Impact of $1/f$ Noise on a 21 cm Neutral Hydrogen Signal Intensity Mapping Survey Simulation

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Introduction

The **B**aryon Acoustic Oscillations from **I**ntegrated **N**eutral **G**as **O**bservations (BINGO; Abdalla et al. (2022)) project is an international collaboration that aims to contribute to data collection for cosmological research. The data capture will be done by mapping neutral Hydrogen radiation (HI; a 21-cm wavelength emission) in the redshift range between 0.127 and 0.449 for detection of Baryon Acoustic Oscillations (BAO) in the radio frequency range (Novaes et al. 2022).

This project investigated the impact of $1/f$ noise, a form of correlated noise that is ever-present to radio receiver systems and manifests as small gain fluctuations (Harper et al. 2018). To achieve this, the code HIDE (HI Data Emulator; Akeret et al. (2017)) was used to simulate the process of collecting astronomical signals using a single-dish radio telescope and provide the results in time-ordered data (TOD) by pixel, that is, the records of the observational survey registered.

Data and Methodology

In this study, the HIDE code was compiled with an incorporated mathematical description of $1/f$ noise (Harper et al. 2018):

$$PSD(f,\omega) = \frac{T_{sys}^2}{\delta\nu}\left[1 + C(\beta, N_\nu)\left(\frac{f_k}{f}\right)^{\alpha}\left(\frac{1}{\omega\Delta\nu}\right)^{\frac{1-\beta}{\beta}}\right] \tag{1}$$

where T_{sys} is the system temperature, $\delta\nu$ is the system channel width, $C(\beta, N_\nu)$ is a constant, f_{knee} is the knee frequency, ω is the inverse spectroscopic frequency wave-number, $\Delta\nu$ is the total receiver bandwidth and β is used to parameterise the spectral index of the Power Spectral Distribution (PSD).

This form of correlated noise, characterized by small gain fluctuations inherent to radio receiver systems, was crucial to simulating the observational conditions of the BINGO radio telescope.

The simulation generated time-ordered data (TOD) files that provide a detailed record of the observational survey to construct a hitmap, which represents the number of observations per pixel. With the map-making process, the hitmap was used to create the naive map, which shows the brightness temperature per pixel.

These steps allowed the analysis of the impact of $1/f$ noise on the detected HI signal, providing essential insights into the challenges posed by correlated noise in radio frequency observations and aiding in developing strategies to mitigate its effects in future surveys.

Results and Conclusions

In order to obtain the images, the HIDE code was compiled, generating the TODs for one day of observation (Figure 1) using a telescope configuration similar to the BINGO radio telescope, with two different background noise settings: without the simulated $1/f$ noise (Figure 2) and with the simulated $1/f$ noise (Figure 3).

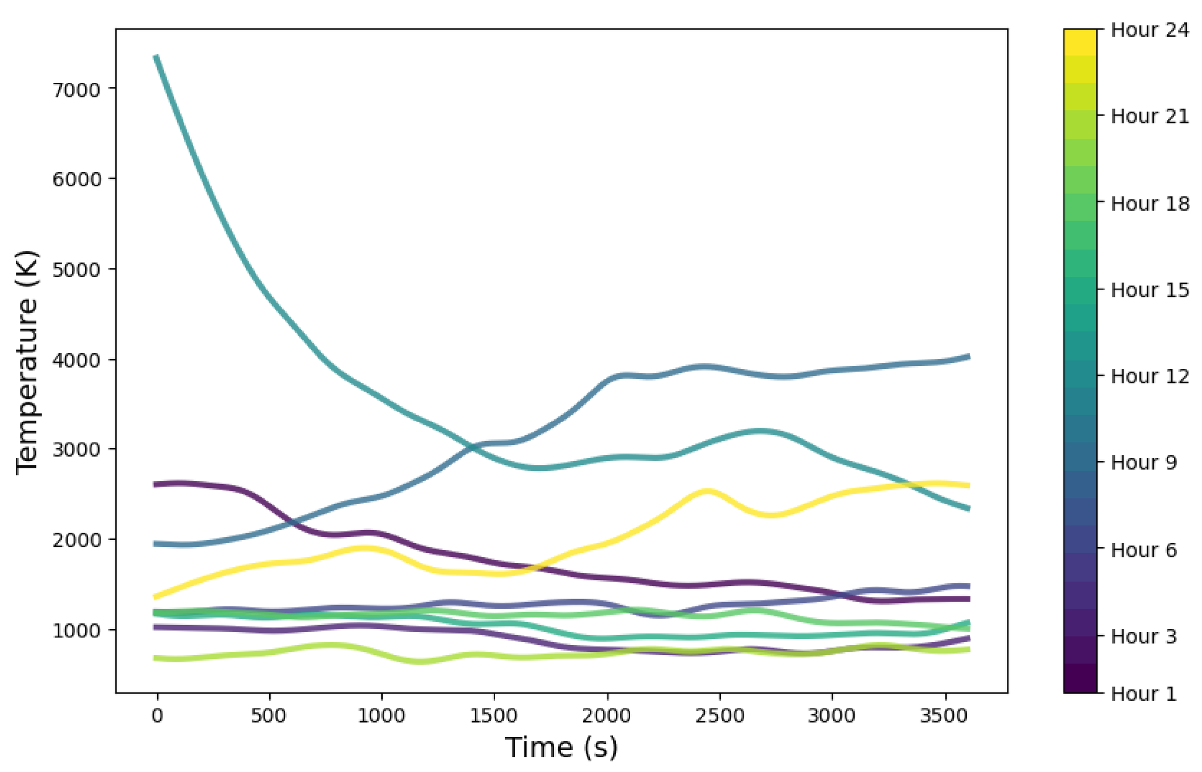

Figure 1. Plot of the time-ordered data obtained with the HIDE code.

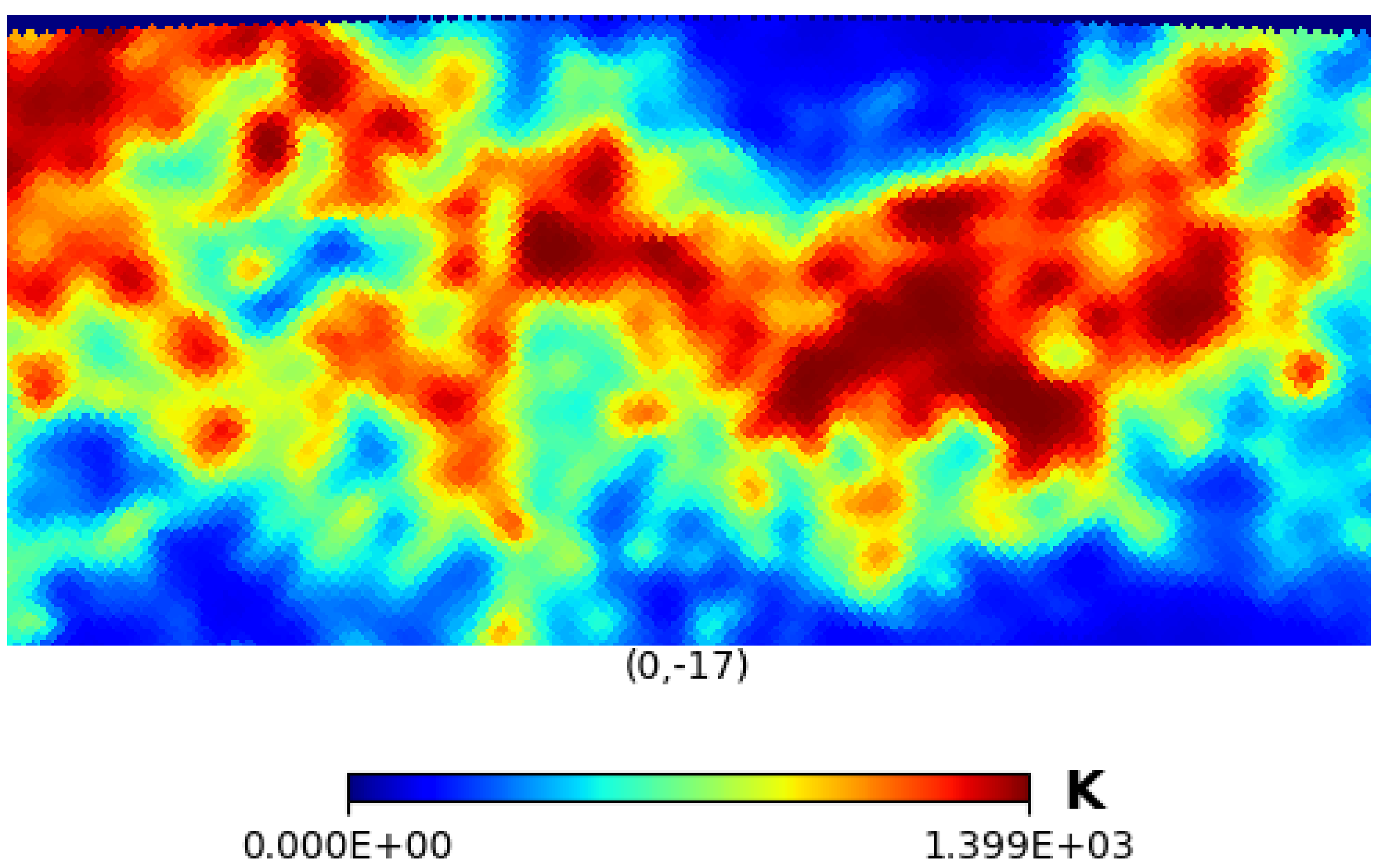

Figure 2. Zoomed naive map image of the sky strip observed by BINGO without $1/f$.

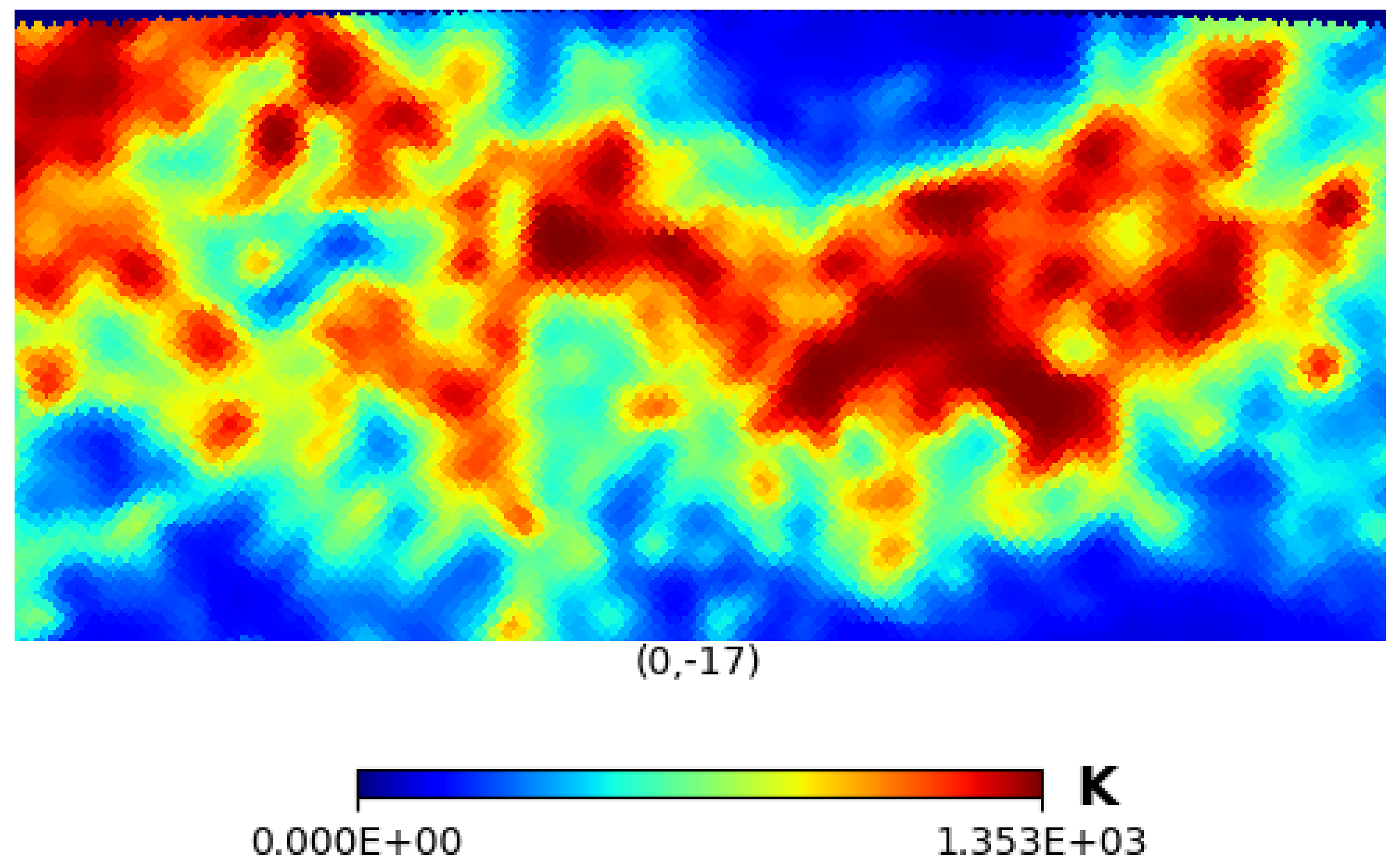

Figure 3. Zoomed naive map image of the sky strip observed by BINGO with $1/f$.

With both maps, it was possible to plot the difference between them in order to better analyse the impact of the $1/f$ noise:

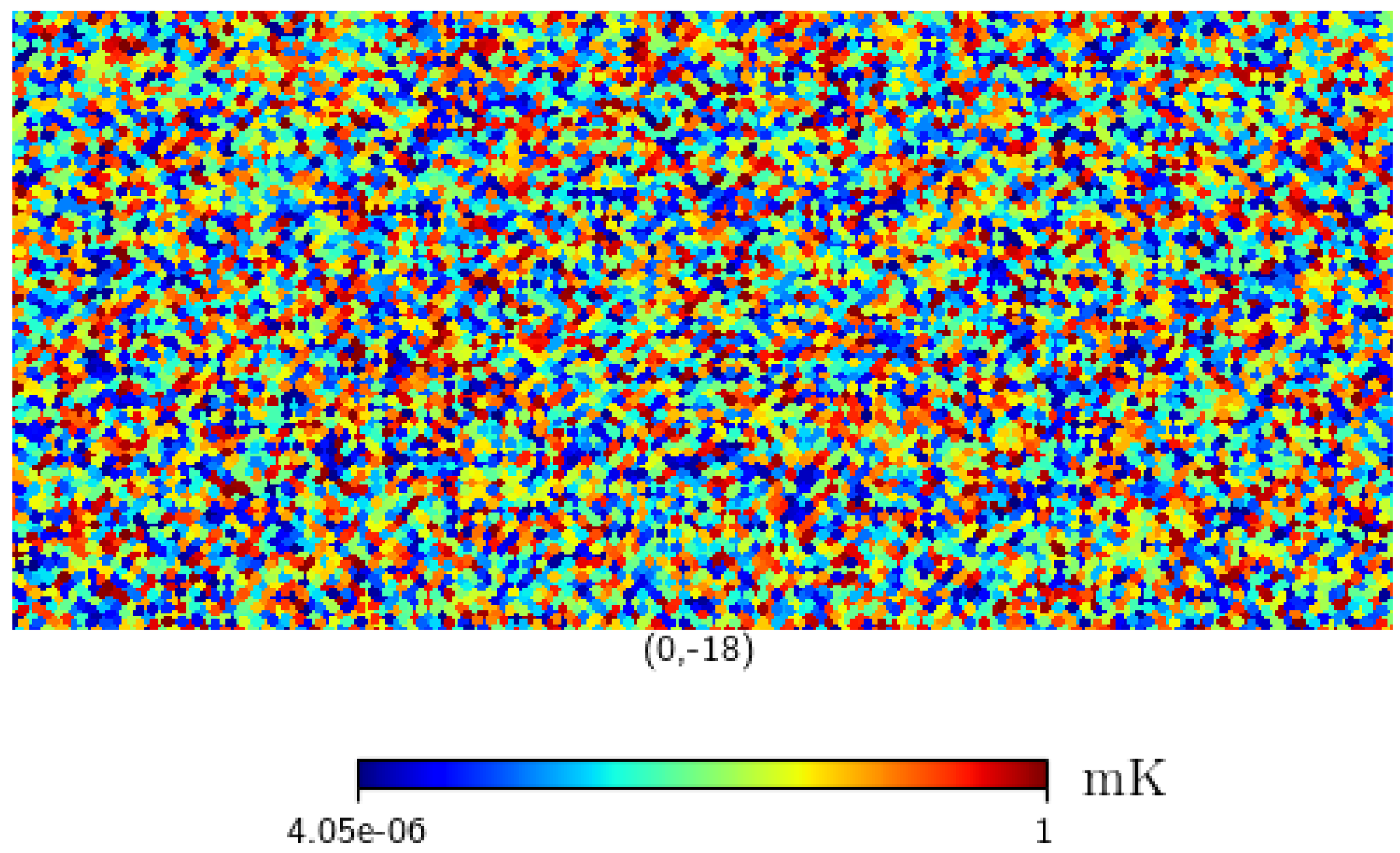

Figure 4. Zoomed naive map image of $1/f$ and thermal noise of the sky strip observed by BINGO.

In the absence of $1/f$ noise, the distribution of observations indicates stable observational conditions. These maps demonstrate a clear and consistent signal without significant noise interference, showcasing the potential quality of HI signal detection under ideal conditions. The presence of $1/f$ noise introduces variations in the temperature, highlighting the noise's effect on data collection stability. The map's temperature is affected by the noise, introducing artifacts and fluctuations, complicating the accurate detection of the HI signal.

In conclusion, the simulations demonstrate the impact of $1/f$ noise on the quality of HI signal detection in radio frequency observations. Including $1/f$ leads to variations in the naive map, emphasizing the challenge it poses for accurate data collection and analysis.

Understanding the effects of $1/f$ noise is crucial for the BINGO collaboration and similar cosmological research projects. These insights guide the development of strategies to mitigate the noise's impact, improving the accuracy of future HI signal intensity mapping surveys.

Future Work

In order to complement the research, the next steps involve incorporating additional types of noise into the simulation to further evaluate their contributions to the 21 cm signal recovery. This will deepen the understanding of the telescope's influence on the observed data and how to conduct further analysis and noise removal.

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References

Abdalla, E. et al. 2022, Astron. Astrophys., 664, A14

Akeret, J., Seehars, S., Chang, C., et al. 2017, Astronomy and Computing, 18, 8–17

Harper, S. E., Dickinson, C., Battye, R. A., et al. 2018, Monthly Notices of the Royal Astronomical Society, 478, 2416–2437

Novaes, C. P. et al. 2022, Astron. Astrophys., 666, A83