A Proposed Signal Design for GNSS2: The Use of Faster and Longer Codes to Provide Real-Time Single Frequency Ionospheric Measurements.

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ABSTRACT

The design of GNSS2 presents the international navigation community a unique opportunity to design a signal for more precise positioning than is currently available with GPS and GLONASS. Faster and longer acquisition codes would improve code positioning accuracy and signal cross-correlation, as well as providing a greater number of unique codes for pseudolites. Furthermore, receivers may be able to exploit the dispersive nature of the ionosphere and make single frequency *measurements,* rather than *modeling* this large source of error. This paper will discuss the numerous advantages of using substantially faster (40-80 Mbps) and longer (16-256 Kbits) acquisition codes for GNSS2. Sample plots will demonstrate that the ionosphere introduces both amplitude and phase modulation for large bandwidth signals, and that these perturbations may permit single frequency ionospheric corrections.

GPS and GLONASS have led to a revolution in positioning and navigation. While both systems provide basic accuracy within 100 meters, it should be possible to provide basic accuracy less than 10 meters, after the elimination of ionospheric errors and Selective Availability (GPS only). Currently, stand alone users rely on a simple model of the ionosphere to remove 50-60% of the ionospheric range error. Authorized military users of GPS can make dual frequency measurements and remove more than 90% of the error, depending on the accuracy of the inter frequency bias calibration. Spatial decorrelation and localized scintillation even effect differential users, despite receiving ionospheric corrections. All users would benefit from a system that can *measure* the local ionospheric conditions and compensate without depending on outside differential corrections.

The large frequency difference between L1 and L2 (~350 MHz) permits dual frequency measurements of the ionosphere. This implies that ionospheric measurements should be possible with one high-bandwidth signal. This hypothesis was verified using a computer simulation developed to examine the time domain effects of the ionosphere on a modified GPS signal. A hypothetical GNSS2 (BPSK circularly polarized) signal was synthesized in the frequency domain. The standard model of the ionosphere was used to generate phase corrections equal to $-80.6*\pi*TEC/f$. The 'modified' signal was then transformed to the time domain and compared to a 'direct' signal. The results of this simulation show that both phase and amplitude modulation were introduced by the ionospheric model, and that these effects grew according to the *square* of the bandwidth. Unfortunately these effects are negligible for current GPS and GLONASS signals (code $\leq$ 10 Mbps). Time domain plots from this simulation show that even with white noise, these modulations should be measurable for faster signals.

This paper presents new ways to examine and understand the effect of the ionosphere on a GNSS signal. Single rectangular pulses are examined after passing through the ionosphere. This general case allows a simple method of assessing the distortion. The rectangular pulse is convolved with a short series of impulses to reproduce results for an arbitrary pattern. Finally, noise is added to show that the amplitude and phase modulations can still be recovered.

This paper demonstrates that significantly faster (40-80 Mbps) and longer (16-256 Kbits) acquisition codes transmitted at a single frequency will produce five clear advantages: 1) reduced pseudorange variance, 2) improved cross-correlation, 3) a greater number of PRN codes for pseudolite use, 4) all transmission power in one signal (simplified electronics), and 5) the potential for stand alone users to measure the ionosphere and generate accurate corrections.

GPS + GLONASS + EVOLUTION => GNSS2

The design and deployment of the next generation Global Navigation Satellite System (GNSS) will be a challenge in many ways. It will require substantial international cooperation and understanding to develop an improved constellation, signal, and monitoring stations, which in turn will produce improved coverage and accuracy. While this paper will review some previous research, it will concentrate on the signal design for GNSS2. A well-designed signal will be the core of GNSS2, and substantial improvements in accuracy for stand alone users will reduce the dependence on differential corrections.

GPS was designed by the U.S. DoD [2] in late 1973, primarily for military use. The signal is transmitted at two frequencies to make ionospheric measurements, and a degraded (civilian) channel to improve signal acquisition.

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Russia has also developed a satellite navigation system [3], known as GLONASS, for their military. While these two systems are quite similar, there are some significant differences that prevent receivers from easily combining measurements from the two constellations. One important difference is the lack of a standard coordinate transformation between the two reference frames. Secondly, the time standards are both based on Universal Time Coordinated (UTC), but there is a bias of milliseconds. One clear advantage of GLONASS is the more highly inclined constellation which improves coverage in high latitude regions, such as Russia. One disadvantage of GLONASS is the use of FDMA which requires more spectrum than CDMA which is used in GPS.

The following tables reveal some of the similarities and differences between GLONASS and GPS. Some proposed attributes for GNSS2 are also listed.

	GPS - Civilian Clear Acquistion	GPS - Military P / Y Code	GLONASS	GNSS2
Center Frequency (MHz)	L1 = 1575.42	L1 = 1575.42 L2 = 1227.60	L1 = 1602+0.5625*N L2 = 1246+0.4375*N N = {1...24}	Low end of L band ~ L2
Multiplexing	CDMA		FDMA	CDMA
Signal Bandwidth	20 MHz		10 MHz	80 MHz ?
Chipping Frequency	1.023 Mbps	10.23 Mbps	511 kbps	~5 Mbps ~40 Mbps
Code Length	1023 chips	6.18e+12 chips	511	
Repetition Time	0.001 second	1 week	0.001 second	>= 0.001 seconds
Selective Availability	L1 = Yes	L2 = No	No	No
Reference Frame	WGS-84 (ECEF)		PZ-90 (ECEF)	ECEF
Time Reference	US Naval Observatory UTC (no Leap Seconds)		Russian UTC	UTC

Table 1 Comparison of Signals from GPS and GLONASS

	GPS - Civilian Clear Acquistion	GPS - Military P / Y Code	GLONASS	GNSS2
# of SV & Period	21 (+3) ~ 11h56min		24 ~ 11h15min	24 ~ 12h 6 ~ 24h
Orbital Planes	6		3	6 ?
Orbital Inclination	54.0 degrees		64.8 degrees	MEO SV > 60 degrees GEO SV ~ 0 degrees
Nominal Accuracy	~100 meters w/ SA ~ 25 meters w/o SA	~15 meters	~ 25 meters	~ 5 meters

Table 2 Comparison of Constellations from GPS and GLONASS

OBVIOUS ADVANTAGES OF LONGER AND FASTER CODES

Several of the advantages of using longer and faster codes are based on fundamental ideas of signal detection. Longer codes offer improved cross-correlation properties. By lengthening the linear shift registers from 10 blocks to 18 or 26 blocks, the maximum code is lengthened from 1023 bits to 262,143 chips or 67,108,863 chips.

For codes of 1023 bits, the worst case cross-correlation (zero Doppler shift) has 23.8 dB of isolation [2]. Increasing the number of shift registers to 18, produces a total of 48.2 dB of isolation. 26 registers would produce 72.2 dB of isolation, 48 dB more than when using only 10 shift registers. The use of longer codes would also provide more codes for alternate ranging sources. This would help prevent the same PRN code from being transmitted by two different pseudolites both visible from an aircraft, a potentially confusing and dangerous situation.

Faster codes are clearly desirable since code tracking is roughly accurate to 1% of a code chip. The precision of GPS C/A code is approximately 3 meters. Whereas for P code, we would expect precision approximately 0.3 meters. However, extremely fast codes (≥ 100 Mbps) require excessive bandwidth will make measurements with precision of approximately 0.03 meters, when the noise is approximately 0.5 meters.

However, one disadvantage of longer codes is longer acquisition time. An increase in code length from 1023 bits to 262,143 bits, implies that acquisition times could be lengthened from 30 seconds to 2 hours, which is clearly unacceptable. GNSS2 could solve this problem the same way that GPS does, using a two signals. The basic signal can be quickly and easily acquired, and is used to bootstrap acquisition of the longer more precise codes that cannot be directly acquired.

PREVIOUS RESEARCH

A previous paper [1] discussed how a substantially faster code chipping frequency could be used to observe and measure the dispersive ionosphere. It showed that the ionosphere introduces both phase and amplitude modulation, but that it is much more pronounced with larger bandwidth signals. However, this method was quite limited, and examined the effect of the ionosphere on only one particular code pattern. Figures 1, 2, and 3 are reproduced from that paper.

Figure 1 shows the basic components of the simulation. The user specifies characteristics such as PRN number, code length, and code chipping frequency; and then a GNSS signal is synthesized in the frequency domain. Phase corrections are added based on the standard model of the ionosphere. The signal is then converted to the time domain and analyzed. This simulation focuses on the third and fourth order phase deviations, and removes the first and second order effects that produce 'code-carrier divergence.' This paper will present several innovations that permit a more generalized examination of the effect of the ionosphere on a widely spread signal.

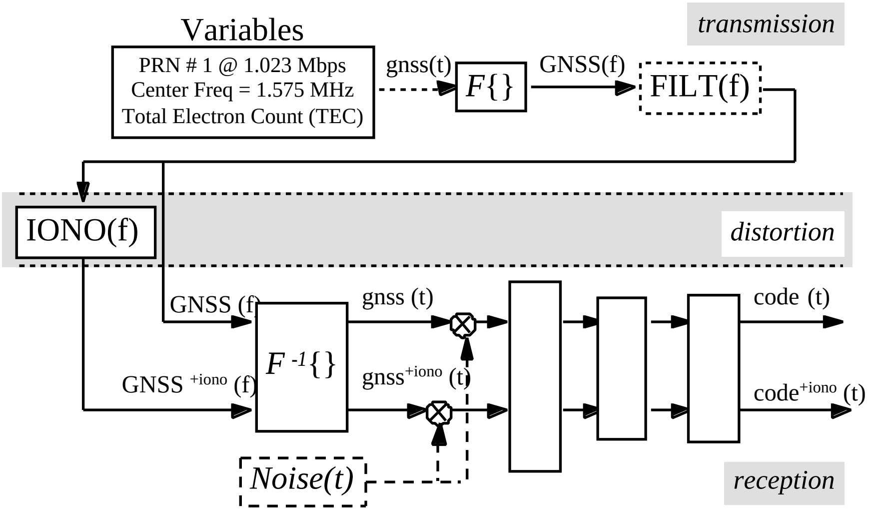
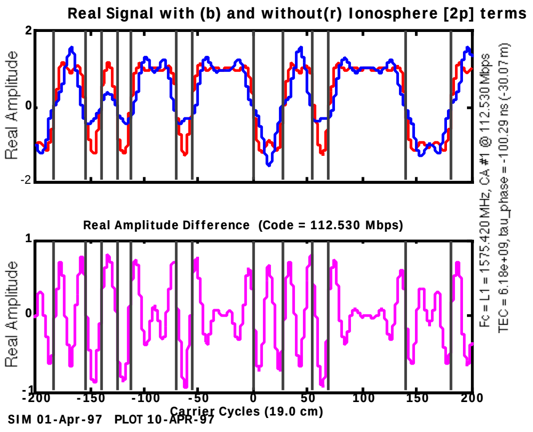


Figure 1 Block diagram of Matlab simulation of GNSS signal.

Figure 2 shows the amplitude modulation caused by the ionosphere. The upper two panels show the real amplitude of the signal with and without ionosphere, after down converting to baseband. The ionosphere reduces the peak excursion of the signal and slows the bit transitions. The lower panel shows the difference of the two signals. The difference signal has smaller magnitude in longer code blocks (near cycle 100) and is larger near the vertical hash marks which denote changes in code polarity. Note that this plot only shows the real amplitude. The signal after the ionosphere has a significant *imaginary* amplitude, which appears as phase fluctuations.



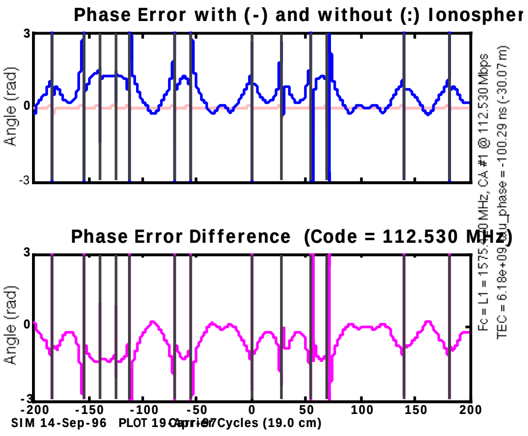


Figure 2 Amplitude modulation due to ionosphere. Figure 3 Phase modulation due to ionosphere.

Figure 3 shows the phase modulation caused by the ionosphere. The phase of the signal is given by $\phi = \omega t$, which increases linearly with time, and changes by 180 degrees with each code reversal. The upper panel shows the phase of the signal after subtracting $\phi(t)$. The phase modulation of the original signal is nearly zero, with small perturbations near the bit flips, due to filtering effects. The phase of the signal after passing through the ionosphere fluctuates substantially. The lower panel shows the difference of the two signals, and the perturbations are again clustered around changes in the signal polarity.

RECTANGULAR PULSE

It is difficult to make generalized conclusions about the effect of the ionosphere based on a single code pattern, with only a single level of ionospheric activity. For this reason, the computer simulation was modified to examine the effect of single rectangular pulse that is modulated at the carrier frequency, passes through the ionosphere, and is then demodulated.

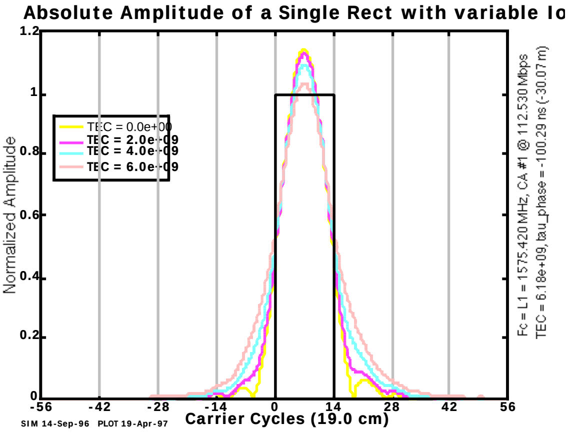


Figure 4 The absolute magnitude of the original and resulting pulses after the ionosphere.

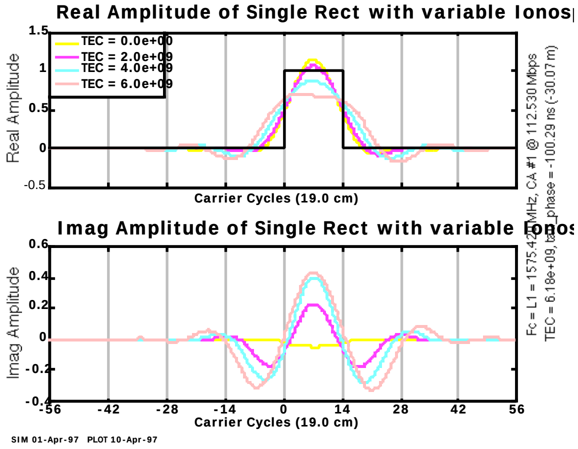


Figure 5 The real and imaginary components of the rectangular pulse.

Figures 4, 5 and 6 reveal that after passing through the ionosphere, the rectangular pulse has been reduced in amplitude, extended in duration and developed a phase offset. These effects make the concept of an ‘envelope’ more difficult to define, since the single pulse no longer passes through the origin. The nominal pulse had a negligible imaginary component that produced small phase excursions from the expected values of 0 and 180 degrees. However, the distorted pulse can produce phase offsets at any angle even for small values of TEC. Some combination of these effects may be used to determine the TEC.

Theoretically a rectangular pulse would have a magnitude of 1 and a duration of 1 chip, or 14 carrier cycles. The actual pulse is not rectangular due to limited bandwidth, and the presence of a bandpass transmission filter. Figure 4 shows that as TEC increases, the peak absolute amplitude of the pulse decreases and the duration increases. The distorted pulses decay more slowly, whereas the original pulse resembles a 'sinc' pattern, decaying quickly and passing through zero at regular intervals. This is due to the fact that the ionosphere does not cause any significant attenuation or power loss, but does change the phase of the various frequency components. It was verified that the power in all of these signals was equal to within 1 part in a million.

The transmitted pulse should be purely real even though it may not be rectangular. Changes in the sign of this real signal produce a 180 degree phase shift in the modulated carrier. Figure 5 shows that the received pulse develops an imaginary component for modest values of TEC (TEC = 2.0E9 @ L1 => delay = 9.7 meters). This imaginary component introduces phase shift in the received carrier.

The signal spreading seen in figures 4 and 5 is known as Inter Symbol Interference (ISI). This signal 'leakage' from its assigned time slot to an adjoining time slot produces interference. Extreme ISI can prevent the transmission of data. However, since the pattern is already known it may be able to measure this interference and estimate the TEC.

Figure 6 shows the relation between the real and imaginary amplitudes. The phase shift due to TEC is roughly constant near the center of the rectangular pulse, but changes rapidly near the end of the pulse, when the polarity of the chip changes.

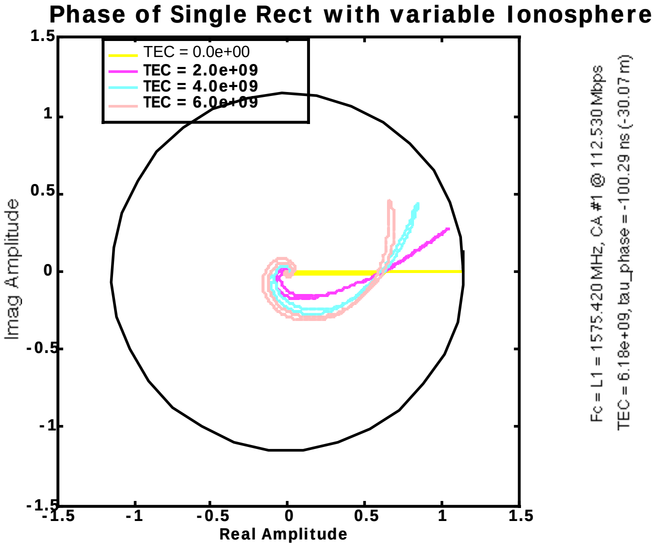


Figure 6 Phase behaviour for a single rectangular pulse with multiple TEC values. Circle denotes amplitude without ionosphere.

CONVOLUTION

The simple rectangular pulse can be used to solve for specific code patterns by convolving with a series of impulses. The rapid decay in amplitude of the rectangular pulse means that a pulse 2 or 3 chips away has very little effect. This permits limiting the convolution to a small number (5 or 7) of impulses, facilitating this numerically intensive process. This technique can predict the behaviour in the middle of an arbitrarily long sequence, by concentrating only on the adjacent impulses. It is possible to build a lookup table after computing a small number of cases ($16 = 2^{(5-1)}$ or $64 = 2^{(7-1)}$) at each desired value of TEC. It appears that linear interpolation is valid for estimating the TEC, based on a given level of envelope distortion.

Figure 7 shows the real amplitude of the convolution of the rectangular pulse with the pattern [0 0 0 0 0], this pattern is equivalent to [1 1 1 1 1]. Those patterns with few if any sign changes exhibit small amplitude fluctuations. The addition of the ionosphere in the right hand panel of figure 7 changes the shape of the pulse, but does not really change the final signal shape.

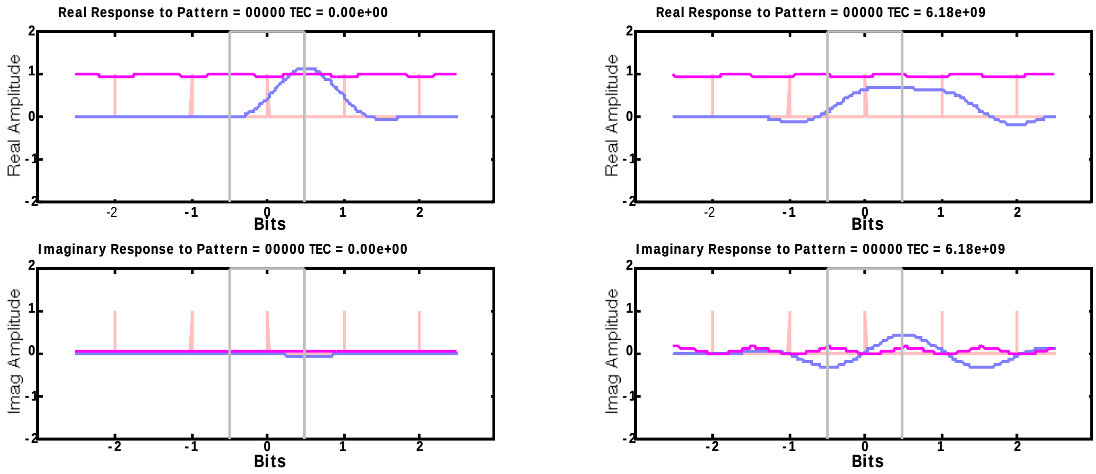


Figure 7 Plot of real amplitude for pattern [0 0 0 0 0] with and without ionosphere.

Figure 8 shows the real amplitude of the convolution of the rectangular pulse with the pattern [1 1 0 1 1]. As shown in the right hand panel, the ionosphere now causes a significant change in amplitude. Impulse patterns with successive sign changes produce more noticeable amplitude differences using this convolution technique. This is consistent with previous work [1] as shown in figure 2 and 3.

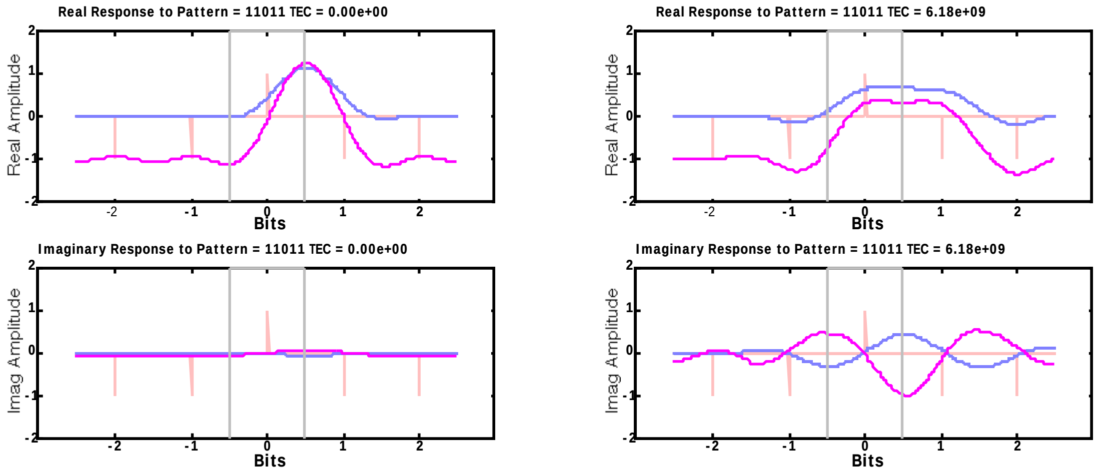


Figure 8 Plot of real amplitude for pattern [1 1 0 1 1] with and without ionosphere.

WHITE NOISE

Zero mean white noise was added to 50 replicas of the signal shown in the lower panel of figure 9. A 2 bit analog to digital converter was implemented to linearize the noise. The upper panel shows the average of 50 trials, and the middle panel shows the result after low pass filtering and is similar to the original signal. Figure 9 reveals that the signal characteristics can still be recognized even in the presence of significant white noise. The gaussian noise had a sigma of 10.0 times the nominal signal amplitude. This is equivalent to 100 times the nominal signal power, or 20 dB, a reasonable value for a GPS receiver using a patch antenna.

This process is already implemented in every GPS and GLONASS receiver. It may be necessary to slightly modify it so that the change in amplitude or phase due to the ionosphere can be measured.

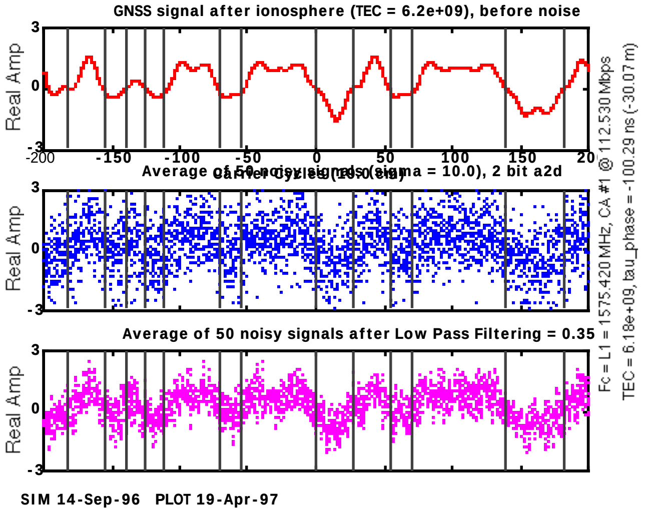


Figure 9 Averaging of gaussian noise, mean = 0, sigma = 10. Equivalent to 20 dB, 50 trials

CONCLUSIONS

This paper reviewed several of the arguments supporting the use of both faster and longer codes. These changes could produce substantially more precise pseudorange measurements than currently possible with GLONASS or civilian GPS. The signal design is only one aspect of the overall GNSS2 system which includes the constellation segment, ground monitoring as well as local and regional augmentations.

GNSS2 should transmit two signals at the primary frequency: a slower code for quick acquisition and basic positioning, and a significantly faster, more precise code. The least expensive receivers would only use the slow code.

The center frequency should be at the lower end of the L band to better exploit the ionospheric dispersion at lower frequencies. The only drawback to this is that the carrier wavelength would increase from 19 cm to 24 cm. It may be desirable to be exactly at L2, since this 20 MHz band is already reserved for satellite navigation, and there should not be any interference between GPS and the longer GNSS codes, even with pulsing pseudolites.

If the C/A code were of length 16,383 bits and were transmitted at approximately 5 Mbps, it would have a duration of 3.3 milliseconds. This duration is short enough to be readily acquired. The precise code might have length 4,194,303 and be transmitted at approximately 40 Mbps, for a duration of 105 milliseconds. Multiple frequencies may also be employed to better measure the ionosphere, although it would slightly complicate the hardware design.

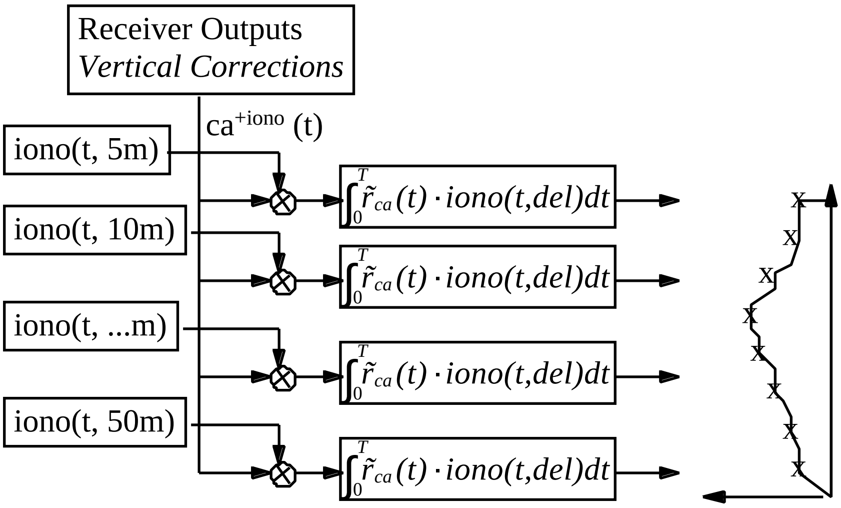


Figure 10 Schematic of "Iono Locked Loop" (ILL), which continuously estimates TEC, for each line of sight.

The "Iono Locked Loop" (ILL) shown in figure 10 is analogous to a delay or phase locked loop. It would constantly center itself on the peak of an ionospheric response function. It remains to be determined what the most sensitive input function to the ILL loop will be. Changes in amplitude modulation and phase modulation are likely candidates. This estimator would utilize the Klobuchar model as its starting point. It should be able to track rapid changes in the observed TEC , such as during scintillations or for low elevation satellites.

The advantages of a direct ionospheric measurement are well known to military GPS users. Pseudorange errors are greatly reduced when corrections are based on specific measurements of individual satellites, rather than relying on a simplistic model of the ionosphere that lumps together all local disturbances into a single correction.

Clearly, the most challenging obstacle to use of such wide spreading is spectrum availability. Hopefully, GNSS2 will offer such precise, affordable, navigational information, that many older navigation aids will be made obsolete. The gradual elimination of these older transmission sources should help to reduce narrow band interference. Future work will examine the possibility of using adaptive, narrow band, notch filters to further eliminate interference, without seriously degrading positional accuracy.

This paper showed that the use of an significantly faster (40-80 Mbps) and longer (16-256 Kbits) acquisition code transmitted at a single frequency will produce five clear advantages:

1) reduced pseudorange variance,
2) improved cross-correlation,
3) a greater number of PRN codes for pseudolite use,
4) all transmission power in one signal (simplified electronics), and
5) the potential for stand alone users to measure the ionosphere and generate corrections in near real-time.

REFERENCES

We would like to thank the FAA for supporting this research.

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