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A Comparative Analysis of Spectral Linearity in the MeerKAT and MeerKAT Extension Receivers

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Abstract

This paper investigates the spectral linearity of the receiver systems in the MeerKAT and MeerKAT Extension radio telescopes. The investigation focuses on the ADCs, critical components in high-sensitivity receivers, and their importance in maintaining spectral fidelity. While previous work identified noise power as a factor influencing spectral non-linearity, this study extends the analysis to compare two distinct receiver architectures. MeerKAT Extension's L-Band receiver employs an ADC with four cores, differential inputs, and a higher full-scale voltage than MeerKAT. Despite these design changes, linearity tests reveal similar spectral responses, suggesting that ADC non-linearity may be intrinsic to ADC devices rather than specific to a back-end implementation. The investigation has implications for designing and using wideband receivers and digital backends. Future work will explore FFT shift schedules and raw ADC snapshots to characterise this phenomenon further.

1 Introduction

Radio astronomy observations require highly stable, sensitive, and linear radio receivers due to the nature of celestial signals. South Africa's MeerKAT telescope, a precursor to the Square Kilometre Array (SKA) Mid-Frequency telescope, has demonstrated exceptional performance in terms of sensitivity and science data processing integrity [1]. The receivers and digitisers play a crucial role in maintaining spectral fidelity, with the analogue-to-digital converter (ADC) being a critical component in the signal chain.

In previous work, non-linearity in the MeerKAT system was observed in response to narrowband radio frequency interference (RFI), where a satellite drifting through the primary beam resulted in a measurable increase in autocorrelation power [2]. Further investigation revealed that input noise power impacts the severity of the non-linear distortion. Increasing the noise power in the system decreases the effects of the non-linearity [3]. This plays into the system's operating power point trade-off. High noise power levels maximise linearity; however, sufficient headroom is needed for strong terrestrial RFI.

This study builds on prior investigations into ADC non-linearity by comparing MeerKAT with the new MeerKAT Extension (MeerKAT+) system, which features a different ADC architecture. Given the rapid advancements in wideband receiver design and digitiser technologies, understanding how ADC non-linearity manifests across different architectures is critical for optimising receiver performance. By isolating the impact of hardware variations on spectral linearity, this study investigates whether noise power non-linearity is an inherent property of wideband ADCs in radio astronomy receivers or can be mitigated through design principles.

2 Signal Chain Architectures

MeerKAT comprises 64 receptors, each incorporating an Offset-Gregorian dish antenna, feeds, and their associated Digitisers. The system temperature mostly depends on the feed, comprising the cryogenically cooled orthogonal mode transducer (OMT) and low-noise amplifiers (LNAs). This front-end system temperature dictates the noise power fed to the Digitiser subsystem. The Digitiser's Radio Frequency Conditioning Unit (RFCU) provides gain control and conditioning through a cascaded system of amplifiers, step-attenuators and filters [4], aimed at delivering optimal power to the ADC. The sampler module containing the ADC is fed directly from the RFCU. The MeerKAT ADC is a single-core 10-bit device with a sampling rate of 2.2 Gsps, optimised for UHF (580–1015 MHz) and L-Band (900–1670 MHz) operation.

MeerKAT+ offers a stepping stone between the MeerKAT and SKA-Mid designs. The dish and feed design has been updated, and a redesigned Digitiser has been introduced featuring a new digitising engine and field-programmable gate array (FPGA). The prototype L-Band Digitiser's RFCU remains unchanged. The primary difference lies in the ADC. These modifications aim to increase alignment with the SKA design and can affect the system's sensitivity and performance. This investigation interrogates whether these changes impact the inherent non-linearity observed in previous tests.

2.1 ADC Characteristics

The MeerKAT Extension system incorporates a redesigned ADC that introduces key architectural changes which impact digitisation accuracy and spectral response.

- The new ADC utilises four cores, allowing a single module to digitise both polarisations instead of requiring two samplers.
- Operation in differential mode, resulting in a 100Ω input impedance and improved common-mode rejection, instead of the 50Ω, single-ended MeerKAT input.
- A full-scale voltage of 500 mV peak doubles the input voltage handling capability.
- An additional 10 dB loss in the RF chain before the ADC to accommodate dynamic range adjustments.

2.2 INL and DNL

ADCs are inherently non-linear devices. Two key specifications that describe ADC non-linearity are Integral Non-Linearity (INL) and Differential Non-Linearity (DNL). These two parameters indicate an ADC's linear performance. DNL describes how each ADC step deviates from the ideal step size of 1 Least Significant Bit (LSB). A bad DNL can indicate non-monotonicity, where a fluctuating input voltage doesn't elicit different output codes, potentially leading to missing ADC codes. INL describes the cumulative deviation of ADC output codes from an ideal straight-line transfer function over input voltage. A high INL indicates a curved transfer function and systematic non-linearity. It is a good measure of overall conversion accuracy. MeerKAT and MeerKAT+ have different linearity metrics resulting from their specific ADCs, as shown in Table 1.

Table 1 indicates that the MeerKAT+ ADC has slightly better ADC INL and DNL. This implies the MeerKAT+ ADC should elicit less spectral non-linearity.

3 System Noise Power

System noise power, or noise floor, depends on the system temperature, T_{sys}, which comprises contributions from the receiver temperature, sky noise, beam spillover, etc. MeerKAT's and its Extension's feeds are designed to minimise receiver system temperature for optimal noise figure and sensitivity [5]. Balancing noise power input to the ADC is critical. The noise power must exceed the digital noise generated by the ADC while preserving linear headroom for strong RFI. Additionally, ADCs generally perform better at higher input power [6]. Figure 1 shows the implemented noise floor headroom in MeerKAT L-Band. The receptor passband is the band shape of the dish structure coupled with the feed. Digitiser passband refers to the band shape of the RFCU. The MeerKAT+ input power must be increased by 13 dB to account for the 10 dB extra attenuation before the ADC and the 3 dB higher full-scale input to keep ADC operating power uniform.

Table 1. INL and DNL Comparison

	MeerKAT	MeerKAT+	
Parameter	**at84as008**	**ev12aq600**	**Unit**
Max DNL	1.5	0.9	LSB
Min DNL	-0.8	-0.7	LSB
Max INL	4	2.5	LSB
Min INL	-4	-2.5	LSB

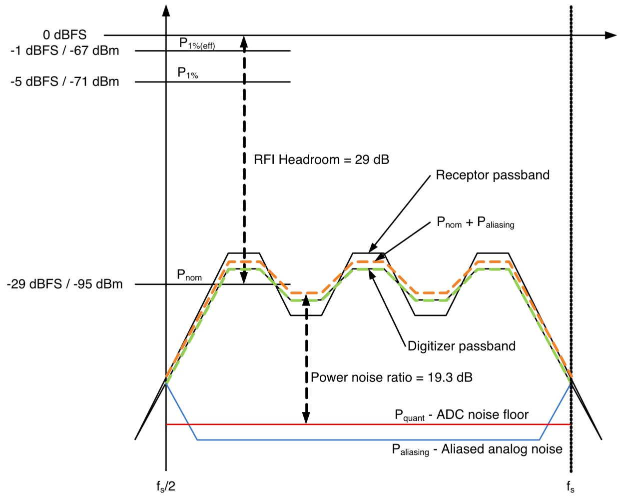


Figure 1. MeerKAT L-Band ADC Headroom and Noise Floor. Adapted from [7].

4 Linearity Test Methodology

A controlled experiment was conducted to evaluate the linearity of both systems under conditions relevant to real-world radio astronomy observations. A broadband noise source was used to simulate a cold sky background, and a signal generator introduced a narrowband interfering tone. The test procedure assesses how ADC non-linearity impacts spectral fidelity in the presence of varying noise power levels and strong interfering signals, which are key concerns for wideband radio astronomy receivers.

Both receivers utilise an onboard spectrometer, employing a poly-phase filter bank (PFB) with an 8-tap filter and a real-valued Fast Fourier Transform (FFT) operation with a 1 s accumulation time. The FFT shift schedule, by default, is set high to 4095 to avoid FFT overflows while accumulating spectra. The MeerKAT Digitiser channelises the data into 4096 channels, while MeerKAT+ channelises into 2048 channels. The test procedure involved incrementally increasing the tone power and exporting accumulated spectra at each power level. A single polarisation is investigated for MeerKAT, while for MeerKAT+, both polarisations can be analysed as they are digitised by the same ADC.

Three input noise power levels are discussed: -39 dBFS, -29 dBFS, and -19 dBFS, to mimic nominal noise ±10 dB. The interfering tone power was swept up in 1 dB steps across a 30 dB range for each noise level and then

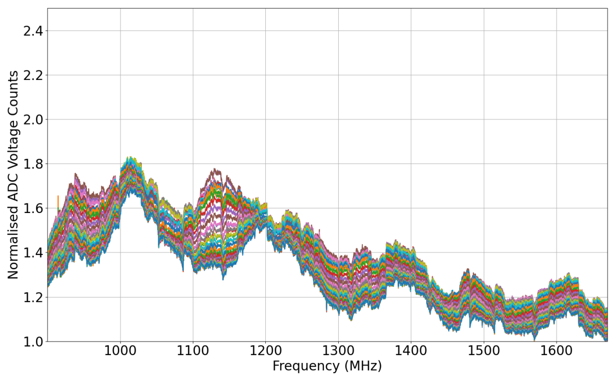


Figure 2. Overlaid MeerKAT L-Band Power Spectra for 30 dB Tone Power Variation at −39 dBFS Noise Input with the Tone Flagged and Removed.

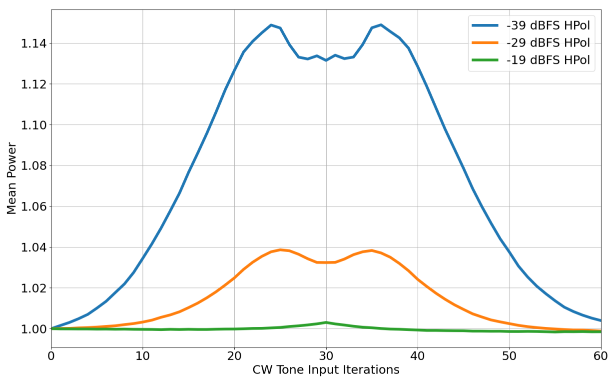


Figure 3. MeerKAT Mean H Pol Normalised Noise Floor Variation Against Input Tone Power for Different Noise Power Levels

swept back down, resulting is 61 power iterations. The recorded spectra were processed to flag the bins containing the injected tone, its harmonics, associated intermodulation products, and the band edges. The remaining spectrum contains only the in-band channelised power in the noise floor, allowing for noise power variation analysis. Figure 2 depicts this noise floor fluctuation at -39 dBFS noise input and a modulated (flagged) tone at ≈ 1065 MHz.

Each spectrum's effective average noise power is calculated by taking the mean of each flagged noise floor. These means are compared to input tone power iteration to show their response to interfering signal power. Any noise variation proxies non-linear distortion in the system and can indicate T_{sys} or gain fluctuation [2]. All spectral data is processed linearly instead of in logarithmic units.

5 Results and Discussion

The linearity tests revealed that both receiver systems exhibited noise power drift in response to increasing tone power. The MeerKAT system's noise power increase, shown in Figure 3, exhibits a maximum of 15% when

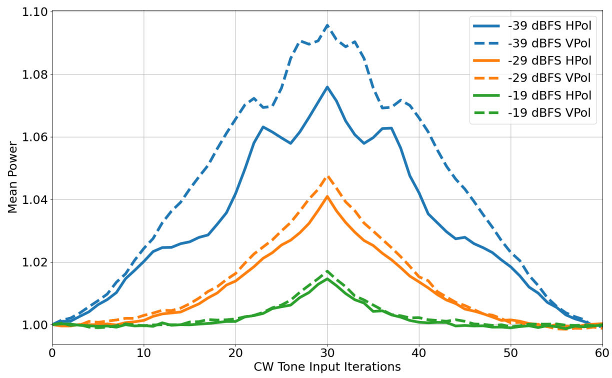


Figure 4. MeerKAT+ Mean Normalised Noise Floor Variation Against Input Tone Power for Different Noise Power Levels

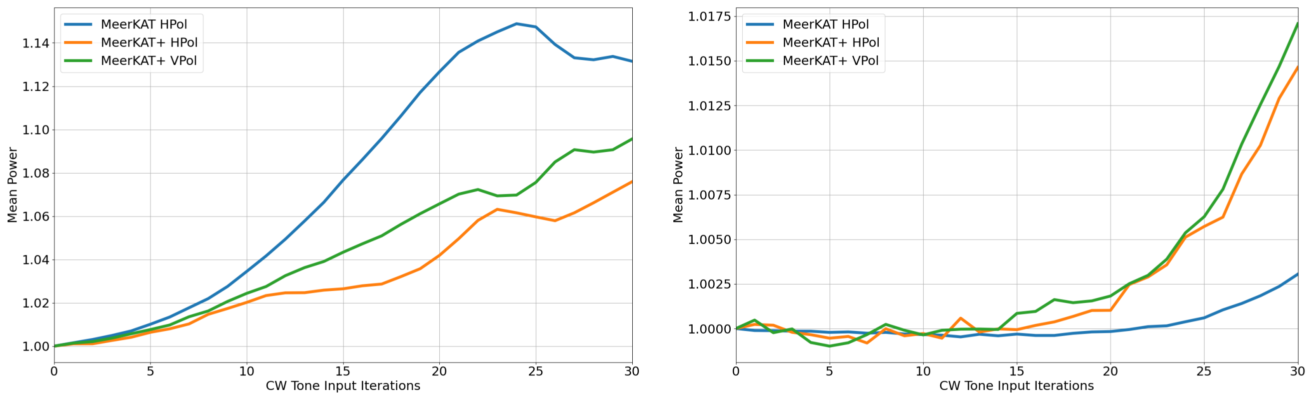
the system is driven by −39 dBFS noise power and the tone power increases. The noise floor variation diminishes at higher noise power levels, indicating that higher noise power diminishes non-linear distortion. When the system is driven by −19 dBFS, the maximum noise power used in this investigation, the distortion is kept below 1%.

In MeerKAT+, both polarisations were recorded. Figure 4 shows that at minimum noise power, −39 dBFS, the worst-case system non-linearity is under 10% power drift in the Vertical Polarisation. The minimum distortion is ≈ 1.5% at −19 dBFS noise in the Horizontal Polarisation. This result reinforces that stronger noise power mitigates the noise floor drift. Additionally, the test indicates a variance between the linearity of both polarisations even though they are digitised by a single ADC.

The receivers' responses to the maximum and minimum noise input were overlaid in Figure 5, indicating that the MeerKAT receiver exhibits worse non-linearity at low noise inputs while performing better than MeerKAT+ at the highest noise input. Table 2 summarises the result. While the decreased distortion exhibited by the MeerKAT+ system at the low noise power level might be attributed to the improved ADC INL over the MeerKAT system, it does not extend to the higher noise power, where non-linearity is increased despite the better INL. The non-linearity can, therefore, not be solely attributed to the ADC INL. Importantly, despite the differences in ADC architecture and spectrometer channelisation granularity, the observed non-linearity is present in both systems. In MeerKAT and MeerKAT+, increasing the nominal noise power input to the system decreases the non-linear distortion.

Table 2. Non-linear Noise Floor Increase as a Percentage

Noise Power In	MK H	MK+ H	MK+ V
−39 dBFS	15%	9.5%	7.5%
−19 dBFS	0.3%	1.4%	1.7%



(a) Noise Power Input: −39 dBFS

(b) Noise Power Input: −19 dBFS

Figure 5. Comparative Analyses of the Noise Floor Variation at the Maximum and the Minimum Noise Power Inputs for the MeerKAT and MeerKAT Extension Systems

These results suggest that using more advanced ADC technology with improved INL and DNL does not necessarily eliminate broadband spectral non-linearity in fields where noise floor fidelity is paramount, like radio astronomy. This has implications for receivers in radio telescopes, particularly in choosing nominal power operating points to balance spectral fidelity with dynamic range considerations. Future receiver architectures must carefully evaluate ADC performance in real-world conditions to optimise sensitivity and balance the input noise power to achieve the best results.

6 Future Work

Several key areas for future investigation remain. One critical factor is the FFT shift schedule in the PFB, which may influence the observed non-linearity due to precision constraints in FPGA-based implementations. Understanding how different shift configurations impact quantisation noise and spectral fidelity is essential for optimising signal processing pipelines.

Additionally, further analysis will be conducted on raw ADC snapshots to determine whether the non-linearity manifests in the time-domain signal before spectral transformation. Investigating the distortions in ADC snapshots will provide further information to clarify the non-linearity as an inherent feature of the digitisation process or a byproduct of the spectral processing chain.

7 Conclusion

This study compared the ADC linearity of the MeerKAT and MeerKAT+ receivers, revealing similar non-linearity characteristics despite differences in digitiser architecture. The findings suggest that ADC non-linearity is not specific to a particular hardware design but may be a fundamental characteristic of ADC operation. Managing noise power levels remains a critical factor in optimising receiver performance. Future work will explore the influence of FFT shift schedules and raw ADC snapshots to refine our understanding of ADC non-linearity in radio astronomy systems.

Acknowledgment

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