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Constraining ICME Magnetic Field Orientations using Low Frequency Radio Polarimetric Observations

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14. ABSTRACT
During this award, extensive progress was made, with an international team, in acquiring and processing solar data from the Murchison Widefield Array (MWA), a low frequency imaging instrumenting western Australia. The principal technical challenge was to achieve high imaging dynamic range so that faint features could be imaged in the presence of the bright radio emission from the Sun. Initial imaging efforts reach dynamic ranges of order 1000-3000, or about 10 times better than any previous low frequency solar imaging. By developing and applying different data correction algorithms, this was improved to yield dynamic ranges of up to 75000. This permitted the detection and characterization of different types of CME-related emission, and paves the way for precision polarimetry of both CME emission, and Faraday rotation of background emission by CME plasma. Both observations yield information of CME magnetic fields. Further dynamic range improvements are anticipated, and the largest remaining data contaminant limiting dynamic range was identified to be small scale irregularities in the ionosphere.

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Summary of achievements

During this award, extensive progress was made, with an international team, in acquiring and processing solar data from the Murchison Widefield Array (MWA), a low frequency imaging instrument in western Australia. The overarching goal was to develop high fidelity imaging capabilities and demonstrate the feasibility of polarization measurements associated with coronal mass ejections. This included both polarized emission from newly erupted CME plasma itself close to the Sun, as well as Faraday rotation effects on background polarized sources due to intervening CME plasma at large heliocentric distances. Such remote-sensing measurements would provide diagnostics of CME magnetic field strengths and configurations over large volumes.

The principal technical challenge was to achieve high imaging dynamic range so that faint features could be imaged in the presence of the bright radio emission from the Sun. The MWA is uniquely well suited for this purpose among existing instruments, owing to an extremely well-sampled aperture with 128 independently processed antenna systems. Initial imaging efforts reached dynamic ranges of order 1000-3000, or about 10 times better than any previous low frequency solar imaging. Extensive efforts were initiated to identify the limiting factors, and two likely culprits were identified, after the team developed powerful new data visualization tools.

The first suspect was related to the high signal strength of solar radio emission, which violates assumptions embedded in standard data processing for radio interferometers - specifically non-linear digital losses, or so-called "van Vleck" corrections that are baseline-dependent rather than antenna-dependent. Software was developed to robustly measure antenna voltage statistics and apply precise corrections.

The second suspect was improper correction for diverse cable delays to different antennas in the array, again causing baseline-dependent errors. Again software was developed and deployed to apply analytical corrections to the data.

The combination of these corrections, combined with exploration of calibration and imaging approaches, allowed the team to generate images with dynamic ranges of up to 75,000. At this level, emission from CME plasma is commonly seen, and a large number of CME events (many tens) were captured by MWA observations and await data reduction. Recent images also allow background radio sources across the sky to be seen while observing the Sun. Demonstration of precise polarimetry of the CME emission and the background sources was not possible during the period of performance, but demonstration of sufficient imaging fidelity to permit such polarimetry was successful.

The final milestone achieved during the project was the robust identification and characterization of the largest remaining data contaminant limiting dynamic range. This is small scale irregularities in the ionosphere, causing differential phase delays of a few degrees, variability on timescales of several seconds, and variations on linear scales of a few hundred meters. Algorithms have been conceived, but not implemented, to solve for ionospheric phase screens in a direction-dependent manner. The expectation is that such algorithms will permit another large improvement in achievable imaging dynamic range.

Changes to original research plans

Originally the intent was to identify and observe limb CMEs with favorable geometry, so that it would be possible to observe them during night-time. This was intended to offer the possibility of Faraday rotation (FR) observations during the award period. To pursue this it was also planned to do a series of night-time observations to create a baseline polarized background against which to see the FR. Early in the project we learned from MWA data that the polarized galactic emission is 2 orders of magnitude stronger than previously believed, when observed at low angular resolution. This rendered the originally planned approach inappropriate, and efforts were redirected toward increasing dynamic range, since it was now possible to contemplate daytime FR observations without designing and building a whole new, optimized array.

Original plans to deliver a design study for such an optimized array were also deferred due to the award of a new 2-year grant in late 2017, since extensive new information informing such a design effort will become available.

Publications generated by the funded team, or enabled by the capabilities created by the work of the team:

Benkevitch et al. Van Vleck correction generalization for complex correlators with multilevel quantization, arXiv160804367B (2016)

Lonsdale et al. Solar imaging using low frequency arrays, PRE8 conference proceedings, p425 (2017)

Suresh et al. Wavelet-Based Characterization of Small-Scale Solar Emission Features at Low Radio Frequencies, Astrophysical Journal, 843, 19 (2016)

Morgan et al. Interplanetary Scintillation with the Murchison Widefield Array I: A sub-arcsecond Survey over 900 square degrees at 79 and 158 MHz, Monthly Notices of the Royal Astronomical Society, 473, 2965 (2018)

McCauley et al. Type III Solar Radio Burst Source Region Splitting Due to a Quasi-Separatrix Layer, Astrophysical Journal, 851, 151 (2017)

Mohan and Oberoi, 4D Data Cubes from Radio-Interferometric Spectroscopic Snapshot Imaging, Solar Physics, 292, 168 (2017)

McCauley et al, Densities Probed by Coronal Type III Radio Burst Imaging, Solar Physics, in press

Mondal et al., Unsupervised generation of high dynamic range solar images: A novel algorithm for self-calibration of interferometry data , ApJ, in press

Mohan et al., Evidence for Super-Alfvenic oscillations in sources of Solar type III radio bursts, ApJ, in press