Multi-channel GPS RF Data Logging and Playback Facility

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ABSTRACT

The development and initial testing of a GPS data logging facility is described. The main purpose of the facility is to record digital data from a GPS L-band antenna array during field trials and later play the data back through different antenna electronics units. The hardware can also be used as a multi-channel GPS signal generator which could prove very useful for evaluating adaptive antenna arrays. The current system can log raw RF data from four antenna channels at a 20 MHz bandwidth at either L1 and/or L2 for a duration of 2 hours. The data is stored on hard-drives and can then be played back on four antenna channels. As this system is designed for testing high dynamic range anti-jam units, the overall dynamic range had to be maximised and the mismatch between antenna channels minimised. The overall system design as well as initial test results of the dynamic range and mismatch obtained in the current system will be presented.

KEYWORDS: GPS, GPS data recording, L-band data capture

1. INTRODUCTION

GPS jamming trials are essential in evaluating the actual performance of emerging GPS anti-jam technologies in the field. This is of particular concern due to the rapid proliferation of GPS receivers, which are being integrated into an increasing number of systems, including safety of life applications, such as aircraft. However, jamming trials are costly and have the potential to disrupt civilian GPS users. There is thus a need to obtain the maximum benefit from each trial. One way of achieving this is to log the raw RF data directly from the antenna elements. The stored data can then be later replayed through a large range of anti-jam units in the laboratory, thus exercising them against the same jamming scenario encountered in the trial.
In this paper the description of a multi-channel GPS data recording and playback facility that was developed by the CRC for Sensor Signal and Information Processing at the University of Adelaide for the Australian Defence Science and Technology Organisation is described. A four channel unit has been built, tested in the laboratory and successfully deployed in experimental field trials to collect specific signals of interest.

2. SYSTEM REQUIREMENTS

The main parameters of any data logging system include the number of channels that can be recorded, the signal bandwidth in each channel and the fidelity of the recorded data.

The number of channels recorded equals the number of GPS antenna outputs. For example, typical GPS anti-jam adaptive antenna arrays have up to 8 antenna elements. It is thus desirable that the data logging system be able to record time-synchronised data from up to 8 antenna elements although with the advent of dual polarised GPS antennas this number may be doubled in the future. However, due to budget constraints only four channels were implemented in the current system.

The bandwidth of each channel needs to be at least 20 MHz to record P-code signals, while a 24 MHz bandwidth may be sufficient for M-code signals. The bandwidth of the current system is set to 20 MHz, with possible future expansion to 24 MHz.

The fidelity of the replayed data should be such that the overall recording operation maintains the integrity of the original data and the stringent requirements of GPS anti-jam provide a useful and practical set of design criteria. Thus the design goal set was that the facility should be able to record GPS signals in the presence of various interferences with sufficient accuracy such that when the total recorded waveforms were played back through a typical multi-channel GPS anti-jam unit the anti-jam characteristics were not degraded. To ensure this is the case, several key system parameters were considered, including the system noise figure, dynamic range and channel mismatch.

The recording system will always have a finite noise figure and will thus introduce some extra white noise onto all the antenna channels, which will degrade the SNR of all GPS signals.

The dynamic range of the recording system will potentially limit the interference cancellation ratio of the anti-jam unit (input over output interference power) by introducing non-linear distortion on the recorded signal. It was thus necessary to ensure that the dynamic range of the recording system was high enough so that the non-linear distortion levels did not limit the cancellation ratio of the anti-jam unit under test. Commercially available anti-jam units typically achieve cancellation ratios between 20 and 40 dB, these cancellation ratios were used to determine the dynamic range requirements of the data recording system.

Finally any significant mismatch in the frequency response between channels may also impact the achievable cancellation ratio of most anti-jam unit. Whilst channel mismatch may not be an issue for some high end anti-jam units that incorporate space time/frequency processing, it was decided to incorporate equalisation filters to minimise the effect of channel mismatch.
3. SYSTEM OVERVIEW

A top level diagram of the data logging system and photograph of the equipment is given in Figure 1. The current system has four channels, but it can be expanded to 16 channels in the future.

In record mode, data from each antenna enters the RF down converters, which amplify, band-limit, and convert each channel to an intermediate frequency of 75 MHz. Each down converted signal is then sampled by a 100 MHz, 14 bit A/D converter. Further decimation filtering and channel equalisation is then carried out in an FPGA, before the data is streamed onto hard disks. Due to the high data rates required to digitise a 20 MHz bandwidth, dedicated hard-drive StreamStor controllers were used for each data channel. The data is transferred directly to these StreamStor controllers via an FPDP bus (Front Panel Data Port) without going through the PCI bus, which allows the system to be easily expanded without causing data throughput bottlenecks. The final sample data sample rate, after the decimation filters, is 50 MHz, resulting in a data rate of 100 MB/s per channel. Each StreamStor controller can handle up to 200 MB/s, thus two A/D converter channels are connected to each StreamStor controller card.

In playback mode the data is streamed from the hard drives onto the FPGA at 50 MSPs (100 MB/s) per D/A channel. Interpolation filters are then applied within the FPGA which increase the sample rate to 200 MSPs per D/A. The outputs from the 14 bit D/A converters are then band-limited, attenuated and converted back up to the input RF frequency at L1 or L2.
4. KEY PERFORMANCE MEASURES

This section briefly considers the expected performance of the system in terms of noise figure, dynamic range and channel matching.

4.1 System Noise Figure

The system noise figure will be considered in two parts: the recording and then the combined recording plus playback system.

The noise figure of the data recording sub-system is fundamentally limited by the noise figure of the first amplifier, which is approximately 3 dB in the current system. Any cabling prior to the first amplifier will further increase the noise figure. The noise figure is potentially degraded further by the A/D converter if the RF front end does not have sufficient gain. In the current system the gain of the RF front end was set so that the thermal noise power in the 20 MHz signal bandwidth was approximately 10 dB above the A/D quantisation noise power. This will reduce the dynamic range of the A/D by about 10 dB, but results in a negligible loss in noise figure. Thus the overall noise figure of the data recording sub-system should be slightly higher than 3 dB.

The noise figure of the overall system is estimated by simply modelling the data recording system as a single amplifier with gain \( A_1 \) and noise figure \( F_1 \), and the data playback system as a single attenuator with an attenuation of \( L_2 \) and the input stage of a GPS receiver connected to the anti-jam unit as a single amplifier with a noise figure of \( F_3 \). The overall noise figure, \( F \) is thus given by:

\[
F = F_1 + \frac{1}{A_1} + \frac{F_3 - 1}{L_2} \tag{1}
\]

The overall noise figure thus depends on the amount of attenuation in the play-back system.

Two cases were considered:

(a) The attenuation in the play-back sub-system equals the gain in the data recording sub-system. In this case the final signal output levels will be the same as the recorded signal levels. It can be shown that in this case the noise figure of the overall system is approximately given by \( F = F_1 + F_3 \), assuming \( A_1 \) is much larger than unity. Thus the overall system noise figure is simply the noise figure of the combined data record/playback system plus the noise figure of the low noise amplifier (LNA) in the GPS receiver.

(b) If the output power levels were significantly higher than the input power levels, then the noise figure of the overall system, \( F \), would approach \( F_1 \).
4.2 Dynamic Range

The dynamic range of the data recording system is driven mainly by the A/D converter. The 100 MHz 14 bit A/D has a maximum SINR (Signal to Interference plus Noise Ratio) of around 70 dB for a sinusoidal signal. As the noise power from the RF front end is amplified to be 10 dB above the A/D noise power, the dynamic range of the A/D is reduced to 60 dB for sinusoidal signals. For noise like signals, the dynamic range is typically reduced by a further 10 dB, resulting in an overall dynamic range of around 50 dB, which should still be adequate for testing anti-jam units with cancellation ratios up to 40 dB.

Another factor that limits the dynamic range of the system is non-linear distortion in the analogue components of the RF front ends. An approximate expression for the dynamic range is given by:

\[
\text{Dynamic Range} = \frac{2}{3} (\text{IIP3} - \text{MDS})
\]

where IIP3 is the combined input IP3 point of all the components used in the down converter referenced to the input, and MDS is the minimum detectable signal power, which is assumed to be equal to the thermal noise power in the signal bandwidth (20 MHz bandwidth), i.e., the noise floor. The components in the RF front end were chosen such that an overall dynamic range of 65 dB was achieved in the RF front end, which should be more than adequate for testing anti-jam units with interference cancellation ratios over 40 dB.

4.3 Channel Matching

Finally, the matching in phase and amplitude across each channel should be good enough to give cancellation ratios of up to 40 dB. It was very difficult to achieve such accurate matching in the analogue filters, while also maintaining high out-of band attenuation levels of over 50 dB. Thus it was decided to allow some mismatch in the analogue filters and amplifiers and apply digital equalisers in the FPGA to compensate for any mismatch. Provided the mismatch originates from the analogue filters, and is not due to non-linear distortion then using a sufficient number of taps allows for frequency dependent phase and amplitude matching across the signal bandwidth.

5. MEASURED PERFORMANCE

In this section laboratory measurements of system performance are presented

5.1 System Noise Figure

The noise figure of the recording sub-system was estimated to be around 4 to 5 dB. This is slightly higher than the expected noise figure of 3 dB, possible due to cabling/connector losses prior to the first amplifier or inaccuracies in the measurements.
To check the noise figure of the combined data record and playback system, live GPS signals were recorded and then played back into a GPS receiver as shown in Figure 2 below.

![Figure 2 System Noise Figure Test](image)

The GPS receiver used in these tests required an active antenna, thus an amplifier with a noise figure of approximately 3 dB was inserted prior to the GPS receiver. This amplifier drove the noise figure of the RF front end in the GPS receiver.

Firstly the signal from the GPS simulator was played directly into the GPS receiver, as shown in Figure 2(a). The GPS signal power at the output of the simulator was set to $-150$ dBW, which corresponds to a C/No of approximately 54 dB. The C/No values measured on the GPS receiver were around 47 dB. A 3 dB loss is expected due to the noise figure of the amplifier, the remaining 4 dB loss are assumed to be due to processing losses within the GPS receiver (eg. correlation losses due to band-limiting and digitisation) as well as additional thermal noise introduced by the GPS simulator.

Secondly the noise figure of the data recording/playback system was estimated by recording a signal from the GPS simulator and then playing it back into the same GPS receiver as shown in Figure 2(b). From equation (1), the noise figure of the complete system will depend on the relative power level of the recorded and played back signal. Initially the played back signal was 12 dB above the recorded signal, and thus the total noise figure should approximately equal the noise figure of the data recording system, $F_1$. The actual C/No values observed on the GPS receiver were around 44 dB, which by comparison with the previous result from the set-up in Figure 2(a) indicates a total noise figure of $3 + (47 - 44)$ dB = 6 dB. If the loss of the cable connecting the simulator to the data recording system is accounted for (1 dB loss) the total system noise figure is approximately 5 dB. Next the output level of the data playback system was reduced by 12 dB, to make the final output signal levels equal to the input signal levels. In this case the total noise figure should be equal to the noise figure of the data recording system plus the noise figure of the amplifier, and thus the C/No values on the GPS receiver should drop by 3 dB. In practice a drop of 2 dB was observed.
5.2 Channel Mismatch

Additional tests were performed to estimate the channel mismatch and the resulting limit on the interference cancellation ratio. Broadband noise was played into two of the receiver channel and the data logged. The initial amplitude mismatch between the two channels across the frequency band is shown in Figure 3(a).

![Channel Mismatch Over Signal Bandwidth](image1)

![Cancellation Ratio](image2)

(a) Channel Mismatch  (b) Cancellation Ratio

**Figure 3** Channel Mismatch Test

The amplitude mismatch in the analogue filters is over 1 dB over the entire frequency band, however the mismatch is reduced to less than 0.05 dB after equalisation with a 7 tap digital equaliser. The fact that the signal can be equalised so well indicates the absence of non-linear distortion in the RF front end. The equalised signal is then subtracted from the other channel to determine the achievable interference cancellation ratio. The results are shown in Figure 3(b), where the black line indicates the spectrum of the digitised interference signal, and the blue line the error signal after the two channels are subtracted from each other. The red line shows the spectrum of the thermal noise, and indicates that the cancelled signal is within 3 dB of the thermal noise on one of the channels suggesting complete interference cancellation. The difference between the black and blue line is 50 dB, which demonstrates that after equalisation the system is capable of maintaining interference cancellation ratios of over 50 dB. The digital equalisers have now been incorporated directly in the FPGA code, but further test are required to estimate how often the coefficients need to be updated to maintain adequate channel matching.
6. CONCLUSIONS

A four channel GPS data recording facility has been designed and built using a dedicated A/D board with an on board FPGA. Preliminary testing supported by recent field trials indicates that the system is capable of recording GPS signals in the presence of interferences with a high degree of accuracy.

The primary design goal of the system of being able to record GPS interferences for the off-line testing of modern multi-channel GPS anti-jam units has been achieved and future, alternative uses of the facility are being considered.

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