

Working Principle of the Calibration Algorithm for High Dynamic Range Solar Imaging with Square Kilometre Array Precursor

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Abstract Imaging the low-frequency radio Sun is an intrinsically challenging problem. Meter wavelength solar emission span angular scales from a few arcminutes to a few degrees. These emissions show temporal and spectral variability in sub-second and sub-MHz scales. The brightness temperature of these emissions also varies by many orders of magnitude, which requires high-dynamic-range spectroscopic snapshot imaging. With the unique array configuration of the Murchison Widefield Array (MWA), and the robust calibration and imaging pipeline, AIRCARS produces the best spectroscopic snapshot solar images available to date. The working principle and the strength of this algorithm are demonstrated using statistical analysis and simulation. AIRCARS uses the partial phase stability of the MWA, which has a compact core with a large number of antenna elements distributed over a small array footprint. The strength of this algorithm makes it a state of the art calibration and imaging pipeline for low-frequency solar imaging, which is expected to be highly suitable for the upcoming Square Kilometre Array (SKA) and other future radio interferometers for producing high-dynamic-range and high-fidelity images of the Sun.

Keywords: Sun, Radio Sun, Square Kilometer Array, Murchison Widefield Array, Calibration, Self-calibration, Imaging, Solar imaging

1. Introduction

The solar emission covers the entire electromagnetic spectrum starting from γ -rays to radio wavelengths. Different physical mechanisms produce emissions at different wavelengths. Several emission mechanisms like plasma emission, thermal bremsstrahlung, and gyrosynchrotron produce the meter wavelength solar

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emission at the solar corona. Low-frequency radio observations are particularly important to measure the coronal magnetic fields and the nonthermal electron population, which are rather hard to do using observations at other wavelengths. Despite its well-appreciated importance, low-frequency imaging observation of the Sun is one of the least explored areas of solar physics. The brightness temperature (T_B) of the low frequency solar emissions can vary from $\sim 10^3 - 10^4$ K for gyrosynchrotron emission from CME plasma (Bastian *et al.*, 2001; Mondal, Oberoi, and Vourlidas, 2020) to $\sim 10^{13}$ K for bright type III radio bursts (McLean and Labrum, 1985; Reid and Ratcliffe, 2014) (shown by red bars in Fig. 1) over a background quiescent T_B of $\sim 10^6$ K. Depending upon the emission mechanism at play, the polarization fraction of the meter wavelength solar emission can also vary from $\leq 1\%$ to $\sim 100\%$ (McLean and Labrum, 1985; Nindos, 2020) (shown by the blue bars in Fig. 1).

Imaging the Sun at low radio frequencies with high fidelity is an intrinsically challenging problem. The Sun is an extended source having morphology spanning a large range of angular scales, from a few degrees to a few arcminutes at meter wavelengths. The meter wavelength solar emission varies over small temporal and spectral scales, which imposes a requirement for snapshot spectroscopic imaging. The need to be able to see features varying vastly in T_B , highlights the need for a high imaging dynamic range. Only recently it has become possible to meet these exacting requirements for solar radio imaging using the Murchison Widefield Array (MWA; Tingay *et al.*, 2013; Wayth *et al.*, 2018) operating at 80 – 300 MHz with an instantaneous bandwidth of 30.72 MHz. The MWA has a large number of antenna elements distributed over a small array footprint and is especially well suited for snapshot spectroscopic imaging. To produce high-dynamic-range high-fidelity spectroscopic snapshot solar images from the MWA solar observation, Mondal *et al.* (2019b) developed a novel calibration and imaging pipeline called “Automated Imaging Routine for Compact Arrays for the Radio Sun” (AIRCARS).

AIRCARS has been used on a set of MWA solar observations at different solar conditions, and successfully produced the best spectroscopic snapshot images of the Sun at low frequencies obtained to date. The dynamic range (DR) of the images produced by AIRCARS varies between > 300 to about 10^5 . It has led to many new discoveries over the last few years (Mohan *et al.*, 2019b,a; Mondal, Oberoi, and Vourlidas, 2020; Mondal, Oberoi, and Mohan, 2020; Mondal and Oberoi, 2021; Mohan, 2021b,a). Mondal *et al.* (2019b) described the implementation of AIRCARS and also demonstrated that it can even perform the calibration without any dedicated calibrator observation. However the explanation provided by Mondal *et al.* (2019b) as to why the algorithm works was rather limited. Additionally, due to some unappreciated aspects which have been understood since then, the way the algorithm works is different from the description they provided. Here this difference is discussed and demonstrated the working principle of AIRCARS using statistical and quantitative analysis.

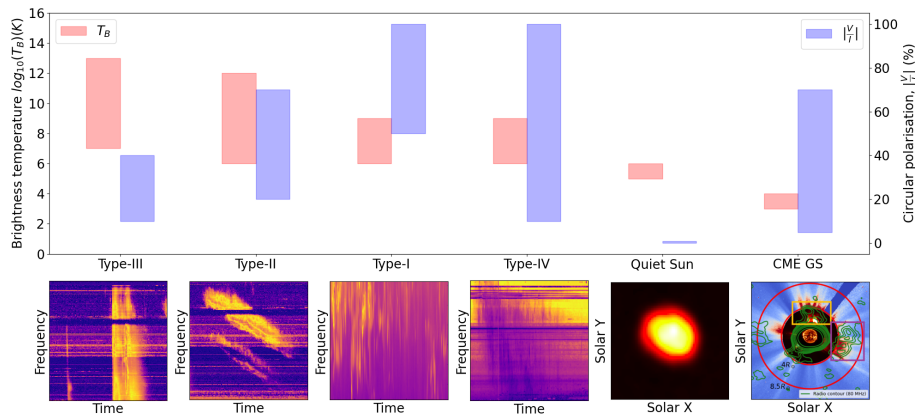


Figure 1. Top panel : The expected range of brightness temperature (T_B) and circular polarization fraction for different kinds of low-frequency solar radio emissions are shown by the blue and red bars respectively. **Bottom panel :** Sample dynamic spectra for type-I, II, III, and IV radio bursts. Type-II, III, and IV dynamic spectra have been obtained from the Learmonth Radio spectrograph. Type-I dynamic spectrum is obtained from the MWA. Dynamic spectra have different spectro-temporal structures spanning a large range of spectral and temporal widths. The images of the last two panels show the Quiet Sun emission and gyrosynchrotron emission from a CME. These emissions have spatial structures spanning a large range of angular scales. The images of the Quiet Sun and CME are from MWA.

2. Suitability of the Array Configuration of the MWA for High-fidelity Spectroscopic Snapshot Solar Imaging

Radio interferometric imaging is a Fourier imaging technique (McCready, Pawsey, and Payne-Scott, 1947; Thompson, Moran, and Swenson, 2017). A radio interferometer is made up of multiple antenna elements (or dishes) distributed over the ground. Each antenna element of the array receives radio emission from the sky and convert them into electronic voltage. The cross-correlation of the measured voltages between the antenna pairs is known as *visibilities*. Each of these visibilities corresponds to a single Fourier component of the sky brightness distribution in a 2-dimensional Fourier plane, which is known as *uv*-plane. The inverse Fourier transform of the measured visibilities on *uv*-plane gives the true sky brightness distribution. Ideally, the *uv*-plane has to be sampled at the spatial Nyquist resolution. Most of the conventional radio interferometers, like the VLA (Perley *et al.*, 2009), uGMRT (Gupta *et al.*, 2017), WSRT (van Cappellen *et al.*, 2021), LOFAR (van Haarlem *et al.*, 2013) etc, have a limited number of antenna elements distributed sparsely over a large area on the ground. Hence, the instantaneous sampling of the *uv*-plane is very sparse and does not meet the Nyquist criteria.

One way to sample the *uv*-plane densely is the so-called “large-N” array configuration. The MWA array design follows the “large-N” array configuration. It has 128 antenna elements distributed over a small array footprint and provides dense spectroscopic snapshot *uv*-coverage. The MWA has two phases of operation. The MWA Phase-I (Tingay *et al.*, 2013), has a compact condensed core of ~ 1.5 km in diameter with a quasi-random distribution of antenna elements. The other

antenna elements are distributed over a region up to 3 km in diameter. The MWA Phase-II (Wayth *et al.*, 2018) has two configurations – “compact” and “extended”. The phase-II extended configuration has baselines up to ~ 5.3 km in diameter and the compact configuration has the maximum useful baseline for snapshot imaging up to ~ 0.4 km in diameter. The radio Sun has an angular diameter of ~ 40 – 60 arcmin at 150 MHz. The size of the point spread function (PSF) for the compact configuration ~ 20 arcmin at 150 MHz. Hence, hardly 8 PSFs can be fitted inside the radio Sun at these frequencies, and the compact configuration is not favorable for solar observation. On the other hand, the phase-I provides angular resolution of ~ 2.5 arcmin and the phase-II extended configuration provides angular resolution of ~ 1.5 arcmin at 150 MHz, and the most favorable configurations for solar observations.

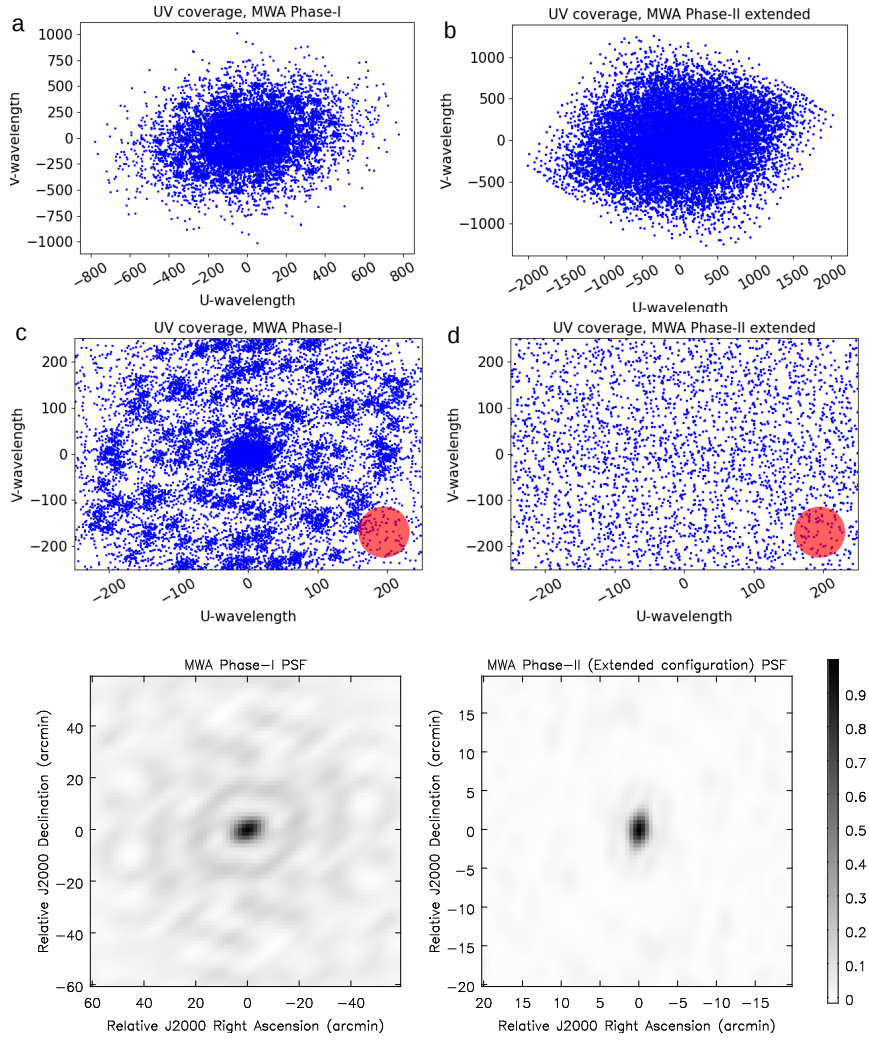
The snapshot uv -coverage of MWA phase-I and phase-II extended configurations are shown in Fig. 2a and b respectively. The zoomed-in versions over a square of 250λ are shown in Fig. 2c and d respectively. The red circle shows the uv -cell required for Nyquist sampling for a source with 1° angular scale, which is the approximate angular size of the Sun at the meter wavelengths. It is evident from Fig. 2c and d that, the density of uv -sampling approaches or even exceeds the Nyquist criterion over a significant part of the uv -plane. The bottom left panel of Fig. 2 shows the naturally weighted and un-tapered spectroscopic snapshot PSF for the phase-I and the right panel is for the phase-II extended configuration. These snapshot PSFs are extremely well-structured, which reduces the deconvolution artifacts in the final images. These properties of the MWA array configuration make it well-suited for the high-dynamic-range spectroscopic snapshot solar imaging.

3. A Brief Overview of Radio Interferometric Calibration

The true source visibility, V_{pq} , between a antenna pairs, p and q, is corrupted by the complex instrumental gains and due to the atmospheric propagation effects. At low radio frequencies, the ionospheric propagation effect is the major atmospheric propagation effect. In practice, both the instrumental gain and ionospheric propagation effect are merged into a single complex gain term. The measured visibility, V'_{pq} , can be written in terms of the V_{pq} as

$$\begin{aligned} V'_{pq}(\nu, t, \vec{l}) &= J_p(\nu, t, \vec{l}) V_{pq}(\nu, t, \vec{l}) J_q^\dagger(\nu, t, \vec{l}) + N_{pq} \\ &= |J_p(\nu, t, \vec{l})| |V_{pq}(\nu, t, \vec{l})| |J_q^\dagger(\nu, t, \vec{l})| e^{i[\phi_p(t) - \phi_q(t)]} \\ &\quad + N_{pq} \end{aligned} \quad (1)$$

where, $J_p(\nu, t, \vec{l})$ and $J_q(\nu, t, \vec{l})$ are the complex gain terms incorporating both the instrumental and the ionospheric effects, N_{pq} is the additive noise. ν , t , \vec{l} represent the observing frequency, time and direction in the sky plane respectively and ϕ_p and ϕ_q are the phase parts of J_p and J_q respectively. Equation. 1 is popularly known in literature as the *measurement equation* (Hamaker, Bregman, and Sault, 1996) for a radio interferometer. One has to estimate



Snapshot uv -coverage of MWA Phase-I, and **b)** Phase-II extended configuration. **c,d)** Zoomed-in version of the uv -coverage over a region of size 100λ . Red circles correspond to the uv -cell for a source with 1° angular scale.

Bottom panel : Left. Un-tapered and naturally weighted PSF of MWA Phase-I, and **Right.** Phase-II extended configuration at 150 MHz.

Figure 2. Snapshot uv -coverage and point spread function (PSF) of the MWA at 150 MHz. Top panel : a)

$J_p(t, \nu, \vec{l}) = G_p(t)B_p(\nu)E_p(\vec{l})$ for all the antenna elements and correct them to obtain V_{pq} from the V'_{pq} . $J_p(\nu, t, \vec{l})$ can be decomposed into two major parts

1. **Direction independent terms :** $G_p(t)$ and $B_p(\nu)$ are the two direction independent components of J_p . $G_p(t)$ represents the time variable instrumental and ionospheric gain and $B_p(\nu)$ is the instrumental bandpass.
2. **Direction dependent terms :** Direction dependent effects arise either for the array with large field of view (FoV) (Lonsdale, 2005). Propagation of radio emission from different parts of the sky through different parts of the ionosphere introduces direction dependent complex gain, $E_p(\vec{l})$.

The standard practice in radio interferometric calibration is to observe a calibrator source with known flux density, spatial structure, and spectral properties, and use it to estimate the $G_p(t)$ and $B_p(\nu)$. For wide FoV instruments, instead of a single calibrator source, a global sky model is also used to estimate the direction-dependent gain term, $E_p(\vec{l})$.

4. Challenges of the Solar Observation With the MWA

Being an aperture array instrument, the MWA poses several challenges for Solar observation. Hence, the standard calibration methods are not applicable for the solar observation with the MWA. The challenges and differences are as follows –

1. The MWA has a large FoV. Based on the FWHM of the primary beam, at 150 MHz the FoV of the MWA is ~ 610 degree² (Tingay *et al.*, 2013). Being an aperture array instrument, the primary beam sidelobes of the MWA is very high; $\sim 10\%$ (Sokolowski *et al.*, 2017; Line *et al.*, 2018). Hence, any calibrator observations during the daytime are corrupted by the solar flux.
2. At the MWA, calibrators are routinely observed either before sunrise or after sunset and used to determine antenna gains of the array.
3. At daytime, the ambient temperature of the surroundings increases, and increases the receiver temperature ¹. This increase in temperature changes the length of the cables connecting the antennas and introduces a different amount of additional phases to the different antennas.
4. The daytime ionosphere (Mondal *et al.*, 2019a) and night time (e.g. Loi *et al.*, 2015; Loi *et al.*, 2015; Hurley-Walker and Hancock, 2018, etc.) over the MWA array can be significantly different.
5. Both temperature increase and different ionospheric phases cause a significant difference between the complex gains during daytime and that obtained at nighttime. These differences in the phases of the antenna gains are shown in Fig. 3. The difference can be as large as ~ 80 degrees.
6. Due to this significant difference between antenna phases, nighttime calibration solutions do not necessarily provide a good starting point for the daytime solar observations.

¹https://wiki.mwatelescope.org/download/attachments/14156367/MEMO_MWA_Beamformer_Temperatures_v1.2018-11-12.pdf?version=1&modificationDate=1542348740955&api=v2

Moreover, during the initial phase of its operation (2013 to 2015), most of the solar observations with the MWA did not have a dedicated nighttime calibrator observation with the same spectral configuration of solar observation. These require relying on a self-calibration-based approach for MWA solar observation.

4.1. Requirement of direction dependent calibration

For the wide FoV instruments like the MWA, direction-dependent calibration is necessary, and it is implemented in the standard calibration and image processing pipeline for the MWA (Mitchell *et al.*, 2008, RTS). But, the Sun is the source with the highest flux density in the low-frequency radio sky. The flux density of even the quiet Sun is more than 10^4 Jy, which can increase by a few orders of magnitudes during an active emission. On the other hand, the flux densities of only a handful sources lie in the range of hundreds of Jy and that for the vast majority of sources lie in the range of Jy and lower. This effectively reduces the solar observation to a small FoV problem, with a single bright source at the phase center, that dominates the overall visibility. Hence, for MWA solar observation, direction-dependent calibration is not required and is not implemented in AIRCARS.

5. Tackling the Challenges : A Brief Description of AIRCARS

AIRCARS is an automated and robust self-calibration-based calibration and imaging pipeline for the MWA solar observation (Mondal *et al.*, 2019b, M19 hereafter). A brief overview of the AIRCARS is described below.

5.1. M19 Algorithm

The M19 algorithm is as follows,

1. When a dedicated nighttime calibrator observation is available for solar observation, calibration solutions obtained from nighttime calibrators are applied first. If this is not available, AIRCARS starts the calibration using the source model made from the uncalibrated observed visibilities.
2. Choose the visibilities only between core antennas (shown by the blue points in Fig. 2 of M19) of the MWA and make a low-resolution source model of the Sun.
3. Perform phase-only gain calibration using the source model, apply the gain solutions, and make an improved source model.
4. When the DR has converged, antennas lie in group with increasing distance from the core are added in small steps. These additional antennas do not have the gain solutions from the previous self-calibration rounds.
5. One round of phase-only self-calibration is performed after the addition of the new antennas.
6. When all antennas are added in the self-calibration, AIRCARS starts amplitude and phase self-calibration with all antennas into consideration. This process continues until the DR of the image has converged.

7. AIRCARS uses a certain convergence in the dynamic range given by the user. There is a minimum number (about 5) of fixed iterations after the amplitude and phase self-calibrations, after which the convergence is checked. This has been done to avoid some local convergence.

5.2. Implemented Algorithm

AIRCARS uses the Common Astronomy Software Application (CASA; McMullin *et al.*, 2007) for radio interferometric calibration and imaging. While the algorithm described by M19 is as presented in the Sec. 5.1, their implementation was different. This difference stems from the peculiarities of CASA, which was only discovered during our implementation of an improved version of AIRCARS, now christened P-AIRCARS (Kansabanik, Oberoi, and Mondal, 2022). AIRCARS uses the CASA task *tclean* for the imaging and deconvolution and produce a source model. To choose the baselines which were to be used for generating the source model, a list of antennas are passed to the *tclean*. They believed that CASA will only use the baselines between those antennae which were in the list. However, in this case, the implementation of CASA uses all baselines between antennas p and q , where p is the antenna in the list and q is any other antennas where $p < q$. This implies that the implementation of M19 generated the starting model using all the baselines originating from the core. As will be discussed later, this “error” made a significant contribution to producing the high dynamic range images, which AIRCARS went on to produce.

As all core-core and core-noncore baselines are used in the calibration process from the beginning, first-order gain solutions of all antennas are available at every self-calibration round from the beginning. Baselines originating from antennas at larger distances are progressively added, which in turn add more constraints to the self-calibration problem and improves the gain solutions. When the phase solutions for all antennas are reasonably well constrained, amplitude-phase self-calibration is performed. Since the Sun is a source with very high flux density, any small error in gain amplitudes makes a large error in the amplitudes of the observed visibilities. Hence, the calibration of the instrumental gain amplitude makes a significant improvement in the DR after starting the amplitude phase self-calibration.

In the M19 algorithm, when new antennas are added to the calibration, the DR of the image suddenly drops and the source model also becomes worse, because the newly added antennas do not have any calibration. But, for implemented algorithm, only a small number of baselines with increasing distance are added, and all antennas have a first-order gain solution. This introduces a much smaller error in the source model compared to adding a set of uncalibrated antennas. A comparison of the improvement in DR with self-calibration iterations between these two algorithms is shown in Fig. 4. It is evident from the figure that the DR improves almost monotonically for the implemented algorithm, while there are several drops for the M19 algorithm, which ends up with a smaller DR of the final image. In the case of the implemented algorithm, DR starts to oscillate only after a few rounds of amplitude phase self-calibration. This implies the quicker convergence of the implemented algorithm compared to

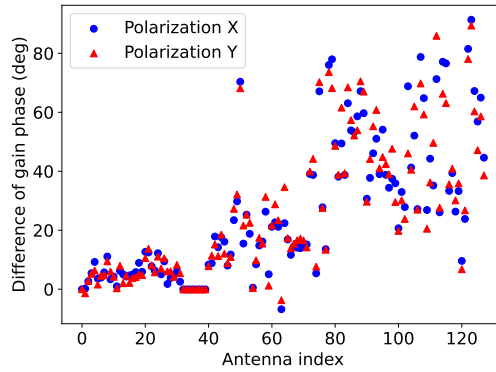


Figure 3. Difference between phases of the nighttime and daytime complex antenna gains. Blue circle and red triangle represent the X and Y polarization, respectively.

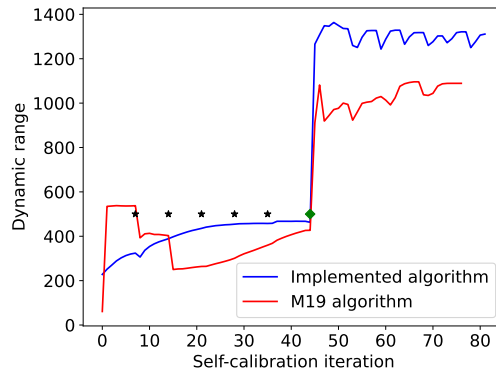


Figure 4. Comparison of the improvements in the dynamic range for M19 and implemented algorithm with the self-calibration iterations. Black stars show the iterations where new antennas are added in the self-calibration process, while performing phase only self-calibrations. The green diamond shows the iteration where amplitude-phase self-calibration starts with all antennas.

the M19 algorithm. In both cases, the DR of the final image is more than 1000. The decrease in DR by $\sim 200 - 300$ may not affect the studies related to very bright radio bursts but is crucial while one tries to detect very weak emissions, like the gyrosynchrotron from CMEs (Mondal, Oberoi, and Vourlidas (2020), D. Kansabanik et al., in preparation) or the Weak Impulsive Narrow-band Quiet Sun Emissions (WINQSEs, Mondal, Oberoi, and Mohan, 2020; Mondal, 2021).

The rest of the paper will focus on the implemented algorithm. One of the unique features of the AIRCARS is that it can start the self-calibration even without any *a priori* calibration solutions obtained from the nighttime calibrators. In the later sections, the explanation behind this unique feature of AIRCARS is discussed in detail.

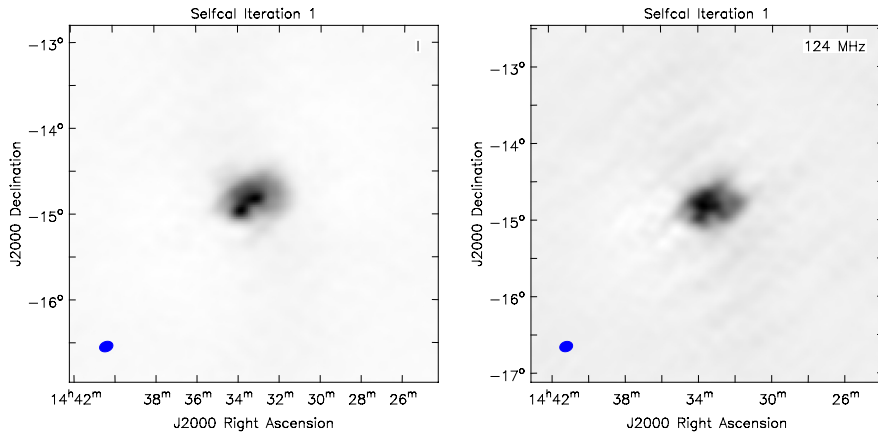


Figure 5. Initial image of the Sun. **Left panel:** Initial image made after applying the calibration solutions from the nighttime calibrator observation. **Right panel:** Initial image made directly from the uncalibrated visibilities which have at least one core antenna.

6. Initial Source Model of AIRCARS

When nighttime calibration is available, the calibration solutions are applied first, and then make the initial image (left panel of Fig. 5). When this is not available, the initial image is made from the uncalibrated observed visibilities (right panel of Fig. 5). There is no drastic difference between these two images. This happens because the phases of the gains during daytime are significantly different from the phases during nighttime (Fig. 3), hence the nighttime calibration solutions may not always produce any noticeable correction to the observed visibilities. In both the cases, there is a significant amount of source flux concentrated near the phase center, because the phase distribution of the antenna gains is not uniform random, which is shown the later in Sec. 7 and 8.

7. Expected Characteristics of the Complex Gains

As described in Sec. 3, $J_p(\nu, t, \vec{l})$ can be decomposed into $G_p(t), B_p(\nu)$ and $E_p(\vec{l})$. As discussed in Sec. 4.1), $E_p(\vec{l})$ can be neglected for solar observation. The algorithm of determining $B_p(\nu)$ is out of the scope of the paper and has already been described in detail at Kansabanik *et al.* (2022); Kansabanik, Oberoi, and Mondal (2022). The only remaining term is time-dependent complex gain, $G_p(t)$. $G_p(t)$ has the contribution from both instrument ($g_p^{\text{instrumental}}(t)$) and the ionospheric ($g_p^{\text{ion}}(t)$). In practice, it is not necessary to separate them and also not done in AIRCARS.

7.1. Expected Characteristics of the Instrumental Gains

The contributions from $g_p^{\text{instrumental}}(t)$ are not expected to originate from a uniform random distribution. There are several reasons behind this –

1. Except for the active dipoles and the low-noise amplifiers (LNA), other components of the electronic chain of the MWA are passive elements (Tingay *et al.*, 2013), and the characteristics of the passive components are extremely stable.
2. The characteristics of the LNA can also be well modeled (Sokolowski *et al.*, 2017) for the MWA, and are similar for all the antenna elements.
3. Temperature variation of the environment changes the cable length and introduces an additional phase to the complex gain. These are small for the core antennas, which are connected using small cables, and, grow larger for the antennas at long baselines connected using longer cables.
4. Despite the well-modeled LNA and passive elements, there are some manufacturing tolerances, which could introduce a spread in the distribution of the instrumental gains.

7.2. Expected Characteristics of the Ionospheric Phases

At low radio frequencies, another major contribution to the complex gain comes from the ionosphere. Mondal *et al.* (2019a) determined the total electron content (TEC) using the daytime observation of the Sun along a single line of sight. They demonstrated that the daytime ionospheric TEC can vary over the MWA array, even over the core. The TEC value varies by ~ 10 mTECU over the core antennas, which corresponds to ~ 50 degrees (Mevius *et al.*, 2016) (left panel of Fig. 1 of Mondal *et al.* (2019a)). Mondal *et al.* (2019a) also showed that the variation is smooth across the array, and the mean subtracted small scale random TEC fluctuations over the array is $\lesssim 1$ mTECU (middle panel of Fig. 1 of Mondal *et al.* (2019a)), which corresponds to a few degrees (Mevius *et al.*, 2016) of ionospheric phase variations. This demonstrates that although there are variations of the ionosphere across the MWA array, and even over the core antennas, this variation is smooth and the random fluctuations are small.

7.3. Expected Statistical Properties of G_p

As described in Sec. 7.1 and 7.2, the core antennas are expected to have a similar phase with a spread from a mean value due to instrumental (temperature variation across the array, manufacturing tolerances) and ionospheric effects. These effects become large away from the core. Hence one can expect the following distribution of the phases of G_p –

1. **Only core antennas:** Distribution will quasi-Gaussian with a small standard deviation.
2. **Only non-core antennas:** Distribution will not be a peaked distribution and the standard deviation will be very large.
3. **All antennas:** Since the core antennas (~ 60) dominate the total number of antennas, distribution will be quasi-Gaussian with a slightly larger standard deviation compared to the distribution of only core antennas.

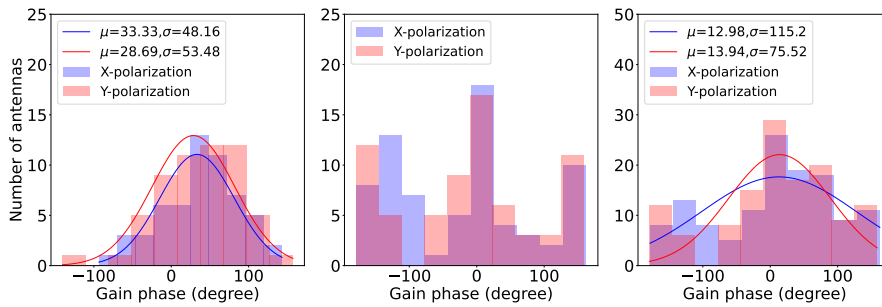


Figure 6. Distribution of phases of the antenna gains at 80 MHz for the observation on 2014 May 05. X polarization is shown by blue and Y polarization is shown by red. Distribution of phases of G_p is shown for **Left panel:** only the core antennas, **Middle panel:** for the non-core antennas, and **Right panel:** for all antennas.

8. Comparison Between the Expected and Observed Statistical Properties of the Antenna Gains

A comparison between the expected and observed properties is done for the three sub-groups of antennas as mentioned in Sec. 7.3. As evident from Eq. 1, the coherency of the visibilities are affected by $\phi_p - \phi_q$. Hence, the statistical properties of the $\phi_p - \phi_q$ are also discussed.

8.1. Observed Properties of Antenna Gains

The histograms of the phases of the complex gains are shown in Fig. 6. It is evident from the left panels that the amplitudes of the gains follow a quasi-Gaussian distribution with a comparatively small standard deviation. The distribution of phases only for the “core antennas” is shown in the left panel and well fitted with a Gaussian distribution with a standard deviation of ~ 50 degrees. The distribution of the phases of only for the “non-core antennas” is shown in the middle panel, and could not be fitted with a Gaussian distribution. The distribution of phase for “all antennas” shown in the right panel can be fitted with a Gaussian distribution, but the standard deviation is larger (~ 100 degrees) compared to “core antennas”. These observed properties match the expected properties as mentioned in Sec. 7.3.

8.2. Observed Properties of $\phi_p - \phi_q$

The histogram of $\phi_p - \phi_q$ for all the baselines originating from the core (core-all) is shown at the left panel and for all baselines is shown at the right panel of Fig. 7. The standard deviation of the fitted Gaussian for the core-all histogram is much smaller (~ 70 degrees) compared to the all baselines (~ 120 degrees). Both these distributions follow a Gaussian distribution but, there are still slight deviations from the true Gaussian distribution at the edges, which is more prominent for all baselines.

The observed statistical properties of both the phases and the difference between the phases of the antenna gains follow a quasi-Gaussian distribution. It

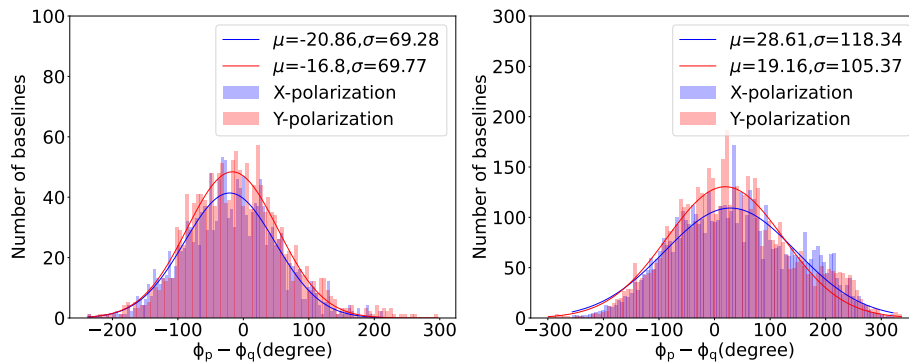


Figure 7. Distribution of $\phi_p - \phi_q$ at 80 MHz for the observation on 2014 May 05. **X polarization** is shown by blue and **Y polarization** is shown by red. **Left panel:** Distribution for core-all baselines. **Right panel:** Distribution of all baselines.

does not follow a “uniform random” distribution. For all baselines, the standard deviation of the Gaussian becomes larger and also starts to deviate from the true Gaussian distribution, and the array loses coherency. But, this standard deviation is much smaller for core-all baselines, which provides better coherency to the uncalibrated observed visibilities. Availability of this starting source model (Fig. 5) is the reason why AIRCARS can produce high dynamic range images through self-calibration approach alone.

9. Simulation

In sec. 8, it is stated that AIRCARS can proceed with the self-calibration from the uncalibrated observed visibilities because the distribution of phase and phase difference is not uniform-random. This phenomenological explanation is verified through simulation in this section.

9.1. Description of the simulation

The simulation is done as follows –

1. A model image of the Sun is obtained from the observation on 2015 November 11 (Fig. 8). This model is obtained using the **imaging and deconvolution** task *tclean* of the CASA. A numbers of Gaussian having multiple sizes (Cornwell, 2008) are used in the deconvolution process to produce this model.
2. The model image is then Fourier transformed to the model *visibilities*; $V_{pq,model}$.
3. Antenna gains (G_p) are simulated from a underlying distribution. Amplitudes are chosen to be unity.
4. Simulated visibilities are obtained as, $V'_{pq} = G_p V_{pq,model} G_q^\dagger$.

The antenna gains are drawn from the two types of distributions between -180 to $+180$ degrees:

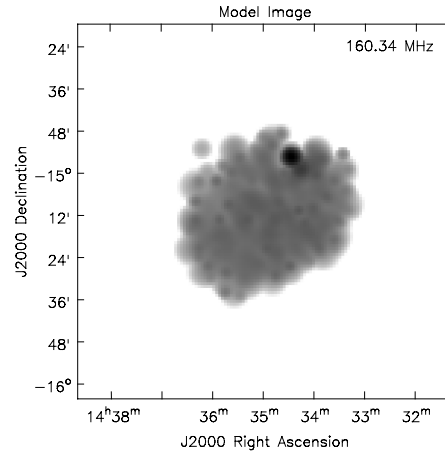


Figure 8. Model image of the Sun from the observation on 2015 November 11 used for simulation.

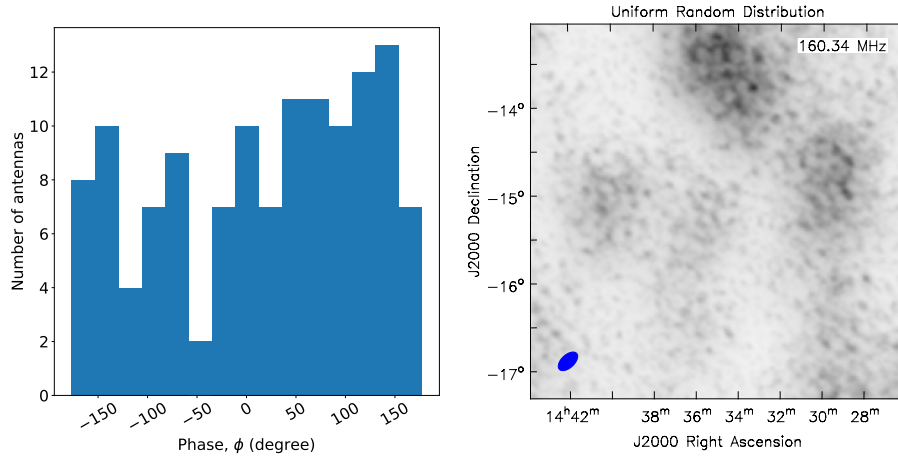


Figure 9. **Left panel:** Uniform random distribution of the phase of the antenna gains. **Right panel:** Dirty image made from simulated visibilities.

1. **Uniform random distribution:** The probability density function of the uniform random distribution is given as,

$$p(x; a, b) = \frac{1}{a - b} \quad (2)$$

within the interval $[a, b)$, and zero outside this range.

2. Truncated Gaussian random distribution: The probability distribution function is given as,

$$p(x; \mu, \sigma, a, b) = \frac{\phi(\frac{x-\mu}{\sigma})}{\Phi(\frac{b-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma})} \quad (3)$$

for $a \leq x \leq b$ and $p = 0$ otherwise. Here, $\phi(\zeta)$ is the probability distribution function of standard Gaussian distribution:

$$\phi(\zeta) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2}\zeta^2) \quad (4)$$

and, $\Phi(\epsilon) = \frac{1}{2}[1 + \operatorname{erf}(\frac{\epsilon}{\sqrt{2}})]$ is the cumulative distribution function.

9.2. Properties of the Initial Images Made from Simulated Visibilities

The prime goal of this simulation is to demonstrate the suitable distribution of the phase, such that uncalibrated visibilities have some coherency and AIRCARS can start the calibration without any dedicated calibrator observation.

The dirty image made from the simulated visibilities for a uniform random distribution of the phase of the antenna gains is shown in Fig. 9. There is no source detected with more than 10-sigma (default value used in AIRCARS to pickup emission in the source model) significance near the phase center and the image looks noise-like. This demonstrates if the phases of the antenna gains follow a uniform random distribution, the array does not have any coherency. Hence, it is not possible to start the self-calibration without any dedicated calibrator observation.

These simulations are done for a wide range of standard deviations. Here the results from 3 sample standard deviations 28, 74 and 108 degrees are shown. The distribution of the simulated phases is shown in the left panels of Fig. 10. The dirty images made from the simulated visibilities are shown in the right panels Fig. 10. In all three situations, there is a source emission detected with more than 10-sigma detection near the phase center. The DR of the images decreases with the increase in the standard deviation of the truncated Gaussian distribution. The DR of the images are 300, 110, and 55, respectively, for the truncated Gaussian distributions with 28, 74, and 108 degrees. DR is plotted against σ in Fig. 11, which monotonically decreases with the increase in σ . It has been found that for $\sigma \geq 120$ degrees, DR becomes lower than 20.

10. Discussion and Summary

AIRCARS is a self-calibration-based algorithm. Any self-calibration-based algorithm has some intrinsic limitations like the loss of absolute flux density scale and the astrometric accuracy. Both the flux density calibration and astrometric accuracy is important for cross-comparisons with observations at other wavelengths.

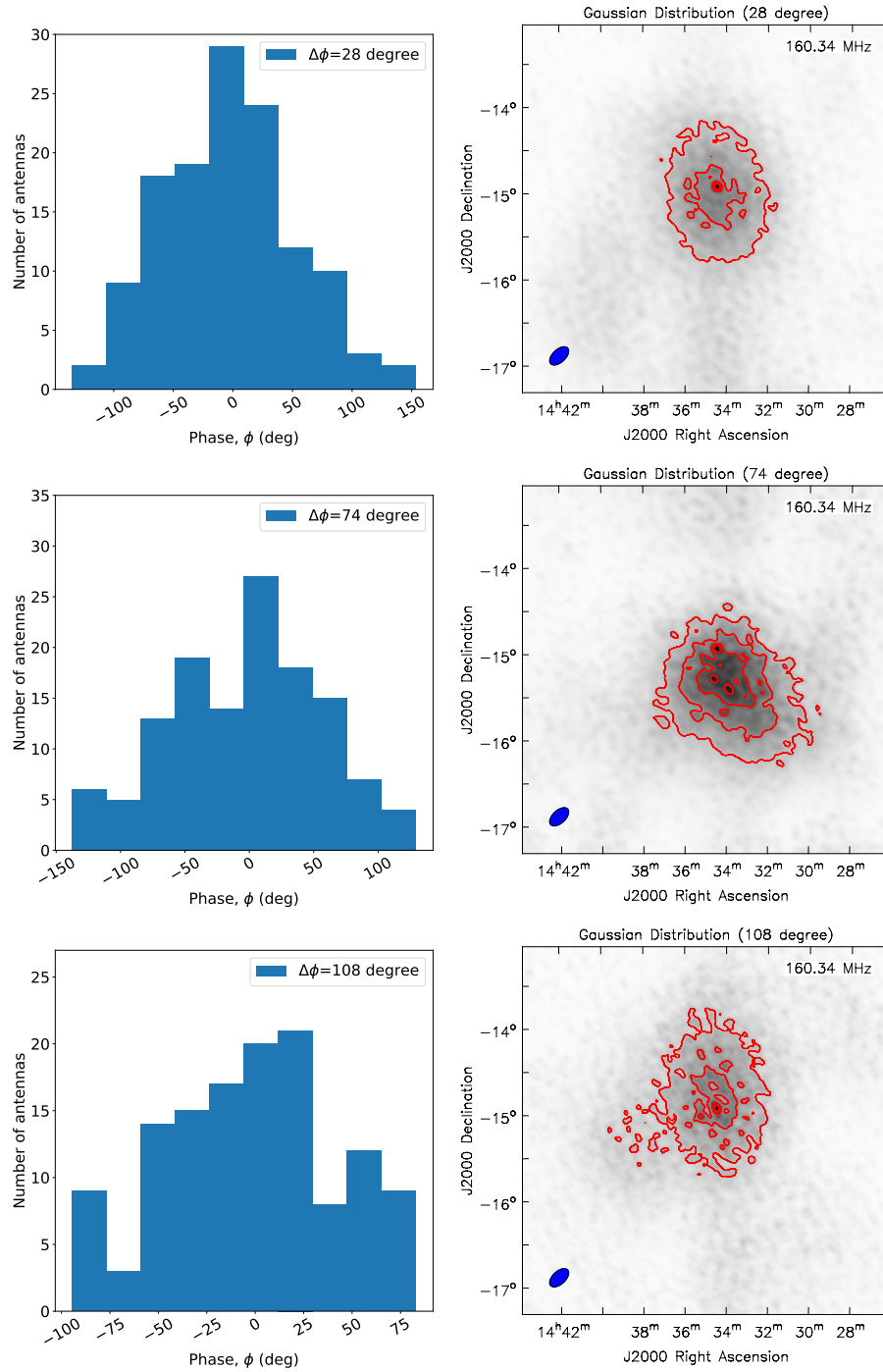


Figure 10. Dirty images from simulated visibilities from truncated Gaussian phase distribution of antenna gains. Left panels show the distribution of the simulated phases and the right panels show the corresponding dirty images. Results are shown for three truncated Gaussian distributions with standard deviations; **Top panel:** 28 degrees. **Middle panel:** 74 degree, and **Bottom panel:** 108 degree.

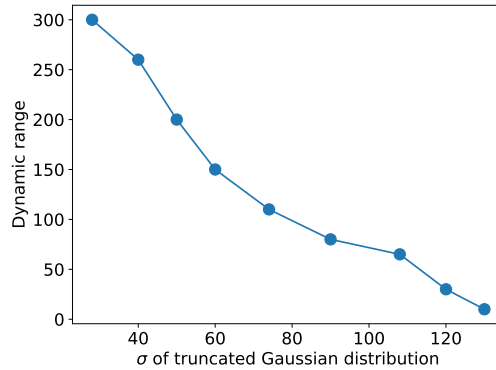


Figure 11. Variation of DR with the σ of the truncated Gaussian distribution.

In the past the solar flux density calibration was done using an instrumental gain-independent method described by Oberoi, Sharma, and Rogers (2017) and Mohan and Oberoi (2017). Recently a new technique has been developed which utilizes the instrumental characterization and very stable instrumental bandpass of the MWA (Kansabanik *et al.*, 2022). This flux density calibration method is much more general and is now the default technique for this purpose. The astrometric correction in AIRCARS is done based on an image-based approach, which provides astrometric accuracy better than the PSF size (a few arcmins). The detailed description of that method is out of the scope of this paper and will be described in a forthcoming paper (D. Kansabanik, *et al.*, in preparation).

One of the novel features of AIRCARS is that it can perform the calibration of the solar observation with the MWA even without any dedicated calibrator observations exploiting the partial coherency of the MWA array. The partial phase stability is demonstrated using simulation for Gaussian distribution (Fig. 10), but in practice, the distribution of phase may not follow a true Gaussian distribution. But, the fact that the phase distribution (Fig. 6) has a strong peak, and the baselines comprising the antennas whose phase lies close to the strong peak will have always some coherency between them and hence can be used to produce a reasonably accurate source model to start the self-calibration procedure even in the absence of calibrator observation.

During solar maxima ionospheric activities are expected to be larger. Hence it is instructive to test the AIRCARS on the datasets from both solar maxima and solar minima. All the examples shown in this paper are from 2014 and 2015, which is close to maxima of the solar cycle 24. AIRCARS has been tested on dataset covering both from solar maxima and solar minima, and has led to a large number of new discoveries (e.g. Mohan *et al.*, 2019b,a; Mondal, Oberoi, and Mohan, 2020; Mondal and Oberoi, 2021; Mondal, 2021; Mohan, 2021b,a; Kansabanik *et al.*, 2022, etc.). This demonstrates the robustness of the AIRCARS algorithm, which is independent of the solar and ionospheric conditions.

This paper demonstrates this statistically and quantitatively. It is anticipated that AIRCARS will serve the purpose of calibration and imaging for the future radio interferometers if certain conditions are satisfied by the array:

1. Instrumental gains of all antennas should be similar. This demands the precision in manufacturing of the antenna elements.
2. The delays introduced by the electronic cables needs to be measured properly in a regular interval and should be corrected before performing the cross-correlation. This will reduce the loss of coherency.
3. A large number of antennas needs to be distributed over a small array footprint, such that all the baselines originated from the core are dominated by the core-core baselines independent of the array footprint.

Among these three criteria, the third criterion depends on the array configuration. This is expected to be satisfied by the future SKA and, some other next-generation radio interferometers; like the Next Generation Very Large Array (ngVLA, Di Francesco *et al.*, 2019), and the Frequency Agile Solar Radiotelescope (FASR, Gary, 2003; Bastian, 2005; Bastian *et al.*, 2019). ngVLA is planned to observe at 1 – 115 GHz and has three separate array configurations that operate in parallel. Among these three array configurations, the Short Baseline Array (SBA) consists of 19×6 m antennas located at the current VLA site and is highly suited for high-fidelity spectroscopic snapshot imaging of the Sun. FASR will be a solar dedicated radio interferometer operating at 0.2 – 20 GHz. Two separate array configurations have been proposed (Bastian *et al.*, 2019) for FASR, which provide dense *uv*-coverage over the large bandwidth. The array footprint of FASR is similar to the MWA Phase-I, hence AIRCARS is expected to work efficiently on future FASR observation (Surajit Mondal, private communication).

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Data Availability

MWA solar observations used in this work came from 2014 May 05, and 2015 November 11 under the project id G0002, which are publicly available at <https://asvo.mwatelescope.org>.

Conflicts of Interest

The author declares that there are no commercial or financial relationships that could be regarded as a potential conflict of interest.

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