MUSER Visibility Data Integration Methods and Implementation Postprint

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Abstract

Radio observations constitute a crucial diagnostic tool for investigating solar activity. The Mingantu Spectral Radioheliograph (MUSER) in China is primarily utilized for studying the physical processes within the initial energy release region of solar eruptive events, and its observations will open a new window in solar radio imaging. Imaging processing represents an essential component of data processing, and improving imaging quality stands as a current research focus in data processing. This work first introduces the fundamental theory of radio interferometric imaging, subsequently analyzes the necessity of integrating observed visibility data, and presents a detailed discussion of two integration methods—averaging through stacking short-duration visibility data and stacking long-duration UV coverage—along with a complete implementation. Through implementation code and experimental verification, both integration approaches can effectively improve the signal-to-noise ratio, yielding significantly enhanced image quality.

Full Text

Preamble

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Integral Method and Implementation of Visibility Data for MUSER

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Abstract

Radio observation is a crucial detection method for studying solar activity. The Mingantu Spectral Radioheliograph (MUSER) is primarily used to investigate the physical processes in the initial energy release region of solar eruptive events, and its observations will open a new window in solar radio imaging. Imaging processing is a vital component of data processing, and improving imaging quality is a key focus of current research. This paper first introduces the fundamental theory of radio interferometric imaging, then analyzes the necessity of integrating visibility data obtained from observations. We discuss in detail two integration methods—short-term visibility data averaging and long-term UV coverage stacking—and provide a complete implementation. Through code implementation and experimental verification, both integration methods can effectively improve the signal-to-noise ratio and significantly enhance image quality.

Keywords: MUSER; average integration; coverage integration; aperture synthesis imaging

1. Basic Principles

1.1 Radio Interferometry Imaging Theory

Radio astronomy is a branch of astronomy that uses radio telescope systems to study radio waves from deep space, including various celestial objects [1]. To advance radio observation technology and fill the international gap in high-resolution radio imaging observations of the initial energy release region of solar flares in the decimeter waveband [2-3], China has constructed the Mingantu Spectral Radioheliograph (MUSER), a cm-dm wave radioheliograph operating in the 0.4–15 GHz range. It can simultaneously observe the Sun' s dynamic properties with high temporal, spatial, and frequency resolution in an ultra-wide frequency band, exploring the origin of intense solar activity [4]. The MUSER antenna array comprises a low-frequency array (MUSER-I) operating at 400 MHz–2 GHz and a high-frequency array (MUSER-II) operating at 2 GHz–15 GHz, with two polarization modes observed in each band. Each band contains 33 channels of data per polarization direction [5]. The key to scientific research is obtaining solar images from raw observed visibility data through a series of calibrations and calculations.

Foreign equipment for solar radio imaging observations mainly includes the Nobeyama Radioheliograph in Japan, the Nançay Decameter Array in France, and the Siberian Solar Radio Telescope. These radioheliographs typically perform integration processing directly in the receiver with an integration time of about 25 ms, resulting in relatively low time resolution [6-7]. The Mingantu Spectral Radioheliograph in Inner Mongolia has been completed, and software for real-time and post-processing of scientific data has been developed [8-9]. To further improve imaging quality, this paper analyzes the basic principles of imaging and proposes two methods to enhance the signal-to-noise ratio of solar images based on aperture synthesis imaging principles: average integration and UV coverage integration.

A correlation interferometer transmits radiation received from a celestial source by two antennas separated by a certain distance to a correlator for correlation processing. Assuming the sky brightness distribution is $I(l,m)$, the interferometer output response has a Fourier transform relationship with the sky brightness. The interferometer output $V(u,v)$ is given by [10]:

$$V(u,v) = \iint I(l,m)e^{i2\pi(ul+vm)}\,dl\,dm$$

where l,m represent the sky plane coordinates and u,v represent the projected plane, also known as spatial frequencies. The components $V(u,v)$ are collectively called the complex visibility function. Equation (1) shows that the interferometer output is the Fourier transform of the brightness distribution, which is known as the principle of aperture synthesis imaging [10].

The inverse Fourier transform of the complex visibility function yields the sky brightness distribution:

$$I(l,m) = \iint V(u,v)e^{-i2\pi(ul+vm)}\,du\,dv$$

The complex visibility function is a continuous complex function. For any brightness distribution $I(l,m)$, there is always a corresponding complex visibility function $V(u,v)$. However, an antenna array can only form a finite number of baselines, meaning only a limited number of samples of the complex visibility function can be obtained. Let $S(u,v)$ be the sampling function:

$$S(u,v) = \sum_k \delta(u-u_k, v-v_k)$$

The output of the sampling function is the actual observed visibility data. Performing an inverse Fourier transform on these data yields the dirty image:

$$I^D(l,m) = \iint S(u,v)V(u,v)e^{-i2\pi(ul+vm)}\,du\,dv$$

1.2 MUSER Integration Fundamentals

The current MUSER data processing pipeline has completed the conversion from raw observation data format to UVFITS file format, as well as the processes of generating dirty images and clean images [8]. Taking high-frequency array observation data at 04:04:38 UT on July 5, 2016 as an example, after calibrating the observation data, the resulting dirty image and clean image are shown in [Figure 1: see original paper]. The signal-to-noise ratio of solar images reconstructed from single-frame sampling data is very low, making it impossible to clearly identify the location of solar bursts. Even after cleaning the dirty image to obtain a clean map, the burst location cannot be clearly analyzed. To obtain better quality imaging results for scientific research, integration processing of the sampling data is necessary to improve image quality and increase the signal-to-noise ratio [12].

Based on scientific research requirements and the characteristics of MUSER observations, this paper analyzes two aspects: averaging short-term visibility data and increasing UV coverage using Earth' s rotation. According to different integration time requirements, we propose average integration, UV coverage integration, and a mixed integration method combining both.

1.2.1 Average Integration MUSER operates in snapshot mode with an integration time of 3 ms. To improve spatial resolution under high time resolution conditions, data averaging is implemented. Taking the high-frequency array as an example, each complete frame of data contains 2,560 sampling points with real and imaginary parts. The sampling output is V_{tc}, where t_c is the single-frame integration sampling time. The integration is expressed as:

$$V_{tI} = \frac{1}{N}\sum_{i=1}^{N} V_{tc}$$

where t_I is the integration time. The conventional approach involves averaging the sampled complex visibility functions while also averaging the sampling functions. The dirty image is obtained using the averaged sampling function and complex visibility function.

1.2.2 UV Coverage Integration UV coverage plays a crucial role in imaging. Since the sampling function $S(u, v)$ directly affects the dirty beam, which in turn affects imaging, image quality can be improved by increasing UV coverage. Methods to increase UV coverage include: (1) increasing the number of array telescopes; (2) increasing the effective radius of sub-apertures; and (3) utilizing Earth' s rotation [12]. Given fixed costs, increasing the number of telescopes is not feasible, and increasing sub-aperture radius may lead to insufficient sampling rates. Therefore, increasing UV coverage through Earth' s rotation is a direct and viable method.

As Earth rotates, the baseline vectors projected on the celestial plane change continuously, allowing acquisition of different spatial frequency components. The sampling function and sampling output after UV coverage increase can be expressed as:

$$S_{ta}(u,v) = \sum_{i=1}^{N} S_{tinterval}(u,v)$$

$$V_{ta}(u,v) = \sum_{i=1}^{N} V_{tinterval}(u,v)$$

where $t_{interval}$ is the time interval for stacking, and t_a is the total integration time. For an antenna array composed of n antennas, $n(n-1)/2$ data sampling points can be obtained. This significantly improves the imaging quality of sparse sampling.

1.2.3 Mixed Integration Both methods above can improve imaging quality. Mixed integration combines averaging and UV coverage increase. With an integration time of t_I and interval $t_{interval}$ for UV coverage increase, the sampling function and sampling output for mixed integration can be expressed as:

$$S_t(u,v) = \frac{1}{M} \sum_{j=1}^{M} \left(\sum_{i=1}^{N} S_{tinterval}(u,v) \right)$$

$$V_t(u,v) = \frac{1}{M} \sum_{j=1}^{M} \left(\sum_{i=1}^{N} V_{tinterval}(u,v) \right)$$

Within total time t_a, the UV coverage increases by $t_{interval}$, with each group of increased UV coverage being averaged over time period t_I before stacking.

2. Integration Process Implementation

2.1 MUSER Imaging Procedure

The MUSER imaging process involves preprocessing and correlation calibration of raw data [13], followed by integration processing, gridding, Fourier inversion to obtain dirty images, and finally clean algorithm processing to obtain clean images. [Figure 2: see original paper] illustrates this procedure.

2.2 Integration Operation Flow

MUSER integration data for each polarization and channel are visibility data obtained from observations and preprocessed through correlation calibration. The system receives one frame of observation data every 3 ms. Integration operations are performed on these data to obtain integrated data.

Average Integration: The specific operation flow is shown in [Figure 3: see original paper]. For each frame of data in the high-frequency array, the real and imaginary parts of the 2,560 sampling points are accumulated and averaged. The average integration data volume is the same as single-frame data. The averaged UU, VV coordinates and visibility values are then subjected to gridding and Fourier inversion.

UV Coverage Integration: The operation flow is shown in [Figure 4: see original paper]. UV coverage integration also uses complete data frames. However, since the sampling function and sampling values change very little in short periods, using consecutive frames to increase UV coverage is inefficient. Therefore, data frames are stacked at intervals. UV coverage integration yields data volumes that increase exponentially, significantly improving the quality of sparsely sampled images and increasing the signal-to-noise ratio.

Taking high-frequency array data as an example, a single frame' s UV coverage contains 2,560 data points (6,560 after conjugation). After 60 minutes of integration, the data points increase to 393,600 (7,872,000 after conjugation). For a 2,560×2,560 pixel image, the single-frame UV coverage rate is only 0.054%, while 60-minute integration increases the coverage rate to 0.324%. [Figure 5: see original paper] and [Figure 6: see original paper] show the UV coverage for a single frame and for one hour' s integration, respectively.

3. Integration Code Implementation

The three integration modes—average integration, UV coverage integration, and mixed integration—are implemented in a single interface with mode selection. The Python program interface is as follows:

```
def clean_integration_R(self, sub_ARRAY, is_loop_mode, start_time, end_time,
                          TASK_TYPE, time_average, time_interval, BAND, CHANNEL,
                          PLOT_ME, WRITE_FITS, P_ANGLE, DEBUG, outdir):
```

Parameters: - `sub_ARRAY`: Array selection (MUSER-I or MUSER-II) - `start_time`, `end_time`: Integration start and end times - `TASK_TYPE`: Integration mode selection (average integration, UV coverage integration, or mixed integration) - `time_average`: Integration time for average integration - `time_interval`: Time interval for UV coverage stacking - `BAND`, `CHANNEL`: Band and channel selection - Other parameters control output options

The code is written to handle integration for any time period of data acquisition. [Figure 7: see original paper] shows the integration task running in the MUSER data processing system.

4. Experimental Validation

Using mixed integration mode as an example, data from 04:04:38 UT on July 5, 2016 were integrated for 10, 20, 30, 40, 50, and 60 minutes. The dirty images are shown in [Figure 8: see original paper]. From left to right and top to bottom, corresponding to integration times of 10, 20, 30, ⋯, 60 minutes, the solar 轮

廓 becomes progressively clearer, with the solar disk and burst locations clearly visible. As integration time increases, dirty image quality improves significantly.

The clean images obtained after CLEAN processing are shown in [Figure 9: see original paper]. The images become increasingly clear with longer integration times, showing the solar limb and burst positions distinctly. The signal-to-noise ratio improves substantially, with multiple bright spots at the beginning converging to a single prominent burst point after 60 minutes.

[Figure 10: see original paper] compares the 60-minute integrated solar image from MUSER-II at 8 GHz with that from the Nobeyama Radioheliograph at 17 GHz (observed at 04:00:02 UT). The results are basically consistent, demonstrating the reliability of the integration implementation.

5. Conclusion

Integration processing of sampled data produces significant imaging improvements. Dirty images obtained after data processing clearly show the solar limb and burst locations. Using mixed integration of 10-minute averaging and interval UV coverage as an example, the signal-to-noise ratio improves dramatically, with image quality enhancing as integration time increases. This approach proves effective for obtaining high-quality MUSER observation results.

Current image processing has improved substantially, but challenges remain: UVFITS file generation is slow before imaging, requiring efficiency improvements. Future work will explore optimal integration parameters using evaluation metrics to determine quantitative values for average integration time, UV coverage integration intervals, and total integration time.

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