

Investigating the Effects of Noise Power on Spectral Linearity in the MeerKAT System

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Abstract—An investigation into the effects of input noise power on the spectral non-linearity in the digitisers used by the MeerKAT system is presented. The signal chain is introduced, identifying the analogue-to-digital converter (ADC) as the most likely source of non-linearity. Linearity tests emulate telescope operation alongside terrestrial interfering signals and measure the variation of the noise power in the system noise floor in response to injected sinusoidal tone power. The results indicate that, at nominal noise power, a noise floor variation of up to 15% is observed when tone power is increased. However, this effect is mitigated to less than 1% by increasing the noise power input to the system, highlighting a key operational adjustment to maintain system linearity.

I. INTRODUCTION

Radio astronomy relies on highly stable, sensitive, and linear receivers due to the faint and noise-like nature of celestial radio signals. MeerKAT and the Square Kilometre Array (SKA) represent critical advancements in this field, with MeerKAT being one of the most sensitive radio telescopes globally [1]. The performance of their receivers and signal chains, particularly the ADCs, is paramount.

This study investigates spectral non-linearity observed in the MeerKAT system's digitisers, attributed to ADC behaviour under varying input sinusoidal power. The findings reveal that noise power significantly influences linearity. This paper presents the linearity measurements, explores the impact of noise power levels, and outlines future investigations for characterising and mitigating these effects.

II. MEERKAT SIGNAL CHAIN AND ADC

The MeerKAT system is a radio interferometer with 64 receptors, each comprising an offset Gregorian dish antenna and associated feeds and digitisers [2]. Each feed includes a corrugated choke horn antenna connected to a cryogenically cooled orthogonal mode transducer (OMT) and lumped low-noise amplifiers (LNAs). The digitiser comprises the Radio Frequency Conditioning Unit (RFCU) and the ADC.

The RFCU supplies modular gain by cascading amplifiers with step-attenuators and includes filters, couplers, power detectors, and limiters to protect the ADC. The ADC, a single-core 10-bit converter with a maximum sampling rate of 2.2 Gsps, is optimised for MeerKAT's UHF (580–1015 MHz) and L-Bands (900–1670 MHz). However, its inherent non-linearities make it the primary suspect for system-level non-linearity.

The signal chain is set up such that the ADC will clip before the analogue electronics are driven into compression.

This design choice arises because the ADC clipping flag can notify the user when clipping occurs, whereas there is no direct indication of analogue compression. Additionally, utilising as much of the ADC's bit depth as possible during digitisation is advantageous, allowing occasional clipping to be acceptable. The observed non-linear distortion [3], or gain instability, manifests as an increase in the noise floor of the spectrum when a strong interferer is present, even within the system's 'linear' region where the ADC is not clipping and the signal chain is not being compressed.

III. SYSTEM TEMPERATURE AND NOISE POWER

System temperature, T_{sys} , informs a system's sensitivity and thermal noise floor, comprising contributions from the receiver temperature, sky noise, beam spillover, etc. MeerKAT's feeds are designed to minimise receiver system temperature for optimal noise figure [4]. 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 terrestrial radio frequency interference (RFI). Fig. 1 shows the implemented noise floor headroom. Receptor passband refers to the bandshape of the dish structure coupled with the feed. The Digitiser passband refers to the bandshape of the Digitiser's RF module. Maintaining spectral linearity over long observations is essential for high-quality data.

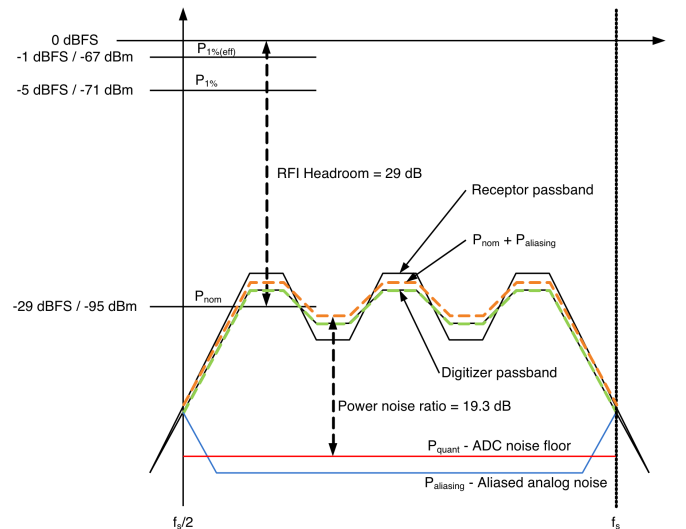


Fig. 1: ADC Headroom and Noise Floor. Adapted from [5].

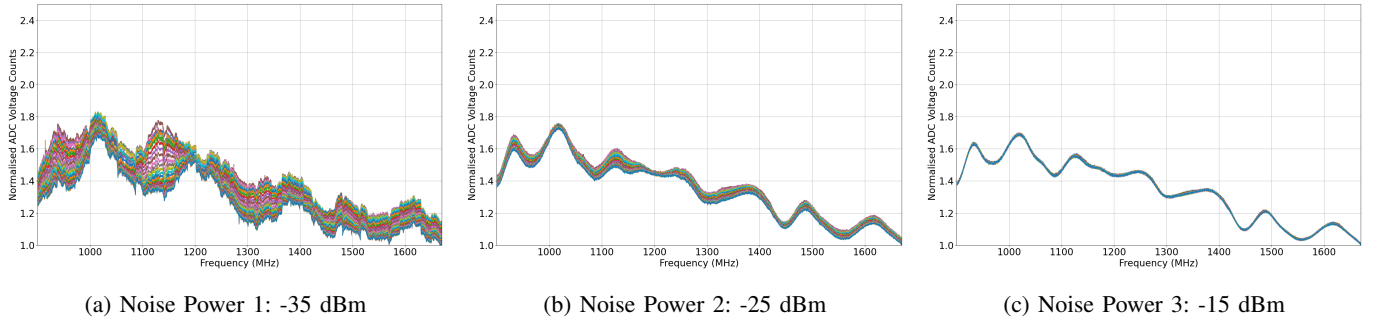


Fig. 2: Overlaid Noise Floor Spectrum Measurements for Modulated Tone Input Power at Six Noise Power Inputs

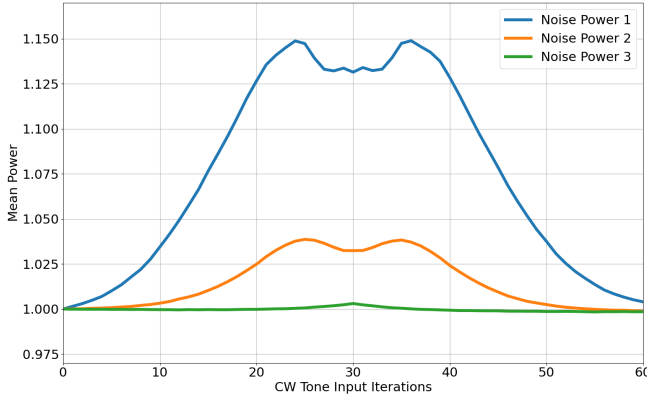


Fig. 3: Mean Normalised Noise Floor Variation Against Input Tone Power for Different Noise Power Levels

IV. LINEARITY TESTS

Linearity tests emulate telescope operation using a noise source to simulate a cold sky and a signal generator to simulate narrow-band interference. These tests focus on the digitiser subsystem, where the ADC is the most non-linear component. The onboard spectrometer employs a poly-phase filter bank (PFB) with a Hamming window, 8 filter taps, and a 4096-channel real-input Fast Fourier Transform (FFT).

Six noise power levels were used: -35 dBm (MeerKAT nominal noise), -32 dBm, -25 dBm, -22 dBm, -15 dBm, and -12 dBm. For each noise power, the generated tone power was incrementally increased in 30 1 dB steps until the receiver's compression limit was reached, and then the power decreased back to the starting level, acquiring spectra at each step. The accumulated spectra were processed to flag and remove peaks, including the injected tone, isolating the baseline noise floor. Fig. 2 shows overlaid normalised noise spectra for three of the six noise power levels.

V. DISCUSSION

Fig. 2 illustrates the spectral noise floor for varying tone power inputs at three noise levels. At the lowest noise power (-35 dBm), the noise floor increases by up to 15% as tone power increases, even after removing the tone and associated harmonics. This behaviour indicates non-linearity. As noise

power increases, the noise floor variation diminishes, confirming that higher noise power mitigates this effect. At noise power levels of -15 dBm and higher, the variation becomes negligible (less than 1%).

The relationship between input tone power and noise floor variation is plotted in Fig. 3. These results underscore the importance of optimising noise power input to balance linearity and RFI tolerance. Importantly, the observed gain instability is a function of noise power variance rather than ADC clipping, highlighting the need for careful control of noise power levels.

VI. CONCLUSION

Linearity tests on the MeerKAT digitisers reveal that noise power significantly impacts the noise floor's linearity under strong interfering signals. Insufficient noise power leads to a non-linear noise floor response, with up to 15% variation observed. Increasing noise power mitigates this effect to less than 1%, but at the cost of reduced ADC headroom for RFI. A balance is to increase the noise power level to mitigate non-linearity while maintaining sufficient ADC headroom to keep clipping within an acceptable margin. These findings emphasise the need for careful noise power optimisation in radio astronomy systems. Future work will examine the spectrometer's role in mitigating non-linearity and explore strategies to enhance ADC performance.

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REFERENCES

- [1] D. B. Davidson, "MeerKAT and SKA phase 1," in *ISAPE2012*, Oct. 2012, pp. 1279–1282.
- [2] S. Malan and H. Kriel, "Digitiser Design Document," National Research Foundation, Tech. Rep. M1130-2000-002, Dec. 2016.
- [3] G. R. Young, M. Gouws, W. Steyn, and D. I. L. de Villiers, "Investigating Nonlinearity in Radio Telescope Receivers Using the MeerKAT System," in *AP-S/URSI 2024*, Jul. 2024, pp. 2–3, iSSN: 2573-3036.
- [4] R. Lehmensiek and I. P. Theron, "Minimizing the MeerKAT system noise temperature," in *2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*, Aug. 2014, pp. 1–4.
- [5] P. L. Herselman, "L-Band ADC Headroom and Efficiency Calculations," SKA SA, Technical Memo M1130-0000-007, Feb. 2012.