Visibility Data Integration Method and Implementation Postprint

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Date: 2017-09-26T00:00:00+00:00

Abstract

Radio observation is an important detection method for studying solar activity. The Mingantu Spectral Radioheliograph (MUSER) in our country is mainly used to study the physical processes in the initial energy release region of solar eruptive activities, and its observations will open a new window in solar radio imaging. Imaging processing is an important component of MUSER data processing, and improving imaging quality represents a current research focus in data processing. First, the basic theory of radio interferometric imaging is introduced, followed by an analysis of the necessity for integrating visibility data obtained from MUSER observations. Two integration methods–the averaging of short-duration visibility data through stacking and long-duration UV coverage stacking–are discussed in detail, and a complete implementation is presented. Through experimental verification of the correctness of the method and implementation, both integrations can effectively improve the signal-to-noise ratio, and image quality is significantly enhanced.

Full Text

Integral Method and Implementation of MUSER Visibility Data

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Abstract

Radio observations serve as a crucial tool for studying solar activity. The Mingantu Spectral Radioheliograph (MUSER), designed to investigate the physical processes in the initial energy release region of solar eruptions, will open a new window in solar radio imaging. Imaging processing constitutes a vital component of MUSER data processing, and improving image quality represents a key research focus. This paper first introduces the fundamental theory of radio interferometric imaging, then analyzes the necessity of integrating visibility data obtained from MUSER observations. We discuss in detail two integration methods—short-term visibility data averaging and long-term UV coverage stacking—and provide a complete implementation. Experimental verification demonstrates the correctness of our methods and implementation; both integration approaches effectively improve the signal-to-noise ratio and significantly enhance image quality.

Keywords: MUSER; UV averaging integration; UV coverage integration; synthetic aperture imaging

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-wave band [2-3], Chinese astronomers have constructed the Mingantu Spectral Radioheliograph (MUSER), a centimeter-decimeter wave solar imager operating in the 0.4–15 GHz range. MUSER can simultaneously observe solar dynamic properties with high temporal, spatial, and spectral resolution across an ultra-wide frequency band, enabling exploration of the origins of intense solar activity [4].

The MUSER antenna array comprises a low-frequency array (MUSER-I) and a high-frequency array (MUSER-II). MUSER-I consists of 40 antennas of 4.5 m diameter, observing at 400 MHz–2 GHz across four bands with two polarization modes (left-hand and right-hand circular), with each band containing 16 channels. MUSER-II comprises 60 antennas of 2 m diameter, observing at 2–15 GHz across 33 bands with two polarization modes, also with 16 channels per band [5]. Both the high- and low-frequency arrays generate one frame of observational data every 3 ms (comprising data from 16 channels for one band and one polarization direction). A critical challenge in MUSER scientific data processing is deriving research-quality solar images from raw visibility data through a series of calibration and computational steps.

Currently, major solar radio imaging instruments abroad include the Nobeyama Radioheliograph in Japan, with an integration time of 25 ms [6]; the Nançay Decameter Array in France, with an integration time of 1 s[1]; and the Siberian Solar Radio Telescope, with an integration time of 0.336 s [7]. The integration processing for these radioheliographs is typically performed directly in the receiver, resulting in relatively low temporal resolution. The Mingantu Spectral Radioheliograph at the observatory station in Inner Mongolia has been completed, and software for both real-time and post-processing scientific data has been developed [8-9]. To further improve imaging quality, this paper analyzes the fundamental imaging principles and proposes two integration methods—UV averaging integration and UV coverage integration—to enhance the signal-to-noise ratio of solar images.

1.1 Principle of Synthetic Aperture Imaging

A correlation interferometer receives celestial radiation with two antennas separated by a certain distance and transmits the signals to a correlator for processing. According to interferometric imaging principles, the interferometer’ s output response bears a Fourier transform relationship with sky brightness. Assuming the sky brightness distribution is $I(l, m)$, the relationship is given by [10]:

$$V(u, v) = \iint I(l, m) e^{-2\pi i(ul+vm)}\, dl\, dm$$

Converting the discrete summation to continuous integration yields [10]:

$$V(u, v) = \iint I(l, m) e^{-2\pi i(ul+vm)}\, dl\, dm$$

where (u, v) represents the spatial frequencies on the projection plane, and (l, m) denotes the conventional sky plane. Equation (2) indicates that the interferometer output corresponds to a component of the Fourier transform of the brightness distribution. By varying (u, v), different spatial frequency components can be obtained. The collection of all spatial frequency components is termed the complex visibility function. Performing an inverse Fourier transform on the complex visibility function yields the sky brightness distribution—the image—constituting the principle of synthetic aperture imaging [10].

For any brightness distribution $I(l, m)$, there exists a corresponding complex visibility function $V(u, v)$. While the visibility function is a continuous complex function, an antenna array can only form a finite number of baselines, meaning only a limited set of samples of the visibility function can be obtained. The sampling function is defined as $S(u, v) = \sum_k \delta(u - u_k, v - v_k)$, where k indexes all (u, v) points. The output of the sampling function represents the actual data acquired by the antennas. Performing an inverse Fourier transform on these data yields the dirty image [11]:

$$I^D(l, m) = \iint S(u, v) V(u, v) e^{2\pi i(ul+vm)}\, du\, dv$$

1.2 Basic Principles of MUSER Integration

The current MUSER data processing pipeline has completed the transformation from raw observational data format to FITS files, including observation data calibration, polarization and channel mapping, and imaging processes from dirty images to cleaned images [8]. Taking high-frequency array observations from

July 5, 2016, at 04:04:38 UTC as an example, the generated dirty image (Fig. 1(a)) and cleaned image (Fig. 1(b)) are shown below.

[Figure 1: see original paper]

As evident, the solar images produced from single-frame sampling data exhibit very low signal-to-noise ratios, making it difficult to clearly identify the location and outline of solar eruptions. Even after deconvolution, the cleaned images remain insufficient for analyzing eruption locations. To achieve improved signal-to-noise ratios and obtain higher-quality imaging results from MUSER reconstructions, integration processing of sampled data is necessary to enhance image quality [12]. Based on scientific research requirements and integration time constraints, this paper investigates two methods: UV averaging integration (summing and averaging visibility data) and UV coverage integration (increasing UV coverage through Earth' s rotation).

1.2.1 UV Averaging Integration MUSER operates in snapshot mode with an integration time of 3 ms. To improve spatial resolution and image quality under such high temporal resolution, we implement UV averaging by averaging the UV coordinates and their output data obtained from 3 ms observations.

Taking MUSER-II as an example, where the single-frame integration sampling time is t_c, and assuming the UV integration time is t_I, with single-frame sampling function $S_t(u,v)$ and sampling output $V_t(u,v)$, UV averaging integration is expressed as:

Sampling function:

$$S_I(u,v) = \frac{1}{N}\sum_{i=1}^{N} S_{t_i}(u,v)$$

Sampling output:

$$V_I(u,v) = \frac{1}{N}\sum_{i=1}^{N} V_{t_i}(u,v)$$

UV-averaged dirty image:

$$I_I^D(l,m) = \iint \left[\frac{1}{N}\sum_{i=1}^{N} S_{t_i}(u,v)\right]\left[\frac{1}{N}\sum_{i=1}^{N} V_{t_i}(u,v)\right] e^{2\pi i(ul+vm)}\, du\, dv$$

Equation (4) implements averaging of the sampled complex visibility functions while simultaneously averaging the sampling functions, thereby achieving UV averaging integration.

1.2.2 UV Coverage Integration UV coverage plays a crucial role in imaging quality. Since the Fourier transform of the sampling function $S(u,v)$ yields the dirty beam (also called the synthesized beam), which directly affects imaging, image quality can be improved by increasing UV coverage. Three methods exist to increase UV coverage: adding more telescopes to the array, increasing the effective aperture radius of sub-apertures, and utilizing Earth' s rotation [12]. Adding telescopes incurs significant cost and is therefore impractical under fixed budget constraints. Increasing sub-aperture radius may lead to insufficient sampling rates. Under existing cost constraints, leveraging Earth' s rotation provides a direct and feasible method for increasing UV coverage.

As Earth rotates, UV coordinates change. However, these changes are minimal over short periods. Therefore, assuming UV coverage is increased at intervals of $t_{interval}$ with total integration time t_{at}, the sampling function and sampling output after UV coverage increase can be expressed as:

Sampling function:

$$S_{at}(u,v) = \frac{1}{N}\sum_{j=1}^{N} S_{t_j}(u,v)$$

Sampling output:

$$V_{at}(u,v) = \frac{1}{N}\sum_{j=1}^{N} V_{t_j}(u,v)$$

UV coverage-enhanced dirty image:

$$I_{at}^{D}(l,m) = \iint \left[\sum_{j=1}^{N} S_{t_j}(u,v)\right]\left[\sum_{j=1}^{N} V_{t_j}(u,v)\right] e^{2\pi i(ul+vm)}\,du\,dv$$

Equation (5) shows that increasing UV coverage at intervals of $t_{interval}$ with total integration time t_{at} can increase the number of UV data points by a factor of N. For an antenna array with n antennas, $n(n-1)/2$ data sampling points can be obtained. Through UV coverage increase, the total number of sampling data points becomes $N \times n(n-1)/2$, substantially improving imaging quality under sparse sampling conditions.

Both methods can enhance imaging quality, and combining them yields further improvements. We therefore propose a hybrid approach that first performs UV averaging integration followed by UV coverage integration.

1.2.3 Hybrid Integration of UV Averaging and Coverage Increase Assuming the UV integration time is t_I, the sampling function within this period is $S_{t_i}(u,v)$ and the sampling output is $V_{t_i}(u,v)$. With UV coverage increased at intervals of $t_{interval}$ and total integration time t_{at}, the hybrid integration sampling function and sampling output can be expressed as:

Sampling function:

$$S_{mix}(u,v) = \frac{1}{M}\sum_{i=1}^{M}\left[\frac{1}{N}\sum_{j=1}^{N} S_{t_{ij}}(u,v)\right]$$

Sampling output:

$$V_{mix}(u,v) = \frac{1}{M}\sum_{i=1}^{M}\left[\frac{1}{N}\sum_{j=1}^{N}V_{t_{ij}}(u,v)\right]$$

Within the total time t_{at}, UV coverage increases by a factor of M. Each increment of UV coverage represents an average over time period t_I before being superimposed.

2 Implementation of MUSER Integration Process

The MUSER imaging process proceeds as follows: celestial radiation from the target source is sampled by the interferometer; the raw sampled data undergo preprocessing, correlation calibration [13], and polarization/channel mapping; integration processing is then performed, followed by gridding and inverse Fourier transform to obtain the dirty image; finally, deconvolution algorithms produce the clean image. This procedure is illustrated in Fig. 2 [Figure 2: see original paper].

[Figure 2: see original paper]

2.1 Integration Operation Flow MUSER receives one frame of observational data every 3 ms. Integration operations are performed on these data to produce integrated visibility data that have been preprocessed, correlation-calibrated, and mapped to specific polarizations and channels. The specific operational flow for UV averaging integration is shown in Fig. 3 [Figure 3: see original paper].

[Figure 3: see original paper]

In MUSER-II, each complete data frame contains 33 sub-frames. UV averaging integration accumulates and averages the UU, VV coordinates and the corresponding real and imaginary parts of the sampled data across consecutive frames. The resulting UV-averaged integrated data maintain the same quantity as a single frame. For example, if a single MUSER-II frame contains 3,540 UV points with sampled real and imaginary parts, the UV-averaged integration yields the same number of 3,540 UV points and their sampled values.

The operational flow for implementing UV coverage integration is shown in Fig. 4 [Figure 4: see original paper]. Similar to UV averaging, UV coverage integration uses complete data frames. However, because both the sampling function and sampled values change minimally over short periods, using consecutive frames to increase UV coverage proves ineffective. Therefore, frames must be separated by time intervals to increase UV coverage effectively. UV coverage integration produces data frames 叠加后的数据帧 (superimposed data frames) over a time interval, with data volume increasing multiplicatively. This operation significantly improves image quality under sparse sampling conditions and enhances the signal-to-noise ratio.

[Figure 4: see original paper]

Using one hour of integrated data as an example, UV coverage integration multiplies the sampling data, which is crucial for improving image quality and signal-to-noise ratio under sparse sampling. A single MUSER-II frame contains 1,770 UV data points (3,540 points after including conjugates), producing a 2,560×2,560 pixel image with a coverage rate of only 0.054%. After integrating data for one hour with UV coverage 叠加 (overlap) at 10-minute intervals, the total number of data points increases to 10,620 (21,240 after conjugation), raising the coverage rate to 0.324%. Selecting 60 ms sampling data for averaging and increasing UV coverage every 10 minutes yields the UV coverage patterns shown in Fig. 5 [Figure 5: see original paper] and Fig. 6 [Figure 6: see original paper].

[Figure 5: see original paper] [Figure 6: see original paper]

2.2 Integration Code Implementation To implement UV averaging integration, UV coverage integration, and their hybrid, we developed Python code. To simplify the program, all three integration modes are incorporated into a single interface that allows mode selection. The 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):
```

Key parameters include: `sub_ARRAY` selects the MUSER phase (MUSER-I or MUSER-II); `start_time` and `end_time` define the integration period; `TASK_TYPE` selects the integration mode (UV averaging, UV coverage, or hybrid); `time_average` specifies the UV averaging integration duration; and `time_interval` determines the time interval for UV coverage 叠加 (overlap). The integration task running in the MUSER system is shown in Fig. 7 [Figure 7: see original paper].

[Figure 7: see original paper]

The code can be applied to any time period for which data have been collected. The implementation supports flexible integration modes for various observational scenarios.

3 Experimental Analysis

We demonstrate the hybrid integration mode using integration periods of 10, 20, 30, 40, 50 minutes, and 1 hour. The processing involves UV averaging integration over 60 ms intervals, followed by UV coverage increase every 10 minutes. The resulting dirty images are shown in Fig. 8 [Figure 8: see original paper].

[Figure 8: see original paper]

Fig. 8 displays dirty images after 10, 20, 30, ···, 60 minutes of integration (left to right, top to bottom). The solar 轮廓 (contour) becomes progressively clearer from the first to the last image. As integration time increases, dirty image quality improves markedly, with the solar disk (the circular feature in the center) and bright eruption locations becoming distinctly visible. This clearly demonstrates that integration effectively enhances image quality.

The corresponding cleaned images are shown in Fig. 9 [Figure 9: see original paper].

[Figure 9: see original paper]

Fig. 9 shows cleaned images after 10, 20, 30, ···, 60 minutes of integration. The improvement in clarity is evident as integration time increases, with both solar 轮廓 (contours) and eruption bright spots clearly visible. The number of bright spots decreases from multiple locations in early images to a single prominent eruption point in the final image, indicating substantial signal-to-noise ratio improvement.

Fig. 10 [Figure 10: see original paper] presents solar radio images observed by MUSER-II at 4.1878 GHz on July 5, 2016, at 04:04:38 UT, using one hour of integration time. Compared with solar images from the Nobeyama Radioheliograph at 17 GHz on July 5, 2016, at 04:00:02 UT, the MUSER-II results show good consistency, demonstrating the reliability of our integration method and implementation.

[Figure 10: see original paper]

Through integration processing of sampled data, the hybrid method of 60 ms UV averaging combined with 10-minute UV coverage intervals produces remarkable imaging results. The resulting dirty images clearly reveal solar limb contours and eruption locations, with significant signal-to-noise ratio improvement. Image quality continues to improve with longer integration times. This integration approach proves valuable for obtaining high-quality MUSER observational results. While current image processing has improved substantially, the generation of UVFITS data files prior to imaging remains time-consuming and requires efficiency optimization. Future work will explore optimal integration parameters, using evaluation metrics to determine quantitative values for UV averaging duration, UV coverage interval length, and total integration time to achieve the best results.

References

[1] Xiang Delin. Radio Astronomical Observations[J]. Beijing: Science Press, 1990.

[2] Gary D E, Keller C U. Solar and space weather radiophysics - current status and future developments[M]. Netherlands: Kluwer Academic Publishers, 2004.

[3] Wang W, Yan Y, Liu D, et al. Calibration and Data Processing for a Chinese Spectral Radioheliograph in the Decimeter-Wave Range[J]. Publications of the Astronomical Society of Japan, 2013, 65(sp1):2226-2237.

[4] Yan Yihua, Zhang Jian, Chen Zhijun, et al. Progress on Chinese solar radioheliograph in cm-dm wavebandes [J]. Astronomical Research & Technology—publications of National Astronomical Observatories of China, 2006, 3(2):91-98.

[5] Mei Ying. Research on Key Technologies for MUSER Massive Data Preprocessing[D]. Kunming: Kunming University of Science and Technology, 2015.

[6] Nakajima H, Nishio M, Enome S, et al. The Nobeyama radioheliograph[J]. Proceedings of the IEEE, 1994, 82(5):705-713.

[7] Grechnev V V, Lesovoi S V, Smolkov G Y, et al. The Siberian Solar Radio Telescope: the current state of the instrument, observations, and data[J]. Solar Physics, 2003, 216(1-2):239-272.

[8] Wang F, Mei Y, Deng H, et al. Distributed data-processing pipeline for Mingantu Ultrawide Spectral Radioheliograph[J]. Publications of the Astronomical Society of the Pacific, 2015, 127(950):383-396.

[9] Wei S, Wang F, Deng H, et al. OpenCluster: a flexible distributed computing framework for astronomical data processing[J]. Publications of the Astronomical Society of the Pacific, 2016, 129(972): 1-14.

[10] Thompson A R, Moran J M, Swenson Jr G W. Interferometry and synthesis in radio astronomy[M]. Berlin: Springer, 2001:648-648.

[11] Luo Hongli. Research and Implementation of Grid Technology in MUSER Imaging[D]. Kunming: Kunming University of Science and Technology, 2016.

[12] Ségransan D. Observability and UV coverage[J]. New Astronomy Reviews, 2003, 51(8–9):597-603.

[13] Mei Y, Liu D, Wang F, et al. The data format preprocessing system for Chinese spectral radioheliograph[J]. ICIC Express Letters, Part B: Applications, 2015, 6(5): 1467-1472.

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[1] http://secchirh.obspm.fr/index.php

Note: Figure translations are in progress. See original paper for figures.