IL NUOVO CIMENTO **42 C** (2019) 9
DOI 10.1393/ncc/i2019-19009-x

Colloquia: SoHe3 2018

Imaging of the solar atmosphere in the centimetre-millimetre band through single-dish observations

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received 28 December 2018

Summary. — Solar observations offer both a rich interdisciplinary laboratory on fundamental astrophysics and precious tools for Space Weather applications. The involved plasma processes determine a complex radio emission picture that could be efficiently explored through single-dish imaging at high frequencies. In particular, mapping the brightness temperature of the free-free radio emission in the centimetre and millimetre range is an effective tool to characterise the vertical structure of the solar atmosphere. We are performing continuum imaging of the solar chromosphere in K-band (18-26.5 GHz, spatial resolution $\sim$1 arcmin) with the 32-m diameter Medicina radio telescope and with the 64-m diameter Sardinia Radio Telescope (SRT), as a first scientific demonstration test for the potentialities of Italian single-dish antennas in this field. This will also be useful for the assessment of observation parameters aiming at studying in detail the chromospheric brightness temperature of the quiet Sun, the solar flares, active regions and the sunspots, at high radio frequencies. These early observations proved that our antennas and K-band receivers are stable during solar pointing and could provide full mapping of the solar disk in $\sim$1 hour exposure using state-of-the-art imaging techniques.

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1. – Introduction

Fundamental solar physics science offers a rich interdisciplinary laboratory on astrophysics, plasma physics and nuclear physics (see e.g. [1]). Furthermore, the magnetic and radiative activity of our star has an enormous impact on planetary magnetospheres and ionospheres ranging from subtle climate dependencies to severe radiation phenomena affecting operations and safety of our technologies on Earth (see e.g. [2]).

All these plasma processes (e.g. magnetic reconnections, shocks, particle acceleration [3]) contribute to a complex and not fully understood radio emission picture needing spatially-resolved and time-resolved scientific data in order to fully explore their nature, complementing the wealth of existing information in the optical/UV/IR domain. Mapping the brightness temperature of the free-free continuum radio emission in the centimetre and millimetre range is an effective tool to characterise the vertical structure of the solar chromosphere (see e.g. [4]). In perspective, this application will be suitable for detailed measurement of the chromospheric brightness temperature of the quiet Sun, the sunspot umbrae, and active regions, contributing to Space Weather monitoring networks and forecast.

For these scientific applications, smart single-dish radio mapping of the solar disk is more suitable than interferometric observations, especially at high-frequencies (see e.g. [5][6]). In fact, synthesis images through interferometric networks cannot be easily obtained for frequencies >10-20 GHz on relatively large sources, with the exception of dedicated short-baseline facilities (for example the Nobeyama Radioheliograph; http://solar.nro.nao.ac.jp/norh/) requiring non-trivial calibration and data analysis processes. We present early images of the solar atmosphere in K-band (18-26 GHz) with the Medicina 32-m and SRT, as a first test of solar observations using the Italian radio telescopes operating in single-dish mode.

2. – Medicina 32-m Radio Telescope

After preliminary and feasibility tests [7], we carried out pioneering monitoring observations of the solar atmosphere at high frequencies with the 32-m Medicina radio telescope (www.med.ira.inaf.it). The observations provided an effective image resolution of less than 2' and used state-of-the-art imaging techniques [5][6]. Fast On-The-Fly (OTF) mapping (scan speed 6 arcmin/s) offers a sky coverage efficiency doubled in the case of the dual-feed K-band receiver (18-26.5 GHz, with an instantaneous bandwidth of 2 GHz). The map interleave is set so as to acquire 4.5 scans per beam size. The output of each feed consists in two separate lines: LCP (Left Circular Polarisation) and RCP (Right Circular Polarisation). Most of the maps are performed setting the two feeds in different dynamic ranges, in order to coevally acquire data on the bright solar disk and on the much fainter coronal structures as observed at these frequencies. This is accomplished via a double layer of variable attenuators. To acquire spectral information, observations are carried out at the boundaries of the available RF band: $\sim$80'$\times$80' maps are performed first at 18 GHz, then at 26 GHz, in total requiring about 2.5 hours for each complete observing session.

Flux density calibration is mostly achieved through mapping of bright sources having well-known flux densities. In particular, the Supernova Remnant Cas A, with a flux density of $\sim$2400 Jy at 1 GHz, is best suited for calibration using the same attenuation setup employed for solar disk observations, in order to obtain the conversion factor from arbitrary instrument counts to flux density units (Jy) and brightness temperature (kelvin).

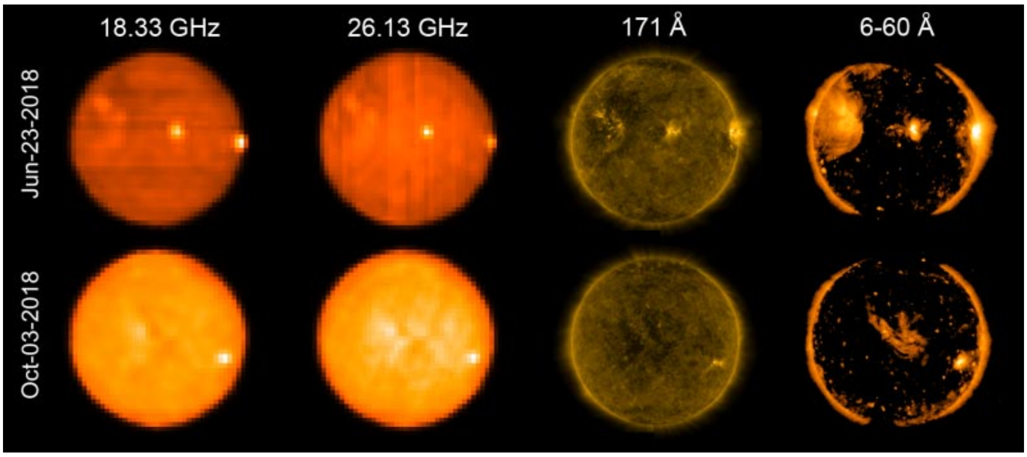

Fig. 1. – Set of preliminary solar disk maps collected at different frequencies with the 32-m Medicina Radio Telescope on June 23^{th} and October 3^{rd} 2018, in comparison with EUV/X-ray images (Credit: NOAA/NASA/SXI). Active regions and disk structures are clearly detected also in the radio images allowing multi-wavelength spectral analysis.

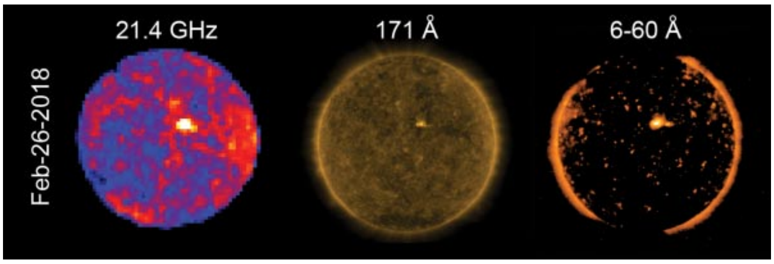

Fig. 2. – First Solar disk image at 21.4 GHz obtained with the Sardinia Radio Telescope during early tests on February 26^{th} 2018. Actual image resolution is ∼0.8'. The Active region SPoCA 21600 is evident in the radio/EUV/X-ray images (Credit: NOAA/NASA/SXI).

The OTF scan are binned through ARC tangent projection using pixel sizes 1/4 of the half power beam width (HPBW, 2.0' at 18 GHz and 1.5' at 26 GHz), which corresponds to the effective resolution of the images. Since the apparent proper motion of the Sun in celestial coordinates is about 2.5'/hour, a blurring effect comparable to the beam size affects the raw images during the typical mapping time. In order to obtain corrected and unblurred astrometric images, we subtracted the actual coordinates of the Sun centroid from the celestial coordinates of each OTF scan. DS9 FITS images (http://ds9.si.edu) are then produced; they are suitable for multi-wavelength scientific analysis with SAOImage (image rms, dynamic range, brightness profiles etc.).

A typical resulting image of the solar disk by Medicina 32m observations is represented in Figure 1. On average, such images reach a sensitivity of ∼5 mJy (∼1 mK). This allows us to appreciate very small (<0.05%) brightness fluctuations and provide helpful scientific insights on the structure of the solar chromosphere as a baseline model for the monitoring of brightness anomalies (e.g. active regions and flares). We concluded a first monitoring campaign in the January-November 2018 time frame, totalling ∼30 observing sessions, mostly in suitable weather conditions. A comprehensive analysis of our early results at high radio frequencies is ongoing. Brightness temperatures and spectra of the observed quiet-Sun structures and active regions will be provided in the so far poorly known and transitional 18-26 GHz frequency range (Pellizzoni, Righini et al., in preparation).

3. – Sardinia Radio Telescope

The Sardinia Radio Telescope (SRT) (www.srt.inaf.it) is a 64-m diameter radio telescope with Gregorian configuration located on the Sardinia island (Italy). Operated by INAF (Italian National Institute for Astrophysics) and ASI (Italian Space Agency), SRT is designed to observe in the 0.3-116 GHz frequency range from different focal positions (primary, Gregorian and Beam waveguides). At present, receivers are available for observations in the 0.3-26.5 GHz range [8], including a K-band (18-26.5 GHz) seven-beam dual-polarisation cryogenic receiver at the Gregorian focus. SRT offers advanced technology via the implementation of an active surface on the primary mirror, allowing to compensate the gravitational deformations of the backup structure and to flatten the antenna efficiency versus elevation resulting in optimal spectro-polarimetric imaging performances [6, 9, 10]. In the perspective of the implementation of new Q-band (33-50 GHz) and W-band (75-116 GHz) multi-feed cryogenic receivers for the Gregorian focus, full imaging of the solar chromosphere can be obtained through on-the-fly scans in a few minutes exposure with an angular resolution of less than 30". Early solar imaging tests by SRT in K-band were performed in February 2018 (see Figure 2), after thermal and electrical assessments of the SRT set-up, in order to prevent structural damaging and saturation of the receivers during solar exposures.

4. – Future prospects

Our pioneering and explorative observations could represent a first "breadboard" for the high-frequency radio monitoring and Target-of-Opportunity (ToO) observations of the solar chromosphere using Italian antennas. In perspective, a comprehensive solar radio monitoring service inclusive of multi-frequency spectro-polarimetric imaging could be provided by coupling the complementary potentialities of the Italian radio telescopes. This Italian radio network facility will close different gaps that presently exist in the worldwide observing scenario, and will empower the present capabilities by introducing state-of-the-art techniques.

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