Murchison Widefield Array: Tracing Solar Disturbances from the Sun to the Earth

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Abstract

The unique and powerful diagnostic capabilities of low radio frequencies for solar, heliospheric, and ionospheric science have long been recognized, but the challenges associated with high-fidelity low frequency radio imaging have limited their exploitation. The Murchison Widefield Array (MWA) is a pioneering new interferometer, currently under construction in the radio-quiet Western Australian outback, which exploits the recent advances in digital signal processing to rise to this challenge. We present an overview of the exciting new solar, heliospheric, and ionospheric science which this instrument will enable, along with early results from a prototype array.

1. Introduction

Though radio astronomy was born at low radio frequencies, the quest for higher resolution along with challenges arising due to reasons ranging from ionospheric distortion to the numerical complexity of processing large fields–of-view associated with low radio frequencies led to a shift to higher frequencies. The recent advances in the computational capacity and affordability of digital signal processing, and the design of clever algorithms are believed to have brought the challenge of high-fidelity wide field-of-view imaging at low radio frequencies within reach. A number of low-frequency array initiatives are in varying stages of development across the world today. The Murchison Widefield Array (MWA) is one such pioneering instrument [1]. The MWA design is characterized by a large-N design (where N refers to the number of interferometer elements), a compact footprint, array elements designed to operate at the high frequency end of the range feasible for: dipole arrays, and a flexible digital architecture. The key strengths of MWA, of relevance in the present context, are its unprecedented high fidelity snapshot imaging capability for every individual spectral channel; the ability to flexibly distribute its 30.72 MHz processed bandwidth across the 80-300 MHz band accessible to the instrument; the wide fields-of-views which instantaneously provide access to a large part of the sky; and the simultaneous availability of multiple digital tied-array beams, which use the entire collecting area and bandwidth. The MWA is being built in a radio-quiet region of the Western Australian outback.

Solar, Heliospheric and Ionospheric (SHI) science forms a key science goal of the MWA project. The diverse set of measurements made with the MWA will allow tracking of solar disturbances from their inception close to the Sun, through the heliosphere, to the terrestrial ionosphere. The performance of the MWA is expected to far exceed that of any current or earlier instrument and it is expected to make significant contributions to the field of SHI science. MWA measurements directly address space weather, i.e. the study of the impact of the Sun on the Earth and its neighborhood, our technology assets in space and on the human society itself. The SHI science goals can be subdivided into three parts, one each for solar, heliospheric, and ionospheric science, and are briefly discussed in the following sections.

2. Solar Science

The complex and dynamic emission features which evolve rapidly in space, time and frequency make the Sun a difficult source to image. The limited spectral and spatial frequency coverage provided by the present day radio arrays is inadequate for resolving transient solar phenomenon simultaneously in space, time and frequency. The MWA will provide an unprecedented high-fidelity spectroscopic imaging capability with 0.5-8s time resolution and 40 kHz spectral resolution. For the transient emissions, this will enable detailed imaging studies of the dynamics and evolution of emission associated with solar flares and coronal mass ejections (CMEs), their relationship to features seen in other

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wavelengths and studies of the well established solar type I through V bursts. For the quiet Sun, the MWA will be able to provide information about large scale electron density and temperature distribution in the corona, the line-of-sight coronal magnetic field component, evidence of coronal heating via non-thermal emission features and constraint coronal turbulence characteristics. Recent work using the data from an engineering prototype provides an example of the nature of MWA solar imaging capabilities and substantiates our expectations [2]. In addition there is a strong possibility that some of the MWA elements will be equipped to provide dynamic spectra spanning the entire 80-300 MHz band with a temporal cadence below 1 ms.

3. Heliospheric Science

There are many dedicated instruments observing the Sun which span an impressive range of the electromagnetic spectrum, all the way from gamma rays to few tens of kHz. There are however far fewer means available to investigate the solar wind in the vast inner heliosphere. Ironically, it is the evolution and dynamics of the solar wind in this region which play the dominant role in space weather and need to be understood to relate the observations close to the Sun to the *in-situ* measurements close to 1 AU. The magnetized and turbulent solar wind plasma, however, leaves an imprint on the background electromagnetic radiation which passes through it. At low radio frequencies these effects become significant enough to be used to investigate the solar wind itself. The MWA plans to use two such propagation effects for studying the solar wind and CMEs, namely Interplanetary Scintillation (IPS) and Faraday rotation (FR). Both are discussed briefly in the following sections.

3.1. Interplanetary Scintillation

IPS was among the earliest techniques to investigate the solar wind and provided some key insights well before satellite based *in-situ* measurements [3]. The sophistication in the application of the IPS technique and the ability to extract information from it have grown considerably since the early days. The last significant development was the demonstration of 3D reconstruction of the solar wind structure in the inner heliosphere [4-6], which has since been improved to include limited time evolution as well. As argued in Ref. [7], the returns from the current IPS observations are limited in a large measure by the insufficient sampling of the heliosphere provided by the current instrumentation. The 16 simultaneous tied-array beams provided by the MWA, which can be pointed arbitrarily within the large field-of-view, are akin to having 16 copies of the instrument available simultaneously. This, along with agility provided by electronic array pointing, will lead to a large improvement in the heliospheric sampling and attendant improvements in the fidelity of heliospheric reconstruction. More details on the application of IPS with the MWA are available in [7].

3.2. Faraday Rotation

The geo-effectiveness of CMEs depends on their magnetic field topology, in particular, the presence of a negative B_z component. Determination of CME magnetic fields, however, has long been regarded as the "missing link" of space weather prediction. Radio observations of FR provide the *only* known remote sensing technique to estimate CME magnetic field strength and direction. The MWA is expected to observe a large number of Galactic and extra-galactic sources with sufficient linearly polarized signal to be able to track the observed FR. By observing a large number of lines-of-sight threading the CME plasma one can expect to arrive at fairly robust estimates of CME magnetic field orientation [8-9]. The MWA will attempt these pioneering observations to invert the observed FR to estimate the CME magnetic fields. If successful, this will allow the prediction of CME geo-effectiveness from a few days to many hours before their arrival at Earth, as compared to about an hour to few tens of minutes possible now based on *in-situ* observations at the first Lagrange point.

4. Ionospheric Science

High-fidelity MWA imaging requires correcting for both ionospheric distortion and FR with high accuracy. The information gathered in this process of ionospheric calibration carries unprecedentedly detailed and precise information about the ionosphere itself. This information will be used to pursue novel ionospheric science; e.g. measuring waves in the total electron content (TEC) associated with traveling ionospheric disturbances (TIDs) in the wide MWA field-of-view; monitoring the development of sharp TEC gradients during storm-time conditions; and studying the onset and evolution of UHF scintillation associated with the development of irregularities. The MWA observations will be placed in context of the larger ionospheric region by utilizing data from GPS receivers and the Formosat-3 / COSMIC constellation of satellites. The MWA calibration data will also provide information to develop an initial climatology of the ionosphere over the MWA.

5. Conclusions

The innovative MWA design exploits the recent availability of powerful digital signal processing systems to provide a good match to the challenging needs of SHI science. By providing measurements with unmatched fidelity and detail, the MWA will play a very useful role in improving our understanding of both the quiet and the dynamic Sun, and of space weather phenomena. The spectroscopic MWA solar images with unprecedented dynamic range and fidelity will allow us to build a better understanding of our Sun, in particular of the bursts and CMErelated phenomena, the IPS and FR observations will allow us to trace the solar activity as it travels through the heliosphere, and the by-product of ionospheric calibration will provide far more detailed and precise information about the ionospheric response to solar forcing than available today. Any foray into an unchartered part of the phase space is often associated with new discoveries, one can reasonably expect MWA to reveal its fair share of unanticipated SHI phenomena.

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