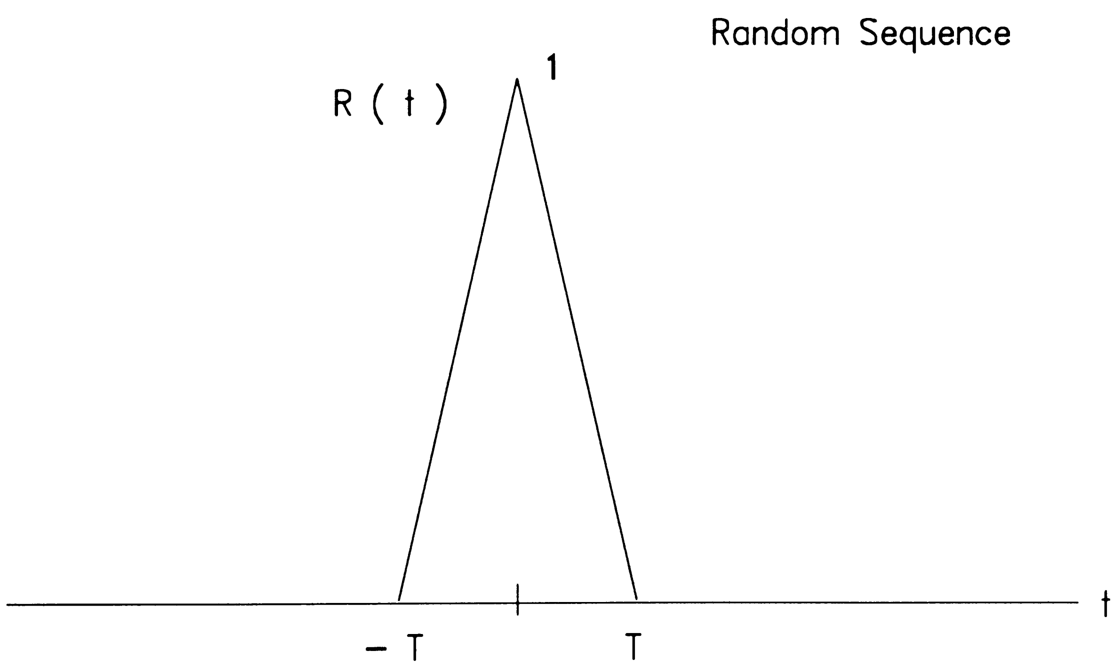


Figure D-1. Time autocorrelation function for a random signal

C. Autocorrelation of the GLONASS C/A Code

Utilizing the definition of time autocorrelation presented above, the autocorrelation characteristics of the GLONASS C/A code may now be examined. Considering the possible states of the GLONASS C/A code as possessing values of 1 and -1, then the time autocorrelation function is:

$$R_i = \frac{1}{511}\sum_{0}^{511} S_{GLO}(t)\,S_{GLO}(t+i)$$

A simple Pascal program was written which computes the time autocorrelation value for the GLONASS C/A code. Rather than implement the time autocorrelation function as specified above, this program views the two-state pseudorandom GLONASS C/A code as Boolean values of 1 and 0. An equivalent realization for the time autocorrelation functions then becomes the difference between the number of correlation "hits" and "misses" as divided by the total number of chips (pseudorandom bits).

For example, at any offset other than 0 chips, the total number of correlation "hits" is 255, and the total number of correlation "misses" is 256, resulting in a difference of -1. Dividing by the total number of pseudorandom chips, then the time autocorrelation value is equal to -1/511, or equivalently, a power signal -54.17 dB down from the primary correlation peak occurring at zero offset. At zero offset, the correlation value is equal to 511 "hits" minus 0 "misses", divided by 511 chips, which results in the expected value of 1. These values are summarized below in Table D-i.

Table D-i. GLONASS C/A code autocorrelation levels

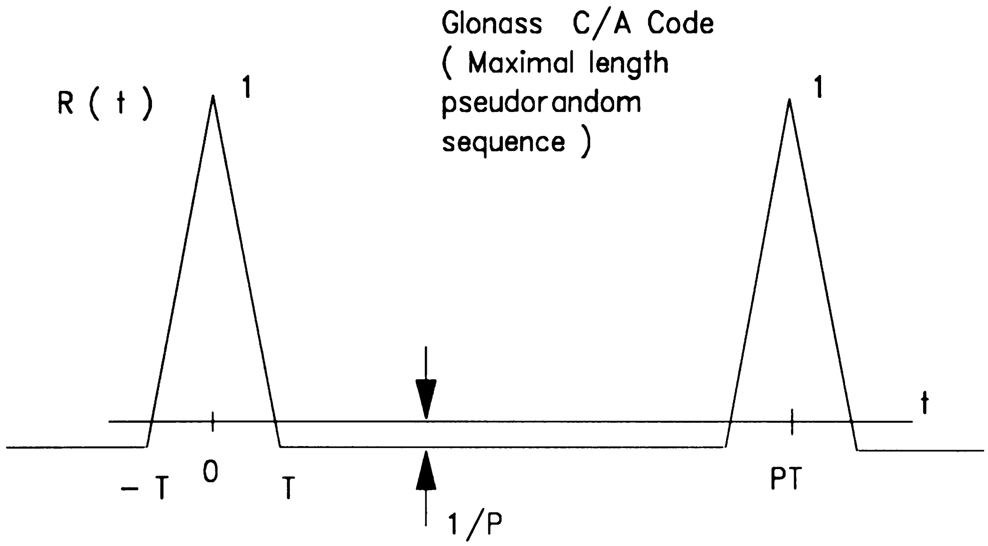
Corr. Levels	dB Below Peak
511/511	N/A
- 1/511	- 54.17

These results come as no surprise, for as described in Appendix A, the GLONASS C/A signal is a maximal length pseudorandom noise sequence, and any maximal length sequence possess exactly the time autocorrelation response described above [45]. A graphical representation for the time autocorrelation function for the GLONASS C/A code is presented in Figure D-2.

D. Autocorrelation of the GPS C/A Codes

Similar to the GLONASS C/A case just examined, a simple Pascal program was written which computes the autocorrelation levels for the 36 unique GPS C/A codes. (There are actually 37 GPS codes defined, but PRNs 34 and 37 are identical.)

The results of this program are summarized in the two tables, Table D-ii and D-iii, both of which follow later in this section. As indicated by Table D-ii, all of the GPS C/A codes possess a four-level autocorrelation function. At zero offset, the correlation level is 1. At other offsets,



Code Period (P) = 2 ** 9 - 1 = 511

Figure D-2. Time autocorrelation for the GLONASS C/A code

the three remaining levels correspond to power signals -23.9, -24.2, and -60.2 dB down from the primary correlation peak at offset zero. The correlation levels corresponding to the power signals of -23.9 and -24.2 dB are referred to as the C/A code autocorrelation sidelobes, and their significance shall be discussed in the following section.

Table D-ii. GPS C/A code autocorrelation levels

Corr. Levels	dB Below Peak
1023/1023	N/A
- 1/1023	- 60.2
- 65/1023	- 23.9
63/1023	- 24.2

A pictorial representation of the four-level time autocorrelation function for the GPS C/A code is presented in Figure D-3. Even though all GPS C/A codes possess the same relative values for autocorrelation levels, the distribution of these levels differs among the C/A codes. Table D-iii presents the relative frequency of occurrence for these three non-zero offset autocorrelation levels as a function of the GPS Pseudorandom Number (PRN).

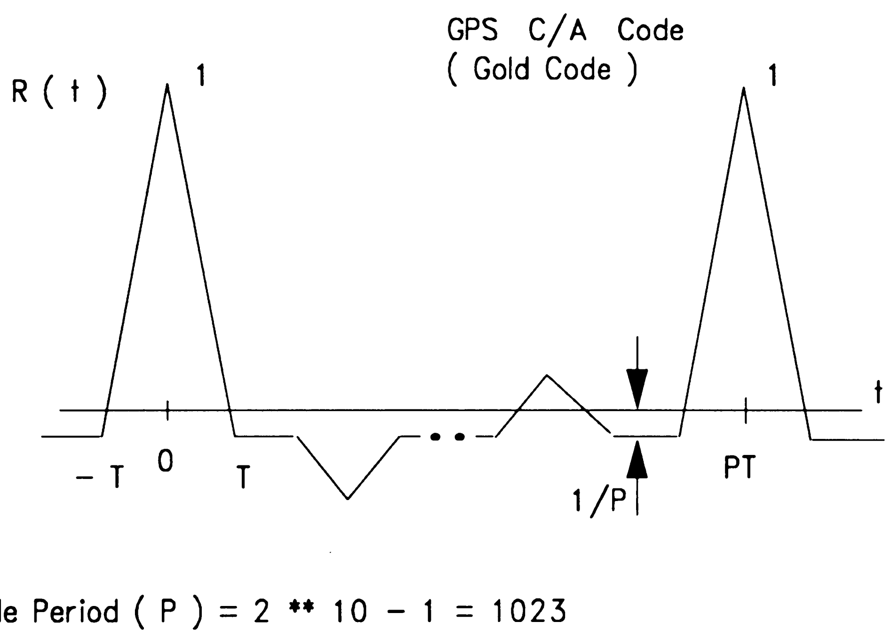


Figure D-3. Time autocorrelation function for GPS C/A code

E. Contrasts of the Autocorrelation Characteristics

The time autocorrelation functions presented in the previous sections for the GPS and GLONASS C/A codes differd in

Table D-iii. Frequency-of-occurrence for correlation sidelobes in the GPS C/A code

C/A PRN	- 60.2 dB	- 24.2 dB	- 23.9 dB
1	782	120	120
2	774	124	124
3	785	132	132
4	798	112	112
5	766	128	128
6	702	160	160
7	822	100	100
8	742	140	140
9	734	144	144
10	750	136	136
11	790	116	116
12	718	152	152
13	806	108	108
14	758	132	132
15	774	124	124
16	782	120	120
17	782	120	120
18	726	148	148
19	718	152	152
20	782	120	120
21	766	128	128
22	742	140	140
23	742	140	140
24	726	148	148
25	806	108	108
26	750	136	136
27	742	140	140

Table D-iii. (continued)

C/A PRN	- 60.2 dB	- 24.2 dB	- 23.9 dB
28	718	152	152
29	790	116	116
30	750	136	136
31	766	128	128
32	782	120	120
33	774	124	124
34	830	96	96
35	734	144	144
36	758	132	132

one important manner. The GLONASS C/A code time autocorrelation levels for non-zero offsets were all at a uniform level, -54.2 dB below the primary correlation peak. In comparison the GPS C/A code time autocorrelations, regardless of PRN number, possessed three separate levels for the non-zero offsets, with the two largest autocorrelation sidelobes -24.2 and -23.9 dB below the primary correlation peak. These GPS autocorrelation sidelobes are only half as deep as the non-zero offset autocorrelation levels of GLONASS.

The practical significance of this becomes apparent when one considers the methods by which these spread spectrum signals are detected. Initially, the receiver will possess some uncertainty in its estimates of position, velocity, and time. It must thus search through various combinations of pseudorange and doppler uncertainty in order to match the locally generated pseudorandom code to the received signal. This process is typically performed either as a maximal search, or as a threshold search, both processes defined by the following paragraphs.

For the purposes of this discussion, assume that the frequency uncertainty is limited to one doppler window. Under the maximal search, the acquisition process searches the entire code uncertainty, monitoring the correlation test statistics throughout the scanning process. When the entire code uncertainty has been searched, the code phase corresponding to the maximum test statistic is repositioned for subsequent tracking attempts. Although this process may provide a high level of certainty that the correct code phase for correlation has been found, this process may result in long acquisition times since the entire code uncertainty must be searched.

An alternative to the maximal search is the threshold search. While the code scanning process is underway, the detector test statistics are compared against a previously computed set of acquisition threshold(s). In the most simple of cases a single threshold will be computed as a function of receiver noise measurements, and upon desired probabilities of acquisition and false alarm.

When the detector output exceeds this threshold, signal presence is declared, and tracking is attempted at that corresponding code phase without further code searching. Thus, the threshold test only searches as much code uncertainty as necessary to find the pseudorandom signal. When compared to the maximal search, this shorter acquisition time is a suitable trade-off for potential mistakes in the code detection process, a process which can be made more secure by adding multiple thresholds and subsequent dwells for signals falling in gray regions of the decision process.

A problem with the threshold test for GPS C/A acquisition is that under strong signal conditions the GPS correlation sidelobes may be high enough to falsely trigger the detection threshold, resulting in a failed acquisition attempt. Previous studies [46] have shown that these sidelobe spurious correlations under strong signal modes become a problem at C/No's of 48 dB-Hz, and they almost completely prevent acquisitions for C/No's greater than 53 dB-Hz. Although C/No values in this range would be atypical, the maximum received signal level specifications of ICD-GPS-200 [14] would permit such C/No values to be obtained. Potential solutions to this problem include the use of more complex, adaptive detection thresholds, and/or the inclusion of mechanisms which allow the resumption of acquisition once the error has been discovered.

The significance for the GLONASS or GPS/GLONASS user is that since the GLONASS C/A code does not possess these correlation sidelobes, then for the same high signal levels, the GLONASS C/A code will be immune from these spurious correlations. And since the secondary correlation level for the GLONASS C/A code is nearly another 25 dB below that experienced for the GPS C/A code, a substantial margin should prevent the occurrence of this problem for the GLONASS C/A acquisitions.