Indian Institute of Technology Jodhpur

DESIGN AND IMPLEMENTATION OF GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) RECEIVER

Final Report of BTech Project

Submitted by

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Mentor

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Chapter 1

INTRODUCTION

1.1 Background

In recent times there have been several emerging applications of location based solutions and satellite navigation systems. Automobiles with satellite navigation systems can display moving maps and information about nearby landmarks. Aircraft, boats and ships can use it to navigate around the world. Surveying and mapping is another major application area. Location information of users can be used to provide location based advertisements, emergency services, or for tracking movements of vehicles or persons over time. Satellite navigation systems also have several applications critical for national security. They allow to precisely deliver missiles to targets, and to organize the movement of forces during war.

Satellite navigation systems help a user to determine position and accurate local time. Satellite systems that have global coverage are referred to as Global Navigation Satellite Systems. At present, there are two GNS systems in operation – Global Positioning System (GPS), owned by the United States and Global Navigation Satellite System (GLONASS), owned by Russia. Several other systems are in the process of being established – Galileo (Europe), COMPASS (China) and Indian Regional Navigation Satellite System (IRNSS) (India).

1.2 Working Principle of Satellite Navigation Systems

Satellites that form part of the satellite navigation system transmit navigation messages. The receivers calculate the delay undergone by these signals while travelling from the satellite to the receiver, by a process called correlation which is explained later. This delay is multiplied by the speed of light to compute the distance to the satellite. The same process is repeated for four satellites in order to compute the user position $(u_x, u_{y,} u_z)$ (by solving four equations (1-4). This method is called trilateration.

$$(s_{1x} - u_x)^2 + (s_{1y} - u_y)^2 + (s_{1z} - u_z)^2 = c^2(t_1 + \Delta t)^2 \tag{1}$$

$$(s_{2x} - u_x)^2 + (s_{2y} - u_y)^2 + (s_{2z} - u_z)^2 = c^2(t_2 + \Delta t)^2 \tag{2}$$

$$(s_{3x} - u_x)^2 + (s_{3y} - u_y)^2 + (s_{3z} - u_z)^2 = c^2(t_3 + \Delta t)^2 \tag{3}$$

$$(s_{4x} - u_x)^2 + (s_{4y} - u_y)^2 + (s_{4z} - u_z)^2 = c^2(t_4 + \Delta t)^2 \tag{4}$$

Here (s_{ix}, s_{iy}, s_{iz}) are the coordinates of satellite 'i' (which is known from the navigation message) while t_i denotes the delay undergone by signal from satellite 'i'. Ideally only three satellites would be enough to compute the three coordinates of the user. But there is an additional unknown parameter, which is the offset between receiver clock and GNSS time. Δt is the difference in delay computed by the receiver due to this offset. The time maintained in satellites is very accurate as it is based on atomic clocks. The receiver clock is a crystal oscillator and hence would suffer from drift, which gives rise to this offset. A fourth equation is required to compute this offset.

There are several parameters that characterize the performance of a satellite navigation system. These include:

1. Availability
   Availability is the probability that 4 satellites would be visible for computing the position solution at a given place, at any time. GPS guarantees an availability of 95%[1] at an elevation angle of 5 degrees. For this reason, we have considered an availability of 95% as the minimum acceptable level for usage of a navigation system.
2. Continuity
   Continuity is the probability that 4 satellites would continue to remain visible for the duration in which location information is needed at a given place.
3. Accuracy
   Accuracy refers to the accuracy of the computed user position. One of the many factors that affect accuracy is Geometric Dilution of Precision (GDoP). GDoP measures the effect of satellite geometry on calculated position information.
4. Time to First Fix (TTFF)
   TTFF refers to the time required from starting of a receiver to obtaining the first position solution.

1.3 Motivation

Currently available receivers use 4 satellites of a single system to calculate the position solution by triangulation. However in urban areas with high rise buildings, satellites have to be at high enough elevation angles to be visible (see Figure 1). The probability that four satellites of a single system will be at this elevation is low, thus limiting the chances of obtaining a position fix. This problem assumes importance considering the fact that most of the users would be present in these urban areas.

[1] Availability value calculated in this study is slightly larger than actual values as isotropic antenna was considered, different from the actual GPS antenna.

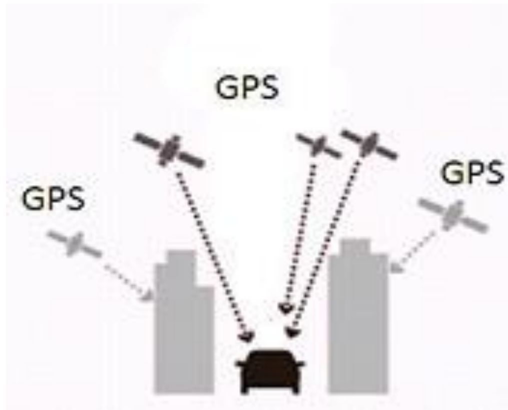
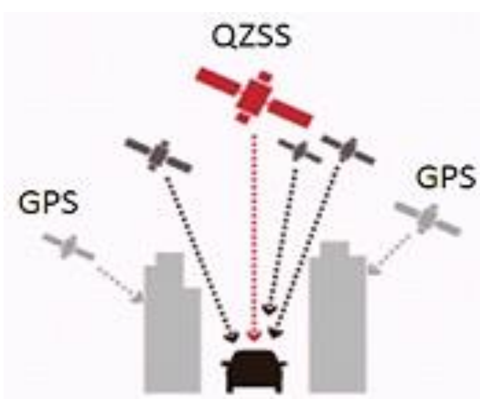


Figure 1. Satellites have to be present at high elevation angles to be visible to the receiver in urban areas

This problem has been solved in Japan, by having an additional satellite system, called the Quasi Zenith Satellite System (QZSS), which is so designed such that satellites from this system will be present always at a high elevation angle, and augment the positioning provided by GPS (See Figure 2a). However, QZSS is a three satellite system, intended for service within the area of Japan. The number of satellites required and hence the cost would be more for providing similar services over larger countries such as India.

Another solution is to use a hybrid receiver, which has dedicated channels (4 each) for GPS and GLONASS (See Figure 2b). The drawback is that such a receiver can work only if 4 satellites, all from one system (either GPS or GLONASS) are present, for which the probability is again low. Moreover, it would be expensive to have 8 channels, besides making the receiver bulky and increasing power consumption, which would make it unsuitable for small consumer applications, such as in mobile handsets.

Figure 2(a) 

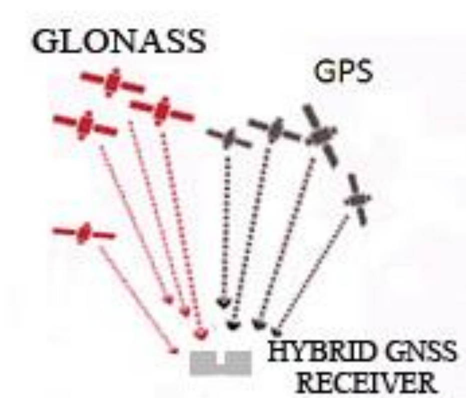
2(b) 

Figure 2 (a) QZSS system (b) Hybrid receiver

The solution that we propose, which also overcomes these challenges, is to use an integrated receiver, which uses the same 4 channels to obtain signals from 4 satellites, which may be any combination consisting of GPS and GLONASS satellites (2 GPS + 2 GLONASS or 1 GPS + 3 GLONASS etc.). Thus a position fix can be obtained if any 4 satellites from the total constellation of GPS and GLONASS (60 satellites) are at the required elevation, for which the probability is much higher compared to that for 4 satellites, all of which are from either constellation (30 satellites) (See Figure 3).

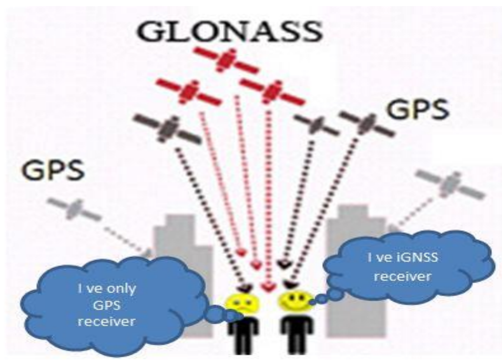


Figure 3. IGNSS receiver can compute the position solution, where a conventional receiver (GPS or GLONASS) or hybrid receiver cannot

An integrated receiver will have the following advantages:

- Improved Availability
  In chapter II we have obtained quantitative results for the availability for a GNSS receiver as compared to a GPS only receiver as the elevation angle increases.
- Improved Continuity
  Continuity is the probability that the minimum number of satellites will continue to remain visible for the duration in which location information is needed. It is evident that a GNSS receiver will have improved continuity due to reasons stated previously.
- Improved Accuracy
  Accuracy refers to the accuracy of location information. Since a GNSS receiver can utilize signals from any system, it can choose the optimal combination of five satellites to achieve maximum accuracy, as it will have more satellites to choose from at a given time.
- Integrity Information
  Integrity is the ability of the system to inform the user if the calculated position information is unreliable as it may contain large errors. This capability is not supplied by

any system (GPS or GLONASS). But a GNSS receiver can provide this information as it can compute position using different combinations of satellites and it can identify if one satellite is out of order as then those combinations involving that satellite will give location information with large error. A conventional receiver cannot give this information as it does not have the freedom to choose different combinations.

However, with all its advantages, there are several challenges related to the design and implementation of a GNSS receiver. An obvious challenge is the interoperability and compatibility issue in integrating different satellite systems. However, many of the problems in this area, such as with regard to coordinate systems, signal structures etc., have been addressed either by mutual agreement between the organizations operating these systems, or by technological advancements such as software defined radio, and hence they were not the focus of this study. The problems dealt with have been elaborated in the problem definition, along with an outline of our contributions.

Chapter 2

PROBLEM DEFINITION

The block diagram of a GNSS receiver is given in Figure 2.

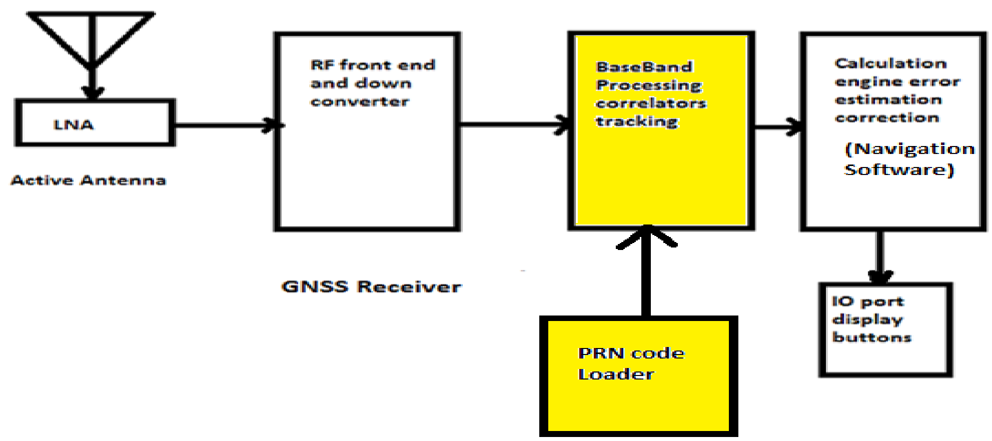


Figure 1

The GNSS receiver consists of several parts such as

1. Antenna and RF Front End
2. Correlation Receiver and PRN code loader
3. Navigation Software and User interface

Many parts of the GNSS receiver are common with the already available GPS receivers, and they can be used as such without much modification. However other parts require modifications to deal with several challenges unique to GNSS. The RF front end is not in the scope of this work, as we deal with Software Defined Radio (SDR) implementation of the GNSS receiver. The main challenges lie in

1. Designing a correlation receiver that can track signals with added noise in case of GNSS receivers in urban environments. See section 2.1 for more details.
2. Modifying the PRN code loader to reduce Time to First Fix (TTFF) when large numbers of satellites are present from multiple constellations. See section 2.2 for more details.
3. Modifying the navigation software to perform ionospheric corrections. The signals from satellites get diverted from straight line path while travelling through the ionosphere. GPS satellites have started transmitting signals on two civilian frequencies to correct for this error. However GLONASS does not have this provision at present. We would like to utilize signals from multiple satellites from different systems transmitting at different

frequencies to perform ionospheric correction; similar to what is performed using multiple frequencies.

In the present work, based on the available time, we have studied and proposed solutions for the first two challenges. The third challenge is also relevant, and it can be considered for future work in this area.

2.1 Correlation Receiver

GNSS systems operate based on Code Division Multiple Access (CDMA) technology. Different satellites transmit their navigation message, which is modulated on a Pseudo Random Noise (PRN) code, unique to that satellite. The PRN codes used by GPS are called Gold codes. GPS signal characteristics are given in table 2. They are generated by adding two maximal length sequences that are delayed with respect to each other. The Gold codes are orthogonal even when not synchronized, meaning that the cross correlation of two different Gold codes will be close to zero. Thus Gold codes have a high autocorrelation value and a very low cross correlation value. The received CDMA signal from a particular satellite is decoded by correlating the received signal with the PRN code of that satellite.

Table 2

	C/A	P(Y)	Navigation Data
Chipping Rate	1.023 Mbps	10.23 Mbps	50 Mbps
Length Per Chip	293 m	29.3 m	5950 km
Repetition	1 ms	1 week	N/A
Code L2Type	Gold	Pseudo random	N/A
Carried on	L1	L1,L2	L1,L2
Feature	Easy to acquire	Precise positioning , jam resistant	Time ,ephemeris , HOW

$$x_1 = c_1 \, o \, d_1 \tag{5}$$

$$x_2 = c_2 \, o \, d_2 \tag{6}$$

$$x = x_1 + x_2 \tag{7}$$

$$y_1 = c_1^T x \tag{8}$$

$$y_1 = c_1^T (c_1 \, o \, d_1 + \, c_2 \, o \, d_2) \tag{9}$$

$$y_1 = d_1 + c_1^T (c_2 \, o \, d_2) \tag{10}$$

In the above equations, c_1 denotes the code of satellite 1, d_1 denotes the data of satellite 1, x denotes the transmitted vector, y_1 denotes the decoded signal of satellite 1. Transmitted signals

x_i would be noiselike by the property of the Gold codes. We have obtained the desired data for y_1 as $c_1^T c_1$ would be 1 after normalization (Autocorrelation). Ideally, we would like the cross correlation $c_1^T c_2$ to be close to zero. However this cross correlation is not perfect, and a value similar to noise would be obtained for the interfering signal, just like that for x_2 or other users, by the property of Gold codes. As the number of users increases, the noise also increases.

Correlation of the incoming signal with delayed replicas of the PRN code is used to determine the delay caused to the signal while travelling through the distance from the satellite to the receiver. The delay is multiplied by the speed of light to determine the range to the satellites.

The determination of delay by the correlation receiver has to be very accurate as any error in the delay would be multiplied by the speed of light (c = 3 x 10^8 m/s), in determining the range. Thus an error of just 1ms in the delay will cause a large error in range of about 3 x 10^5 m.

In CDMA based systems, as each user transmits based on a PR noise code, the noise level keeps on increasing as the number of users in the system increases. The same phenomenon happens with the GNSS receiver, as it operates based on CDMA. As the number of satellites increase when more satellite systems are included, the noise level at the receiver keeps on increasing. Also in urban areas, due to multipath fading effects caused by the presence of numerous buildings, the signal level decreases. As a combined effect of these two phenomena, the Carrier to Noise Ratio (CNR) at the receiver decreases. Thus it is important to have a correlation receiver that can accurately determine the delay even at low CNR values.

2.2 Time to First Fix (TTFF)

Time to First Fix (TTFF) of a GNSS receiver consists of the time from starting of the receiver to the computation of the first position solution. It is an importance performance parameter of the receiver and it is desired that it be as small as possible. TTFF consists of the time to acquire and lock the satellites, and the time to decode the navigation message and compute the position solution. Of these, the time for acquisition and locking is generally higher, and reducing it is the focus of reducing TTFF in this work.

Depending on the scenario, there may be three types of ‘start’ of the GNSS receiver: Hot Start, Warm Start and Cold Start.

Hot start is the case when the receiver has knowledge of its last calculated position, visible satellites, almanac, and UTC Time. It then attempts to lock the same satellites based on this information. This takes the least Time to First Fix (TTFF), but it is the case only when the receiver has momentarily lost its lock, and is very close to its last calculated position

Warm start is the case where the receiver has knowledge of its last calculated position, almanac, and UTC Time, but not which satellites were in view. Based on the almanac and the knowledge of its last calculated position, the receiver can predict which satellites may be visible. This scenario has a larger TTFF than hot start but lesser than cold start.

Cold start is the case where the receiver does not have sufficient knowledge to even predict which satellites may be currently visible from its location. This is the case when either the Almanac has become invalid, or the receiver has moved far (>300 km) from its last known position or both. This scenario has the largest TTFF.

The state of the art scheme in this case is that the receiver loads iteratively, random satellite combinations, until one satellite gets locked. The almanac is then obtained from this satellite, and the other three satellites can be loaded using this information if the receiver has not moved far. However downloading the almanac takes about 12.5 minutes, and if the receiver has moved, the almanac is of not much use. This problem has been solved in [5] for GPS based receivers. Here the GPS constellation was studied, and conditional probability tables were obtained for every pair of satellites. When one satellite is locked, the satellites having high conditional probabilities with respect to that satellite are loaded in the next iteration. This approach is applicable to GNSS receivers as well, and we have calculated the conditional probability tables of (GPS+GLONASS) constellation for this purpose.

However, the problem of locking the first satellite in the minimum number of iterations still remained. Current receivers try to solve this problem in two main ways. One is to increase the number of channels from four to seven or eight. This allows loading eight different satellites at a time, and thus minimizing the time to first lock. However, this is a highly hardware intensive approach, as each additional channel increases the cost by a large amount. We would like to have only four channels and still reduce the time to first lock. The second currently used way is to have assisted GNSS, in which information from cellular networks is used to help the receiver in identifying the visible satellites, by giving position, time or almanac information. This approach cannot be used in many cases where such assistance is not available such as in remote places without cellular networks, or in car GNSS systems which are not connected to such networks. Thus we would like to have a standalone system which can still have a low TTFF.

The problem of reducing TTFF becomes even more important for integrated GPS+GLONASS systems as compared to GPS alone systems, as the random loading scheme would take more iterations to cover all 60 satellites of the combined constellation, than what it takes to cover 31 satellites of GPS constellation. The problem becomes more severe as other systems such as Galileo and Compass are also included.

2.3 Contributions

We have proposed and tested a new discriminator for the correlation receiver that gives accurate results for the delay value even at low CNR values of 30 dB. We have also proposed a new intelligent algorithm for loading satellites which can reduce the TTFF in standalone systems with the same four channels. We have studied the GPS and GLONASS constellation to derive this algorithm, which has been described below. Another main advantage of our scheme is that it is scalable - as the number of constellations increases, there would not be any major reduction in performance, unlike the random loading scheme.

Chapter II

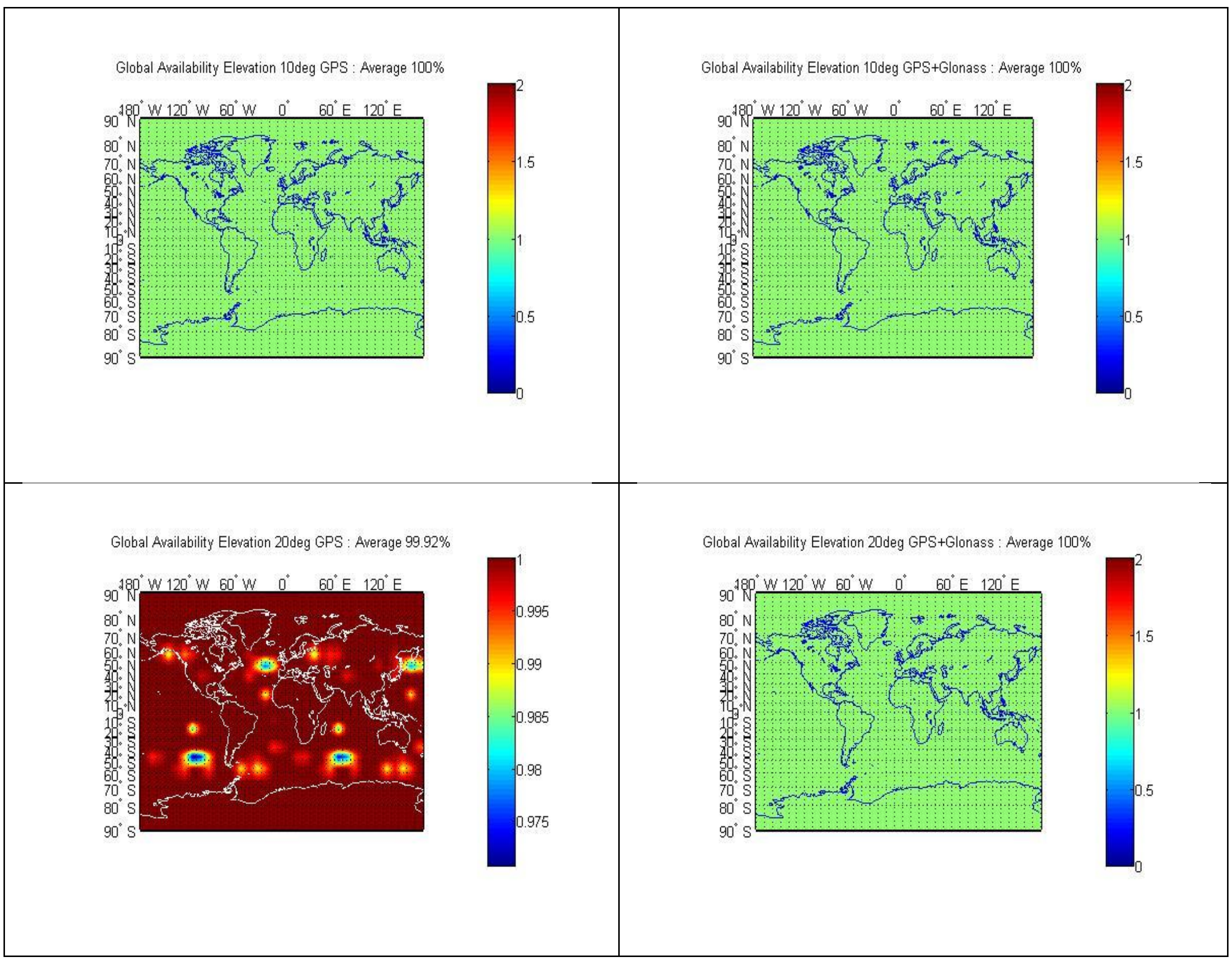
GNSS Global Availability

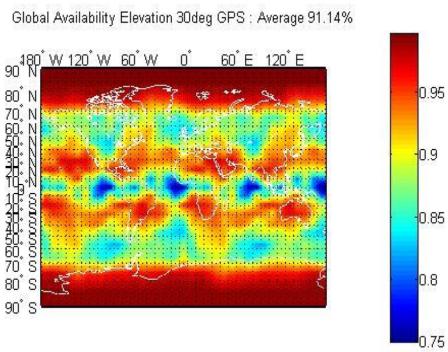
In order for a GNSS receiver to compute the position solution at any given location, it needs to have at least 4 satellites visible from that location. The elevation angles of surrounding structures affect the visibility of satellites. GPS guarantees that 4 satellites will be visible from any location on the Earth with 95% probability, provided that the elevation angle is 5 degree. The value of 5 degree is chosen as below this ray bending of the satellite occurs as it travels more distance through the troposphere. However in urban areas with high rise buildings, the elevation angle may be in the range of 30 to 40 degree. In such situations, the availability guaranteed by GPS will not be valid, and the receiver may not be able to calculate the position solution. Including the GLONASS constellation along with GPS can significantly raise the availability.

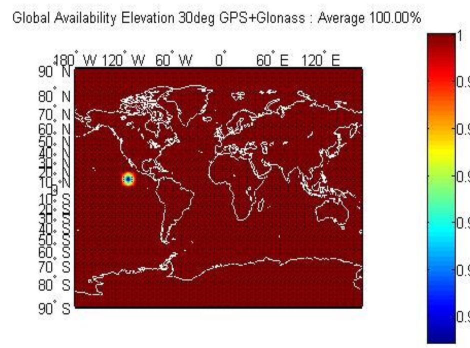
We have calculated and obtained quantitative results of the variation of availability – at each place as well as global average, for a GPS only and GPS+GLONASS constellation as the elevation angle increases from 10 degrees to 70 degrees in steps of 10 degrees. Details are given in the Appendix. Results are given in Figure 1 and Table 1

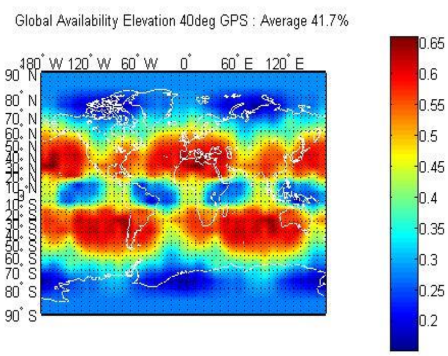
Figure 2

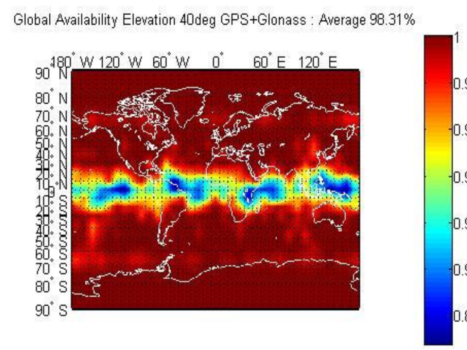
<u>Global Availability Plots</u>

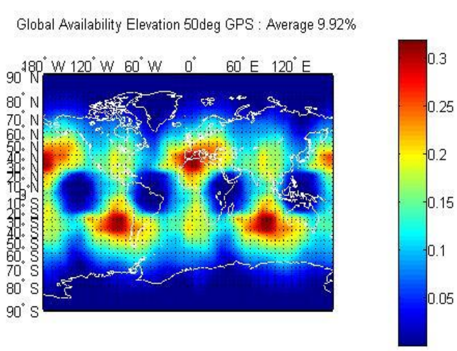


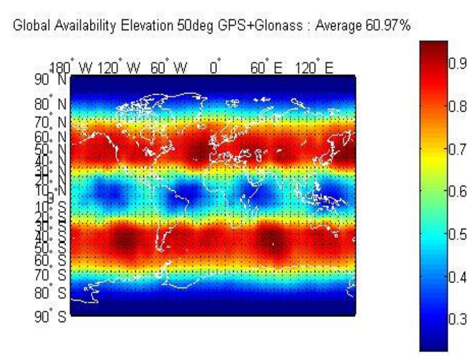

Global Availability Elevation 30deg GPS : Average 91.14%
0.95
0.9
0.85
0.8
0.75


Global Availability Elevation 30deg GPS+Glonass : Average 100.00%
1
0.9998
0.9996
0.9994
0.9992
0.999
0.9988


Global Availability Elevation 40deg GPS : Average 41.7%
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2


Global Availability Elevation 40deg GPS+Glonass : Average 98.31%
1
0.98
0.96
0.94
0.92
0.9
0.88


Global Availability Elevation 50deg GPS : Average 9.92%
0.3
0.25
0.2
0.15
0.1
0.05


Global Availability Elevation 50deg GPS+Glonass : Average 60.97%
0.9
0.8
0.7
0.6
0.5
0.4
0.3

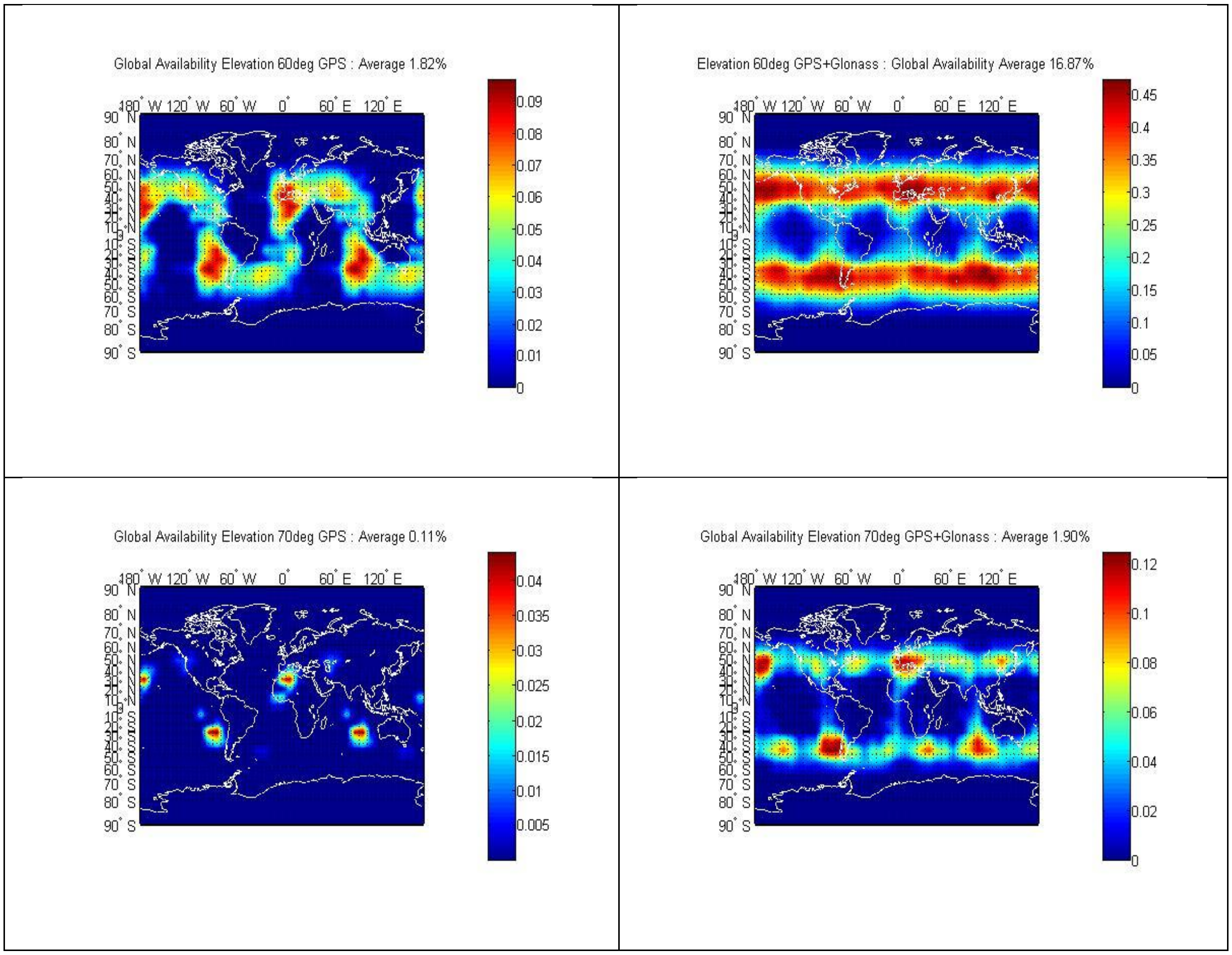


Table 1

Elevation Angle	Global Average of Availability (GPS)	Global Average of Availability (GPS + GLONASS)
10°	100%	100%
20°	99.92%	100%
30°	91.14%	100%
40°	41.7%	98.31%
50°	9.92%	60.97%
60°	1.82%	16.87%
70°	0.11%	1.9%

Discussion on Results

From the results, it is clear that GPS availability decreases rapidly after 30°. At 40°, we see that while GPS availability is about 42%, (GPS+GLONASS) availability is more than 98%. This is a significant improvement. Its importance increases considering the fact that elevation angle of 30° to 50° are common in urban areas with high rise buildings. Thus we have obtained quantitative results that prove that availability increases significantly with (GPS+GLONASS) constellation.

For very high elevation angles beyond 50°, including GLONASS alone does not solve the problem completely. However, as more satellite systems such as Galileo and Compass are deployed, their inclusion would raise the availability further, just as it was raised by GLONASS. These constellations were not considered in the present study, as they are yet to be fully deployed, having only 4-5 satellites at present.

Chapter 3

Proposed Solutions, Results and Discussion

3.1 Correlation Receiver

A simulation of the correlation receiver was developed in MATLAB. A random data sequence of length 10 bits was multiplied with the gold code for a GPS satellite. The bit sequence was modulated by Binary Phase Shift Keying (BPSK) modulation, which is used by GPS satellites in L1 C/A, L2C and L5 frequencies. The signal was delayed and noise was added according to a desired Carrier to Noise Ratio (CNR) value. The signal was filtered by a low pass filter of appropriate cut off frequency to obtain the received signal at the correlator input.

In the absence of distortion introduced by the filter and noise, the signal can be tracked by the correlator receiver by using a single correlator. The signal would be tracked when the correlation value exceeds a preset threshold. But after passing through the low pass filter the response of the single correlator develops a flatness instead of a single sharp peak near the actual delay value, as the sharp transitions in the signal are smoothed out removal of high frequency components. In such a situation, if noise is present, it may cause the correlation values near the actual correlation peak to exceed the peak value or the threshold (since the values near the peak would be very close to the peak due to flatness), thus causing error in delay determination (see Figure 5). To solve this problem, instead of a simple threshold detection, a scheme involving parallel correlators was implemented, which is described as follows.

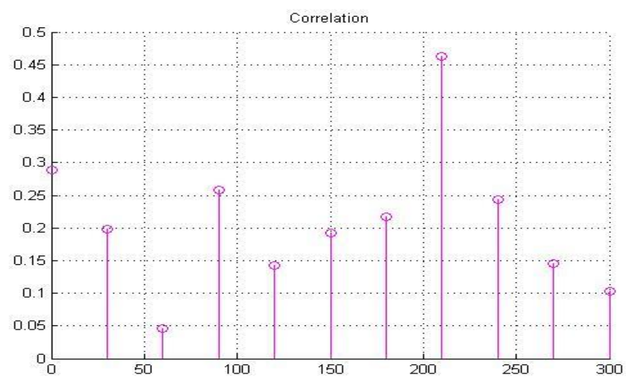


Figure 5. Correlation function in the presence of noise (CNR = 10dB) Actual delay value = 314

At the correlator receiver, three delayed replicas of the PRN code were generated, successively delayed by half a chip. These were used to run three parallel correlators (Early, Late and Prompt) for correlating the code with the input signal.

The correlator receiver has two loops –acquisition and tracking. In the acquisition loop, the three correlators were advanced by thrice of half-chip duration, and the loop is broken when any of the three correlators exceeds the threshold value, giving an approximate value of the delay. Then the receiver enters into the tracking loop, where the three correlators are advanced by a single sample. When early correlation becomes equal to the late correlation the signal is tracked, and delay determined, which is used to estimate the pseudo range. The delay value determined can then be also used to decode the received signal and obtain the input bits of the navigation message.

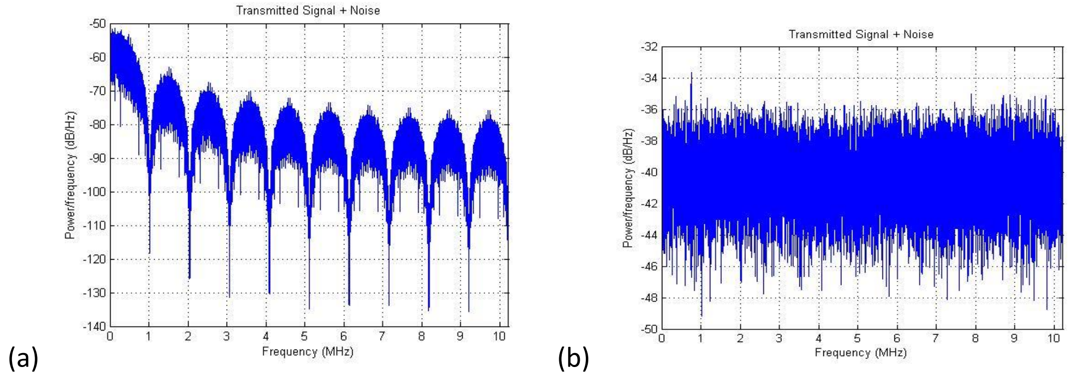


Figure 3. BPSK Transmitted Signal + Noise Spectrum (a)CNR = 300dB (b)CNR = 10dB

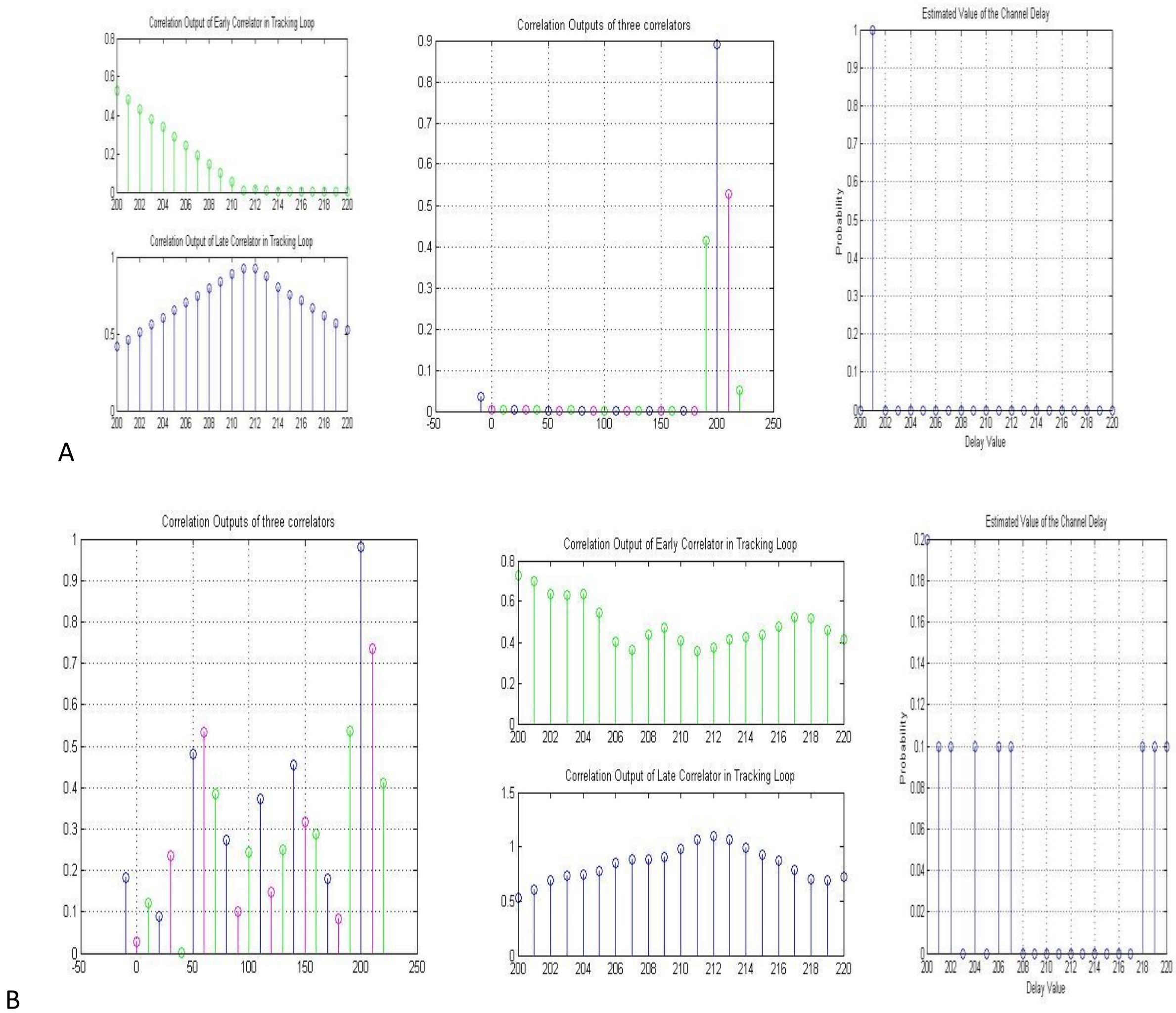


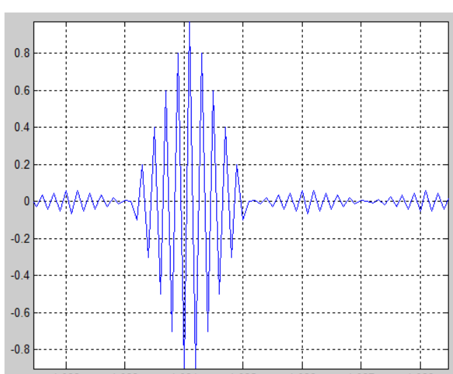
Figure 4. Correlation Outputs for A. CNR = 300dB B.CNR = 10dB

The modernized L1C frequency of GPS and other satellite navigation systems which are being established uses Binary Offset Carrier (BOC) modulation, where a square wave subcarrier is multiplied with the signal. This helps in reduction of intra system interference, as the energy moves from the carrier to side lobes. By varying the subcarrier frequency, different satellites or systems can coexist without interference.

$$s[n] = c[n]sign[\sin[2\pi f_s n]] \tag{11}$$

Equation 11 shows the expression for the signal in BoC modulation, where s[n] is the signal, c[n] is the code (multiplied with data, as required), and $sign[\sin[2\pi f_s n]]$ denotes the sign of the sine function.

The autocorrelation function for BOC modulated signals are as given in figure 5a. As can be seen from the plot, the delay cannot be accurately determined even using three correlations functions as there are multiple peaks or 'triangles' around the actual correlation peak. Early correlation will be equal to Late correlation with Prompt having a high value at each of these peaks, thus giving an incorrect estimate of the peak. Hence we need to use two additional correlators – Very Early and Very Late. The signal would be tracked only when Early = Late and Very Early = Very Late.

(a)


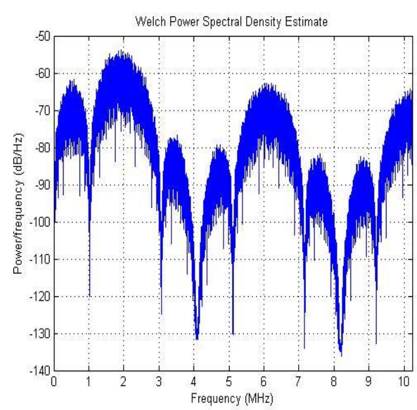
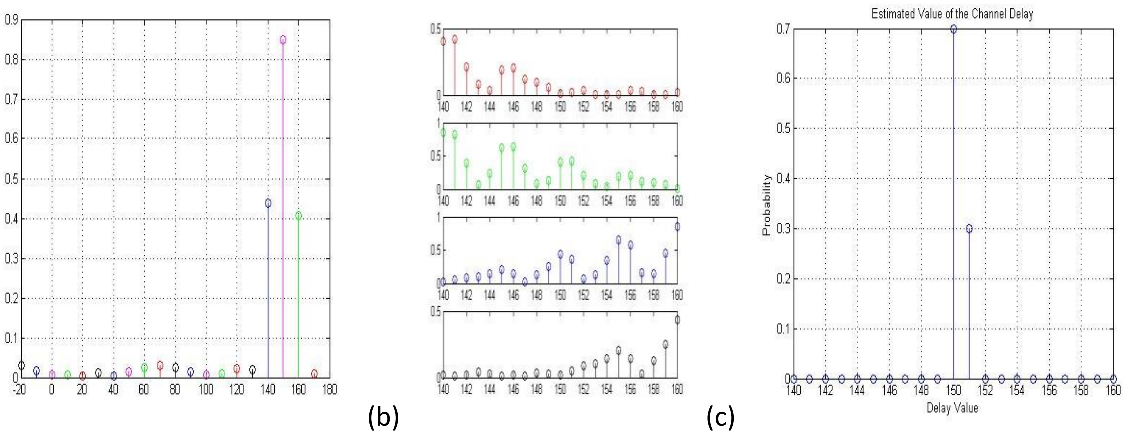
(b)


Figure 5.(a) Autocorrelation function of BOC modulated signa (b) BOC spectrum

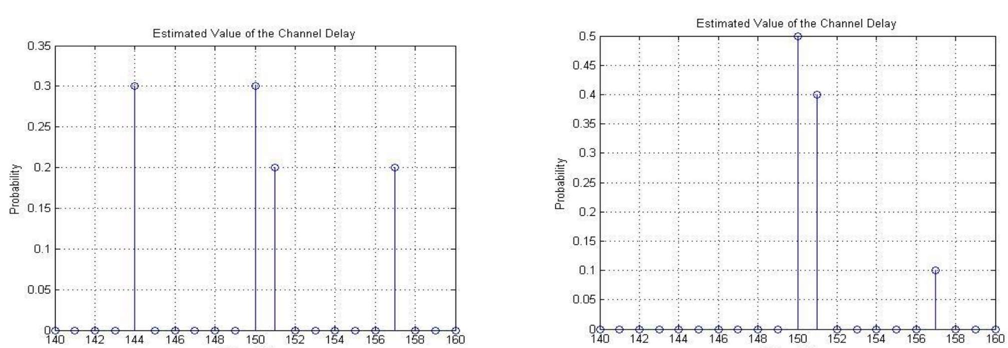


(a) (b) (c)

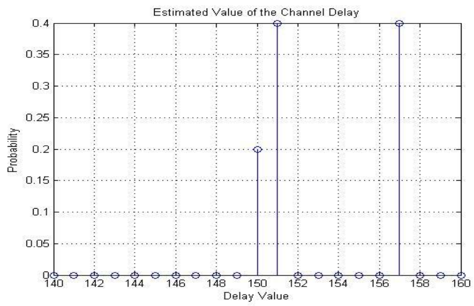
Figure 6 CNR = 30dB, Delay = 150 chips (a)Five Correlator Outputs (Acquisition loop)

(b)VE, E, L, VL Correlators (Tracking loop) (c) Delay Estimate

Different discriminators used in state of the art devices were tested at the low CNR value of 30 dB. It was found that thay did not give accurate result as they did not give enough weightage to the prompt correlator output. Noise could corrupt the early-late differences to move the tracking away from the true correlation peak. By giving equal weightage to the Prompt correlator output, this drifting could be prevented. The only state of the art discriminator that gave some weightage to Prompt was (Early – Late)/Prompt. However, as shown in the Appendix, this discriminator has less sensitivity to the Prompt correlator values when (Early – Late) is a very small value, which is the case near the correlation peak. We proposed a discriminator of the form (E – L) + (VE-VL) + (1-P), which gives weightage to the Prompt correlator output with a high constant sensitivity of -1, in addition to equalizing the early and late outputs. The delay estimate of this discriminator is shown in figure 9c. The delay estimates by different state of the art discriminators, for an actual delay of 150 chips are as given in Figure 10 (all estimates at CNR = 30dB). It was seen that the proposed discriminator had the best accuracy, as shown in Table 2.



A. B.

C. 

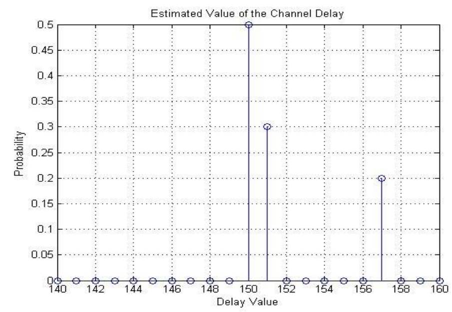
D. 

Figure 7. Delay estimates of different disriminators; CNR=30dB Delay = 150 chips (a)Normalized Early – Late Envelope (b)Early – Late Envelope (c) Early-Late Power (d)(Early-Late)/Prompt

Table 2. RMS error for proposed scheme (yellow) and state of the art schemes at CNR = 30dB

Scheme	Root Mean Square Error (chips)
E-L Envelope norm	4.56
E-L Envelope	2.3
E-L Power	4.47
(E-L)/P	3.18
(E-L) + (1-P)	0.55

Thus our scheme achieved a significant improvement in accuracy of delay estimation in low CNR scenarios.

3.2 Reduction of Time to First Fix (TTFF)

For selecting four satellites to be loaded in the first iteration, the main requirement is that the satellites should have minimum overlap between their footprint areas, and that they should be well separated in 3D space.

Taking inspiration from molecular geometry, we find that the Tetrahedral Geometry (Fig 3), found in many covalent molecules of carbon, such as methane, maximizes the separation of 4 points in three dimensional spaces and also automatically minimizes the footprint overlap. In a tetrahedral molecular geometry (Fig 8), a central atom is present along with four substituents that are located at the corners of a tetrahedron. The bond angles are $\cos^{-1}(-1/3) \approx 109.5°$ when all four substituents are the same, as in CH_4. The four covalent bonds of methane consisting of shared electron pairs with four hydrogen atoms arrange themselves in this tetrahedral configuration, as predicted by VSEPR theory. This is in order to minimize repulsions between bonds. Thus it can be concluded that the tetrahedral geometry maximizes the separation between 4 points in three dimensional space, which is our objective in selecting an arrangement of satellites.

By studying the constellation, we found 4 satellites that formed the best tetrahedron (Fig 4b) (by minimizing variance from tetrahedral angle of 109.5 degree), and these were loaded in the first iteration. The results obtained were much better than that for the random scheme.

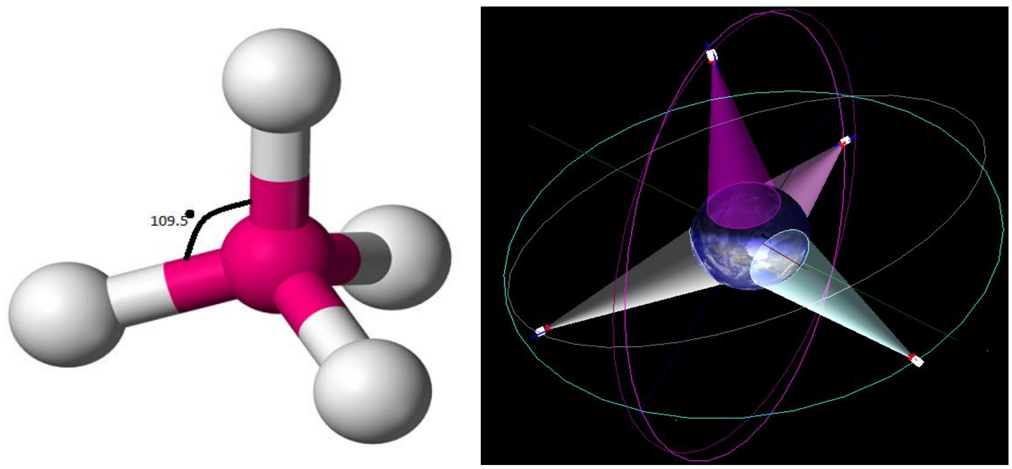


Figure 8. (a) Tetrahedral geometry(source: Wikipedia) (b) Actual tetrahedral satellites in GNSS constellation (simulated)

Thus we propose the following algorithm for finding satellite combinations to be loaded in each iteration. This algorithm can be executed offline and the combinations can be calculated. The receiver can use these combinations at any place as they are globally optimized.These combinations can also be used for a long time period of about 1 year even after the almanac has become invalid. This is because they have been selected based on the relative arrangement of satellites in the constellation, which is a design parameter normally kept unchanged. The combination needs to be recomputed only when new satellites are added into the constellation or existing satellites are removed, which do not occur very often for a stable constellation such as GPS or GLONASS.

Algorithm

Step 1: Select the four satellites of the constellation that maintain minimum variation from Tetrahedral geometry.

Step 2: Select two satellites that pass through the gap in coverage provided by the four satellites, and choose the best tetrahedron formed by them for loading in the next iteration.

Step 3: Repeat Step 2 for ((number of satellites)/4) times to get combinations till the maximum iteration

Details of execution of the steps 1 and 2 are given in the Appendix.

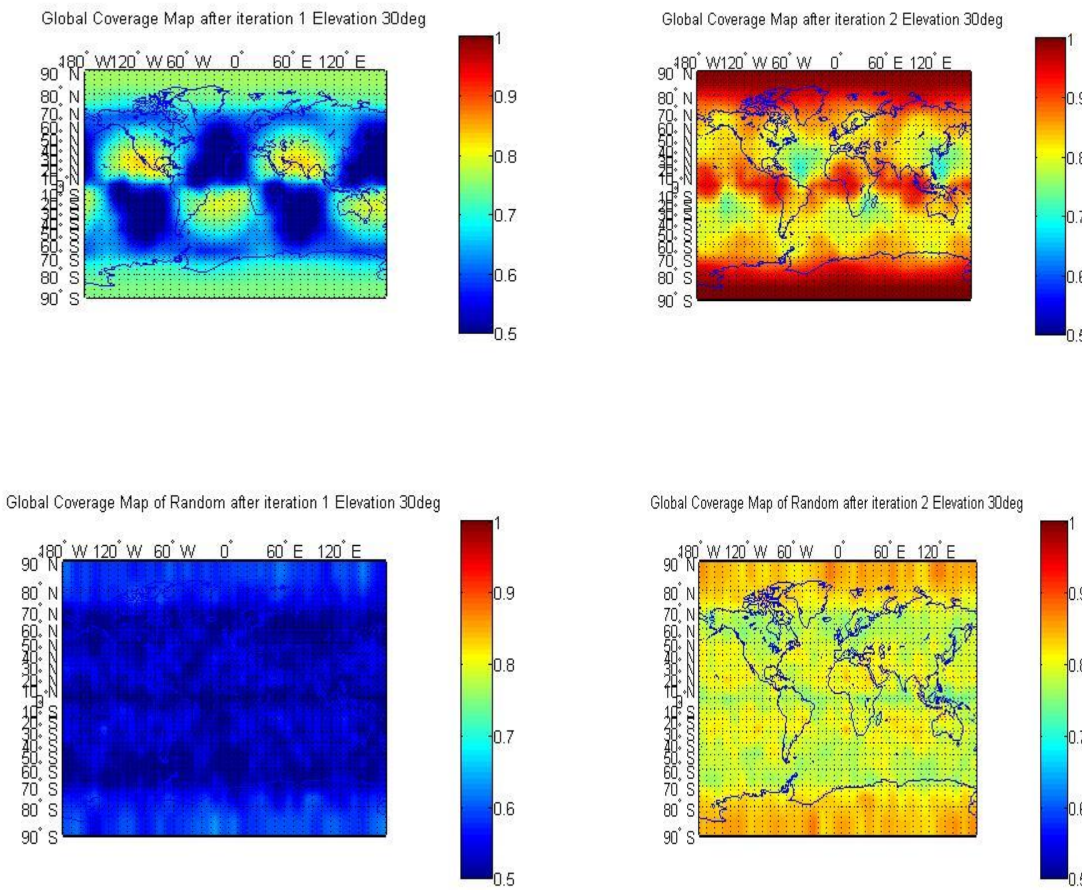


Figure 9. Global Coverage Maps after each iteration. The colour shows probability of locking at least one satellite

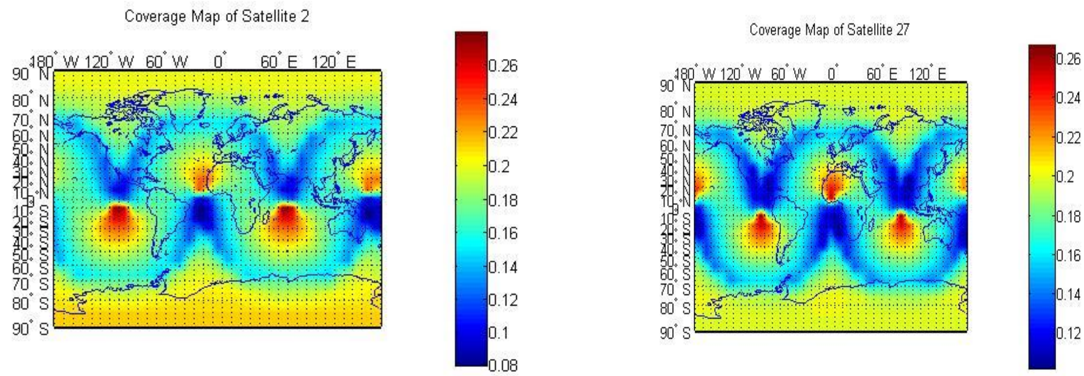


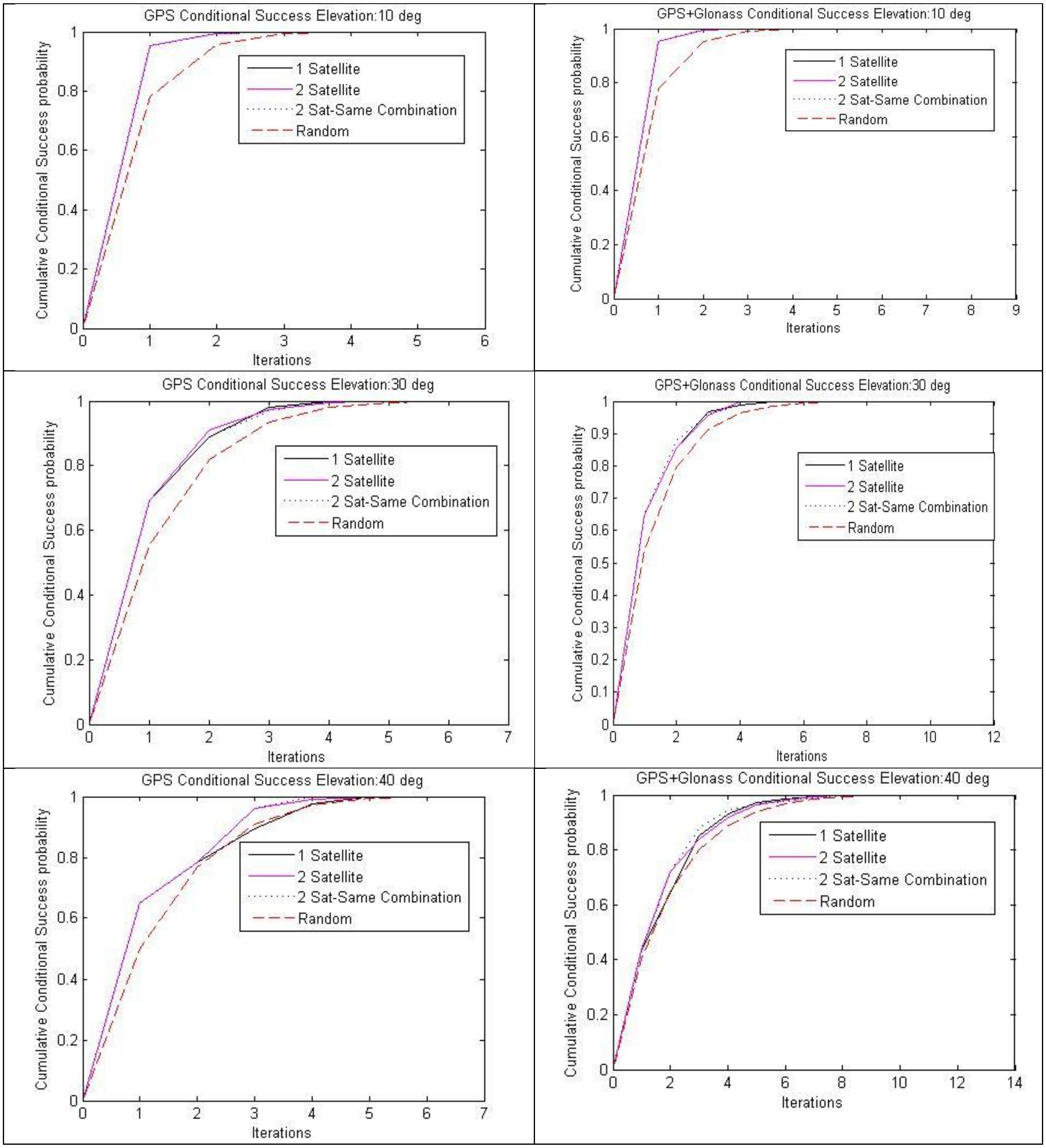
Figure 10. Coverage maps for Satellites 2 and 27 which pass through the gap in coverage after

For GPS alone, the algorithm in which for second iteration onwards 1 satellite was chosen, and the best tetrahedron was selected, gave good results. However for GPS + GLONASS, this algorithm gave poor results, especially for elevation angle 50 degree. This improved when two satellites (the present algorithm) was used. This was because, for a single satellite, there are several possibilities for forming a tetrahedron, while if two satellites are fixed, the tetrahedron is defined.

Strictly speaking, the combinations would depend upon the elevation angle, as both availability as well as coverage depend on the elevation angle. However it is inconvenient for a user to find out the elevation angle of the surroundings and choose the combination accordingly. Hence we calculated the performance of the combination computed for 70 degree elevation at all other elevation angles, and found that it performed as good as the strictly computed combinations, except for a slight decrease at 60 degree. Hence in general we can use a fixed combination for all elevation angles, which is the proposed scheme in this work.

The conditional cumulative probability of success (conditioned on availability) for GPS as well as (GPS + GLONASS) for various schemes have been plotted. In most of the cases we find that our scheme (2 Sat-Same Comb) is better than random in terms of the rate of approaching towards 100% (Table 2) .

Simulations for iteration number are carried out only upto elevation angle of 40 degree as beyond that, availability of GPS as well as (GPS +GLONASS) is below 80%, much below the minimum required level for usability as defined based on GPS (95%) .


GPS Conditional Success Elevation:10 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
Random
GPS+Glonass Conditional Success Elevation:10 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
Random
GPS Conditional Success Elevation:30 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
Random
GPS+Glonass Conditional Success Elevation:30 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
Random
GPS Conditional Success Elevation:40 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
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GPS+Glonass Conditional Success Elevation:40 deg
Cumulative Conditional Success probability
Iterations
1 Satellite
2 Satellite
2 Sat-Same Combination
Random

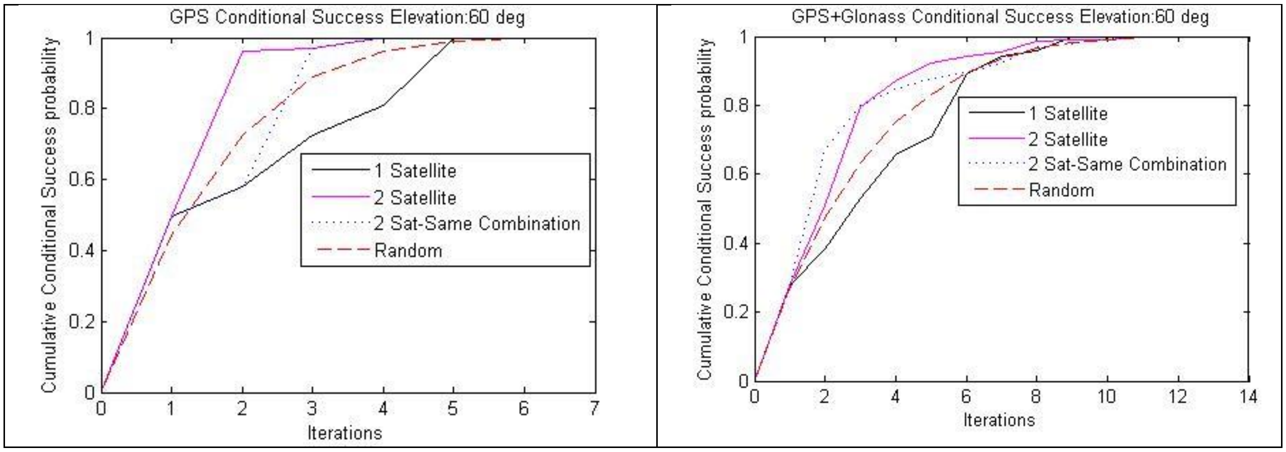

Figure 11. CDF of conditional probabilities for different schemes and proposed one at several elevation angles

The number of iterations required to reach 99% conditional probability was tabulated (Table 3). Again we see that the proposed scheme achieves significant reductions in number of iterations for both GPS as well as (GPS + GLONASS).

Table 3

Number of Iterations required to reach 95% conditional probability				
	Elevation Angle	Algorithm Avg It	RandomAvg It	Reduction (%)
GPS	10	1	2	50
	20	2	3	33.33
	30	3	4	25
	40	3	4	25
(GPS + GLONASS)	10	1	2	50
	20	2	3	33.33
	30	3	4	25
	40	5	6	16.66

These tables may lead one to believe mistakenly that the performance in GPS+GLONASS scenario is poorer than that of GPS in terms of number of iterations. However it should be remembered that these are conditional probability values, conditioned on availability. When we calculate the net probability at each iteration for the 40 degree case for the proposed scheme (by taking the product with availability), we see that the GPS + GLONASS case performs significantly better. Note that while GPS + GLONASS reaches 95% probability in about 6 iterations while GPS can never reach that value as it saturates at approximately 40% probability, due to the low availability.

Figure 6

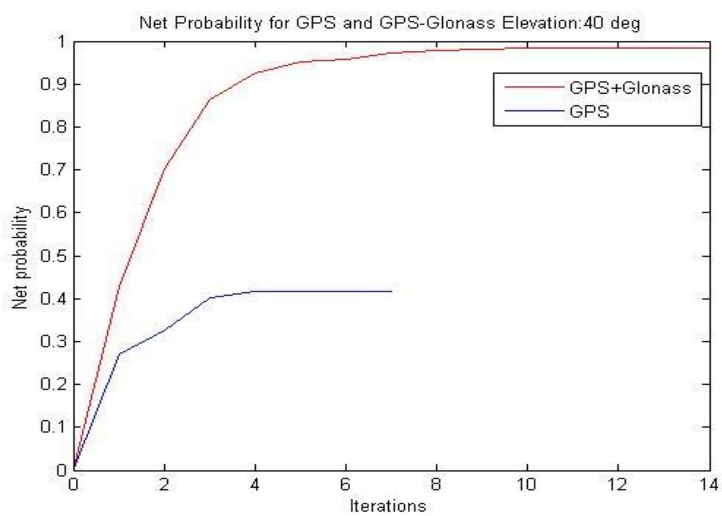

Figure 7

Thus our algorithm has performed consistently and significantly better than the conventional random loading scheme at all elevation angles for both GPS as well as (GPS + GLONASS) constellations. More improvement can be expected for higher elevation angles as other constellations are included.

Hence we have solved the two main challenges in the design and implementation of a GNSS receiver that was our objective in this work.

Chapter 6

Conclusion and Future Directions

In this project we have worked on the problem of design and implementation of an integrated Global Navigation Satellite System receiver. Initially we performed the calculation of availability and we verified that significant gains in availability can be obtained by using an integrated GPS+ GLONASS receiver instead of a GPS only one. We initially worked on the correlation receiver, which is the most crucial part of the GNSS receiver. We simulated the GPS and GLONASS signals, including Binary Offset Carrier (BoC) modulated signals at the correlation receiver input, and arrived upon a discriminator that provides an accurate delay estimate as compared to currently used schemes reported in the literature for the low CNR scenario, which is the scenario relevant to GNSS receivers. We then solved the second major challenge for such a receiver which is reducing the Time to First Fix (TTFF), by studying the GNSS constellation and proposing an algorithm which permits computation of satellite combinations offline and we have obtained significant improvement over the state of the art scheme in this area. Additionally, our scheme has also been tested for GPS only scenario, and found to perform much better than current schemes. Hence it can be used for GPS only receivers as well. Thus we have worked on and found solutions for two of the most important challenges in designing and implementing an integrated Global Navigation Satellite System receiver.

Future work in this area can try to include other satellite systems such as Galileo and Compass when they are fully deployed. Their inclusion can raise the performance further as more satellites would be available at higher elevation angles. Other areas of work can be to solve the challenge of absence of ionospheric correction data for GLONASS, unlike GPS, and to find the optimal Geometric Dilution of Precision (GDoP) combination of four satellites. Thus this research area of integrated GNSS receiver still presents other interesting research problems for the future.

Appendix

I. Calculation of GNSS Global Availability

In figure 1, the circle with centre O represents the Earth. PT is the tangent at T. T is any point at the edge of the visibility area of the satellite. Thus ϴ represents the minimum elevation angle at which the satellite can be seen, which is defined by the elevation angles of surrounding structures. Satellite position S, Satellite height Q, Radius of the Earth R_T, D' is the half-angle subtended by the footprint area of the satellite; D is the central angle between the point directly below the satellite and the observation point L. D' was calculated by cosine rule.

$$\cos(90+\theta) = \frac{X^2+R_T^2-(R_T+Q)^2}{2R_TX} \quad (1)$$

$$X^2 + 2(R_T\sin\theta)X + (R_T^2 - (R_T+Q)^2) = 0 \quad (2)$$

$$\cos D' = \frac{R_T^2+(R_T+Q)^2-X^2}{2R_T(R_T+Q)} \quad (3)$$

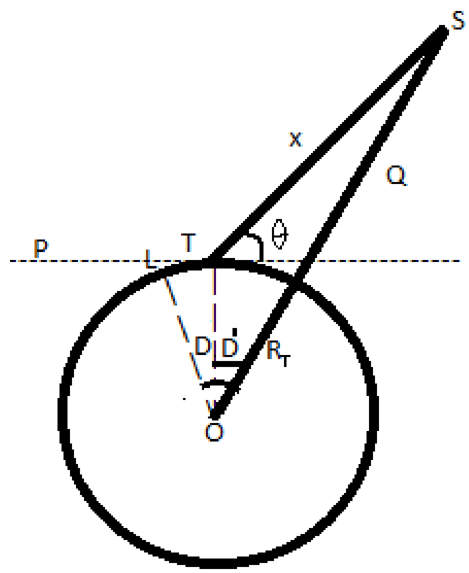

Figure 1

D was computed by calculating the central angle between L and S, by using the Haversine formula of navigation.

$$\Delta lat = \Delta lat1 - \Delta lat2 \quad (4)$$

$$\Delta long = \Delta long1 - \Delta long2 \quad (5)$$

$$a = sin^2(\frac{\Delta \text{lat}}{2}) + \cos(lat1) \, . \cos(lat2) . sin^2(\frac{\Delta \text{long}}{2}) \quad (6)$$

$$\text{D} = haversine^{-1}(a) \quad (7)$$

Satellite positions in terms of latitude and longitude were generated using the GPS 25 software. This software uses Two Line Element (TLE) data to predict satellite positions, using the SGP4 orbital model. TLE data for all satellites were obtained from [8]. The visibility of all satellites over a period of 1 month at 1 hour steps, at places around the world (grid of step size 10° in latitude and longitude) were calculated to determine probability of availability of minimum 4 satellites at each place. This was averaged to find the global availability average.

II. Discriminator Analysis

The sensitivity of (Early-Late)/Prompt, for Prompt correlator values is

$$\frac{d}{dP}\frac{(E-L)}{P} = \frac{-(E-L)}{P^2} \quad (8)$$

Near the correlation peak the value of $(E - L)$ would be small which reduces the sensitivity. For our proposed discriminator, the sensitivity for is

$$\frac{d}{dP}\big((E - L) + (1 - P)\big) = -1 \quad (9)$$

Thus the sensitivity is a constant value which would not be affected by being near the correlation peak. This allows to give good weightage to the Prompt correlator output along with equalizing Early and Late, and hence determine the delay accurately.

III. Algorithm Details

Step I

For loading satellites in the first iteration, for each combination of four satellites, calculated the variance from ideal tetrahedron, according to the following formula:

$$Tetravariance(i,j,k,l) = \{\sum_{i=1}^{N}[(Angle(i,j) - \theta_T)^2 + (Angle(i,k) - \theta_T)^2 + (Angle(i,l) - \theta_T)^2 + (Angle(j,k) - \theta_T)^2 + (Angle(j,l) - \theta_T)^2 + (Angle(k,l) - \theta_T)^2]\} / N \qquad (10)$$

Here N is the number of data points used for simulation of satellite positions, which is 24x31 in this case (1 hour steps for 1 month). θ_T is the tetrahedral bond angle of 109.5°. The combinations were sorted according to this variance, and the one with minimum variance was chosen as the best tetrahedron to be loaded.

Step II

We then generated a global coverage map of the four satellites in the first iteration (Fig 9, in text). Coverage maps were generated using an algorithm similar to that of availability. For selecting satellites for the second iteration, we found two satellites that passed through the blue areas that are not covered in the first iteration. We also put weight to the variance of the best tetrahedron formed by these two satellites from the ideal tetrahedron. Weight was also assigned to the coverage of high availability areas by the satellite. This is so as increase the conditional probability of successfully locking a satellite given that four satellites are available. This is the meaningful performance metric, as locking one satellite is meaningful only if the position solution can be computed, which requires that four satellites should be visible. Thus the final metric is as follows:

$$Metric(i,j) = CoverageIT(It-1) + Coverage(i) + Coverage(j) + (1 - Availability) + TetraVar(i,j) \qquad (11)$$

Here, CoverageIT(It-1) is the global coverage of the previous iteration, Coverage(i) is the coverage of satellite I, Availability is the availability matrix, and TetraVar(i,j) is the variance from ideal tetrahedron of the best tetrahedron formed by satellites i and j. All are matrices of dimension 19x36, as the step size on the globe is taken to be 10 degrees in latitude and longitude. They are normalized to prevent biases. The weights to different components were adjusted by tuning. The two satellites which minimize this metric are chosen, and the best tetrahedron formed by them is chosen for the next iteration. This is continued for all subsequent iterations.

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