Each year the complexity and number of Global Navigation Signal Satellites (GNSS) increases significantly. There have been a range of innovative processes created to analyse these signals however demonstration of these algorithms in publications is generally limited to a small set of signals, with no consistency between authors. Public repositories of GNSS satellite recordings are virtually non-existent and not produced using a standardised method. In this project a processing tool was implemented that can effectively process GPS signals and correlate them with a set of PRN sequences. In this project, processing methods were implemented that were able to analyse GPS L1CA and L2C and other satellites of a similar structure that had been obtained from CSIRO Australia. A range of signals have been acquired from CSIRO for the Beidou, Galileo, QZSS, and GPS GNSS’s and have been stored for global access. All of the processed signals were collated into a catalogue that exhibits key information. The results of the processing method confirm the signal identities, with scope for more complex signal processing to be implemented in the future.
I. Introduction

A. Motivation

Each year more satellites equipped with modern technologies and communications systems are becoming operational – Australia is one of the only regions in the world where a majority of these satellites orbit, since some systems are regional using Geostationary or Geosynchronous orbits. The characteristics of these satellites are described in their documentation, but actual recordings not catalogued or readily available. There are a vast range of post processing techniques and programs that are available to process the Global Navigational Satellite System (GNSS) signals however they are generally specific and not equipped to process a range of signals. The information that can be obtained through signal processing provides details on the functionality of a specific GNSS satellite. Many different institutions have published a range of GNSS signals, however they are very limited. A catalogue of GNSS signals will allow for a qualitative comparison of known GNSS signals and processing methods and also be an effective research and learning tool. By implementing a signal catalogue with a standardised range of signals that have all been measured in the same why, by the same equipment, will ensure that processing algorithms are able to be qualitatively compared. It will form a benchmark for testing. Students and researchers will have access to the recordings – who would have otherwise been unable to due to equipment. The signals produced are of a high quality and realistically represent the GNSS signals which ensures that they are able to be used as an education tool.

B. Aims

Create a versatile GNSS signal processing tool that is equipped to process a range of signals and develop a catalogue with a standardised range of GNSS signals.

II. Background

GNSSs are a class of satellite systems that provide signals from space allowing users to derive positioning and timing data [1]. GNSS family is comprised of Global Positioning Service (GPS), Galileo, Beidou, GLONASS, and QZSS GNSS’s which work together to provide an autonomous geo-spatial with global coverage [2]. Figure 1 shows the allocation of the frequency bands amongst the GNSS systems.

As can be seen in figure 1, the GNSS signals are quite complex and cluttered with many different shapes and structures. Each year more signals become operational that are more complex, and are able to achieve a wider range of applications. GNSS is a highly evolving area that has seen significant change in the past decade with new non-traditional signals being created. It is very important to thoroughly understand and document these signals to ensure that the receiver and processing algorithms can be optimised. The GNSS signals characteristically have a relatively large bandwidth and small received signal power which results in a lot of the signals being below the noise floor – this results in the need for highly directed antennas with significant gain and low receiver noise.

The focus of GNSS as a field has increased drastically in the recent years and many research organisations are processing the signals with their own algorithms and receiver equipment. Due to the rapid expansion of processing, no standardised catalogue of GNSS signals was ever created. The processes that have been created are not comparable because different results are used – there is no benchmark for quality signal recordings. These signals are significantly below the noise floor and require the use of large aperture antennas with high gain and low receiver noise that result in recordings with a high Signal to Noise Ratio (SNR) – quality recordings of this level are in short supply.
1. **Multiple Access Techniques used in GNSS Satellites**

GNSS satellites use two different access techniques being Code Division Multiple Access (CDMA) and Frequency Division Multiple Access (FDMA). Multiple access is a process where multiple communications streams are being transmitted from multiple sources through a single channel. In FDMA, the available bandwidth is divided into small bands that can be accessed by a single user for an infinite amount of time. In CDMA, several transmissions can take place at a single time on the same frequency bandwidth – this is shown in figure 2. The user data at the transmitter is combined with a spreading code and then transmitted – the receiver uses the same code for matched detection [2]. CDMA implements a technique called Direct Sequence Spread Spectrum (DSSS) and is commonly referred to as DS-CDMA. DSSS is a spread spectrum technique where an XOR is used to combine the data with a pseudo random noise (PRN) spreading code in the digital domain. The spreading code has a higher chip rate which results in a wideband scrambled signal. The processing methods generated in this project process CDMA signals as they are more widely used and FDMA is becoming less common [3].

2. **Spreading Techniques**

The two primary spreading techniques used in satellite communications are variations of Binary Phase Shift Keying (BPSK) and a modern variation of DSSS BPSK, Binary Offset Carrier (BOC). PSK is a modulation technique where the phase of the carrier is changed by varying the sine and cosine inputs at a particular time. Binary PSK (BPSK) is where each bit is assigned to a sinusoidal wave 90 degrees out of phase to each other, thus making two symbols. A common implementation of PSK is Quadrature PSK (QPSK) which processes two bits per symbol in the in-phase and quadrature direction [3]. BOC modulation uses a rectangular subcarrier of frequency which is equal to or higher than the chip rate. The multiplied signal is then split up into two parts which produces two identical spectrums [4]. In reality the BOC technique is implemented in the digital domain – effectively creating a DSSS function that has most of the power centered in the Upper and Lower Sidebands. In a DSSS based GNSS system each satellite continuously transmits a unique periodic code signal, which is modulated by the different spreading techniques explained earlier. The code sequence is a spreading sequence made of a certain number of chips with an associated sequence length. The overlapping data streams for the satellites on each band are separated by the multiplication with an aligned replica of the spreading code. The cross correlation at the software defined receiver allow for the required satellite signal to be isolated from all the others [4].

A. **Signal Plans**

1. **Global Positioning System**

The GPS was developed by the United States (US) Military and achieved full operational in 1995. This system provides two levels of use being a standard positioning system (SPS) for general civil use and precise positioning service (PPS) for military use in the US and its allies. There are currently 30 operational GPS systems in orbit [5]. There are three frequency bands in the signal plan which provide various services: L1 band is used for navigational purposes, the L2 band is a modernized civil signal with P(Y) and M code (M code is military code and P(Y) code is the precision code) [6].
All of the code in the L1 GPS band have a center frequency of 1575.43MHz – with the CA and P(Y) using BPSK modulation and the L1C and M Code using BOC. The CA code has code frequency of 1.023MHz and a PRN code length of 1023 bits. The L2 band has a center frequency of 1227.6 MHz with the L2CM and L2CL code having BPSK modulation. The code frequency of the L2CM and L2CL code are both 511.5KHz, and the PRN code length is 10230 and 767250 bits, respectively. The frequency information for the GPS L1 and L2 bands are shown in figures 3 and 4.

2. **Beidou**

The Beidou navigational system is China’s second generation satellite navigation system and provides positioning, navigation, and timing services to worldwide users [1]. The Beidou constellation currently has 21 satellites in orbit [21]. The Beidou satellite system operates on two different bands being B1 and B2 which operate in both I and Q Planes due to QPSK modulation. The access technique for the Beidou satellite is CDMA.

The B1 band operates with two carrier frequencies 1561.098MHz and 1589.742 MHz. The access technique for this band is CDMA. The bandwidth is 4.092 MHz with a chip rate of 2.046 cps [1]. The B2 band operates with a center frequency of 1207.14 MHz and has a code frequency of 2.046 MHz and 10.23 MHz. The bandwidth of this signal is 24MHz. The B1 and B2 signal plans are shown in figure 5 and 6.

3. **Galileo**

The Galileo satellites is Europe’s own GNSS satellite which provides a highly accurate global positioning service and is fully interoperable with other GNSS satellites internationally. Currently there are 14 Galileo satellites in orbit. The signal plan for this satellite has four bands being E1, E6, E5, and C.

The E1 band shown in figure 7 uses a Composite Binary Offset Carrier (CBOC) which is the implementation of a Multiplexed BOC (MBOC) signal is the result of multiplexing a wideband signal BOC(6,1) with a narrowband signal BOC(1,1). The Galileo E1 signal is a multiplex of the E1 Open Service (OS) Data Channel, the E1 OS Pilot Channel and the E1 Public Regulated Service (PRS) Channel. The center frequency of this band is 1575.42 MHz and the access technique is CDMA. The E1 OS channel uses a CBOC(6,1,1/11) spreading modulation which has subcarriers of 1.023 MHz and 6.138 MHz. The code frequency for this channel is 1.023MHz. The E6 band is comprised of three components being the E6 Commercial Service data channel, the E6 Commercial Service pilot channel, and the E6 PRS channel. The center frequency of this band is 1278.75 MHz and the access technique is CDMA. The E6 CS Data and CS Pilot both use BPSK(5) modulation, where 5 is the chip rate. The E6 PRS uses a **BOC**(10,5) modulation scheme with a sub carrier frequency of 10.23 MHz [7].

![Figure 5 - Beidou B1 Band Signals](image5)

![Figure 6 - Beidou B2 Band Signals](image6)

![Figure 7 - Galileo Frequency Band Allocation](image7)
4. Quazi-Zenith Satellite System (Japan)

The QZSS is a regional satellite used by Japan and currently has four satellites in orbit that operate on the L1, L5 and E6 frequency bands. An interesting detail about QZSS is that it operates in the Asia Pacific region and travels most significantly over Australia – which is a key characteristic the signal recordings as they are not able to be seen globally. The QZSS regional orbit is shown in figure 8.

The L1 band operates the C/A and L1C code which use BPSK and BOC modulation, respectively. The centre frequency of this band is 1575.42 MHz, and the code frequency is 1.023Mbps. The L2 band operates the L2C signal which is exactly the same as the GPS L2C signal with the interleaved long and medium code. The L5 band operates the L5I and L5Q signals which are both BPSK with a 10.23MHz code rate. The final band is the E6 band where the LEX signals operate with a centre frequency of 1278.75MHz and the modulation scheme is BPSK [8]. The signal plan for QZSS is shown in figure 9.

B. PRN Code Generation

The primary GNSS system that was focused on in this project is GPS. GPS is one of the earlier commercially available satellite systems that populated almost all of the GNSS existence for two decades. It was the fundamental building block of the GNSS’s that we see today – the communication schemes and theory have evolved from GPS; having a fundamental understanding of the technicalities of GPS allows for a relatively easy transition into the understanding of other systems.

Each GPS satellite in orbit has a PRN code which is unique and determined by the unique identifier. PRN code is not actually random as the name would suggest, and actually varies based on the iteration of a shift registers which designates the unique identifier. The code allows for the receiver to be able to identify which specific satellite is being received [8].

1. GPS L1 Band

As outlined previously there are three codes in the L1 band being: M code, P code, C and CA code. The code used for correlation in the L1 band is CA code with a length of 1023 bits. Each satellite transmits code that is generated from two 10 bit shift registers and then modulo-2 added to form CA code. The first set of code is constant, whereas the second is created by combining the contents of two bins in the second shift register that is also 1023 bits long [9]. The first and second sets of code are G1 and G2 respectively – the CA generator is shown in figure 10.
2. **GPS L2 Band**

The GPS L2 band is comprised of the L2C and P code – the code used for correlation is L2C code which is interleaved with long code (CL) and code medium (CM) code. The CM code contains 10230 chips which are repeated every 20ms and modulated with the message data. The CL code contains 767,250 chips with a length of 1.5s. A linear shift register is used to generate both of these codes – each register has 27 stages with 12 feedback channels. For acquisition and code tracking it is desirable to use the CM code due to its shorter length [10]. Because L2C alternates between CM and CL chips which both have a chipping rate of 511.5KHz, the resulting frequency after time division multiplexing is 1.023MHz which is the same as L1 CA code. Once the signal has been effectively correlated the stored phase will allow for the CL code to be more easily correlated. The L2C code generator is shown in figure 11.

![Figure 10 - CA Code Generation](image1)

![Figure 11 - L2C Code Generation](image2)

3. **Other GNSS Signal Structures and Code Generation**

GPS was the first functional satellite system to become operational, and many of the designs that followed had fundamental structure similar to GPS with some functional differences. The Beidou B1 and B2 signal are generated by multiplexing ranging code with Neumann Hoffman Code – the data is then multiplied with the navigation data and placed onto a carrier. This is completed in the in phase and quadrature directions resulting in a QPSK modulated signal. The code rate of the B1 and B2 signals are 2.046Msps [11].

In Galileo the E6 Commercial service channel is formed by modulo-2 adding the navigation data stream to the channel code seqeuncy (similar to PRN) – the resulting wave is a BPSK (5) with a code rate of 5.115MHz. E6 commercial service pilot channel is formed by modulo-2 adding the pilot channel with a BPSK (5) at 5.115MHz. The total code length is 10230 bits with a code rate of 10.23 Msps after both channels are modulo-2 added [7].

![Figure 12 - Beidou B1 Signal Generation](image3)

III. **GNSS Signal Processing**

A. **Intermediate Frequency Detection and Demodulation**

The correlation process for GNSS signals involves the correlation of an incoming signal with a locally created replica of the signal code. The signal code is sampled at a certain rate that allows for the replica code and sampled signal code to have the same chip period for correlation. After the signal file has been processed into the system, an FFT is performed with the length adjusted to the sampling frequency – this allows for the carrier frequencies to be obtained. The carrier is used to create local oscillators which are multiplexed with the original signal to produce the baseband signal. When the signals are mixed, lower and upper sideband a created – the lower sideband is filtered by a band pass filter. The result of the multiplexing and filtering is the baseband code in either the real or imaginary domain.
The intermediate frequency (IF) for the signal file varies from the actual signal carrier frequency due to the characteristics of the receiver. The IF is created by mixing a carrier with a local oscillator which results in a signal frequency difference – the incoming signal is shifted to an IF before further processing. By reducing the high frequency signal to a lower IF, the signal is able to be processed more easily with standard tools. Because the IF is just a shift in frequency, the signal characteristics such as bandwidth remain the same. The process outlined above determines the IF by identifying the frequency with the largest magnitude and multiplying it by the ratio of the sampling frequency verse the length of the signal FFT. This process spreads the frequency to the correct number of samples with correct orders of magnitude for the theoretical signal spectrum.

B. Correlation

Correlation is simply defined as the similarity between two signals, and the degree by which they match. In correlation all of the possible PRN codes are created at the receiver. This incoming baseband signal is then compared bit by bit to each of the PRN codes by shifting the replica code. Upon each shift, the degree of matching is recorded numerically – the closer that the two streams match the larger the correlation value. The maximum correlation for each PRN set is compared and then the overall maximum is determined. The receiver is then able to detect which PRN code matches, and how many bits across it was aligned. The process for signal acquisition and correlation is shown in figure 13.

![Figure 13 - GPS Signal Acquisition and Correlation Process](image)

IV. GNSS Processing Code

All of the processing of the experimental data is carried out in MATLAB. The signal file is first parsed into the system using a FIFO process, the FIFO being necessary because the files are too large to fit in standard computer memory. Initially an FFT of the signal is performed to verify that the file has been parsed correctly and determine the IF. The maximum frequency value is then used to compute the spread spectrum center frequency for the correct bandwidths. The IF signal in the first sets of sample data are sampled at a rate of 128Msps to create synchronised sine and cosine oscillators to downshift the signal to a nominally zero IF. The parsed signal file is multiplexed with the oscillators both the in phase and quadrature components. The result of the multiplexing is phase and quadrature BPSK signal. The code has been designed to demodulate signals with a BPSK baseband however the correlation process is arbitrary with the chipping rate being able to be changed. The code to process the PSD’s and simple baseband acquisition for Beidou, Galileo, and QZSS has all been written.

The user is able to choose which frequency band they would like to analyse and the respective codes in that band. The code information is then sent to a switch statement that creates the code based on the input. The next stage of the processing is correlation which compares the sampled baseband signal and the locally created replica code – the signal code is sampled to reduce the bit length to 1us which ensures that it has the same bit period as the code. Both the CA and L2C code has a chipping rate of 1.023MHz which allows for both types of file to be processed with the same sampling data. A small sample of the signal file is correlated with the code file by iterating through the sequence. The correlation returns a value at each step which is stored and then processed to determine the maximum value from firstly the single PRN code, and then secondly compared to determine which PRN code matched the most. Upon completion of the processing a range of plots are produced including power spectral densities, baseband signals and the PRN correlation data.
A. Code Generation

The PRN code files used in this project were obtained online from Daniel Pascuals ‘GNSS Code Signal and Spectrum Generation for MATLAB’ [12]. These files were chosen to be used as they were a well accepted and freely available version of the spreading codes. The files were modified to be implemented in the processing code that was created.

The L2C code is interleaved with CL and CM code with one-bit period for each signal. The L2C code is two times the length of the CL code which is 767250 bits long which results in a total length of 1534500 bits. The CM code has a length of 10230 bits which is repeated 75 times in the CL sequence length. The CM code was placed in every second position between each CL bit until the end of the sequence. The CL and CM sequences are inverted relative to each other. The codes were generated based on the code that was required for the specific signal file. The CL and CM code can be analysed separately or as an interleaved L2C – however all options should produce the same PRN. The combinations for code correlation are shown below where each bit is 1us long.

V. Data Collection and Processing

A. Signal Requests and Data Collection

A signal capture request outlining the required GNSS was submitted to Commonwealth Scientific and Industrial Research Organisation (CSIRO) for this project. The list outlined the range of signals that were required including key frequency information and the associated unique identifier – the unique identifier was included so that the location of the satellite could be easily acquired for tracking. A range of signals have been acquired and stored in various formats. The signals are recorded using a radio astronomy long baseline interferometry technique which is stored as a VLBI data interchange format (VDIF).

B. Signal Processing

The signals used for the following process were obtained from Navstar70 which has a PRN of 6. The recordings of the signals were stored as VDIF files with 2 bits per sample. The files were then sampled at 128Msps. An FFT was performed on the signal file to retrieve the IF and calculate the Doppler. The IF was obtained via observation. The resulting Power Spectral Densities (PSD’s) were analysed and compared to known frequency characteristics of the signal to ensure that the process was being carried out correctly and that the files are actually what was expected.

The first file to be processed resulted in the PSD shown in figure 14 which show frequency bandwidths characteristic to the L2 band. The IF for the first file was 31.6MHz. The primary central peak normalized at the IF frequency is the GPS L2C code and the side lobes with a bandwidth of 30MHz in total are likely to be M Code. The second file to be processed resulted in the PSD shown in figure 15 which matches the characteristics of the GPS L1 band. The IF for this file was 32.24MHz which resulted in the CA, M, and P code to be identified.

![Figure 14 - GPS L2 Band Power Spectral Density](image1.png)

![Figure 15 - GPS L1 Band Power Spectral Density](image2.png)
The intermediate frequencies were used to create local sine and cosine oscillators for demodulation. The signal was multiplexed with the coherent oscillators and filtered with a low pass filter (LPF) to produce the baseband of the signal. The LPF was implemented to remove all frequencies greater than the oscillator frequency and had a bandwidth of 1MHz. Although there are other signals present in the L1 and L2 frequency band, the L2C and CA is able to be isolated due to the relatively smaller bandwidth. The baseband BPSK signal of an L2C band is shown in figure 16. The L1 signal was also processed and the baseband BPSK signal is shown in figure 17.

The isolated BPSK signal is processed to be an array of ones and negative ones so that it can be correlated with the local replica code. To ensure that the signal operating at the same bit rate as the replica code, the 128Msps sampled file is stepped through with the same bit length. The structure of the L2C code is such that every second bit is either CL or CM code with every space filled with the opposite. To ensure that the correct bit is being correlated, the signal bit stream is split into two streams – one which should correlate with CM and one that should correlate with CL. Both of the streams are correlated to determine which stream has the highest matched value. The CA code only has one stream which means that the signal bit stream does not have to be split up.

The xcorr function is used in MATLAB to compare a 150 bit sample to the code array, which is 32 shifted versions of the code. The correlation results are saved, and the maximum value and index is obtained to determine which PRN corresponds to the signal file. Figure 18 shows that the maximum correlation of the L2C signal file correlated most significantly with PRN 6 of the interleaved L2C code. Figure 19 shows the correlation of the L1 band with the CA code which also corresponded to PRN 6. The figures above below that the code is able to process both L1C and L2C signals and produce the correct PRN. The correlation results for the L2C code produced a constant magnitude for all of the incorrect PRN’s with the correct value producing a significant jump. The L1C code had a large peak correlation however the other correlation values were not as small in magnitude as the L2C code. The L2C correlation produced a max correlation value that was 3.57 times greater than the magnitude of the averaged incorrect correlations whereas the L1C correlation max value was only 2.7 times greater. It is evident that L2C correlation provides a larger correlation result which is expected due to the length of the L2C code compared to the L1C.
VI. GNSS Signal Catalogue

The GNSS signal catalogue contains a range of signals that have been acquired from CSIRO. Each of the files have been processed through the code explained above to produce PSD plots, spreading code plots, correlation code, associated PRN numbers, and analysis of key frequencies. All of the signal files have been acquired through the same means and processed consistently to ensure standardisation. The signal files have been acquired in both 2 and 8 bit with approximately ten one minute recordings for each bit number and satellite type. The signals have all been processed basically to produce a power spectral density and verifying that the recordings were what was expected.

Figure 20, 21, 22 and 23 show a PSD of each of the GNSS’s that were acquired. The full range of signals is in appendix A. The signal recordings spectrums were analysed using the fundamental code frequency of 1.023MHz to verify whether the recordings are correct. Figure 21 is the PSD of a QZSS L2C signal recording, the main lobe bandwidth was calculated to be 2.045MHz which is expected as it is twice the code frequency. Figure 23 is the PSD of a Beidou B2I and B2Q signal which have bandwidths of 2.46MHz and 20.46MHz which is expected for BPSK(2) and BPSK(10).

![Figure 20 - Galileo E1 OS Signal PSD](image1)

![Figure 21 - QZSS L2C Signal](image2)

![Figure 22 - GPS L5 Signal PSD](image3)

![Figure 23 - Beidou B2 Signal PSD](image4)

The signals were further verified by reducing the recorded signal to the baseband spreading code. The signal is multiplied with the local oscillator with the observed intermediate frequency. Figure 22 shows the baseband spreading code of a QZSS L2C signal with BPSK(1) modulation. It is evident that there is some interference from higher order modulations from other signals in the frequency band.
The signal recordings are of high quality and have been acquired significantly above the noise floor by using a high gain antenna. The quality and range of the signal recordings makes them suitable to be used potentially as a standard for GNSS processing algorithm testing. As stated earlier, the complexity of GNSS has increased significantly over the past decade and the receiver and processing techniques have not evolved in parallel. Because there are a range of non-standard signals coming into service it is important that the receiver techniques are optimised. To validate that the optimal algorithms and processes are being carried out, a set standard of data must be used. The signal catalogue is useful for educational purposes as the data is available freely without the requirement of extensive equipment.

VII. Conclusions

Using a set of standardised signal recordings for algorithms allows for repeatable results and independent verification to be carried out. The recordings will form a benchmark for algorithms to be compared qualitatively. The tool was validated correct with the application of three different signal files from Navstar 70 which demonstrated the ability to process and correlate L1CA and L2C signals. The signal catalogue contains a range of GNSS’s including recordings from Beidou, Galileo, GPS, and QZSS satellites. The data recordings will be available globally for both researchers and students for use in both signal processing and navigation data processing. The processing tool will be used as a learning tool for understanding of post processing and nuances in GNSS signals. It is intended that these recordings will form a baseline for the testing and application of various GNSS signal post-processing algorithms.

Future work towards fully understanding the nuances of GNSS’s signals should be now be considered through (i) the development of a detailed processing and correlation tool for complex signals that exhibits technical modulation methods such as BOC, AltBOC, and CBOC to assist in the generation of receiver techniques and processing algorithms (ii) the development of a thorough theoretical GNSS signal communications package that allows for the modification of theoretical signals – resulting in a detailed understanding of GNSS signal theory.

VIII. Acknowledgements

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IX. Works Cited


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