Optimal Empirical Values of w-plane in Wide-Field Imaging Gridding Algorithms (Postprint)

Authors: Yu Xiaoyu, Deng Hui, Mei Ying, Wei Shoulin, Shi Congming, Wang Wei, Dai Wei, Wang Feng

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Abstract

The w-term must be considered in the gridding process of radio interferometer wide-field imaging. w-projection and w-stacking are two important wide-field imaging gridding algorithms, and the w-plane parameter is a crucial factor affecting computational speed and imaging quality in these algorithms. This study investigates both w-projection and w-stacking gridding algorithms, utilizing SKA1 low-frequency array station data and the ASKAP software package for simulated observations, and performs quantitative analysis and comparison of the imaging speed and imaging quality of the two algorithms under various w-plane parameter values. The results further demonstrate that w-plane is an important parameter for performance improvement; for the w-projection algorithm, the w-plane value should be larger than the commonly given empirical value to achieve better imaging quality. Although the w-stacking algorithm offers significant speed advantages, the influence of w-plane is more pronounced in its implementation, and this paper provides recommended w-plane values. This work constitutes fundamental research on wide-field imaging algorithms and provides valuable reference for pipeline design in future SKA scientific data processing.

Full Text

A Study on Optimal Empirical Values for the W-plane in Wide-Field Imaging Gridding Algorithms

Yu Xiaoyu[1], Deng Hui[1,2], Mei Ying[1], Wei Shoulin[1], Shi Congming[1], Wang Wei[3], Dai Wei[1], Wang Feng[1,2] [1]Key Laboratory of Computer Technology Application, Kunming University of Science and Technology
[2]Center for Astrophysics, Guangzhou University
[3]National Astronomical Observatories, Chinese Academy of Sciences

Abstract

During the gridding process in wide-field imaging for radio interferometer arrays, the effect of the w-term must be considered. W-projection and w-stacking are two important wide-field imaging gridding algorithms, and the w-plane parameter is a crucial factor affecting both computational speed and imaging quality. This paper investigates these two gridding algorithms using SKA1 low-frequency array station data and the ASKAP software package for simulated observations, providing quantitative analysis and comparison of imaging speed and quality under different w-plane parameter settings. The results further demonstrate that the w-plane is a key parameter for performance improvement. For the w-projection algorithm, the w-plane value should be larger than the generally recommended empirical value to achieve better imaging results. While the w-stacking algorithm offers significant speed advantages, the impact of the w-plane is more pronounced in its implementation. This paper provides recommended w-plane values. This work constitutes fundamental research on wide-field imaging algorithms and offers valuable reference for pipeline design in future SKA scientific data processing.

Keywords: SKA-SDP; wide-field imaging; gridding algorithm

The Square Kilometre Array (SKA) will be the largest synthetic aperture radio telescope constructed internationally, consisting of thousands of reflector antennas and up to one million low-frequency antennas, with a total collecting area of one square kilometre. The SKA Science Data Processor (SDP) represents a critical component of the SKA design, focusing on developing hardware platforms, software, and algorithms to process observational data from the radio telescope. SDP design faces multifaceted challenges, most notably the need to handle massive data volumes from the telescope. SKA1 (approximately 10% of the full array) will generate data at a rate of 300 PB per year. To meet the requirements of SKA scientific research, SDP pipeline design must carefully balance processing performance with data quality. Since SDP processing requires computational power two orders of magnitude greater than existing astronomical data processing systems, its key algorithms must achieve exascale performance levels, with SKA2 computational demands estimated to reach 4 Exaflops. Therefore, research on key algorithms in SDP data processing to improve performance is of significant importance.

Gridding algorithms are essential in synthetic aperture telescope data processing, accounting for a substantial proportion of computational overhead. Optimizing gridding algorithms offers significant value for SDP. Wide-field imaging for low-frequency radio telescopes is constrained by numerous factors, with the non-coplanar baseline effect being the most critical. Under wide-field and non-coplanar baseline conditions, direct Fourier transformation of visibility data leads to severe image distortion, making the mitigation of w-term effects crucial in wide-field imaging. Current algorithms addressing these challenges include faceting, three-dimensional Fourier transform, w-projection, w-stacking, warped snapshots, and various hybrid approaches. Among these, w-projection and w-stacking are the most widely adopted gridding algorithms. The w-projection algorithm offers superior computational speed and error control at the cost of increased memory usage. It supports both traditional CLEAN deconvolution and multi-scale CLEAN methods, providing advantages in high dynamic range imaging with minimal phase center distortion. The w-stacking algorithm processes the w-term in Fourier space at the expense of additional memory in image space, offering faster computation than w-projection.

In implementing w-projection and w-stacking algorithms, the w-plane parameter plays a vital role. Multiple w-planes are created between the minimum and maximum w-values, with different convolution kernels applied to visibility data from different w-planes. Consequently, the number of w-planes directly impacts algorithmic computational speed, memory overhead, and imaging quality. This paper experimentally investigates the w-plane parameter in both algorithms through simulated observations using SKA1 low-frequency array station data and the ASKAP software package, aiming to understand its influence on overall computational performance and provide guidance for pipeline system design in future SKA-SDP and domestic scientific data center construction.

1. The W-plane Parameter

The non-coplanar baseline effect represents the most significant factor affecting wide-field imaging in low-frequency radio telescopes. Under this effect, w-term values become much greater than 1, violating the conditions required for direct two-dimensional Fourier transformation of visibility data. To address this issue, astronomers have proposed various algorithms to mitigate image distortion caused by non-coplanar baselines. The w-projection algorithm eliminates w-term effects by projecting visibility data with different w-values onto the w=0 plane, thereby improving imaging quality. The w-stacking algorithm corrects phase offsets caused by non-coplanar baselines in the image plane, effectively restoring the sky brightness distribution.

1.1 W-plane in the W-projection Algorithm In radio synthesis imaging processing, the relationship between visibility data and sky brightness is given by Equation (1). The w-projection algorithm projects visibility data with different w-values onto the w=0 plane, simplifying Equation (1) to Equation (2). Through straightforward exponential operations, Equation (1) transforms into Equations (3) and (4). These can be rewritten as Equation (5), where the convolution kernel is approximated using Equation (6).

This process demonstrates that the convolution kernel is central to the w-projection algorithm. Ideally, visibility data located at different w-planes should employ distinct convolution kernels. In practice, the minimum and maximum w-values are calculated and divided into multiple evenly spaced w-planes. Convolution kernels are computed for each w-plane using Equation (6) and stored.

Each visibility data point is then convolved with the kernel from its nearest w-plane, achieving projection onto the w=0 plane.

Clearly, larger w-plane values yield better projection effects but require greater computational and memory resources, while smaller values reduce overhead at the cost of inferior projection quality. When the number of w-planes is zero, the algorithm reduces to standard two-dimensional Fourier transformation. Cornwell et al. previously recommended using the square root of the maximum w-value as an empirical setting.

2. W-plane in the W-stacking Algorithm

The w-stacking algorithm was also developed to eliminate non-coplanar baseline effects in wide-field imaging, but unlike w-projection, it does not remove the w-term; instead, it applies corrections.

Transforming from uv-space to lm-space according to Equation (1) yields Equation (7). Integrating both sides of Equation (7) over the w-range produces Equation (8), where maxw and minw represent the maximum and minimum w-values. The right side of Equation (8) comprises two components: a two-dimensional Fourier transform and a complex integral over w. Discretizing the right side of Equation (8) yields Equation (9).

The w-stacking algorithm implementation proceeds as follows: (1) Set the subdivision granularity of w-planes based on the w-range of visibility data; (2) Grid visibility data onto appropriate w-planes according to their w-values; (3) Perform two-dimensional Fourier transformation on each w-plane' s visibility data to obtain corresponding images; (4) Apply phase corrections to each w-plane' s image based on w-values; (5) Weight and sum all images to produce the final result.

In w-stacking implementation, excessively coarse w-plane division introduces artifacts, while overly fine division increases computational load and memory consumption. However, the algorithm treats visibility data on different w-planes as independent, enabling parallel two-dimensional Fourier transformations and phase corrections across planes, thus providing advantages for parallel implementation.

3.1 Experimental Environment

To validate the impact of w-plane and identify optimal values that reduce processing time while ensuring imaging quality, we conducted a series of experiments using the Australian SKA Pathfinder (ASKAP) data processing software system. ASKAP employs the ASKAPsoft system for telescope control and data processing, which consists of three components: the telescope observation system, processing center, and science data archive. ASKAP forms data processing pipelines by combining ASKAPsoft programs through bash shell scripts, with primary pipelines including data ingestion, calibration, and imaging pipelines.

Experiments were performed on eight Hanpower servers with the hardware configuration detailed in Table 1 .

Table 1. Hardware Device Parameters

Server Model	CPU	Memory	Network
C640 G3 (8)	Intel Xeon E5-2620 v3	128GB	Infiniband + 10Gb Ethernet

3.2 Simulation and Imaging Processing

To analyze the effect of w-plane on w-projection and w-stacking algorithms, we employed a methodology of simulated observation, imaging, and subsequent image analysis to verify impacts from different w-plane settings.

1. Simulated Observations

The experiments utilized antenna station coordinate data for 512 SKA1-Low telescope antennas, with the layout shown in Figure 1 [Figure 1: see original paper]. The sky model comprised 73 point sources arranged in a "rice" character pattern, as illustrated in Figure 2 Figure 2: see original paper. The simulation employed 16 compute nodes, each processing one channel with 1 MHz bandwidth, yielding a total frequency coverage of 16 MHz. The integration time interval was 150 seconds, with a total simulated observation duration of 6 hours. The SKA1-Low antenna frequency range spans 50–350 MHz; this experiment used a central reference frequency of 100 MHz with 16 channels of 1 MHz bandwidth each, resulting in an observed frequency range of 92–108 MHz.

The simulation observation program generated 18,837,504 rows of visibility data totaling 5.5 GB across 16 channels.

2. Imaging Processing

Using w-projection and w-stacking algorithms, we performed continuum imaging on the 16 channels of simulated visibility data. The ASKAP imaging pipeline operated in parallel across 8 compute nodes, with each node processing two channels. During the experiments, we varied the number of w-planes, obtained images under different settings, and recorded imaging times for subsequent analysis. Figure 4 Figure 4: see original paper shows the variation in processing time for both algorithms as the number of w-planes increases.

Figure 2(b) displays the image obtained through two-dimensional Fourier processing, where smearing effects caused by the w-term are clearly visible. Figure 3 [Figure 3: see original paper] presents images processed with w-projection and w-stacking algorithms using 171 w-planes, showing suppressed smearing but imperfect restoration of peripheral simulated sources.

3. Image Quality Evaluation Method

To evaluate imaging quality under different w-plane configurations, we employed the SELAVY software package, which implements the Duchamp source-finding algorithm within ASKAPsoft for detecting sources in observational results. Since the simulation preset 73 sources with known positions, we compared SELAVY-detected sources against the known sky model, using the number of correctly recovered sources as a rapid quality metric. Figure 4(b) illustrates the variation in the number of point sources detected by SELAVY as w-plane count increases.

3.3 Results Analysis

The maximum baseline length in this experiment was 81,602 meters, with a maximum w-value of approximately 28,000 wavelengths. Based on previous research by Cornwell et al., the w-plane value is typically set to the square root of the maximum w-value, which would be 167.

Figure 4(a) reveals that w-projection runtime increases approximately linearly with w-plane value. In contrast, w-stacking runtime shows distinct behavior: when w-plane values are smaller than the w-value, computation time is significantly less than w-projection; however, beyond the w-value, runtime increases rapidly and exceeds w-projection when w-plane surpasses 1.5×w. This occurs because excessive w-planes in large-image imaging require substantial phase corrections, dramatically increasing computational overhead and eliminating w-stacking’ s speed advantage.

SELAVY source statistics for both algorithms across different w-plane settings show that at small w-plane values, w-stacking recovers more sources than w-projection, but imaging quality becomes comparable as w-plane increases.

The experimental results deviate from the conventional empirical value of $\sqrt{w}$. When w-plane exceeds 1.5×w, imaging quality improves significantly, with SELAVY recovering all 73 sources. Therefore, to obtain high-resolution sky images, w-plane values should exceed 1.5×w. Although both algorithms achieve similar imaging quality, w-stacking maintains substantial speed advantages when w-plane $<$ w, but loses this advantage when w-plane $>$ w.

Analysis of imaging quality and runtime trends indicates that w-stacking is better suited for cases where w-plane $<$ w. To compensate for reduced imaging accuracy at smaller w-plane values, future work could combine multi-beam observations with SKA’ s LINMOS (Linear Mosaic Applicator) package for linear mosaicking of multiple images to improve quality. Conversely, w-projection is better suited for achieving higher accuracy through increased w-plane values.

4. Conclusion

In summary, regarding the application of w-projection and w-stacking algorithms in processing pipelines, we conclude:

1. **Optimal w-plane selection is critical for imaging.** Experiments demonstrate that w-plane values should be **1.5 times the empirical √w value** to achieve excellent imaging quality with both algorithms, representing a deviation from Cornwell' s original estimate.
2. **W-plane values strongly correlate with result accuracy.** Only sufficiently large w-plane values can fully recover sky information. Future data processing must balance accuracy requirements against computational time constraints. When w-plane $<$ w, w-stacking offers significant computational advantages over w-projection. However, for high-resolution imaging requiring w-plane $>$ w, w-stacking loses its speed advantage.

This work demonstrates that SKA-SDP data processing pipelines should select appropriate gridding algorithms based on specific requirements. Future research should focus on improving computational speed and algorithmic parallelism to achieve better processing capabilities.

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