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Measurement and Analysis of Impulsive, Transient Sources of Radio Frequency Interference and their Impact on Radio Telescopes

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This paper presents the measurement and analysis techniques employed by the SARAO RFI team to detect transient impulsive RFI and quantify its impact on MeerKAT and the future SKA-Mid telescope. Impulsive RFI measurement is discussed, emphasising the importance of analysing the problem in the time domain and its contrast to typical EMC measurements. Tradeoffs of the instrumentation utilised to acquire the required data are outlined. The compliance metric for impulsive RFI primarily relates to the risk of instantaneous saturation of the telescope receiver. Time occupancy statistics and pulse train repetition rate are under investigation and will inform an update to the SKA impulsive RFI specification.

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1. Introduction

The Square Kilometer Array (SKA) project is an international collaboration to construct one of the world's largest radio telescopes [1]. The SKA Mid-Frequency Telescope is under construction in South Africa's Northern Cape region, around the South African Radio Astronomy Observatory's (SARAO's) MeerKAT telescope. Measuring impulsive Radio Frequency Interference (RFI) is less mature than persistent spectral RFI, and its effects on radio astronomy are nontrivial to quantify. Both self-generated impulsive RFI from telescope equipment and intermittent RFI from the construction of the SKA must be considered. We have developed instrumentation, measurement protocols and data analysis techniques for characterising impulsive RFI. This paper presents our approach to pulsed RFI on MeerKAT and SKA-Mid.

2. Interference

RFI is one of the most significant risks to radio astronomy. Depending on the type of signal, it can affect the different science data processing pipelines in different ways. Narrow bandwidth continuous signals can severely impact spectral line science, and broadband spectral emissions can obscure continuum mapping. For observations requiring long integration, like the major imaging surveys, sporadic interfering signals with a low time occupancy rarely affect the data products significantly [2]. Because they appear briefly and inconsistently, their effects can be smeared out over the observation. However, they can severely impact pulsar survey projects, which search for celestial transient signals and cannot rely on long integrations to minimise terrestrial pulses' effects. SARAO's RFI team protects MeerKAT and the future SKA from interference, therefore requiring the capability to detect and deal with impulsive transient signals.

3. EMC Measurement

Electromagnetic Compatibility (EMC) measurement of persistent sources is a mature process. SARAO conducts its measurements using various reverberation chambers, open-area test sites, and an anechoic chamber. Test procedures generally involve using a spectrum analyser-type receiver to capture a spectrum of emissions from the device under test. The acquired spectrum is compared to the applicable standard.

3.1 Radio Astronomy Protection Levels

The South African Radio Astronomy Standards (SARAS) were developed to ensure compliance with radio science needs and the SKA Thresholds. They are based on the ITU-R RA.769-2 standard. SARAS protects both continuum and spectral line observations. For continuum observations (1), a bandwidth ratio of 1% of the observing frequency is required. For spectral line observations (2), a bandwidth ratio of 0.001% is used, resulting in a 15 dB relaxation of the continuum threshold. The following equations [3] are defined in power spectral density (PSD) for $50\text{MHz} \leq f < 2\text{GHz}$. They provide a standard for persistent narrowband signals in the frequency domain.

$$PSD_{cont}[\text{dBm/Hz}] = -17log_{10}(f[\text{MHz}]) - 192 \tag{1}$$

$$PSD_{spec}[\text{dBm/Hz}] = -17log_{10}(f[\text{MHz}]) - 177 \tag{2}$$

3.2 Sensitivity

RFI measurements must be extremely sensitive to evaluate against the stringent levels the SARAS thresholds allow. Low-noise amplifiers (LNAs) enhance the system's signal chain gain and minimise the system temperature. The resolution bandwidth (RBW) can be narrowed to lower the noise floor of the measurement; however, it must be kept at least as large as the bandwidth of the measured signal. The only mechanism remaining to increase sensitivity is integrating over time to better resolve the signal from the noise, as described in the radiometer equation (3). This method requires that the signal of interest is persistent and present throughout the integration period.

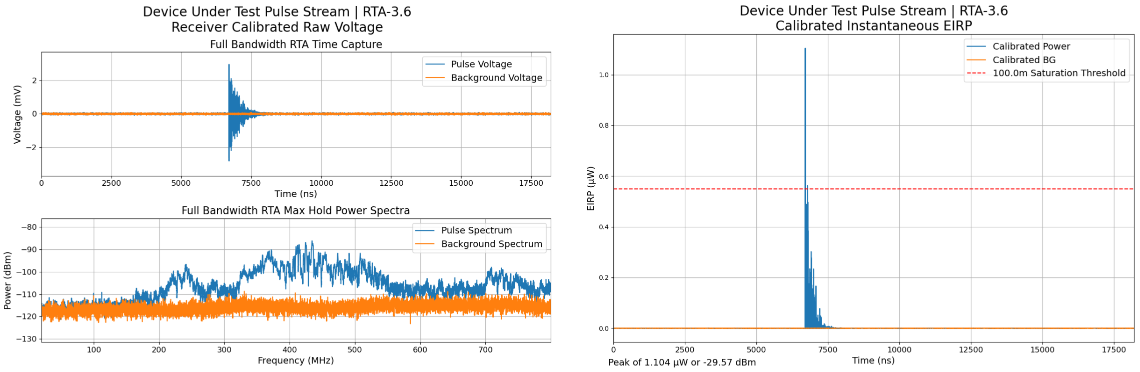
$$\sigma = \frac{kT_{sys}B_{ch}}{\sqrt{\tau_i B_{ch}}} \tag{3}$$

4. Measurement of Pulses

The measurement of impulsive RFI events differs from that of typical continuous emissions. Pulses are typically broadband, requiring a large acquisition bandwidth to capture them and a broad resolution bandwidth to resolve them [4]. Additionally, pulses can present for small time frames, in the order of micro and nanoseconds, requiring fast sampling and prompt triggering to measure them accurately. Therefore, the techniques employed to record faint narrowband spectral emissions cannot be applied to impulsive RFI. It is best to evaluate pulses in the time domain.

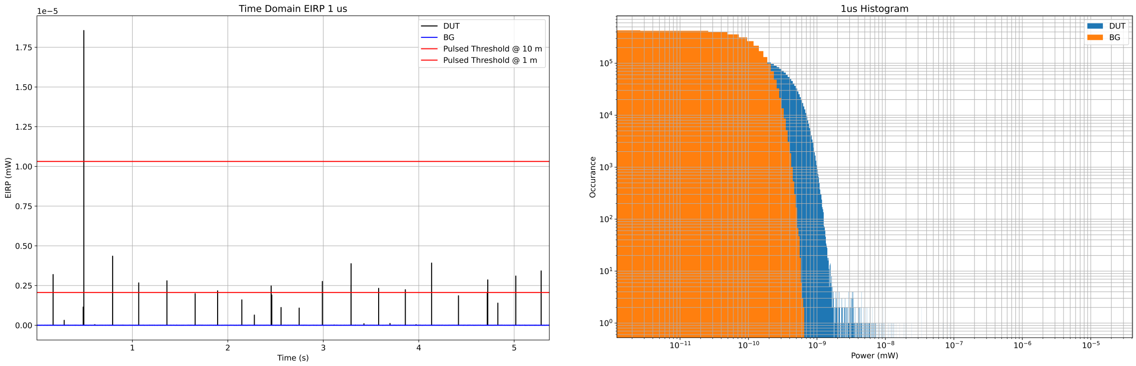
4.1 Receiver Architecture

Historical measurements indicate that most of a pulse's power is concentrated below 1 GHz. SARAO developed the Real-Time Analyser (RTA) for site monitoring and impulsive RFI capture, which can function like an oscilloscope. It samples at 1.8 Gsps, supplying 800 MHz of filtered analogue acquisition bandwidth. The instrument captures 18.2 µs of time, corresponding to 2^{15} samples, and supplies a real-valued Fast Fourier Transform (FFT) of the timestream. The precise triggering mechanism ensures a 100 % probability of intercept (POI) when it is waiting for a trigger. Figure 1a shows the data products an RTA delivers when triggered. The capture contains the recorded voltage and a calculated power spectrum, indicating the broadband nature of the pulse.



(a) RTA Captured Voltage and Spectrum **(b)** RTA Calculated Pulse EIRP

Figure 1: Data Products of an RTA Pulse Capture



(a) EIRP Against Simulated Power Thresholds **(b)** Histogram of a DUT and Background

Figure 2: Data Products of an I/Q Stream Binned to 1µs Integrations

Alternatively, a commercial Real-Time Spectrum Analyser (RTSA) can stream raw In-phase and Quadrature (I/Q) data, which can be analysed in the time domain. SARAO utilises a Tektronix RSA5100 series receiver for EMC testing. It can stream I/Q samples at 200 Msps, delivering 165 MHz instantaneous real bandwidth, which fills up the data buffer after 5.36 s. The I and Q samples can be de-interleaved and processed to generate a timestream, histogram and spectrum.

4.2 Measurement Tradeoffs

Using the RTA or an oscilloscope differs from using an RTSA. The RTA generates far less data and gives instantaneous results. It is headless and requires a control computer. It doesn't dump data while waiting for a trigger, and if triggered, it will dump the data buffer containing 32768 10-bit samples over ethernet, and the computer undertakes the processing and plotting. The RTA can be left acquiring data for extended time periods, dumping small data buffers only when a pulse is captured while displaying real-time data products. A drawback is that a newly triggered data buffer cannot be captured while the data is sent over ethernet. Sending the data takes approximately 0.5 s. Therefore, pulse cadence over long timeframes, like hours, can be indicated, but subsecond occupancy cannot be evaluated. Figure 1 shows an instantaneous pulse capture.

The RTSA's I/Q stream is a continuous accumulation of time data, which can give the precise short-term time occupancy of pulses, as shown in Figure 2. However, large files are generated because the data is continuously captured, taking time to send to a processing computer. Then, post-processing and displaying the data or applying a Fourier transform takes significant computing resources. The data allows for the analysis of multiple back-to-back pulses, but the results take time to generate, and the POI is lower because a sporadic pulse must fall within the finite capture time.

5. Analysis and Compliance

MeerKAT and the SKA can minimise the impact of short transient RFI pulses. The radio receivers exhibit a low-frequency cutoff, the correlator uses hardware integration, and there are zero-dispersion filters in the pulsar pipelines, which utilise the fact that any celestial burst must be dispersed through frequency [5]. Also, the number of baselines of varying lengths in the array can lessen the effect on the entire interferometer. Therefore, the primary metric used to evaluate telescope impact is the risk of saturation, which is defined as the intercepted power level that would cause analogue gain compression in the signal chain or an ADC over range. Noncompliance with the SARAS continuum and spectral line thresholds is not considered. The output of the pulsed measurements is the received voltage, which must be converted into an effective radiated power (ERP). This process involves converting the voltage to integrated instantaneous power using the impedance of the receiver input and then calibrating for the signal chain's cable loss and LNA gain. The chamber calibration factor must be applied if the measurement was conducted in a reverberation chamber. The antenna factor and measurement distance are important if the measurement was conducted in an anechoic chamber or an open area test site. This process moves the calibration plane from the measurement receiver terminals to the device under test itself. Figures 1b and 2a show a calibrated ERP from reverberation chamber measurement data. The maximum impulsive ERP received from the device is compared against the saturation threshold of the telescopes.

6. Future Work

Currently, receptor saturation is the only mature metric used for compliance evaluation. The time occupancy allowance investigation is still underway and will form part of the SKA Impulsive RFI compliance specification. Owing to the resonant nature of reverb chambers, research is being conducted to evaluate reverb chamber pulse interactions and the calibration of short radio bursts within such chambers. Lastly, utilising a commercial RTSA for pulse counting is being investigated.

7. Conclusion

The measurement and analysis of transient pulsed RFI have been discussed. The SARAO RFI team uses custom instrumentation and a commercial RTSA capable of capturing time-domain pulses to evaluate their impact on MeerKAT and the SKA. Pulse compliance depends on comparing the maximum detected ERP to the telescope saturation threshold. Future investigations include incorporating pulse cadence into the specification, increasing the pulse counting capabilities and investigating pulse coupling in a reverb chamber.

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