Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
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First results from Automated Imaging Routine for Compact Arrays for Radio Sun

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At low radio frequencies the solar corona is very dynamic in both spectral and temporal domains. To capture the fine details of this complex dynamics, imaging studies at high temporal and spectral resolution are necessary. The advent of the new instruments like the Murchison Widefield Array (MWA; Tingay *et al.* 2013, Bowman *et al.* 2013), is now making this possible. A significant number of interesting studies exploring new ideas and phase spaces have recently been conducted with the MWA (e.g. Suresh *et al.* 2017, McCauley *et al.* 2017, Mohan & Oberoi 2017, Sharma *et al.* 2018a, 2018b (this volume), Cairns *et al.* 2018). A high level summary is available in Oberoi *et al.* (2018, this volume). The full potential of the MWA and other similar instruments, is however yet to be realized. A key reason behind this is the enormous data volumes these instruments generate ($\sim$1 TB/hr for the MWA). In addition, the high time and spectral resolution requirement imposes an enormous computational burden (5 minutes of MWA data can lead to $\sim 0.5\times 10^6$ images). Making this huge number images manually, as is the norm in traditional radio astronomy, is impractical. This motivated us to develop the Automated Imaging Routine for Compact Arrays for Radio Sun (AIRCARS). AIRCARS is optimized for centrally condensed arrays like the MWA and future SKA Low. It applies some MWA specific corrections to the data and also allows the calibration solutions to be determined at the native resolution of the data. The latter uses the high SNR of solar observations to relax the assumption of the ionospheric stability over the calibration interval (calint), which, in our experience often becomes the limiting factor for imaging dynamic range (DR). AIRCARS builds a source model in an iterative manner by first modelling the large scale structure using the short baselines and then incrementally adding the longer baselines to get the finer structures. Other important features of AIRCARS include a detailed logging mechanism to capture the details of analysis and pipeline configuration; and a reasonable set of default parameters to enable the non-specialist user to run AIRCARS without needing detailed information about the data or the telescope. For the informed user, the pipeline provides considerable flexibility, including specifying calint.

AIRCARS is written in Python. It has been parallelised using Python Multiprocessing module. Currently, it uses functions of the Common Astronomical Software Analysis (CASA) for calibration and subsequent imaging, along with some custom Python scripts. The complexity of the implementation details are, however, not visible to the user. AIRCARS architecture is flexible by design to allow the use of other independent radio interferometry packages, e.g. WSCLEAN (Offringa *et al.* 2014).

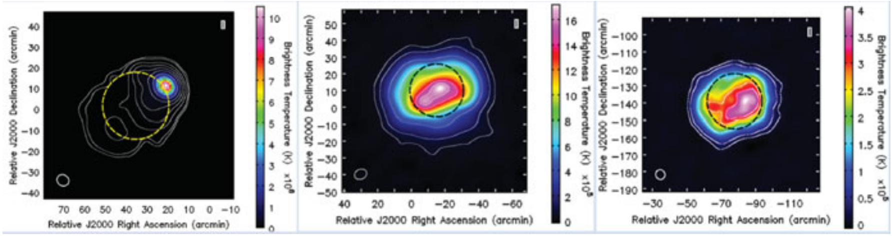

Figure 1. *Left panel*: Solar image during a type II burst, ν_0: 144.32 MHz, $\Delta\nu$: 40kHz, Δt: 0.5s, DR$>$ 72000, T_B Contours: 0.0007, 0.002, 0.02, 0.2,0.4,0.8 of 10^9 K. *Central panel*: Solar image 1 minute before a type III burst, ν_0: 118.78 MHz, $\Delta\nu$: 160 kHz, Δt: 0.5s, DR$>$ 750, T_B Contours: 0.0002, 0.0003, 0.001, 0.003, 0.01, 0.03, 0.1, 0.3, 0.8, 0.9 of 1.7×10^6 K. *Right panel*: Quiet sun (no sunspot on optical disc), ν_0: 239.1 MHz, $\Delta\nu$: 160 kHz, Δt: 0.5s, DR $\approx$ 900, T_B Contours: 0.03, 0.09, 0.4, 0.7, 0.8 of 4.0×10^5 K.

We have tested the performance of AIRCARS using MWA solar data under different solar and ionospheric conditions. The brightness temperature (T_B) of our test datasets ranges from 10^5 to 10^9 K. Example images from these test runs are presented in Fig. 1. For these images, the parameters of AIRCARS were optimized for obtaining high DR images. To the best of our knowledge, the DR of these images ($\sim 10^3$–10^5) are between one and two orders of magnitude greater than previous state-of-the-art under similar conditions. We have successfully produced about fifty thousand images using AIRCARS without human intervention. The processing time depends on the details of pipeline parameters and the nature of the data itself. Producing high DR images is very computing-intensive, with each of the images in Fig. 1 taking between one and two hours on a modern multi-core processor. To maintain a balance between the run time and the image DR, we reduced the DR threshold for the production runs. These images still exceed the DR of images from earlier instruments by large amounts. They are quite sufficient for most science objectives and reduced the run time by a factor between 5 and 10.

In conclusion, AIRCARS represents a big advance towards meeting the need for high DR imaging at low radio frequencies, which arises because of the large intrinsic differences between the T_B associated with different emission mechanisms. In addition, AIRCARS removes the bulk of the human tedium in generation of these images and is also a step towards making solar radio imaging accessible to the non-experts. AIRCARS is already being used for science explorations (Mohan *et al.* 2018). Application of AIRCARS to large datasets is currently limited by its computational efficiency. In spite of our ability to make high DR images, we believe that there is still room for significant improvement in ionospheric calibration. We are currently working on both these aspects. We hope that, in future, AIRCARS will allow us to use the data from the new instruments to their full potential and also facilitate their use by the larger solar community.

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