Bandpass calibration of a wideband spectrometer using pulse injection

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Abstract We present a novel time domain concept for determining the bandpass response of a system by injecting a nanosecond pulse and capturing the system voltage output. A pulse of sub-nanosecond duration contains all frequency components with constant amplitude up to 1 GHz. Hence, this method can accurately determine the system bandpass response to a broadband signal. A train of pulses are coherently accumulated providing very high signal-to-noise calibration. The basic concept is demonstrated using a pulse generator-accumulator setup realised in a Bedlam board which is a high speed digital signal processing unit. The same system was used at the Parkes Radio Telescope between 2–13 October 2013 and we demonstrate its powerful diagnostic capability. We also present some initial test data from this experiment.

Keywords Astronomical instrumentation, methods and techniques — Methods: bandpass calibration, pulse calibration, nanosecond pulse generator

1 Introduction

High precision bandpass calibration of radio telescopes and wideband spectrometer systems can be accomplished by using the information obtained from the raw voltage samples at the system output, recorded prior to obtaining the correlation and Fourier transform. Such additional information, if combined with conventional methods of bandpass calibration in the frequency domain, would increase the calibration accuracy which is critical for a number of astronomical observations, for example...
precision cosmological measurements. In this paper we explore a technique of precision calibration of wideband systems. In this method, a short pulse of nanosecond duration is injected into a system being measured and the raw voltage samples at the sampler output are recorded after coherent accumulation over a duration of time. With an ideal system performance, injection of a single pulse, which is equivalent to a source of broadband noise, should result in a single pulse at the output of the system. The output pulse will be broadened in time and its spectrum should give the response of the system to a broadband noise signal. If the system response to the injected pulse is complex, the Fourier transform of the measured pulse gives the magnitude and the phase of the bandpass.

Based on these ideas, we develop a system using a nanosecond pulse generator and digital signal processing based on a Bedlam board \[1]. A train of short pulses is generated at a user specified rate and injected into the system the bandpass of which is being measured. Individual pulses are attenuated sufficiently to avoid receiver system non-linearity. In order to achieve an improved signal-to-noise ratio many injected pulses are accumulated coherently by the Bedlam board and the accumulator output is then dumped in a general purpose computer after a sufficiently long integration time to achieve the desired signal-to-noise ratio.

In section 2, we describe the advantages and disadvantages of a pulse calibration system compared to conventional frequency-domain bandpass calibration. Section 3 contains a detailed description of the pulse generator and the Bedlam board digital processor used in our experimental work. Application of this calibration method to a system like the SARAS (Shaped Antenna Measurement of background RAdio Spectrum) spectrometer \[2] where the signal propagation paths and other non-idealities are well understood is elaborated in section 4. We use a simple experimental setup which mimics some of the SARAS signal paths to demonstrate the functionality and sensitivity of this pulse calibration system. Finally, in section 5 we show some results when such pulses are injected into the Parkes radio telescope.

2 Comparison between coherent and incoherent calibration

The most widely adopted method for calibration of broadband spectrometers is to inject broadband calibration noise into the system somewhere along the signal path, before or after the antenna and measuring the system response to the calibration noise by taking correlation and Fourier transform of the system output. A short pulse of nanosecond duration has a broadband spectrum. Additionally, the phase of the constituent frequencies is a linear function of frequency, unlike that of broadband calibration noise where the phases of the constituent frequencies are uncorrelated. Therefore, if a pulse is injected into the system instead of a broadband calibration noise, the complex Fourier transform of the system output will yield the magnitude and phase of the system bandpass response. Also, system responses to the subsequent pulses will be coherent with each other. We exploit this property of a short pulse and determine a system bandpass response by investigating the voltage samples at the output of the system, prior to taking correlation and Fourier transform.
While in the frequency domain the pulse energy is distributed across the band, in the time domain, it is concentrated at the sample value where the pulse appears. Therefore, to obtain a required signal-to-noise ratio, the accumulation time needed for bandpass measurement by measuring the pulse is smaller by a factor of number of samples than the time over which the pulse spectrum should be integrated in the frequency domain. Also, in real systems, multi path propagation of the injected pulse internal to the system result in a set of delayed pulses at the output. These reflected pulses manifest themselves in the spectral domain in the form of sinusoidal ripples in the pass band of the system. Multiple reflections over the same characteristic length will generate ripples of higher harmonic frequencies. The amplitude of higher order reflections will decrease and may not be easily detectable using a spectrometer. In the time domain, however, the energy of the reflected pulse power is also concentrated at the sample value where the reflected pulse appear. Hence, the higher order internal reflections are easy to detect. For this reason, this time domain technique becomes a valuable diagnostic of the system behaviour.

The major advantage of bandpass calibration with coherent pulses can be illustrated by examining the relevant scaling relationships. Consider a signal with a root-mean-square voltage $\sigma$, divided into $N$ segments each of length $S$ samples, for a total duration of $T = NS$ sampling intervals. Each segment contains a delta-function pulse with amplitude $A_p \sigma$. A single pulse has a signal-to-noise ratio of $A_p$ in the time domain, or $A_p/S$ in the frequency domain, in which the pulse is distributed over $S$ channels. More conventionally, we would give the signal-to-noise ratio in terms of the power spectrum, where it takes the value $A_p^2/S$.

If the pulses from $N$ segments are combined coherently, the signal-to-noise ratio increases to $\sqrt{NA_p}$ in the time domain, or $\sqrt{NA_p}/S$ in the frequency domain and $NA_p^2/S^2$ in the power spectrum. In terms of the total integration time, this last expression becomes $TA_p^2/S^3$; i.e. the signal-to-noise ratio of the bandpass calibration increases linearly with the integration time.

For comparison, consider conventional incoherent calibration with a continuous added calibration signal of white noise, with root-mean-square amplitude $A_n \sigma$. The signal is divided into $N$ segments each of length $S$ samples, which are individually Fourier-transformed. The signal-to-noise ratio after the Fourier transform, for the spectrum of a single segment, is $A_n$, or $A_n^2$ in the power spectrum. If $N$ such power spectra are summed, the signal-to-noise ratio becomes $\sqrt{NA_n^2}$. In terms of the total integration time, this last expression is $\sqrt{T/SA_n^2}$; i.e. the signal-to-noise ratio of the bandpass calibration increases as the square root of the integration time.

Clearly, for a sufficiently long integration time, coherent bandpass calibration will have a greater signal-to-noise ratio. The crossover point occurs when

$$TA_p^2/S^3 = \sqrt{T/SA_n^2}$$

$$T = (A_n/A_p)^4S^5.$$  (1)

If non-linearity is the limiting factor on the permissible amplitude of the calibration signal, then $A_p$ may be larger than $A_n$ by a factor of a few, as it is necessary only that the peak of a calibration pulse lie within the linear range of the system, whereas a calibration noise signal should be a factor of a few below the limit of this range to
ensure that occasional fluctuations of several times the root-mean-square voltage do not exceed it. Consequently, the first factor in equation 2 may be somewhat lower than unity. The strongest dependency, however, is on the number of samples $S$ in a single Fourier transform, which determines the number of channels in the spectrum and hence the frequency resolution. If the required frequency resolution is low, the signal-to-noise ratio from coherent bandpass calibration will begin to exceed that from incoherent calibration at quite low values of $T$ (measured here in sampling intervals). If the required frequency resolution is high, incoherent calibration may continue to give a higher signal-to-noise ratio until other effects (causing temporal variation in the bandpass) start to dominate the calibration uncertainty.

3 System description

The basic experimental setup for system bandpass calibration is shown in figure 1. We inject a nanosecond pulse to a system being calibrated. System output is sampled and the output samples are accumulated in an accumulator. The system components are described below.

![Diagram of system components](image)

**Fig. 1** Pulse accumulator setup.

3.1 Nanosecond pulse generator

The pulse generator we used for this work and the output pulse it produces is shown in figure 2. This pulse is injected into the system being measured and the system output is sampled.
Since radio telescope receivers have high gain and sensitivity only a low voltage pulse is required, as it is desirable to keep the input voltage excursion of the pulse below the input noise power level, to ensure the system retains a linear response to the pulse input. The pulse is generated with a circuit based upon a high speed positive emitter coupled logic (PECL) D-type flip-flop with reset. The pulse generator board works in two modes: Asynchronous triggering from an on board time base or externally triggered from a supplied event. The generated pulse has the following properties:

- Output pulse width: 350 ps (50% width).
- Output rise/fall time: 240 ps.
- Pulse amplitude: 400 mV unipolar pulse into 50 Ω.

The low intrinsic jitter of 0.2 ps for the PECL D-type flip-flop allows synchronous integration of the received pulses to be performed to high precision as this is negligible compared to the sample period of the following ADC, which is approximately 1 ns. The narrow pulse width and rise/fall time ensure the pulse contains spectral content up to a few GHz, which was sufficient for our purposes. The power requirement for the pulse board is 3.6 V at 100 mA.

3.2 Bedlam Board

In our experiments the trigger signal is sourced from a custom general purpose high speed digital signal processing board, known as Bedlam. The Bedlam board consists of 8 RF input channels feeding two 8-bit quad-channel ADCs (EV8AQ160). The digital sample data from each of two channels of the ADCs are directed to one of four DSP oriented FPGAs (XC5VSX95T). A final logic oriented FPGA (XC5VLX30T) provides dual fast Ethernet and general purpose I/O interface from the board.

The pulse generator output is fed into the system being calibrated and the system output is captured by the Bedlam board (figure 1). In order to improve the signal-to-noise ratio the sample voltages are accumulated inside the Bedlam FPGAs. The accumulator buffer length is programmable with a buffer length of 8192 samples used in the experiments described here. A sampling rate of 1.024 GHz is used such
that each buffer is 8 $\mu$sec long. The pulse generator is then triggered at a rate of 125 kHz so that one pulse is produced every 8 $\mu$sec. The trigger is synchronised with the pulse generator so the pulse amplitudes will be added coherently. The Bedlam board is programmed to dump the accumulated buffer using an Ethernet interface to a general purpose computer, when the required accumulation count is reached. At the pulse repetition rate of 125 kHz, and duration of 1 second, $1.25 \times 10^5$ pulses are accumulated resulting in a 350:1 improvement in the signal-to-noise ratio of the captured pulse. Longer integration periods can be used if desired. Initial tests showed some repetitive weak additive signals caused by sampling clock leakage into the ADC. Since these are clearly synchronous with the sampling clock they were removed by differencing the two halves of the output buffer with the pulse present in only one half, but the clock contamination equal in both halves. The Bedlam board functional schematic and accumulator block diagram are shown in figures 3 and 1 respectively.

Figure 4 shows a typical measured pulse, accumulated over 1 second, after differencing the two halves of the accumulation buffer. Only the first hundred samples are shown to show the output pulse profile. This is the pulse, fed directly to the accumulator, without the system being measured inserted in between the pulse generator and the accumulator.

**4 Experimental setup for bandpass measurements**

The block diagram of the system under test is shown in figure 5 with the pulse generator connected at its input and the accumulator connected to its output. Two channels of the Bedlam board are used with identical accumulator setup and common triggers. After injection, the short pulse is band limited by a lowpass filter of bandwidth up to 500 MHz. Filter output is split into two halves by a power splitter and one is fed
directly to an accumulator via channel B of the Bedlam board output which is used as a reference. The other half is fed to channel A via a T connector. The third input of the T is connected to a 10 dB attenuator via a 5 m long cable and the output of the attenuator is connected to a open load. A part of the incident wave at the input of the T reached channel A of the Bedlam board directly whereas the other part is reflected from the attenuator output and appears as a delayed pulse at the accumulator input in channel A.

Figure 6 shows the direct and the delayed pulses at the output of the accumulator in channel A after 1 second integration. Bandlimiting the signal to 500 MHz results in ringing in the time domain of the pulse. Figure 7 shows the reference pulse in channel B and the pulse received in the channel A. Since the pulse power is decided between the direct and the reflected pulse, the direct pulse amplitude is smaller in channel A compared to the same in channel B.

The true spectrum of the band limited pulse along channel B with the spectrum of the pulse along channel A are shown in figure 8. Introduction of the T and long cable in channel A have two obvious effects. In the time domain the delayed attenuated pulse is clearly seen with a delay of 120 ns and this caused the fast (16 MHz) ripple in the channel A voltage amplitude spectrum. The voltage amplitude spectrum also shows a 320 MHz ripple which correspond to a 6 ns delay and is caused by reflection of the direct pulse between the Bedlam board input and the T output. The 6 ns delay is less conspicuous in the time domain as it is confused with the pulse oscillation caused by the sharp cut-off in the low pass filter.

We have used this setup to make a number of tests of the stability of the coherent pulse calibration scheme. The sample variance for 600 samples each accumulated over 1 sec was 0.06% for the direct pulse and the dynamic range in the 1 sec samples
is 1500:1. This system shows a DC drift over a time scale of 2–5 mins in the output at the same 1500:1 level which we have not pursued.

Since the fractional power in the ns pulse is extremely small compared to the total system temperature, a pulse injection system can be run continuously during any observation to accurately determine the system bandpass response and calibrate the system output. The short duration of the generated pulse enables coherent accumulation of millions of pulses in just one second which results in an increase of 1000:1 in the signal-to-noise ratio compared to that of a of a single pulse. This is a 60 dB increase in power. If the injected pulse power can be made $> T_{sys}$ in a system without saturation, the integration time could be substantially reduced.

5 Pulse calibration tests with the Parkes radio telescope

Three Bedlam boards were used at the Parkes radio telescope between 2–13 October (2013), in an experiment intended to detect pulsed radio emission from atmospheric particle cascades initiated by cosmic rays or gamma rays. The Bedlam boards were used in an alternate mode — for which they were originally designed, for the LU-NASKA experiment [3] — in which they detect and store individual pulses. This experiment required high-precision timing calibration between the beams of the Parkes 21 cm multibeam receiver [4] in order to discriminate between radio-frequency interference, which typically appears in multiple beams simultaneously, and atmospheric particle cascades, which are expected to move from beam to beam with a timescale of nanoseconds. This calibration was achieved with the same pulse generator system.
Fig. 6 Channel A output after 1 second integration of the 1 MHz pulse train.

Fig. 7 Comparison of the channel A and channel B output after 1 second integration of the 1 MHz pulse train.

described in section 3 and so provides a test of this system on an operating radio telescope.
The gross physical experimental setup is shown in figure 9. The signal from the pulse generator was transmitted from the apex of the parabolic dish, received at the focus, and ultimately returned to the Bedlam board, similarly to figure 1. The system under test in this case comprises the large-scale structure of the telescope, the multibeam feed, and the remainder of the receiver signal path, including low-noise amplifiers, downconversion and attenuation. Transmitting the pulse from the apex of the dish was convenient and flexible for this experiment, but may differ in some respects from observations of astronomical sources, which are in the far field of the telescope.

The pulse generator was set to produce pulses at a cadence of 125 kHz. Figure 10 shows the accumulated pulse profile after one second of integration. The direct pulse is most prominent, but there are eight additional pulses also visible, with successively smaller amplitudes, with a spacing of \( \sim 180 \text{ ns} \). These result from the partial reflection of the transmitted pulse, first from the base of the focus cabin, then from the vertex of the dish. These points are separated by 26 m, with a round-trip light travel time matching the observed pulse spacing. In the frequency domain, these reflections create a ripple in the bandpass of the system, which is a well-known problem seen in most radio telescopes; for Parkes, the ripple has a period of 5.7 MHz [5], matching the inverse of the pulse spacing. The higher-order reflections (i.e., the second and subsequent reflected pulses) will result in harmonics which introduce sharper ripples in the system bandpass.

The use of the Bedlam single-pulse storage mode provided an opportunity to directly test the coherent pulse accumulation process. In this mode, the Bedlam board maintains a buffer (with a size of 2 \( \mu \text{s} \), in this case) of the digitised signal in each
Fig. 9 Experimental setup for pulse calibration tests with the Parkes radio telescope. The pulse is transmitted in the band 0.7–4 GHz from the (red) log-periodic dipole antenna (LPDA) at the vertex of the dish surface, and received by the 21 cm multibeam receiver at the focus with a narrower bandwidth (BW) of 300 MHz centred on 1.38 GHz. Some fraction of the pulse is reflected (yellow) from the focus cabin, and is responsible for the reflected pulses described in the text. The received signal is transmitted by cable (dashed) from the focus to a Bedlam board in the control tower. (Schematic by J.M. Sarkissian.)

channel, and copies the contents of the buffers to storage when a pulse is detected. This copying takes 28 ms (for this buffer size) during which the system is unable to respond to further pulses, so pulses can only be recorded in this manner at a cadence of 36 Hz, or around every 3500th pulse given the pulse generation cadence of 125 kHz. These individual pulses can then be aligned based on sample counter values, and combined coherently in software.

The signal-to-noise ratio of pulses coherently combined in the time domain is shown in figure 11. With no further processing, the first $\sim 100$ stacked pulses display no improvement in the signal-to-noise ratio. In retrospect, this is an expected result of the randomisation of the signal phase during downconversion, due to the random additional phase introduced by the local oscillator [1]: both the pulses and the noise are combined with random phases, so the ratio between the two does not change. With the stacking of $\gtrsim 100$ pulses, some fraction of the pulse amplitude does combine coherently, with the signal-to-noise ratio displaying the usual scaling relationship. This may be due to an asymmetric non-linearity in the system response, which would have a consistent phase in the post-downconversion signal. This would also explain the presence of the accumulated pulse trace in figure 10.

The significance of the local oscillator phase was further tested by locking the local oscillator and the sampling clock to a common timing reference, with a 0.02 Hz frequency offset for the former. The one-second accumulated pulse profiles increased in amplitude, as expected from fully coherent combination of the pulses, and dis-
played regular variation in the pulse profile with a period of $\sim 1$ min, as expected from the phase drift caused by the frequency offset. However, the amplitude of the generated pulses in this test was set at a level too low to trigger their storage for individual analysis. Instead, the individually-captured pulses described above were multiplied by the phase factor in the frequency domain which maximised their peak amplitude, in order to consistently set the phase of each pulse to a value close to zero. After this alignment of phases, the pulses combined fully coherently, as seen in figure 11.

The effect of coherent stacking of the pulse on the power spectrum is illustrated in figure 12. Despite the low duty cycle of the pulse and consequent small contribution to the system power — allowing it to be operated continuously with little effect on the noise level — when coherently stacked it rapidly scales to dominate the power spectrum. Approximating the pulse as a delta-function, with a flat spectrum, this provides a measure of the bandpass of the system.

6 Summary

We have explored a new technique for calibration of wideband spectrometers by coherent accumulation of the system output when short pulses are injected at the system input. We describe the pulse generator and the Bedlam board which are used to realise the pulse generator-accumulator setup. We argue for a method of determining the system bandpass response accurately by recording the voltage samples at the system output prior to taking the correlation and Fourier transform in any spectrometer. In an experimental setup where signal propagation paths are similar to those in the
SARAS spectrometer, we determine the system bandpass response from the voltage samples recorded by the Bedlam board. The system is used in the Parkes Radio telescope for determining the bandpass response of the the 21 cm multibeam receiver system. The key advantage of bandpass calibration using nanosecond pulse injection is that the duty cycle of the injected pulses as well as the fractional power is extremely small and therefore the system could be run continuously at the time of observation. The small duty cycle of the pulse requires a very small fraction of the total observing time to determine the system bandpass response. Accumulation of the pulses with very low fractional power results in detection of the repetitive weak signals that are generated due to various system non-idealities.

Any precision measurements at low radio frequencies will require calibration of system bandpass response to adequate accuracy based on their particular science goal. For example, detection of the global signature of the epoch of reionization in the background radio spectrum requires a calibration accuracy of $10^5$. Baryon Acoustic Oscillations are the weak spectral features imprinted on the redshifted 21 cm background having a spectral fluctuations of the order of $10\mu K$ at a redshift of $z \sim 1$. Detection of such spectral fluctuations in the redshifted 21 cm background at $z = 1$ requires a bandpass calibration accurate to $10^6$. Recombination of the primordial plasma to form primordial neutral hydrogen results in a broad spectral ripple in the spectrum of the cosmic microwave background around 2–20 GHz arising due
to the recombination lines. The amplitudes of such spectral features in the Cosmic Microwave Background spectrum are of the order of 50 to 100 nK and in principle are observable at frequencies $\nu > 1.42$ GHz. Detection of such spectral signatures requires a calibration accuracy of $> 1:10^9$. Strategic implementation of the pulse calibration system could in principle enable us to achieve this.

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