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# Regular <u>Solar Radio Imaging at Arecibo</u>: Space Weather Perspective of Evolution of Active Regions

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#### Abstract

The sudden release of magnetic energy on the Sun drives powerful solar flares and coronal mass ejections. The key issue is the difficulty in predicting the occurrence time and location of strong solar eruptions, i.e., those leading to the high impact space weather disturbances at the near-Earth environment. Solar radio imaging helps identify the magnetic field characteristics of active regions susceptible to intense flares and energetic coronal mass ejections. Mapping of the Sun at X-band (8.1 - 9.3 GHz) with the 12-m radio telescope at the Arecibo Observatory allows monitoring of the evolution of the brightness temperature of active regions in association with the development of magnetic complexity, which can lead to strong eruptions. For a better forecasting strategy in the future, such ground-based radio observations of high-spatial and temporal resolution, along with a full polarization capability, would have tremendous potential not only to understand the magnetic activity of solar eruptions, but also for revealing the particle acceleration mechanism and additional exciting science.

# 1 Introduction

The magnetic field in the solar atmosphere essentially controls the plasma structure, storage of free magnetic energy, and its release as flares and/or mass ejections. The areas of strong magnetic field concentration on the surface of the Sun form active regions, which are embedded in a group of sunspots of the same magnetic polarity, followed by a group of sunspots of opposite polarity. They display closed magnetic field lines resulting from the bipolar geometry, as well as complex field structures given by the mixing of fields. An extensive record of sunspot activity shows that the location of sunspot formation on the solar disk and their number count change with time. The direction of the magnetic field associated with sunspots reverses polarity between hemispheres in a period of  $\sim 11$  years. In the subsequent 11-year period, the orientation of the magnetic fields in the northern and southern hemispheres of the Sun restores, taking about 22 years to complete a full solar magnetic cycle (e.g., Hathaway 2015). In each 11-year period, as the magnetic fields change, the amount of magnetic activity above the surface of the Sun, estimated by the number of sunspots, also increases to a peak and then decreases. At the same time, the number and size of sunspots, solar flares, coronal mass ejections (CMEs), the levels of solar radiation and coronal structures exhibit synchronized variations with the phase of the 11-year solar cycle. The rate of occurrence of flares and CMEs maximizes towards the peak of the solar cycle (e.g., Lamy et al. 2019). From the viewpoint of space weather, energetic CMEs create disturbances in the entire heliosphere, driving shocks and accelerating electrons and protons, evidenced by radio bursts and solar energetic particle events.

# 2 Solar Active Regions and Space Weather Conditions

Flares and CMEs are energetic phenomena, involving bursts of electromagnetic radiation and dynamical eruption of plasma and magnetic field from active regions, caused by the magnetic reconnection process (Priest and Forbes 2002). In the context of space weather, intense flares and their associated CMEs, particularly those directed towards the Earth, are important, because they drive the large-scale energetic space-weather storms in the interplanetary space and give rise to hazardous effects at the near-Earth environment (e.g., Xie et al. 2006; Kumar et al. 2011; Manoharan et al. 2018). The essential need of spaceweather forecasting is to monitor the evolution of an active region, as it rotates close to the central meridian of the Sun, and assess its likelihood of releasing an Earth-directed solar flare and/or CME (e.g., Manoharan and Kundu 2005). The X-ray and EUV emissions from the optically-thin corona above an active region, originating at the top of the complex magnetic field network, relate to the inhomogeneous, hot, and over-dense plasma and they provide a diagnostic of the magnetic activity above the active region (Krucker et al. 2008).

Specifically, active regions coupled to the sunspot groups of complex polarity  $\delta$ -spot configuration, as per the Hale or Mount Wilson scheme (e.g., Hale et al. 1919; Künzel 1965), are prone to produce significantly intense flares. However, such spots are limited in number to only ~4% of the total number of spots compared to the numerous  $\beta$  spots of bipolar characteristic, which produce flares of much lower intensity. Along with the number



**Figure 1:** A sample image of the Sun on 25 February 2022 at 8647 MHz made with the 12-m radio telescope at the Arecibo Observatory (left). The intense emitting active regions and the coronal hole of quiet emission are clearly seen in the image. For comparison, a near-simultaneous image of the Sun observed with the AIA/SDO in the 193 Å wavelength band is shown at the right.

of sunspots, as the solar cycle progresses, the latitude of sunspots move gradually towards the solar equator. However, the formation of a complex or a simple active region shows no significant preference of latitude and originates from the same reservoir of flux in the solar interior (Jaeggli and Norton 2016). Thus the continuous monitoring of development of complexity of an active region is indispensable to achieve a reliable predictive capability of solar eruptions, and their effects at the near-Earth space in the context of space weather.

The X-ray and EUV brightness resulting from the magnetic reconnection process serves as a scale to gauge the energy release mechanism in the corona (e.g. Kosugi and Shibata 1997; Priest and Forbes 2002; Krucker et al. 2008). In a similar way, the radio signatures from an active region in the frequency range of 5-10 GHz are the gyro-synchrotron radiation from high-energy electrons trapped in small-scale magnetic field loops and the observed bright features are gyro-resonance emitting regions where the field strength exceeds 600 G (e.g., Bastian et al. 1998; White 1999; Nindos 2020). Typically, the gyro-resonance spectrum peaks in the range 5-10 GHz and corresponds to the transition region and provides a direct measure of magnetic fields above the photosphere (Gary et al. 2018). The important point is that the radio observations in the frequency range of 5 - 10 GHz do not wholly resemble the soft X-ray or EUV, but they do largely imitate the photospheric magnetograms (Dabrowski and Benz 2009; Nita et al. 2004; White et al. 2011). Since the magnetic complexity of an active region crucially determines the occurrence of intense flares and energetic CMEs (Priest and Forbes 2002; Yashiro et al. 2005), this white-paper emphasises the importance of regular radio mapping of the Sun to reveal the magnetic characteristics of an eruptive region in line with the magnetogram data.

# **3** Solar Radio Mapping - Tracking the Evolution of Active Regions

Solar mapping observations with the Arecibo 12-m Radio Telescope were initiated in mid-December 2021. (The Arecibo Observatory is operated by the University of Central Florida under a cooperative agreement with the National Science Foundation, AST-1822073, and in alliance with Yang Enterprises and Universidad Ana G. Méndez.) The 12-m radio telescope presently operates in the frequency ranges of 2.21 - 2.34 GHz (S-band) and 8.1 – 9.2 GHz (X-band) and takes advantage of RFI protection from the Puerto Rico Coordination Zone (PRCZ at frequencies below 15 GHz), which covers Puerto Rico and nearby Puerto Rican islands. The 12-m antenna currently operates with room-temperature receiver systems and records dual polarization signals (https://www.naic.edu/ao/scientistuser-portal/astronomy/12m-radio-telescope). 'East-west' raster scans of the Sun are taken routinely and maps are made from these. Figure 1 shows an example of a full image of the Sun at 8.6 GHz made on 25 February 2022, along with the EUV image of the Sun observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) in the wavelength band of 193 Å (Pesnell et al. 2012; Lemen et al. 2012). The spatial resolution of the 12-m telescope in the frequency band of 8.1 - 9.2 GHz is limited to  $\sim 10$  arcmin. Nevertheless such maps provide a clear view of the emission brightness temperatures of active and quiet regions on the Sun, and regular monitoring is useful to follow the evolution of the emission of active regions. Since the 12-m radio telescope covers the frequency band of 8.1 - 9.2 GHz, several maps are simultaneously made at frequency intervals of  $\sim 170$  MHz. The inter-comparison between these frequency bands is extremely useful and gives a handle on the mitigation and elimination of radio interference, should this be present.

In Figure 2, the peak brightness of the Sun (in kiloKelvin, averaged over the 10 arcmin beam) obtained from Arecibo's 8.6-GHz images is displayed for the period between 13 December 2021 and 31 July 2022, in the ascending phase of the current solar cycle 25, along with hourly-averaged EUV (0.1 - 7 nm) irradiance of the Sun observed by the Ultraviolet Variability Experiment (EVE) on board SDO (Woods et al. 2012) and X-ray (0.1 - 0.8 nm) flux by the Geostationary Operational Environmental Satellite (GOES)-16 (http://www.swpc.noaa.gov/Data/goes.html). At Arecibo, depending on the other astrophysical observing programs, in a day minimum 2 or more images of the Sun are made. In the radio brightness plot, several systematic peaks are seen and each point on the plot indicates the typical average peak brightness on the disk of the Sun. However, when the observation time coincided with a flare, it included the brightening corresponding to the particular phase of the flare. For example, one of the maps on day number 89 (30 March 2022) included the rising phase of the X-1.3 class flare, the first intense flare of the current solar cycle, and recorded a brightness temperature of ~42,000 K (refer to the top panel in Figure 2).

The strong radio emission from the Sun between day numbers 90 and 140, three peaks (indicated by letters 'a', 'b', and 'c') show systematic increase and decrease and are much more prominent than the EUV and X-ray fluxes. These correspond to emission from



Figure 2: Peak brightness (in kiloKelvin) of the Sun at 8.6 GHz obtained from the Arecibo 12-m radio telescope plotted for dates from 13 December 2021 to 31 July 2022, in the ascending phase of the current solar cycle 25 (top). In the middle and bottom panels hourly average EUV (EVE/SDO) and X-ray (GOES) fluxes are plotted for comparison. The three peaks marked on the radio plot with the letters 'a', 'b', and 'c' are dominant, and correspond to strong emission from magnetically-active regions of ' $\beta$ - $\gamma$ - $\delta$ ' configuration.

multiple-pole magnetically-active, ' $\beta$ - $\gamma$ - $\delta$ ', regions developed on the Sun, from where intense flares and energetic CME eruptions were observed (e.g., Jaeggli and Norton 2016; Yashiro et al. 2005), and respectively correspond to active regions AR2975, AR2993/2994, and AR3014. In fact, the *b*-peak's AR2993/2994 were the return of AR2975, which appeared at the east limb of the Sun on 15 April 2022, and in the subsequent rotation decayed to a less active state. For each peak, when the magnetic configuration of the active region attained  $\beta$ - $\gamma$  configuration, the brightness temperature increased to a level of ~13,000 K. As the peak was approached, it reached ~19,000 – 21,000 K and the magnetic configuration developed to  $\beta$ - $\gamma$ - $\delta$ . The notable point is that all the M-class flares were produced when the brightness temperature was  $\geq 13,000$  K, whereas X-class flares occurred close to the peak at ~20,000 K. Figure 3 shows the Arecibo radio images made at 8.6 GHz on 29 March, 24 April, and 17 May 2022, after the development of  $\beta$ - $\gamma$  magnetic configuration, of peak brightness temperatures in the range of 13,000 – 16,000 K. Alongside each radio image, the same day's complex magnetogram of the bright emitting region is shown from the *Helioseismic Magnetic Imager* (HMI) (Scherrer et al. 2012) on board the SDO space mission.



Figure 3: Arecibo radio images at 8.6 GHz made on 29 March, 24 April, and 17 May 2022, of peak brightness temperatures in the range of 13,000 – 16,000 K and of magnetic configurations between  $\beta$ - $\gamma$  and  $\beta$ - $\gamma$ - $\delta$  (left). On the right of each image is the corresponding HMI/SDO magnetogram of the bright emitting portion (courtesy of *SolarMonitor.org*).

Figure 2 additionally reveals the interesting result that the brightness temperature of the quiet Sun, or low-activity region, is ~8000 K as indicated by the dotted horizontal line in the top panel. This is likely in the middle of the chromosphere below 5000 km. With the 12-m radio telescope it would be interesting to detect ultra-intense flares and CMEs, rarely observed, when an active region attains the  $\beta$ - $\delta$  configuration. However, the occurrence of this type of complex active region is infrequent and represented by ~1% of the sunspot population (e.g., Jaeggli and Norton 2016). The regular solar imaging at the Arecibo will be essentially useful to track the formation of active regions, as well as the strong eruptions leading to extreme space-weather storms.

#### 3.1 Callisto: The Low-frequency Solar Radio Spectrometer

The monitoring of the activity of the Sun at microwave frequencies is supported by the operation of the Callisto solar spectrometer at the Arecibo Observatory, in the low-frequency range of 15 - 100 MHz. This allows a study of the radio emission associated with particle acceleration on the Sun and its related network of magnetic fields (*https://www.naic.edu/ao/ blog/ao-callisto-solar-radio-spectrometer*). For example, the fast-drifting Type III radio bursts are due to the acceleration of electrons along the open magnetic field lines in the corona into the solar wind and indicate the path of the energetic particles directed towards the Earth. The shock waves associated with CMEs are recorded as the slow-drifting Type II bursts, which are extremely useful for understanding the initial propagation kinematics of CMEs and the shock-accelerated high-energy particles of space weather importance in the Sun to 1 AU space (Manoharan et al. 2000, Gopalswamy et al. 2013). Apart from the above, other types of bursts, e.g., Type I storms, Type IV bursts (moving as well as stationary), U type bursts, etc., potentially possess information of the different states of the magnetic configurations, as well as the heating of the plasma (Gopalswamy 2016).

### 3.2 The Upgrade of 12-m Radio Telescope

The 12-m radio telescope is currently being upgraded with a wideband, 2.3 - 14 GHz, cooled front-end system, which will considerably enhance its sensitivity, as well as its frequency coverage. Since the new receiver also allows measurement of full-Stokes parameters, its extended bandwidth will provide highly accurate temporal measurements of polarization and dynamic spectra of the solar emission. This will be valuable for studying the evolution of the magnetic-field configurations and plasma conditions in the current sheets of solar eruptions, as required for understanding the origin of space-weather events. Moreover, the mapping of the Sun over a wide frequency band will also provide the temporal and spatial evolution of the eruptive active regions at different layers between the photosphere and the low corona.

In addition, the upgraded 12-m system will allow interplanetary scintillation (IPS) observations of compact background radio sources that can probe the ambient solar wind and structures within CMEs in the three-dimensional inner heliosphere, for regions inaccessible to spacecraft (e.g., Manoharan 2010). The above set of observations of high- and low-radio frequencies, plus IPS measurements, will provide a detailed view of the space weather events in the Sun-Earth space.

#### 3.3 The Involvement of Students in Space-Weather Studies

Over the years, Arecibo Observatory has had a successful track record of implementing research and training programs to a large number of students in the fields of astronomy, planetary science, and aeronomy. A strong student program is required to engage undergraduate/graduate students, especially underrepresented groups, and provide them with an understanding of space-weather system science, including the origins of space weather on the Sun and Sun-Earth connections. In the recent batch of NSF funded Research Experience for Undergraduate (REU) students at the Arecibo Observatory, a space weather research project was introduced. The aim of the current NSF's Partnerships in Astronomy & Astrophysics Research and Education (PAARE) program, 'Enhancing and Nurturing Careers in Astronomy with New Training Opportunities' (ENCANTO), is to raise the number of successful underrepresented students from Puerto Rico and Florida in astronomy and planetary physics. ENCANTO represents an effort between the Arecibo Observatory and multiple higher educational institutions, the University of Central Florida and universities in Puerto Rico, and it includes solar and space weather study projects (http://www.naic.edu/ao/encanto). Further, by involving more students, the Arecibo Observatory will become a thriving center of space weather studies that can increase the U.S. STEM workforce in a broader spectrum of space-weather education.

# 4 Looking to the Future

Space weather is increasingly becoming a key component in the day-to-day operation of several technological systems. Regular solar imaging at high frequencies has the potential for studying the development of solar active regions and tracking the origin of extreme space-weather events. It is shown that the centimetric-wavelength brightness temperature of an active region is the indicator of acceleration of electrons, i.e., magnetic field lines in the region above the photosphere, as well as close to the solar atmosphere. Particularly, in the radio X-band, a brightness temperature above a value of  $\sim 13,000$  K serves to identify an active region of strong eruptions. The great advantage of these measurements is that they can identify an eruptive region when it rotates close to the central meridian of the Sun, about one half to a day in advance, and predict the strongest flares and CMEs. Moreover, for a better forecasting strategy, such radio observations with a larger radio telescope having the high-spatial and temporal resolution, along with a polarization capability, would have tremendous potential not only for following the magnetic activity of the eruptive site, but also for revealing the particle acceleration mechanism and additional exciting science. Designs are currently being developed for a similar-sized replacement of the recently lost 305-m Arecibo radio telescope.

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