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High-Resolution Imaging of the Solar Chromosphere in the Centimetre-Millimetre Band through Single-Dish Observations

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Abstract

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 and partially unknown 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 for characterising the vertical structure of the solar chromosphere. We are planning to perform continuum imaging of the solar chromosphere in K-band (18-26.5 GHz) 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 and the sunspots. In perspective, this study will contribute to Space Weather monitoring networks and forecast, filling different gaps that presently exist in the worldwide observing scenario. We present preliminary tests of single-dish solar imaging at 24 GHz with the Medicina 32-m radio telescope. These observations proved that our antenna and K-band receiver are stable during solar pointing and could provide full mapping of the solar disk in ~1 hour exposure using state-of-the-art imaging techniques.

1. Introduction

Current research in solar astronomy is two-fold. From one side, fundamental solar physics science offers a rich interdisciplinary laboratory on astrophysics, plasma physics and nuclear physics [1]. From the other side, 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 [2]. These Space Weather perturbations are mostly related to plasma processes (e.g. magnetic reconnections, shocks, particle acceleration) triggered in different parts of the Sun's atmosphere and then propagating into the interplanetary medium.

All these processes 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/IR domain. In particular, mapping the brightness temperature of the free-free radio emission in the centimetre and millimetre range is an effective tool for characterising the vertical structure of the solar chromosphere [3]. When fully developed, this application will be suitable for fundamental solar physics studies (e.g. detailed measurement of the chromospheric brightness temperature of the quiet Sun and the sunspot umbrae, solar flares monitoring, etc.) and will contribute 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. In fact, synthesis images through interferometric networks cannot be easily obtained for frequencies >20 GHz on relatively large sources [4].

2. Sardinia Radio Telescope

The Sardinia Radio Telescope (SRT) [5] 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 [6], including a K-band (18-26.5 GHz) seven-beam dual-polarisation cryogenic receiver at the Gregorian focus [7]. 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 [4, 8].

In the perspective of the implementation of a new Q-band multi-feed cryogenic receiver (33 - 50 GHz) 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 are planned by the end of 2018, after thermal and electrical assessments of the SRT set-up, in order to prevent structural damaging and saturation of the receivers during solar exposures.

3. Medicina 32-m Radio Telescope

In preparation of performing high-resolution observations with SRT, we carried out pioneering monitoring observations of the solar chromosphere in K-band with the 32-m Medicina Radio Telescope [9]. The observations provided an effective image resolution of less than 2’ and used state-of-the-art imaging techniques. Preliminary brightness profiles of the solar disk at 24 GHz were recently obtained while checking for instrumentation thermal safety during Sun pointing. The response of the K-band receiver was carefully checked and the attenuation levels verified to avoid saturation and keep gain linearity at each stage of the amplification and backend processing chain.

Figure 1 shows a successful series of mono-dimensional On-The-Fly (OTF) scans on the solar disk, obtained by the Medicina 32-m antenna on December 20th, 2017 at 24 GHz, during good K-band opacity conditions (<0.1 Np). The analysis of the different scan repetitions performed over a time interval of about ~1 hour on the same disk section demonstrates the stability of the acquired signal. In fact, the observed brightness variations (~10% level) along each scan are actual features of the quiet Sun, not related to observing conditions and/or receiver/backend performances (see Fig. 1). Following these preliminary tests, we plan to obtain calibrated OTF scan fully covering the Sun disk in K-band with the 32-m antenna. At these radio frequencies, the middle chromosphere layer will be unveiled with good resolution (<2') in order to obtain a comprehensive map of the brightness temperature, including hot spots, sunspots umbrae ecc., when present.

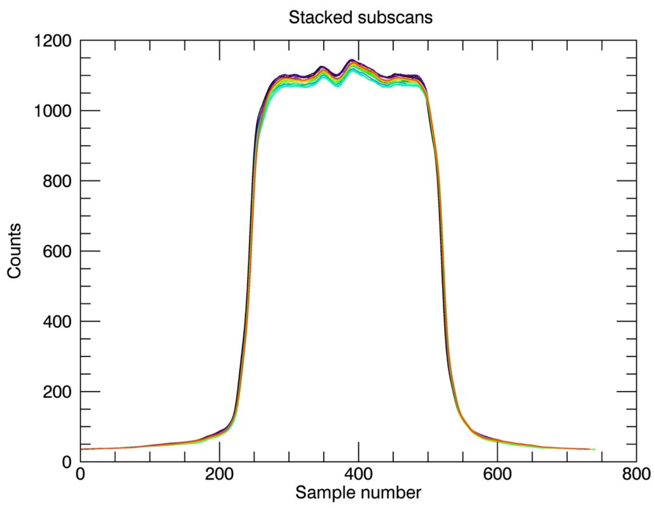

Figure 1. Uncalibrated brightness profile of a section of the solar disk at 24 GHz. The set of 21 OTF scans obtained along Dec direction (1.5° length, duration ~30 s each) are represented with different colours in the plot. The observed fluctuations in the brightness profile are actual features of the quiet Sun. The slight differences in the normalisation of each scan's brightness profile depend on small gain variations as a function of the pointing elevation, during the observing interval.

A full map of the solar disk will require about 1 hour observing time that will provide a sensitivity of ~5 mJy (~1 mK). This will allow us to appreciate very small

(<0.05%) brightness fluctuations and helpful scientific insights on the structure of the solar chromosphere as a baseline model for monitoring of brightness anomalies (e.g. during flares).

A first preliminary "slice" of solar chromosphere was obtained on December 22nd, 2017, combining 8 scans in Ecliptic latitude direction in order to test astrometric parameters and the quality of the adopted imaging technique [4, 10] (see Figure 2). This demonstrates the feasibility of our future goals.

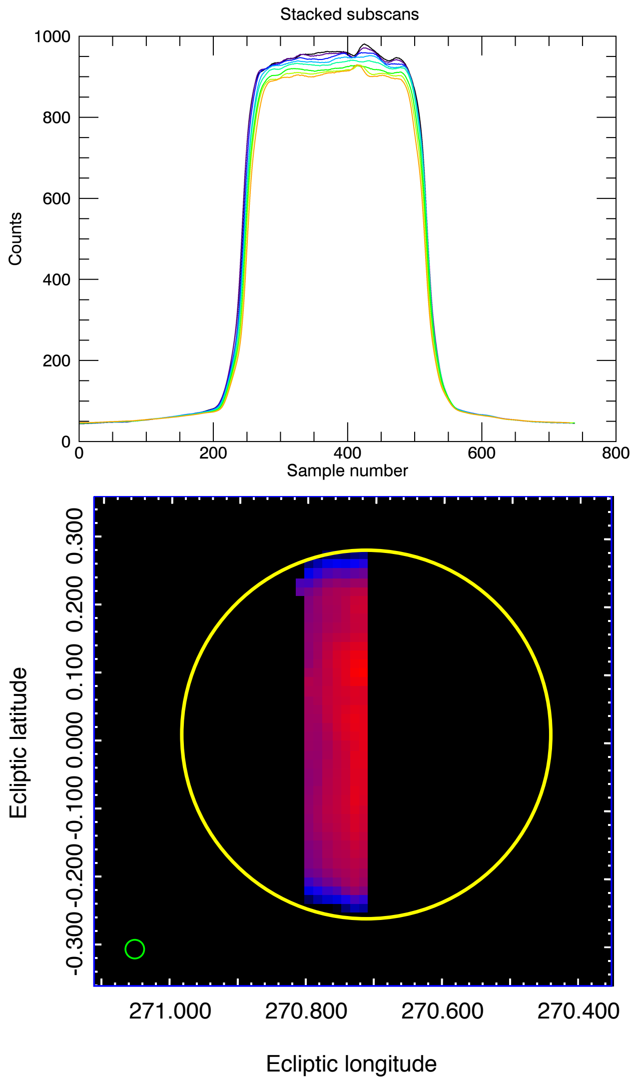

Figure 2. *Top:* set of 8 OTF scans performed at 24 GHz along Dec direction (and separated 0.6' in RA) close to the center of the Sun. These observations were performed to test the mapping strategies and astrometric performances during solar pointing. *Bottom:* uncalibrated image obtained from the above scans projected in Ecliptic coordinates (beam width half maximum 1.65’, green circle). The yellow circle represents the solar optical disk at the observing epoch.

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 the frame of a possible ASI-INAF collaboration on Space Weather applications.

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.

5. References

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