Postprint of Simulation Study on the Impact of Frequency Averaging Effects on SKA1-LOW Imaging

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Abstract

The low-frequency array of the Square Kilometre Array (SKA) radio telescope, SKA1-LOW, will undertake key scientific research tasks such as the study of the Epoch of Reionization (EoR). Frequency averaging can effectively reduce data volume and improve imaging sensitivity; however, the impact of the resulting "bandwidth smearing" on SKA1-LOW imaging still lacks quantitative analysis and research.

This study conducts an in-depth investigation into the effects of frequency averaging using simulation methods. Through full-array simulation, frequency averaging, and CLEAN processing of SKA1-LOW, the restored images of averaged multi-channel and single-channel cases are systematically compared, and the residual maps after subtraction are analyzed. The impact of frequency averaging on the intensity of observed sources is analyzed in depth, yielding quantitative results of peak intensity variations with the number of averaged channels under different imaging weights. This provides a reference for selecting the appropriate number of frequency averaging channels in actual SKA1-LOW observations and holds significant value for conducting scientific research with SKA1-LOW.

Full Text

Preamble

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Simulation Study on the Impact of Bandwidth Smearing on SKA1-LOW Imaging

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Abstract

The Square Kilometre Array (SKA) is the largest synthetic aperture radio telescope currently under construction. Due to the massive volume of data produced by the SKA, it is necessary to perform frequency averaging on the visibility data to reduce data storage and transmission pressure. However, frequency averaging introduces bandwidth smearing (also known as the chromatic aberration effect), which leads to the radial stretching of sources in the reconstructed image and a decrease in peak flux density, thereby affecting the scientific quality of the images. This paper presents a simulation study of the bandwidth smearing effect based on the SKA1-LOW layout. By simulating observations of point sources at different frequencies and varying distances from the phase center, we quantitatively analyze the impact of different frequency averaging widths on imaging quality. The results show that the degree of bandwidth smearing is proportional to the product of the fractional bandwidth and the distance from the phase center. For SKA1-LOW, when the frequency resolution is reduced, the peak flux density of sources at the edge of the field of view significantly decreases, and the source shape becomes distorted. This study provides a reference for selecting optimal frequency averaging parameters in SKA data processing pipelines to balance data compression and scientific accuracy.

Key scientific research tasks include the Epoch of Reionization (EoR) and other critical objectives. While frequency averaging can effectively reduce data volume and improve imaging sensitivity, the resulting "bandwidth smearing" effect on SKA1-LOW imaging still lacks comprehensive quantitative analysis and research. This paper employs simulation methods to conduct an in-depth study of the frequency averaging effect. By performing full-array simulations of SKA1-LOW, followed by frequency averaging and CLEAN deconvolution, we systematically compared restored images from multi-channel averaging against single-channel cases and analyzed the residual maps obtained from their subtraction. We further analyzed the impact of frequency averaging on the intensity of observed sources, yielding quantitative results on how peak intensity varies with the number of averaged channels under different imaging weights. These findings provide a reference for selecting the appropriate number of channels for frequency averaging in actual SKA1-LOW observations and hold significant value for the scientific research conducted with SKA1-LOW.

Keywords instrumentation: interferometers, techniques: interferometric, methods: analytical, methods: numerical **PACS:** P164; **Document code:** A

1 Introduction

The Square Kilometre Array (SKA) [?] is a major radio telescope array project currently under construction, with its first phase (SKA1) representing a significant milestone in the development of radio astronomy. SKA1 consists of a low-frequency array (SKA1-LOW) and a mid-frequency array (SKA1-Mid), designed to address fundamental scientific challenges in astronomy. Specifically, SKA1-LOW is deployed in the desert regions of Western Australia [?], featuring 131,072 wideband dual-polarization antennas operating across a frequency range of 50 MHz to 350 MHz. These antennas are organized into 512 stations, with each station comprising 256 antennas. The construction of SKA1-LOW aims to achieve several critical scientific objectives that will help unravel the mysteries of the universe. High-priority Science Objectives (HPSOs) include the study of the 21 cm atomic hydrogen emission and absorption lines during the Epoch of Reionization (EoR) and Cosmic Dawn (CD), as well as pulsar surveys and pulsar timing observations [?]. Achieving these goals requires multi-band observations of the sky. SKA1-LOW not only possesses a wide bandwidth of 300 MHz but also features extremely high frequency resolution, with individual channel bandwidths as narrow as 5.4 kHz [?]. While such narrow channel bandwidths provide finer spectral data, they also generate massive volumes of data, presenting significant challenges for subsequent data processing.

As the SKA enters the AA0.5 commissioning phase and construction for AA2 is about to begin, the application process for scientific observation proposals is gradually being placed on the agenda. Selecting appropriate observation and data processing modes for different scientific objectives is a crucial prerequisite for conducting future SKA scientific research. To alleviate the burden of data processing, it is common practice to average visibility data along the frequency axis, a process known as frequency averaging. However, while frequency averaging reduces data volume and improves sensitivity, it results in the loss of some spectral structure and causes sources located away from the phase center to exhibit radial elongation and a decrease in peak intensity. This phenomenon is known as “bandwidth smearing” or “bandwidth decorrelation” [?].

The bandwidth effect introduced by frequency averaging is a key issue that must be considered when determining observation strategies. The official SKA website provides a series of online tools to assist scientists in determining SKA observation parameters. Among these, the sensitivity tool is used to help scientists calculate the sensitivity of the SKA telescope given different observation frequencies and frequency averaging configurations [?]. However, this tool cannot provide information regarding the flux changes or the variation in Full Width at Half Maximum (FWHM) for sources away from the phase center; therefore, it cannot evaluate the impact of frequency averaging on imaging. In fact, for SKA imaging observations, considering sensitivity alone is insufficient. Scientists must carefully consider the trade-off between sensitivity and bandwidth smearing effects when applying multiple levels of frequency averaging.

Considering the impact of bandwidth smearing caused by frequency averaging during imaging (dirty maps) and the fact that deconvolution may not be able to eliminate these effects, a quantitative analysis of the image changes induced by frequency averaging can provide critical guidance for determining future SKA observation and data processing modes. This paper systematically investigates the problem of bandwidth smearing in SKA multi-frequency observations and data processing. Section 2 outlines the specific procedures of this study, and Section 3 provides an overview of the results.

2 Simulation-Based Study of Bandwidth Effects

This paper presents a quantitative analysis of the impact of bandwidth smearing, caused by frequency averaging, on imaging performance through simulation experiments. Under the condition that all other observational parameters and deconvolution settings remain constant, this study compares and evaluates the resulting effects by analyzing the differences between averaged multi-channel and single-channel (non-averaged) cases.

The specific steps for generating restored images from the simulation dataset are elaborated in the following sections. The detailed workflow is illustrated in [Figure 1: see original paper], where "ms" denotes the Measurement Set and WSCLEAN refers to the W-Stacking Clean deconvolution software.

[Figure 1: see original paper] Fig. 1 The flowchart from simulation to restored image

2.1 Simulation

First, we utilize the OSKAR software [**?**] to simulate the full SKA1-LOW array. The simulation parameters are as follows: the observation spans 2 hours before and after the transit (totaling 4 hours), with an integration time of 1 s and a sampling interval of 1 h. The central observation frequency is set to 151 MHz, with a single channel bandwidth of 5.4 kHz. The phase center is located at Right Ascension (RA) 358.14° and Declination (DEC) $-35.47°$. To effectively compare the differences between frequency-averaged data and single-channel non-averaged data, we employ frequency averaging factors of 1, 4, 8, 12, 16, 20, 24, 28, and 32 channels.

For the selection of simulated celestial objects, we extracted a subset of data from the GaLactic and Extragalactic All-sky MWA (GLEAM) survey [**?**], which was publicly released by the Murchison Widefield Array (MWA) [**?**]. This subset consists of 81 point sources with spectral indices ranging from $[0.22, -1.57]$. At the 151 MHz frequency, all 81 sources have flux densities below 1 Jy, with a maximum flux of 0.856 Jy and an average flux of 0.23 Jy. Taking the visibility data of 32 channels as an example, the uv coverage before averaging is shown in [Figure 2: see original paper]. Here, uv refers to the u-v plane within the uvw coordinate system, which represents the coordinates in the spatial frequency domain.

[Figure 2: see original paper] Fig. 2 *uv* coverage of the SKA1-LOW full array across 32 channels.

2.2 Frequency Averaging

Based on simulated visibility data (stored in Measurement Set format), frequency averaging calculations were performed. We further developed experimental analysis code based on the RASCIL2 (The Radio Astronomy Simulation, Calibration, and Imaging Library Ver 2.0) software package developed by our team. The specific steps are as follows:

(1) The MS (Measurement Set) file is read by calling the relevant functions, and a custom class inheriting from the base data structure is defined to encapsulate the input information.

(2) Frequency averaging is performed along the spectral axis. During this process, the frequency information is updated synchronously. Consequently, the *uv* coordinates, originally defined in meters, are updated to units of wavelength based on the revised frequency data.

(3) After the averaging process is complete, the resulting data is processed by calling the export functions.

2.3 Imaging and Deconvolution

The functions will export the data into MS (Measurement Set) files. Based on the visibility data obtained after frequency averaging, we utilized the current mainstream radio interferometric data processing software, WSCLEAN [?] (W-Stacking Clean), to perform interferometric imaging and deconvolution using different weighting schemes. Since the simulation involves point sources, the Cotton-Schwab CLEAN algorithm [?] was employed for the deconvolution process.

The specific parameters used when calling WSCLEAN are as follows: an image size of 2048×2048 pixels, a pixel scale of $1''$, a gain of 0.6 per major cycle, a maximum of 50,000 iterations, and a cleaning threshold set at five times the standard deviation (5σ). To conduct a more in-depth analysis of the impact of frequency averaging on the reconstructed images, both natural weighting and uniform weighting were applied. All other settings remained at their default parameters.

3 Analysis of the Impact of Frequency Averaging on Imaging Quality

To analyze the impact of frequency averaging on reconstructed images, this study first examines the intensity residual maps obtained by subtracting the reconstructed image of a single channel from the reconstructed images generated after averaging multiple frequency channels. To further evaluate the influence of frequency averaging on observations, we conduct an in-depth investigation into the intensity variations of the same source across different numbers of averaged channels.

3.1 Comparative Analysis of Image Restoration Results

To analyze the imaging differences caused by frequency averaging, we evaluated the residual maps obtained by subtracting the reconstructed image of a single channel from the reconstructed image averaged over multiple channel frequencies. Due to space constraints, only a selection of these comparisons is presented here.

The differential effects for a point source under natural and uniform weighting are illustrated in [Figure 3: see original paper]. This point source has a brightness of 0.13 Jy and a spectral index of 0.69. As shown in Figure 3, there are significant discrepancies after deconvolution when comparing multi-channel frequency averaging to single-channel imaging, regardless of whether natural or uniform weighting is applied. By comparing the residual maps of uniform weighting and natural weighting, it is evident that the residual range for uniform weighting is smaller. However, under natural weighting, the discrepancies caused by frequency averaging cover a larger spatial extent. Furthermore, as the number of averaged channels increases, the spatial range of these differences gradually expands. This indicates that when a larger number of channels are averaged, frequency averaging exerts a broader influence on the source representation when using natural weighting.

At the same time, it can be observed that the central region of the source consists primarily of negative values. This indicates that, compared to a single channel, the intensity at the central region of the source decreases after multi-channel frequency averaging. To further investigate the impact of frequency averaging on observed sources during the imaging process, this paper will subsequently provide an in-depth analysis of its specific effects on the peak intensity of the source.

[Figure 3: see original paper] Fig. 3 Residual maps for a point source comparing 8 (left), 16 (middle), and 32 (right) channels against 1 channel under natural (top row) and uniform (bottom row) weighting.

3.2 Impact of Frequency Averaging on Observed Source Intensity

To further analyze the impact of frequency averaging on observed sources, we selected the peak intensity variations of three point sources at different positions in the restored images under both natural and uniform weighting as research subjects. The results are shown in [Figure 4: see original paper]. To better illustrate the changes in peak intensity, the vertical axis of this figure represents the ratio of the peak intensity of the point source after multi-channel averaging (I_{avg}) to its peak intensity in a single-frequency image (I_{single}). To clarify the positions of these sources, the distance from the point source to the phase center (θ) is used as a label.

It is evident from [Figure 4: see original paper] that as the distance between the source and the phase center increases, and as the number of averaged channels grows, the peak intensity of the source diminishes under both natural and uniform weighting. Furthermore, the peak intensity decreases more slowly under natural weighting compared to uniform weighting.

Based on these analytical results, reference values can be provided for selecting the number of channels during frequency averaging. For example, in the case of natural weighting imaging for the full SKA1-LOW array (after deconvolution), averaging 32 channels results in a peak intensity loss of approximately 10% for a source located about 1.5° from the phase center compared to single-channel imaging. If uniform weighting imaging is employed, the peak intensity loss for the same source would be even more significant.

3.3 Analysis of Other Image Parameters

In addition to the peak intensity analysis described above, we further investigated the impact of noise on the observations. We analyzed the total flux density of the observed sources, the image noise levels, and the synthesized beam sizes in restored maps generated using various frequency averaging intervals and imaging weights. To facilitate source extraction and statistical analysis of the restored images, we employed the PyBDSF (Python Blob Detector and Source Finder) tool.

[Figure 5: see original paper] illustrates the variation in total flux density. The vertical axis represents the ratio of the total flux density obtained from multi-frequency averaging (I) to the total flux density of a single channel (I_0) for a point source. It can be observed that as the number of averaged channels increases, the total flux density remains remarkably stable across different imaging weights and source positions, with fluctuations limited to approximately 1.32% $\sim$ 5.64%. This minor discrepancy may stem from residual biases introduced during the deconvolution process.

[Figure 4: see original paper] Fig. 4 The peak intensity of point sources at three different locations in the restored image under natural weight (left) and uniform weight (right) varies with the average number of channels, where n_{chan} denotes the average number of channels.

[Figure 5: see original paper] Fig. 5 The total flux of point sources at three different locations in the restored image under natural weighting (left) and uniform weighting (right) as a function of the number of averaged channels.

[Figure 6: see original paper] illustrates the noise levels in the restored images under different imaging weights. As shown in the figure, the noise level decreases for both natural and uniform weighting as the number of averaged frequency channels increases. Furthermore, the noise level associated with uniform weighting is consistently higher than that of natural weighting across all channel averaging scales.

[Figure 7: see original paper] illustrates the variations in the major axis of the synthesized beam. In this figure, the major axis of the point-source beam is measured in arcseconds and plotted along the vertical axis. The results indicate that under natural weighting, the major axes of the beams for the three point sources remain nearly constant. Conversely, under uniform weighting, the major axes for all three point-source beams exhibit an increasing trend. Specifically, the point source located approximately 2° from the phase center shows the most significant increase in its beam' s major axis. The slight anomalies observed in the beam major axis variations under natural weighting may be attributed to biases introduced during the deconvolution process.

[Figure 6: see original paper] Fig. 6 The noise level in the restored image under natural weight and uniform weight as a function of the average number of channels.

[Figure 7: see original paper] Fig. 7 The variation of the major axis of point sources at three different locations in the restored image under natural weight (left) and uniform weight (right) as a function of the average number of channels.

4 Conclusion

In this study, we conducted data simulations using the OSKAR software package, employing a subset of sources from the GLEAM catalog as the simulation dataset. The simulations were performed based on the full array configuration of the SKA1-Low telescope. Subsequently, we utilized RASCIL2 to perform frequency averaging on the simulated data. The resulting frequency-averaged data were then processed using WSClean software for deconvolution and final imaging. By comparing the imaging results obtained from multi-channel frequency averaging against those from single-channel non-averaged data, the study evaluates the impact of bandwidth smearing caused by frequency averaging on deconvolution.

We further conduct an in-depth analysis of how this effect influences the intensity of observed sources, determining the degree to which the peak intensity of point sources at different positions varies with the number of averaged channels under various imaging weights. Additionally, we analyze the evolution of the total flux of observed sources, the synthesized beam size, and the image noise levels as a function of the number of averaged channels.

The research results demonstrate that frequency averaging significantly impacts both the source structure and peak intensity in restored images. Specifically, uniform weighting affects a smaller spatial range of the source compared to natural weighting, but it exerts a more pronounced influence on the peak intensity. We have obtained quantitative results for the peak intensity of point sources, total flux, beam size, and image noise levels under varying conditions.

Based on these findings, researchers can refer to these quantitative results in actual observations and select an appropriate number of frequency-averaging channels based on specific requirements to optimize imaging quality. Overall, this study provides practical guidance for the application of frequency averaging in radio astronomical observations and serves as a valuable reference for future scientific data processing with SKA1-LOW.

It should be noted that this work still has certain limitations. For instance, this study does not account for practical factors such as the primary beam effects of the antennas, leading to a certain discrepancy between the simulation and real observation environments. Future research could further incorporate these practical factors to improve the accuracy of the simulation experiments.

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