# A Prototyping Platform for Multi-Frequency GNSS Receivers

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## BIOGRAPHIES

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## ABSTRACT

The future satellite positioning/navigation systems (i.e. GPS and Galileo) will provide civil signals on multiple frequencies, similar to those currently available for military purposes only. This paper presents a direct RF sampling front end design well suited for multiple frequency satellite navigation receiver design. No frequency downconversion is necessary; rather the particular frequency bands of interest are intentionally aliased using a wide band analog-to-digital converter (ADC). The resulting samples are passed to the memory space of a host PC for storage, and are saved to disk for eventual processing of the multiple frequency transmissions. The present paper describes the design of the front-end, validates its concept with collected data, and discusses the variations on the design of a generic multiple frequency GPS front end. Methods for processing the data obtained by the front end design are also presented.

## INTRODUCTION

The future of civil satellite navigation is in multiple frequency transmissions. This is true for both the US Global Positioning System (GPS) and the proposed European Galileo satellite navigation system. The current civil GPS signal consists of a single frequency transmission on 1575.42 MHz, designated L1. GPS is scheduled to add an additional civil signal at 1227.6 MHz, designated L2, where currently only a military-specific signal exists. Later modernization efforts will add a third civil frequency signal at 1176.45 MHz, that is designated as L5. Galileo, which has yet to be implemented, will be provided from the start with the capabilities of a multiple civil frequency satellite navigation system. The focus of this paper is on GPS, but it is also shown how the same concepts can be applied for Galileo. Further details on the future GPS signals and the associated advantages are available in the proposed signal designs [1, 2]. Proposed Galileo frequency and signal designs can be found in [3].

Multiple frequencies will greatly enhance satellite navigation. One of the most commonly referenced limitations with GPS is the vulnerability of the L1 signal to radio frequency interference (RFI) – either intentional or unintentional. The received L1 signal power is extremely weak, specified at -160 dBW. Frequency diversity will greatly improve this potential limitation of the system, since a multiband receiver presents improved integrity and robustness against jamming attempts, as its accuracy degrades in stages when facing interference in the different frequency bands. In addition, multiple frequencies will provide ionosphere estimation capabilities – removing one of the most significant error sources in the current standalone GPS system. The ionospheric corrections are brought about by measuring the corresponding delay of the electromagnetic waves at multiple frequencies. Lastly, the signal structure proposed for the additional GPS frequency on L5 is designed to have a chipping rate of 10x that currently on the L1 Coarse/Acquisition (C/A) signal and also that being proposed to be added at the L2 frequency. The higher chipping rate, associated with a wider bandwidth, will also improve the overall positioning performance. Moreover, such a system would have a better performance in multipath mitigation, through different phasing of the reflections of the different frequencies. For the reasons above, current research will be a key to incorporating modernization efforts into the next generation receivers as soon as the signals will be available.

The receiver, however, becomes more complex as it is designed to process multiple frequencies. The primary purpose of any satellite navigation receiver is to determine the time of transmission of electromagnetic waves. When more and more frequencies are involved, the front end design grows in complexity. This is a result of the various mixing stages necessary in a traditional receiver design. In addition, it is critical to have equivalent propagation delays for each frequency band, or be able to calibrate any difference, as to not bias the time estimate.

An elegant approach to the multiple frequency front end design challenge is to use direct radio frequency (RF) sampling of the signal, thus intentionally aliasing of the information bands. Such an approach is outlined in [4], where direct RF sampling was used to capture satellite navigation signals from the US GPS and Russian GLONASS systems. In this approach, no mixing is utilized, rather frequency translation occurs via aliasing of the desired input through the sample processing. This technique is also summarized in the current section.

Although no civil signals on L2 and L5 are currently available, it is possible to construct prototype multiple frequency GPS receiver designs to take advantage of those signals which are already available [6] As such, the design is not practical as a general purpose receiver, but the design process itself will be invaluable for future multiple frequency receiver designs.

For example, the L2 transmission currently uses an encrypted pseudo-random noise (PRN) code which can be de-spread only by authorized military users. It is possible to use a high gain antenna focused on a single satellite to capture this signal with a positive signal-to-noise ratio (SNR). If this data can be stored, then the subset of the PRN P(Y)-code captured can be determined and the signal can be post-processed using traditional GPS signal acquisition techniques, allowing the development of dual frequency algorithms for civilian usage. Another example is the rarely used L3 transmission. This signal, at 1381.05 MHz, is for nuclear detection capabilities and it has been detected only for small finite time periods. However, if a data set can be collected during a period in which L3 is on and then stored, it can be included in the post-processing as well, allowing the further development of the multifrequency algorithms. A combination of both the above examples is used here, as a method for working with an assembly of the L1, L2 and L3 usable signals is devised.

The proposed front end design can be easily adjusted to allow for processing of the true GPS civil signal on L5, as soon as it will start to broadcast. Thus, the experience gained through first developing the L1-L2-L3 receiver will help expedite the design of prototype receivers for the actual L1-L2-L5 civil system. Such experience will also allow rapid incorporation of any additional frequencies (e.g. Galileo signals) into subsequent receiver development, as well as laying out Ground and Space Based Augmentation Systems (GBAS and SBAS), in which such civil signals will be extremely valuable.

The traditional front end for a single frequency receiver is illustrated in Figure 1. Extending such a design for multiple frequency bands and compensating for all the interfrequency channel biases is by no means a trivial task. In addition, the spurious signals and the superior harmonics can possibly degrade receiver performance and create the potential for interference issues at intermediate frequency (IF) stages.

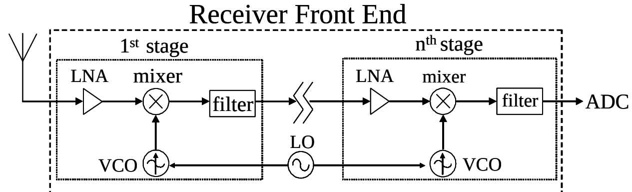



*Figure 1. Traditional Front End Design*

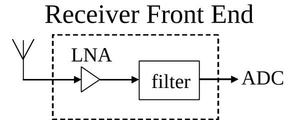



*Figure 2. Single Frequency Direct RF Sampling Front End Design*

In a direct RF sampling approach, no frequency mixing is done (see Figure *2*). In our design, however, it is not necessary to sample the signal at twice the carrier frequency, rather frequency translation is accomplished through intentional aliasing of the frequency band(s) of interest. As such, the sampling frequency needs to be only greater or equal to twice the total bandwidth of interest. This direct RF sampling and aliasing process is depicted in the frequency domain in Figure 3.

An advantage of such a design is that is that it is easily extendable to multiple distinct frequency bands – exactly what is required for the future of GPS and Galileo. The modification from single to multiple frequency is relatively simple – additional bandpass filters need to be added in parallel with the first. The concept is illustrated for the simplest case, of only two distinct frequency bands, in Figure 4. The corresponding frequency domain representation is in Figure 5. It is also important to recognize that the resulting aliased IF is a function of the initial carrier and sampling frequencies only. These two parameters completely specify the outcome. The nonlinear process of computing the resulting sampling frequency is specified in [4].

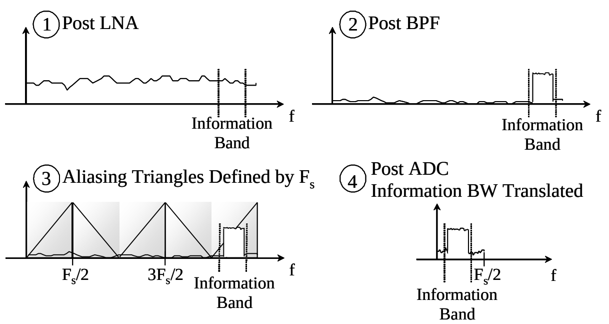



*Figure 3. Frequency Domain Representation of Bandpass Sampling*

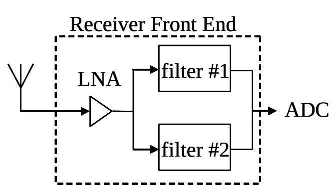



*Figure 4.Dual/ Multiband Direct RF Sampling Design*

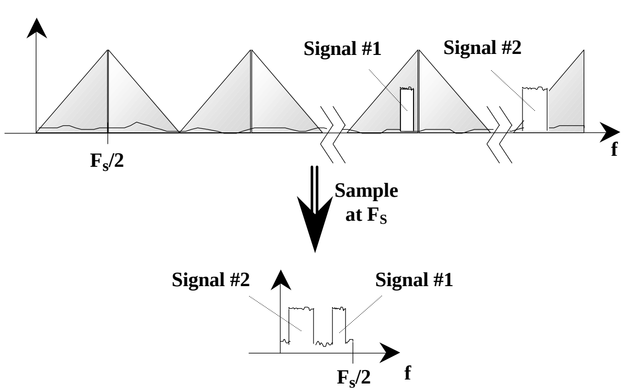



*Figure 5. Frequency Domain Representation of Dual/Multiband Bandpass Sampling*

## FUTURE GNSS DIRECT RF RECEIVERS

As mentioned, the future of GNSS navigation is multiple frequency transmission. The modernized GPS frequency plan [5] is depicted in figure 6. The existing C/A and P(Y) signals on L1 and L2 will be complemented with yet another civil C/A signal on the L2 band and a new wideband civil BPSK(10) (Bi-Phase Shift Keying at 10 MHz) signal broadcast in the L5 band. Further military signals, M-code signals, will be added to the L1 and L2 bands.

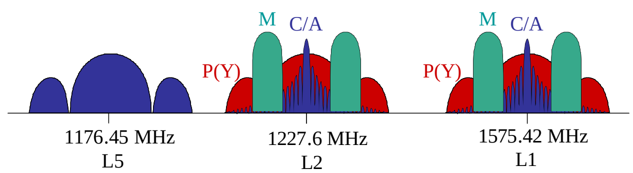



*Figure 6. Modernized GPS Frequency Plan*

Undoubtedly, it is of great interest to investigate receiver architectures that exploit the new GPS signals, for both civil and military applications. Here we propose two civilian GPS direct RF receivers, one that captures the signals on L1, L2 and L5 and another receiver that captures the L1 C/A signal, as well as the P(Y) signals on L1 and L2 . Furthermore, a combined GPS/Galileo receiver and a wideband Galileo receiver are also seen in overview.

### Civilian GPS Direct RF Receiver

The C/A code signals on L1 and L2 will both be BPSK(1) modulated while the L5 signal will be BPSK(10) modulated. When determining the bandwidth needed to capture the various signals, it is crucial to investigate the shape of the correlation function of the received signal as a function of the bandwidth. The more signal energy is received, the sharper the correlation peak will be. A sharper correlation peak allows for more precise code tracking. In a direct RF implementation, it is also important to consider that the Q-factors of the bandpass filters should be as high as possible. Narrow bandpass filters are more difficult to design with high Q-factors compared to wider bandpass filters. Thus, it makes sense to consider a wider filter if that improves the Q-factor. However, one of the adverse effects of this decision is that the wider the band that needs to be captured, the higher the minimum possible sampling frequency will be.

The main lobe bandwitdh of the BPSK(1) modulated signals is 2 MHz wide, while the corresponding bandwidth for a BPSK(10) signal is 20 MHz. The main lobe of a BPSK($n$) signal contains 90.3% of the signal energy. It is possible to design a GPS receiver that only captures the main lobe of the C/A code, but, in order to get a sharper correlation function, it is desired to capture as much as 6 MHz of the C/A signals. With an ideal 6

MHz bandpass filter, 96.6% of the signal energy will be captured. For the BPSK(10) signal, it is sufficient to acquire 20 MHz of the frequency contents, since that is also the approximate specified bandwidth of the satellite signal.

As no filter is ideal, it is desired to select filter bandwidths that are wider than the desired signal bandwidths which need to be captured. As a rule of thumb, bandpass filters that are about 20% wider than the actual signal frequency content desired to capture will be used. Thus, for the proposed civilian receiver, a 24 MHz filter is selected for the L5 signal and 8 MHz filters are selected for both L1 and L2. The frequency plan for the future civilian GPS receiver is shown in figure 7.

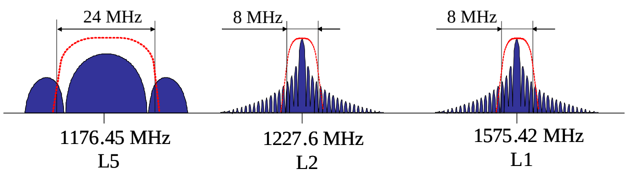



*Figure 7. Frequency Plan for Civilian GPS Direct RF Receiver*

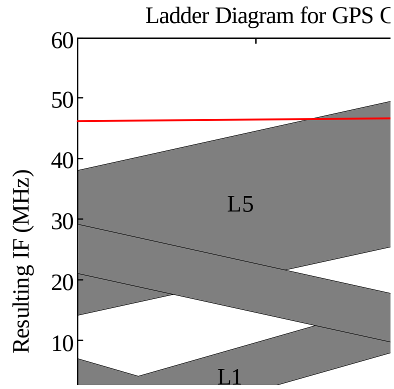
Next step is to determine the sampling frequency for the receiver. In this case, the minimum possible sampling frequency is 80 MHz. However, the lowest feasible sampling frequency, at which there is no overlap between the different bands, is determined to be 93.1 MHz, as shown in the ladder diagram in Figure 8. The highlighted region in the ladder diagram represents the allowable region of sampling frequency.

**Combined GPS/Galileo Receiver**

The European GNSS Galileo will provide multiple frequency signals from the start [3]. Some of these signals will overlap in frequency with GPS signals, which makes it attractive to design front ends that can capture both GPS and Galileo signals. A combined GPS/Galileo receiver that utilizes all the non-encrypted signals from both satellite systems is proposed in this section.

There will be ten Galileo signals on three bands, E5, E6, respectively E2-L1-E1. Different types of services will be available for the various signals. The publicly available Open Service (OS) will be mapped to signals L1a, L1b, E5a and E5b. The receiver proposed here captures the Galileo OS and GPS civil signals.

The Galileo L1a and L1b signals are BOC(2,2) modulated and use the same carrier frequency as GPS L1. The L1a and L1b signals are modulated with the same code, but L1a is not data modulated, as it is a pilot signal. The




frequency spectrum of the L1 band, centered around 1574.42 MHz, is shown in figure 9. The GPS M-code signals and the encrypted Galileo signal are not shown in the figure. As can be seen from the spectrum, the BOC(2,2) signal energy is more spread in frequency than the C/A signal. With an ideal bandpass filter of 8 MHz, 86% of the L1b signal is captured. The corresponding figure for the GPS C/A signal is 97% of the energy. Stating that 8 MHz of information bandwidth is sufficient for the L1 band and using the rule of thumb outlined above, a bandpass filter of 9.5 MHz is chosen for L1.

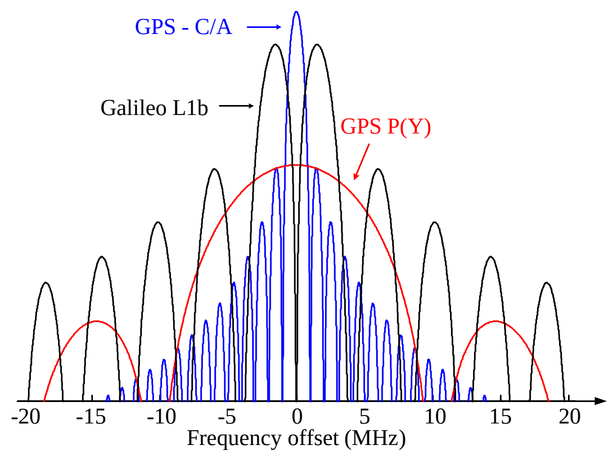



*Figure 9. L1 Frequency Spectrum*

The GPS L2 signal does not overlap with any Galileo signal. Threfore, like in the proposed GPS civilian receiver an 8 MHz bandpass filter will be used for the L2 band.

The Galileo E5 band will overlap with the GPS L5 band. However, the modulation format on the Galileo E5a and E5b is yet to be determined. For that reason, a receiver is proposed that captures the complete E5 band (1164-1214 MHz), corresponding to a signal bandwidth of 50 MHz. When selecting the bandpass filter for the E5 band, it is not scaled to the signal bandwidth, as very little signal energy is expected to be in the edges of the band. Hence a 50 MHz filter is selected.

The derivation of the sampling frequency for the combined GPS/Galileo receiver is shown in the ladder diagram depicted in figure 11. The minimum possible sampling frequency is 136 MHz, but the lowest feasible sampling frequency is 143.9 MHz as shown by the ladder diagram.

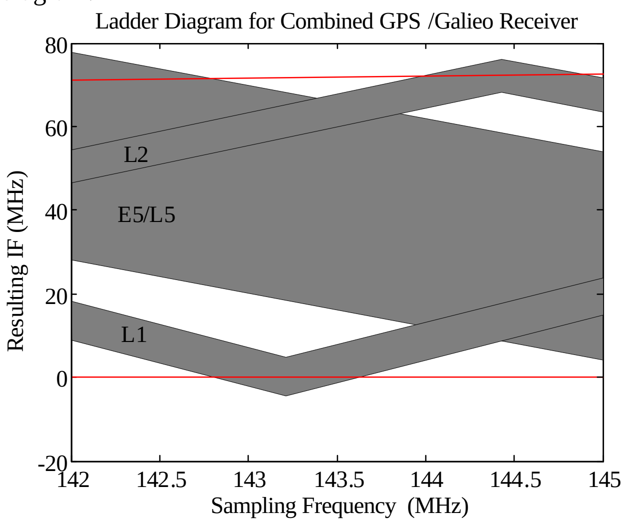



*Figure 11. Ladder Diagram for Combined GPS/Galileo Receiver*

**Wideband GPS Receiver**

In this section a wideband direct RF receiver designed to capture civilian GPS signals as well as the P(Y) signals on L1 and L2 is presented. As for the civilian GPS receiver a 24 MHz wide bandpass filter is selected for the L5 signal. Because the P(Y) signals on L1 and L2 are BPSK(10) modulated, 24 MHz wide bandpass filter are selected for those bands as well.

The minimum possible theoretical sampling frequency for the wideband GPS receiver is 144 MHz. But as can be seen from the ladder diagram in Figure 10 the lowest feasible sampling frequency is 221 MHz, as below that frequency there will be overlap of two or three bands. Compared to the Nyquist rate this is a significant overhead in sampling frequency and may not be feasible for a receiver design. The only option to allow a lower sampling frequency, with no band overlap, is to modify the individual bandwidths of the bandpass filters. When taking a closer look around sampling frequency 149 MHz, as depicted in Figure 10 it can be seen that at 148.77 MHz there is only a small overlap at the edges of the L2 band relative to L1 and L5 band. In fact if the L2 bandpass filter bandwidth is decreased to 23 MHz there will be no overlap. Clearly this is a system trade-off that has to be considered.

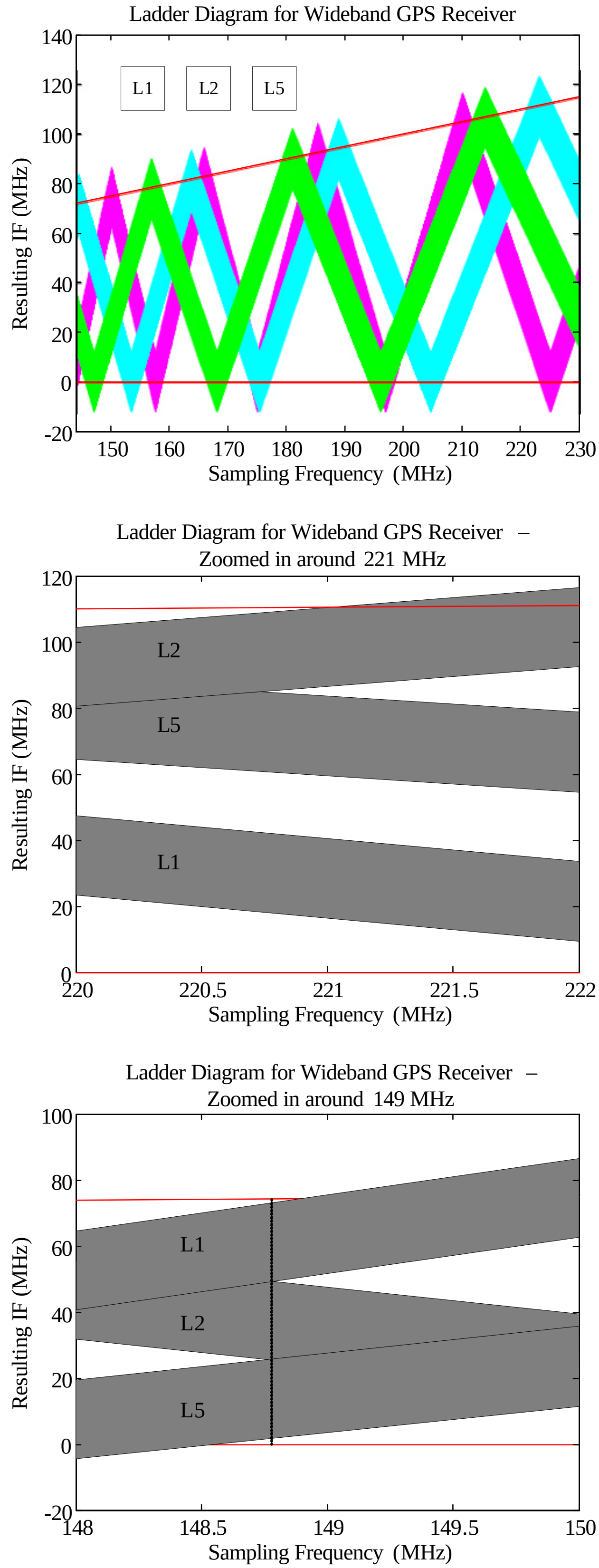



*Figure 10. Ladder Diagrams for Wideband GPS Receiver*

**Wideband Galileo Receiver**

The Galileo signals specified in [3] spans a wide spectrum. A high-end receiver could be designed that captures and processes all Galileo signals. Here a wideband Galileo receiver that captures the complete allocated spectrum is proposed. As previously mentioned

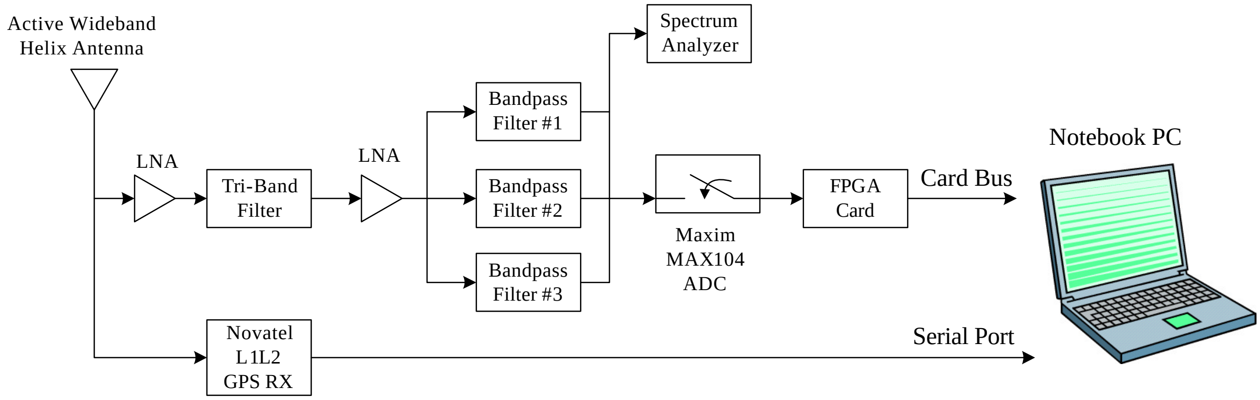



*Figure 13. Hardware Configuration*

the L5 bands is allocated 1164 – 1214 MHz. The E6 band is designated 1260 – 1300 MHz and the E1-L2-E2 band 1559 – 1591 MHz. According to the reasoning that very little signal energy will be at the edges of the respective bands the operational bandwidths of the bandpass filters are chosen to be same as the allocated bandwidth. Thus 50 MHz, 40 MHz and 32 MHz bandpass filters are selected for the bands E5, E6 and E2-L1-E1 respectively. The sum of selected bandpass filters bandwidths correspond to a theoretical minimum sampling frequency of 244 MHz.

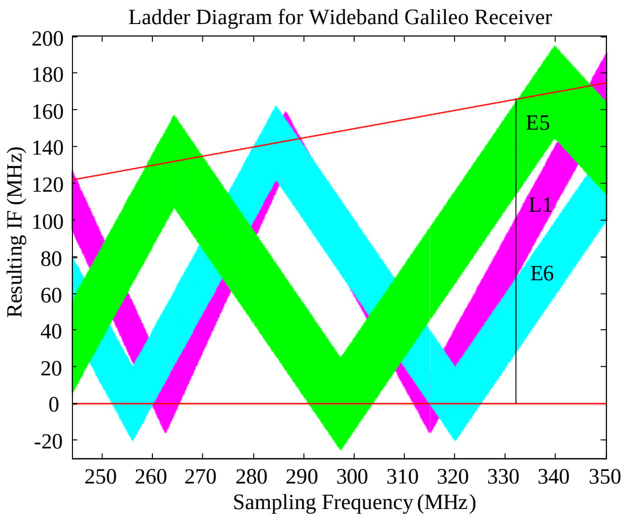



*Figure 13. Ladder Diagram for Wideband Galileo Receiver*

As seen from the ladder diagram for the wideband Galileo receiver, Figure 13, the lowest feasible sampling frequency is 331 MHz. As with the wideband GPS receiver this is a significant overhead in sampling frequency compared to the actual information bandwidth of interest. But in this particular example it is evident from the ladder diagram that in order to lower the sampling frequency significant reductions in filter bandwidths must be considered.

## FRONT END AND DIGITAL INTERFACING HARDWARE

Figure 13 shows a block diagram of the hardware equipment used in the system. A wideband helix antenna is connected to an LNA. A tri-band filter with bandpass filters centered on L1, L2 and L3 limits the signal energy fed to a second LNA. The output of the second LNA is fed to three bandpass filters, one for each GPS band. The RF output from bandpass filters is fed directly to an analog-to-digital converter (ADC) without any down conversion stages. The digital output from the ADC is passed to a commercial FPGA based CardBus card. The FPGA is configured to buffer samples and transfer that data to a portable PC, via the CardBus interface, using Direct Memory Access (DMA) transfers for faster data processing. The host PC can then be used for data storage and processing of the collected data. The ADC and the FPGA based data collection system is further described in [7].

## VALIDATION OF HARDWARE DESIGN

### Overview of signal processing for multifrequency GPS receivers

Multiple frequency GPS signal processing is not a new procedure by all means. Military PPS systems, which have knowledge of the encrypted W-code, use two tracking phases for precise GPS positioning. In a first instance, they perform acquisition on the C/A signal in the L1 band, after which they continue to track the higher frequency P(Y) chips. High-end civil receivers can also use some knowledge of the structure of the P-code for enhanced code tracking of the P(Y) code without knowledge of the specific W code. For example, Ashtech Telesis, Inc. have various patents [8] on advanced GPS data processing by alignment and elimination of the P-code from the GPS signal, in order to achieve higher performance against the noise. Dual frequency GPS L1/L2 receivers can utilize to their advantage the P-code modulated L1 and L2 satellite signals, which have been modulated with a classified security code for restricted military usage. An interpolative technique is generally used for adjusting the phase of the locally generated carriers and code in increments much smaller than the period clock sources. This is called carrier, respectively code tracking. Those locked phases can then be utilized to increase the signal accuracy and hence to better the determination of position, distance, time, etc. Furthermore, knowledge about the P(Y)-code and the ability to remove that from the data will help receivers to achieve a signal gain and therefore improve positioning accuracy when processing for the civilian signal only, for users not having access to the classified W-code.

In true multifrequency receivers, different signal transmission bands (e.g. L1, L2, L3, L5) are utilized and can enhance the positioning accuracy by doing parallel processing in all of these bands. In order to approach the problem of building triple frequency receivers at present, prior to available of such signals from the GPS satellites it is possible to consider those GPS signals currently available (L1, L2, L3). This translates into working with the P(Y) code, which is present in the first two of the above bands. However, the C/A code, which is needed for initial acquisition, is only present in the L1 band. In consequence, semicodeless or codeless techniques for P-code alignment and correlation in the L2 band must be employed, as estimating the differential delay implies the ability to do independent processing of the L1 and L2 signals. The signal in the L3 band has a C/A-like structure, however, this signal is only intermittently available. Therefore, the acquisition process involves long-term monitoring of this frequency band. Nevertheless, once a L1/L2/L3 data set is obtained, it is possible to correlate the information coming from different frequency ranges. This procedure will allow the estimation of both the relative delay between different signals in the same band (due to different receiver inferred delays), as well as the delay between different bands (consisting of the above delay plus a difference in path length within the ionosphere and troposphere at the two frequencies). The above approach will only be used for demonstrational purposes, in order to preview the advantages of doing ionospheric corrections at more than two frequencies. Once modernized GPS signals will be available on L2 and L5, the signal processing algorithms will need to change, and hopefully they will also become much simpler, taking advantage of some of the additional information in the new signals.

### Initial developmental phase of processing algorithms

In a first stage, a procedure will be demonstrated, for processing GPS data from the L1 and L2 bands for a relatively low level of the overlying noise. Later, it will be shown how, after having initial knowledge of the exact code carrier phase, algorithms can be further developed to also process data, which is hidden underneath the noise level. Equivalently, working with high carrier-to-noise (C/N) data with white noise purposely added on top, it will still be possible to lock onto the P(Y) code.

**<u>Stanford Research Institute Dish Antenna</u>**

*150 foot diameter*

- *GPS band (1.2 - 1.6 GHz) approx statistics*
  - *» 0.25 degree beamwidth*
  - *» 50 dB gain*
  - *» 35% efficiency*
- *Capable of elevation angles 3 - 87 degrees*
- *Feed point LNA (30 dB gain, 3 dB NF)*
- *Cable losses of 10 dB*

*Figure 14. The high gain antenna used to collect data (will be referred to as the Stanford dish in this paper)*

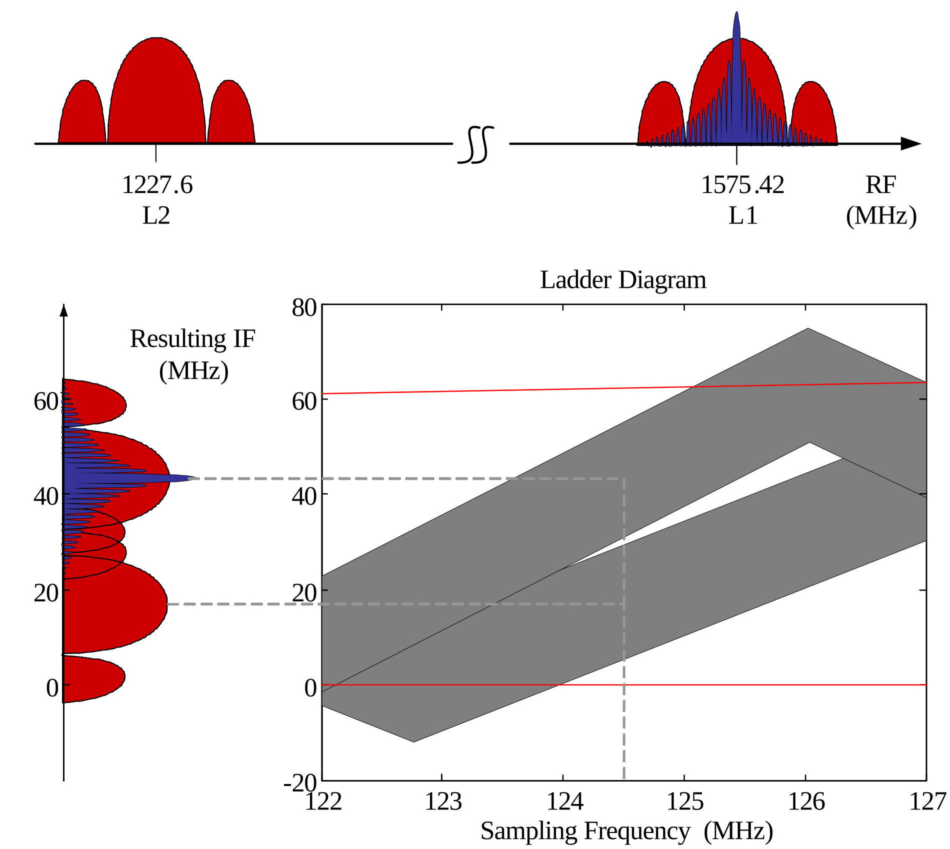



*Figure 15. Ladder diagram for aliasing of L1 and L2 bands in the receiver front-end.*

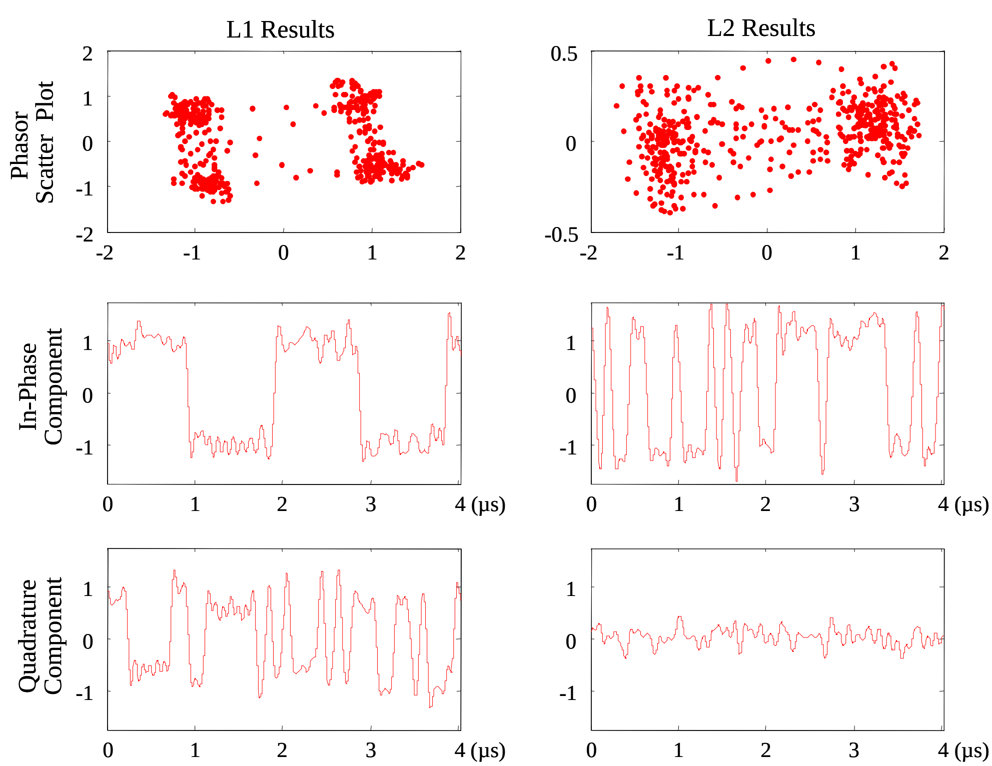



*Figure 16. Results of the phase-lock process, which eliminates and carrier remnants from the signal.*

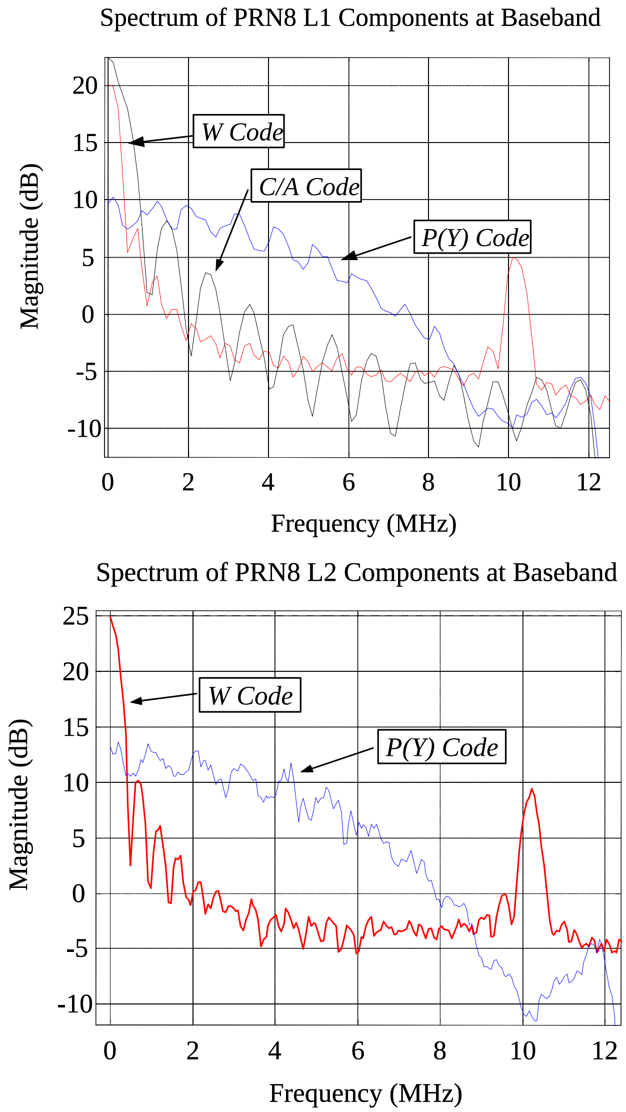



*Figure 17. The components of the signal in the L1and L2 bands viewed in the frequency domain (FFT).*

By using data collected from a high-gain dish antenna, shown in Figure 14, with a relatively high S/N ratio, algorithms can be developed assuming knowledge of the P(Y) code. If a sampling frequency of 124.5 MHz is used, the L1 and L2 signals will alias down to 43.08 and, respectively, 17.4 MHz, such that they can be isolated them in two distinct 24 MHz-wide bands for processing purposes (Figure 15). The filtered signal in the two bands can then be split into in-phase (I) and quadrature (Q) components (Figure 16) and it is also possible to bring it down to baseband by multiplying it with the aliased carrier frequency. Subsequently, it is possible to account for Doppler shift and frequency drift within a phase-lock loop (PLL), which will separate exactly the C/A and P(Y) codes in L1, respectively the P(Y) code in the L2 band. shown in Figure 16 & 17.

At this stage, C/A code tracking is done, after which the navigation data bits are extracted. If a large enough block of data (greater than 6 seconds, in order to ensure a navigation subframe can be decoded) is available for processing, it will definitely contain the time-of-week (TOW) information, which can be decoded from the header of the navigation subframe.

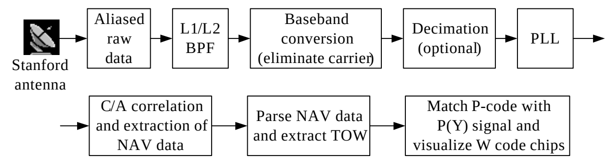



*Figure 18. Analysis plan for high S/N data sets.*

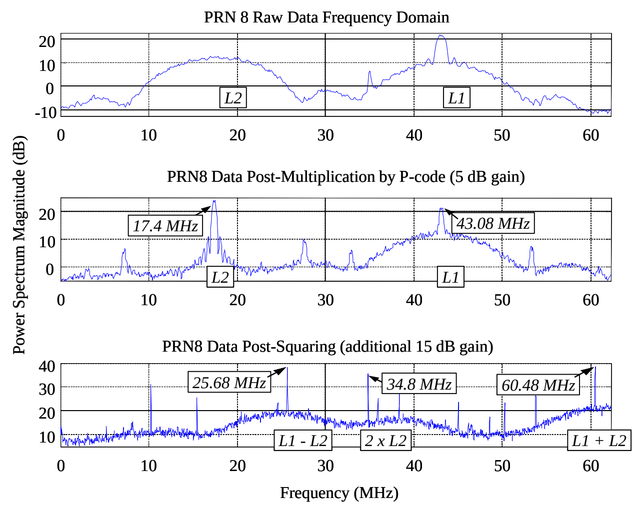



*Figure 19. Frequency domain (PSD) representation of the dish data analysis results.*

With this information in hand, it is immediately possible to generate a short sequence of P-code locally, by following the specifications from the GPS Interface Control document [10]. To recoup from potential differential delays between the C/A and P(Y) signals in the same band, the locally generated P-code can be shift a few samples back and forth until the best correlation with the P-code in the L1 (quadrature) and L2 (in-phase) bands is obtained. Since the S/N ratio is relatively high, it is also possible to look at the signal in the time domain and notice a binary signal coming out from the P-code correlation, at approximately 500 kHz. This is a classified military code, called the W-code, which is used to modulate the P-code in composing the P(Y) code. Its frequency is ten thousand times that of the navigation data used to modulate the C/A code, so the two types of signal are similar in that there are also about 20 P-chips per each W-code data bit (as there are 20 full C/A code periods per navigation bit). In the perspective of the fact that the eventual goal of this enterprise is to achieve the ability to process a much weaker signal, it should be noted that, in the frequency domain, a good alignment between the local and received P-codes collapses all the energy of the 20MHz-wide P(Y) code into a 1 MHz wide band corresponding to the W-code only. The kind of signal processing described above and depicted in Figure 18 & 19 also gives the ability to measure the coarse L1/L2 differential ionospheric delay by P-code alignment with the high S/N data in both bands. The precision to which this delay can be determined is limited to the P-code chip level, since it is obtained from successive P-code correlations in the L1 and L2 bands as shown in Figure 20. Using the resulting IF carriers for each of these bands can, of course, provide even a higher accuracy of the relative delays.

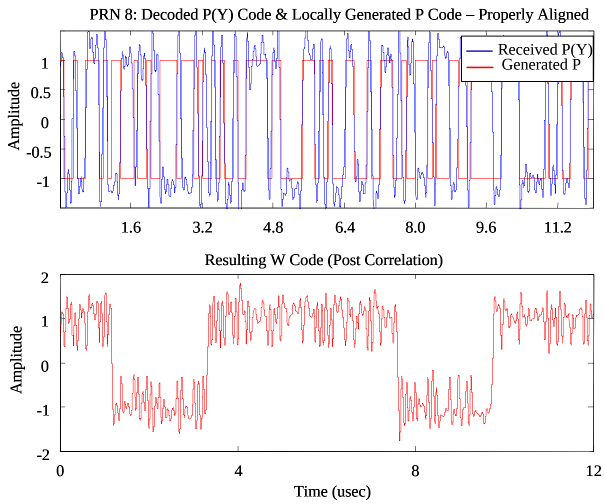



*Figure 20. Time domain representation of our analysis results. Modulation process of the P-code by the W-code in forming the P(Y) signal is evident here.*

After the ability to develop and test analysis methods using data from a high-gain antenna (i.e. the Stanford dish) has been proven, there are additional challenges when attempting to appropriate these methods for working with a classical GPS receiver antenna that yields a much lower power signal, buried under the noise level. Using classical GPS receiver signal processing algorithms, a requirement exists to test the L1/L2 P-code alignment for the case of a weak carrier-to-noise ratio (C/N) GPS signal, when it is not possible to phase lock the P(Y) code. Consequently, the processing needs to rely solely on locking onto the P(Y) code by squaring methods, which collapse its entire energy at a single frequency (viz. the corresponding carrier frequency). This procedure is somewhat similar to C/A code correlation, in that a perfect alignment collapses all the energy of the incoming signal, yielding a peak, which will ideally be greater than the noise floor.

Once more, these methods will be first tested on a low noise (high gain) data, after which the same algorithm will be run on identical data, to which white noise has been added in the software. Ultimately, a L1/L2/L3 dataset collected with a classical receiver antenna will be processed, in order to fully validate this approach.
Having the P-code alignment determined through C/A code tracking and extraction of the navigation data in the L1 band, some of the existing methods reviewed in [9] can be employed for finding a sufficient P-code alignment in the L2 band. These methods have been employed in the ascending order of their performance against background noise, stopping when satisfactorily results are reached, which could guarantee the success of the approach.

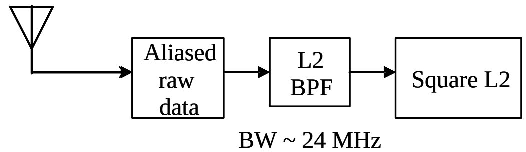



*Figure 21. Signal processing diagram - L2 Squaring*

The first method employed is called *L2 Squaring* (Figure 21). It involves filtering the L2 signal from the raw incoming GPS data for a given SV PRN number and then multiplying it by itself. The signal from all the other SVs is part of the so-called “background noise”, which one attempts to remove. While this procedure guarantees getting the right code alignment and collapsing the entire P(Y) signal energy at twice the L2 carrier frequency, its disadvantage is that it also squares the noise over a 20 MHz band, so, for signal that is obtained from a traditional receiver, this would compromise all the chances to be able to identify the correlation peak. White gaussian noise generated in the software has been added over the “clean” GPS signal from the high gain antenna, in order to simulate the level of noise that would be obtained by using a traditional receiver. However, the squaring peak became unnoticeable for a much lower level of noise, approximately 7-8 dB under what was determined to be the regular noise background in a classical receiver.

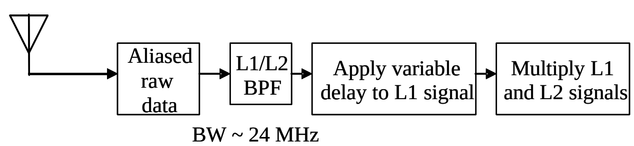



*Figure 22. Signal processing diagram – L1/L2 Cross-correlation.*

Next, the method called *cross-correlation*, shown in Figure 22, will be explored. This procedure involves filtering both L1 and L2 signals in separate arrays, applying a variable delay to one of the arrays until the signals are perfectly aligned, and then cross-multiplying in order to collapse the energy contained in the P-code. Since the energy broadcasted in the L1 band is usually about 3 dB greater than that in the L2 band, this method could bring a marginal improvement over the sheer squaring. Indeed, when trying the process against data with artificial white noise on top, it is still possible to see the correlation peaks at a noise intensity corresponding to about 3-4 dB below the noise floor in a classical receiver. More important, the alignment process between the P(Y) signals in the two bands also allows a concomitant estimation of the value of the L1-L2 differential ionospheric delay.

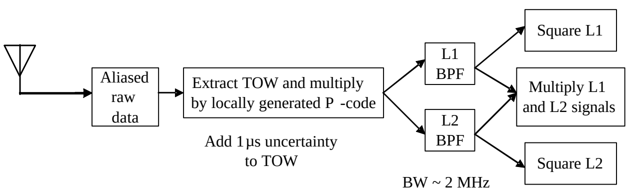



*Figure 23. Signal processing diagram – P-Code Aided L2 Squaring*

The method used on the final attempt managed to significantly improve the data analysis. This method is called *P-code Aided L2 Squaring*, depicted in Figure 23, and it is somewhat similar to what was initially done to process the high gain antenna data. In order to avoid squaring any amount of noise, the GPS signal will be multiplied this time by pure P-code, once an approximate alignment to the L1/L2 P(Y) signal has been found by the means of the TOW information. Afterwards, the remaining W-code energy in a narrow 1 MHz band at the L1 and L2 frequencies can be band-pass filtered and then squared. The benefit of this approach is that one winds up with a much narrower band, 1 MHz instead of 20 MHz, before squaring the noise overlying the useful signal. Consequently, a much better resistance to noise is obtained, thus making this algorithm applicable for use in multifrequency receivers which can process the weak GPS signal.

## Use of the GPS L3 signal for receiver development

The current GPS constellation offers signals on L1 and L2. As described previously, the L2 signal is specified for military use currently but there are algorithms in which it can be exploited by civil receiver.

However, there is no current third frequency utilized by civil or military receivers in the published signal specifications. However, the GPS satellites are equipped with the capability to generate a signal designated L3 on 1381.05 MHz, and integer multiple of the 10.23 MHz clock. The published function of this signal is for nuclear detection capabilities, thus is use is expected to be limited.

A data collection system was constructed to test for the presence of the L3 signal. Details on the implementation and results are provided in [6]. To summarize, it was determined the L3 signal is on approximately 3% of the time over a test window of two weeks. A plot of the data over 24 hours is shown in Figure 24. From this figure it is clear that when L3 is on, it is often on by a majority, if not all, of the satellites in view. The brief duration of the on period, typically from a few seconds to a few minutes, is not a problem for post-processed data collection and processing. The L3 signal itself is a C/A code like variant whose detected power is just visible above the noise floor as shown in Figure 25. Thus this L3 signal is now being incorporated into the signal processing to test algorithms for three frequency GNSS signal processing

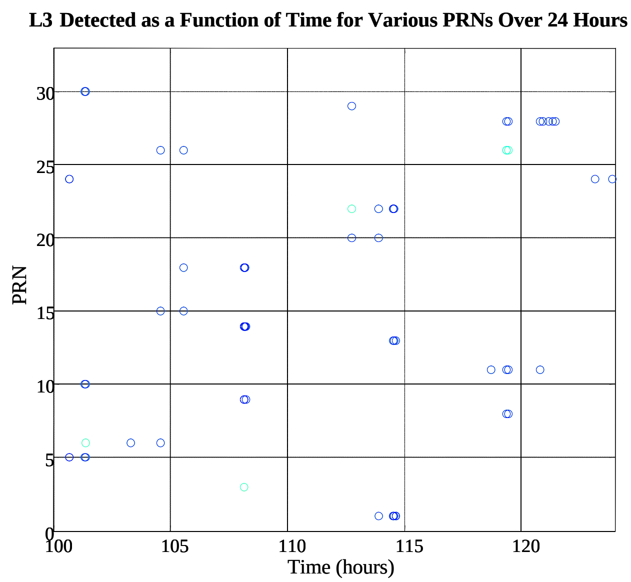



*Figure 24. The presence of GPS emission in the L3 band among the different SV signals within a 24-hour window*

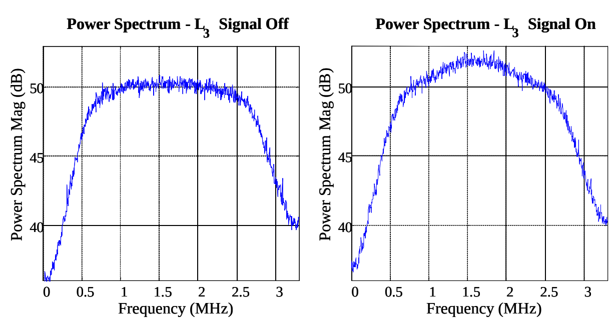



*Figure 25. Detection of signal at1381.05 MHz, frequency domain view.*

## CONCLUSIONS

This paper has described a multiple frequency GNSS direct RF sampling data collection system and the initial processing of three different GPS frequency. Such a platform is invaluable toward the investigation of future multiple frequency GNSS systems and the associated signal processing.

It is critical to begin to examine such multiple frequency satellite navigation receiver designs in advance of such signals being available. The very motivation of this effort is looking ahead into the future design of multifrequency GPS receivers. This would enable an understanding of the enhancements, which usage of multiple frequency bands could bring to GPS/GNSS positioning. Likewise, this effort could contribute to unveiling potential problems with building the corresponding receivers, particularly those related to integrity for aviation applications.

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