Received 26 April 2016; | Revised 6 June 2016; | Accepted 6 June 2016

DOI: xxx/xxxx

ARTICLE TYPE

Solar polarization observations at 3 and 13 mm

Juha Kallunki* | Merja Tornikoski | Petri Kirves | Erkki Oinaskallio | Juha Aatrokoski | Ari Mujunen | Joni Tammi

[1]Metsähovi Radio Observatory, Aalto University, Kylmala, Finland

Correspondence
*Juha Kallunki Email: juha.kallunki@aalto.fi

Present Address
Metsähovi Radio Observatory,
Metsähovintie 114, 02540 Kylmälä, Finland

The first solar radio polarization observations at 3 mm (86 GHz) and 13 mm (22 GHz) were made at Aalto University Metsähovi Radio Observatory in Finland in spring 2019. This was the first time that 3 mm (86 GHz) and 13 mm (1.3 cm) solar polarization observations were made with the same radio telescope. In this paper we describe the observing system and data analysis, and present the first results. We also compare our data with polarization observations made with the Nobeyama Radioheliograph and find that the results are consistent. Additionally, we determine the quiet Sun level brightness temperature at 3 mm (86 GHz) using the New Moon for refererence, and obtain a mean value of 6310 K.

KEYWORDS:
Sun: activity, Sun: chromosphere, Sun: radio radiation

1 | INTRODUCTION

Microwave solar polarization observations give us information about the magnetic field of the solar atmosphere and are important for understanding the various activity phenomena and emission mechanisms related to them. Strong magnetic field above active region could be a sign of gyro-resonance emission (Bogod et al., 2012). The lack of magnetic field usually indicates purely thermal emission.

Polarization properties of solar active regions have been studied earlier mainly at 17 GHz (18 mm) by using the Nobeyama Radioheliograph *e.g.*, Miyawaki et al. (2016); Mouner et al. (2018).

The emission at 17 GHz (18 mm) originates from the upper chromosphere. Currently, only a few instruments can provide solar radio maps at higher frequencies (> 50 GHz), *e.g.*, Iwai et al. (2017). These high frequencies are vulnerable to prevailing atmospheric conditions, and there are more technical and instrumental challenges.

In this article, we present high frequency solar radio polarization observations made with the current 3 mm (86 GHz) receiver at Aalto University Metsähovi Radio Observatory (MRO) in Finland (Helsinki region; GPS coordinates: N 60:13.04, E 24:23.35). 3 mm (86 GHz) observations make it possible to study solar features in the lower chrosmosphere, from where the emission at this waveband originates. Solar observations at 3 mm (86 GHz) have also previously been conducted at MRO *e.g.*, Pohjolainen et al. (2000); Pohjolainen (2000) but not with polarization observing capability.

We also present 13 mm (22 GHz) solar polarization observations taken with the same 14-metre radio telescope at MRO during the same observing season.

2 | INSTRUMENTATION

The RT-14 at MRO is a radome-enclosed Cassegrain type antenna with a diameter of 13.7 m. The usable wavelength range of the telescope is 13.0 cm – 2.0 mm. The antenna is used for solar mapping, partial solar mapping, and tracking of

[0]**Abbreviations:** MRO, Metsähovi Radio Observatory; VLBI, Very Long Baseline Interferometry; GPS, Global Positioning System; LCP, Left Circular Polarization; RCP, Right Circular Polarization; LNA, Low Noise Amplifier; HEMT, High-Electron-Mobility Transistor; IF, Intermediate Frequency; GMVA, Global mm-VLBI Array; NoRH, Nobeyama Radioheliograph; NOAA, National Oceanic and Atmospheric Administration; SDO, Solar Dynamics Observatory; HMI, Helioseismic and Magnetic Imager; QSL, Quiet Sun Level; RMS, Root Mean Square; RT, Radio telescope; QML, Quiet Moon Level; UTC, Coordinated Universal Time

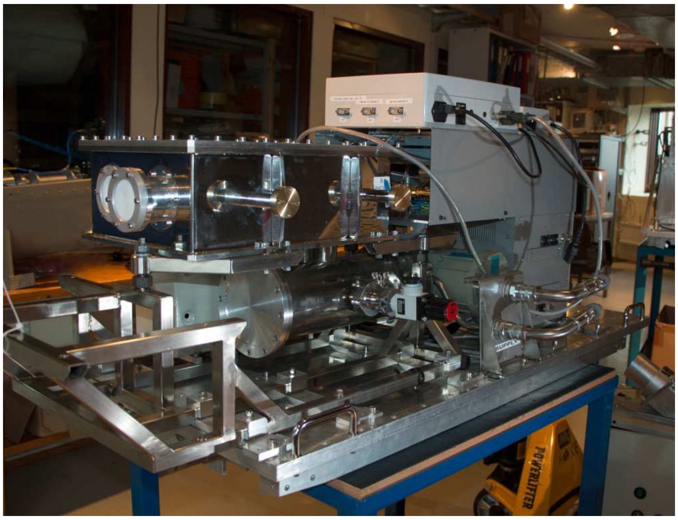

FIGURE 1 MRO's 3 mm (86 GHz) receiver which can also be used for solar observations. The stainless steel shielded front-end is cooled to 30 - 40 K and the grey IF-part works in room temperature.

any selected areas on the solar disk. The general properties of MRO's solar observation capabilities and background are presented in Kallunki et al. (2018).

The 3 mm (86 GHz) receiver is a helium cooled receiver for Very Long Baseline Interferometry (VLBI) observations, and it has been assembled in-house by the MRO staff. The 3 mm (86 GHz) receiver of MRO is shown in Figure 1 . It is a modern dual-polarization receiver with left hand (LCP) and right hand circular polarizations (RCP). The front-end low noise amplifiers (LNA) are based on High-Electron-Mobility Transistor (HEMT) technology and they were manufactured by National Radio Astronomy Observatory in the USA. The receiver has a noise temperature of 120-150 K. The intermediate frequency (IF) signal at 500-1000 MHz is transferred from the receiver to the back-end via a low-loss coaxial cable. The beam size of the telescope is 1.1 arc min at 3 mm (86 GHz).

The 3 mm (86 GHz) receiver is a total-power radiometer without chopping or beam-switching properties. Atmospheric effects or instability of the receiver can thus not be completely filtered out from the observations. Judging from several VLBI observing sessions, however, receiver instability does not seem to be a major problem, but for single-dish solar intensity or polarization observations relatively stable weather conditions are required.

The 13 mm (22 GHz) VLBI receiver has a similar structure as the 3 mm (86 GHz) receiver. The noise temperature of the receiver is around 60 K. The beam size of the radio telescope is 4.8 arc min at 13 mm (22 GHz).

As the signal back-end, we use a self-made detector system which is based on ADL5982 true RMS detector board. ADL5982 can detect a radio frequency signal over a wide frequency range, from 50 MHz to 9 GHz. The dynamic range of the ADL5982 is 65 dB. The detected voltage is sampled with a 10-bit analog-to-digital converter integrated in the Arduino Mega 2560. The Arduino Ethernet shield is attached to the system, thus the values can be read over the Ethernet.

A simple perl-script controlled both the radio telescope movement and the data recording back-end. The output level was adjusted to be suitable for the back-end with an extra 20 dB attenuator. The extra attenuator was removed during the lunar observations.

The regular MRO solar observation control system is not yet fully compatible with 3 mm (86 GHz) or 13 mm (22 GHz) observations. Thus, a simple solar map scanning software was developed. One solar map consists of 1600 samples and it takes about 25 minutes to make one 0.5 deg x 0.5 deg raster scan map. LCP and RCP channels cannot yet be observed simultaneously due to limitations of the back-end.

In Figure 2 , solar radio maps at 3 mm (86 GHz) are presented. The red contour is at RCP and the black one at LCP. The time gap between the maps is about 25 minutes.

3 | OBSERVATIONS

3.1 | 3 mm observations

Observations were made on 4 Apr 2019 just before a regular Global mm-VLBI Array (GMVA) session. The atmospheric conditions were very good during these observations, with a clear sky and no clouds at all. Two pairs of LPC+RCP polarization maps were made. In addition, one pair of lunar maps was made for calibration purposes. Observations were made close to the New Moon; the occurence of the New Moon was 5 Apr 2019.

There was one active region, NOAA 12737, on the Sun at the time of the observations. This is also visible on the 3 mm (86 GHz) solar radio map of (Figure 2). The active region was non-flaring during the observations. In Figure 3 , the magnetogram map of the Sun from Solar Dynamic Observatory (SDO) taken with Helioseismic and Magnetic Imager (HMI) is shown and the active region is clearly visible on the disk. The magnetic field strengths of the active region on the photospheric level were 1054 G (positive polarity) and -948 G (negative polarity). It was classified as β in Hale Class, which means that it is a sunspot group with positive and negative polarities.

3.2 | 13 mm observations

The observations were made on 9 May 2019. The atmospheric conditions were rather favourable during the observations,

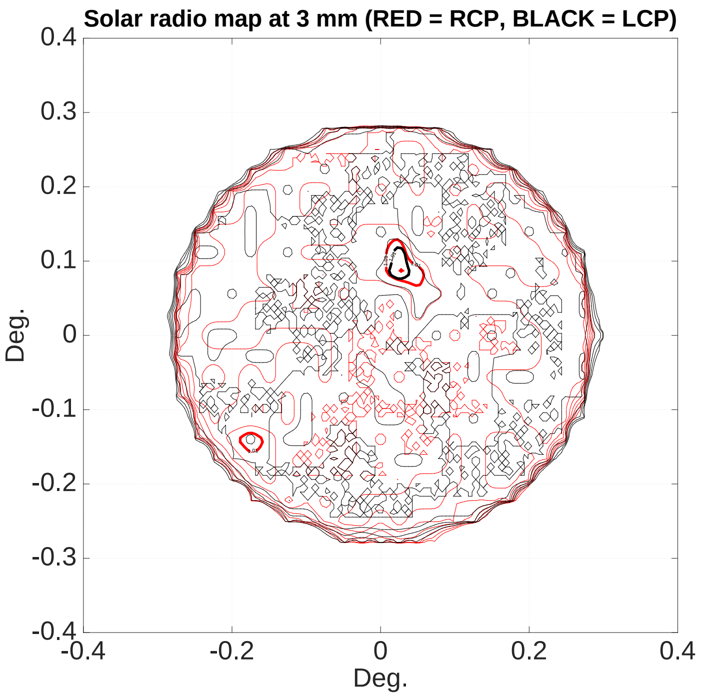

FIGURE 2 Solar radio maps at 3 mm (86 GHz) observed on 4 Apr 2019. The red contour shows RCP and the black one LCP. The maximum brightness temperature is around 102 %.

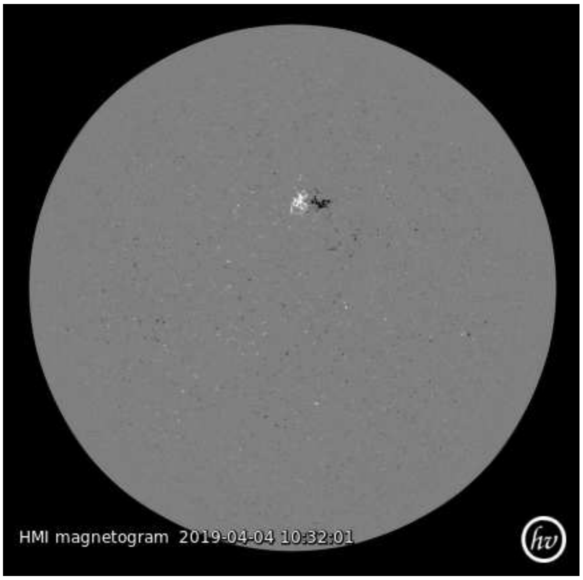

FIGURE 3 The magnetogram map from SDO-HMI on 4 Apr 2019. The active region 12737 is clearly visible on the disk in the northern hemisphere. The positive and negative polarities of the active region can also be clearly seen.

there were only some thin clouds on the sky. One pair of LPC+RCP polarization maps was made. Two active regions, NOAA 12740 and 12741, were on the Sun. These are also visible in the 13 mm (22 GHz) solar radio map (Figure 4). No flaring activity was detected during the observations.

In Figure 5 , the magnetogram map from the HMI instrument onboard SDO is shown. The active regions are clearly visible on the disk. The magnetic field strengths of the active region NOAA 12740 on the photospheric level were 1115 G (positive polarity) and -1885 G (negative polarity) and values for NOAA 12741 were -1783 G and 628 G. The active regions were classified as β (NOAA 12740) and α (NOAA 12741) in Hale Class.

4 | RESULTS

4.1 | 3 mm observations

The observed data give us information about the brightness temperature (Stokes-I), circular polarization (Stokes-V) and the degree of polarization (P). Following *e.g.*, Mouner et al. (2018), we determined the Stokes parameters from our observations:

$$I = \frac{R + L}{2}$$
$$V = \frac{R - L}{2}$$
$$P = \frac{V}{I}$$

where L is the left hand circular polarization and R is the right hand circular polarization. In Figure 6 , the calculated Stokes maps are presented. The figures are zoomed to the active region NOAA 12737. The radio brightening during these observations is rather weak. The maximum brightness temperature is around 102 %, relative to the quiet Sun level (QSL). However, the photospheric magnetic field strength on the top of the active region is, $B \approx 1000$ G, so we could expect to see some polarization features in V- and P-maps, but no polarization features were detected. The other observed LCP- and RCP-map pair showed similar results.

Another solar radio instrument that provides polarization information in LCP and RCP is the Nobeyama Radioheliograph (NoRH) (Nakajima et al., 1994) in Japan (Nagano region, GPS: N 35 56.34 E 138 28.26). It is an instrument operating at the frequencies of 17 GHz (18 mm) and 34 GHz (8.8 mm). NoRH is a radio interferometer and the full solar radio image is obtained by inverse Fourier transformation of visibilities measured by pairs of antennas. The Radioheliograph consists of an array of 84 parabolic antennas, and the diameter of one single antenna is 80 cm. The spatial resolution is 15 arcsec at 17 GHz (18 mm) over the whole solar disk.

In Figure 7 , the Stokes maps from NoRH taken on 4 Apr 2019 at 17 GHz (18 mm) are presented. The figures are zoomed to the active region NOAA 12737. The NoRH map is observed at 02:44 UTC and MRO map is observed at 09:00 UTC. Although the time difference between the observations is approximately six hours, we can assume that the magnetic structure of the active regions stays reasonably static over this period between 02:44 UTC and 09:00 UTC. In NoRH I-map the radio brightening was more powerful than in the MRO 3 mm (86 GHz) I-map. There are several rising magnetic flux structures from an active region or sunspot with varying heights, reaching different solar atmospheric layers. Some of these reach the lower chromosphere (86 GHz emission) and some of them reach the higher chromosphere (17 GHz emission). These rising flux structures can have different temperatures. In addition, the electrons can heat up when they are rising to higher atmospheric layers, and therefore the 17 GHz (18 mm) active region intensity is higher than the 86 GHz (3 mm) active region intensity.

NoRH polarization maps showed similar polarization features, or lack of them, as the MRO polarization maps. We can conclude that at least we did not miss any polarization features.

A degree of polarization is « 0.5 % in both maps on top of the active region. It has been reported that a degree of polarization is more than 0.5 % above the active region if polarization has been detected (Mouner et al., 2018). The low degree of polarization indicates that the emission from this active region is predominantly nonthermal.

4.2 | Quiet Sun level at 3 mm

In addition to solar radio maps, we also observed two sets of lunar maps with each polarizations for calibration purposes. In Figure 8 , the observed 3 mm (86 GHz) lunar map (I-map) is shown. It is very similar to a 8 mm (86 GHz) lunar map Kallunki & Tornikoski (2018). The theoretical lunar brightness temperature is 281.8 K at 3 mm (86 GHz) at -1 day offset from the New Moon (Hafez et al., 2014).

Following the procedure described in Kallunki & Tornikoski (2018) we obtained a Sun-Moon-ratio, i.e., the relation between solar and lunar intensities, of 22.4 and we defined the quiet solar level brightness temperature at 3 mm (86 GHz) to be 6310 K. This was based on very few observations only, but confirms that our calibration method is applicable also at 3 mm (86 GHz). The value that we obtained is smaller than what has mostly been used in the literature so far, 7200 K (Riehokainen et al., 2001), and in the future we aim at making a larger number of Sun-Moon observations to obtain a reliable estimate of the quiet level solar brightness temperature also for this wavelength range.

4.3 | 13 mm observations

In Figure 9 , the calculated Stokes maps for 13 mm (22 GHz) are presented. Both radio brightenings are relatively weak, approximately 102 % of the QSL. However, the photospheric

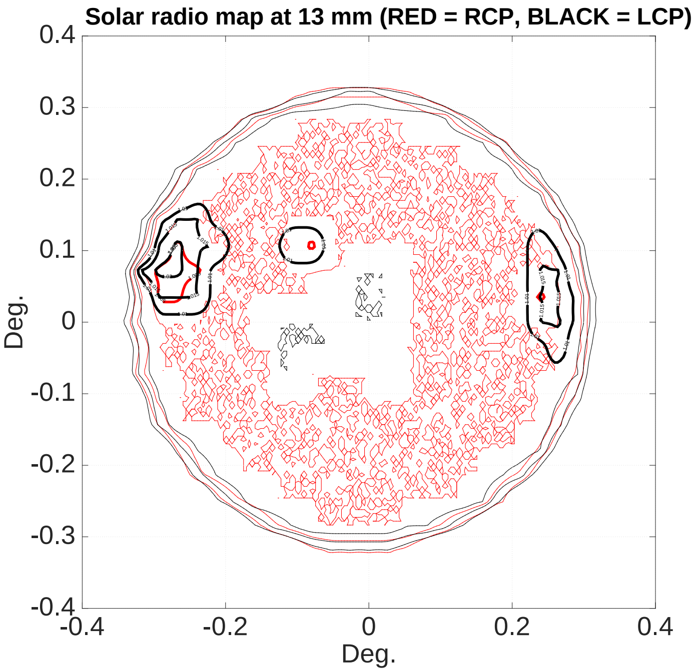

FIGURE 4 Solar radio maps at 13 mm (22 GHz) observed on 9 May 2019. The red contour shows RCP and the black one LCP. The maximum brightness temperature is around 102 %.

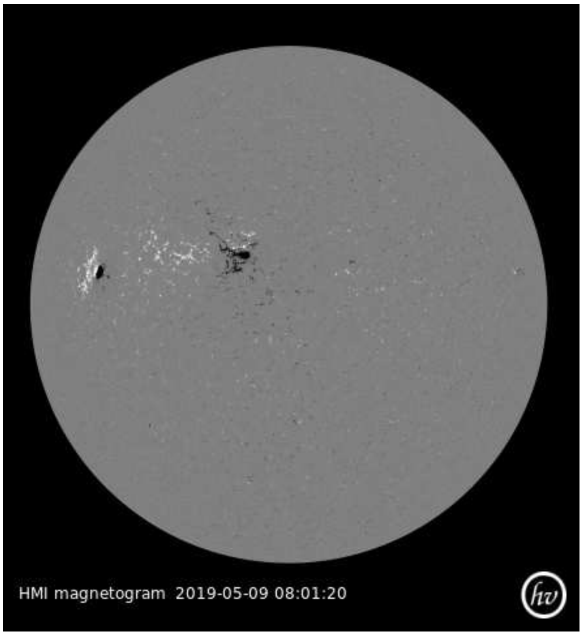

FIGURE 5 The magnetogram map from SDO-HMI on 9 May 2019. The active regions 12740 and 12741 are clearly visible on the disk in the northern hemisphere. NOAA 12741 is closer to the solar limb. The positive and negative polarities of the active regions can also be clearly seen.

magnetic field strengths on the top of the active region are, $B \approx$ 1700-1900 G, so we could expect to see some polarization features in V- and P-maps. We can clearly see that there are some polarization features (Figure 9). NoRH observations were unfortunately not available at May 9 2019 for comparison.

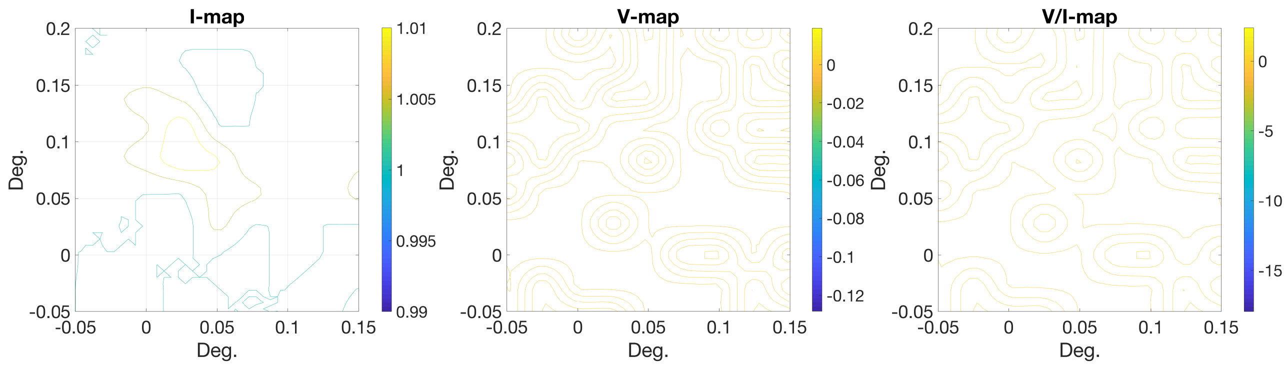

FIGURE 6 MRO 3 mm (86 GHz) maps taken on 4 Apr 2019. In the left Stokes I-map (intensity is relative to the QSL), in the middle Stokes V-map, and in the left the degree of polarization.

4.4 | 8 mm observations

Two hours after the 13 mm (22 GHz) observations the MRO-14 observing system was back to the configuration that is mostly used for solar radio observations and where solar observations at 8 mm (37 GHz) are made on a daily basis. These 8 mm (37 GHz) observations produce intensity maps (I-map) only, and maps obtained two hours after the 13 mm (22 GHz) observations are shown here for comparison (Figure 10). The active regions can also be seen in these maps. The intensity of the maximum radio brightening is approximately 105 % of the QSL.

5 | FUTURE WORK

The main observing setup at MRO enables almost daily 8 mm (37 GHz) solar observations, but as shown here, in connection to 3 mm (86 GHz) and 13 mm (22 GHz) VLBI sessions also solar observations can be done. Especially the 3 mm (86 GHz) GMVA sessions take place typically only twice a year, and observing conditions can be very unoptimal for solar observations because of the weather or the limited visibility of the Sun in winter months. In the future we aim at ensuring a higher number of good-quality solar observations also at 3 mm (86 GHz) by scheduling dedicated solar observing sessions during the summer season.

13 mm (22 GHz) VLBI sessions are scheduled more frequently than the 3 mm (86 GHz) GMVA sessions, but we also aim at devoting more time for solar observations in connection to these sessions.

The back-end of our observing system should be modified and expanded so that both polarization channels can be recorded simultaneously, possibly also with a higher sampling rate. This modification is expected to be relatively straightforward.

After the signal back-end stability and dynamic range properties will have been improved, we expect the detection limit of the polarization to be below 1000 G.

In addition, we will adapt our regular solar observing control system to include also 3 mm (86 GHz) and 13 mm (22 GHz), to allow for consistent observing parameters and faster operations.

It should be also possible to add a chopper wheel and other necessary quasioptics to the 3 mm (86 GHz) receiver to remove atmospheric fluctuations from the final results. After

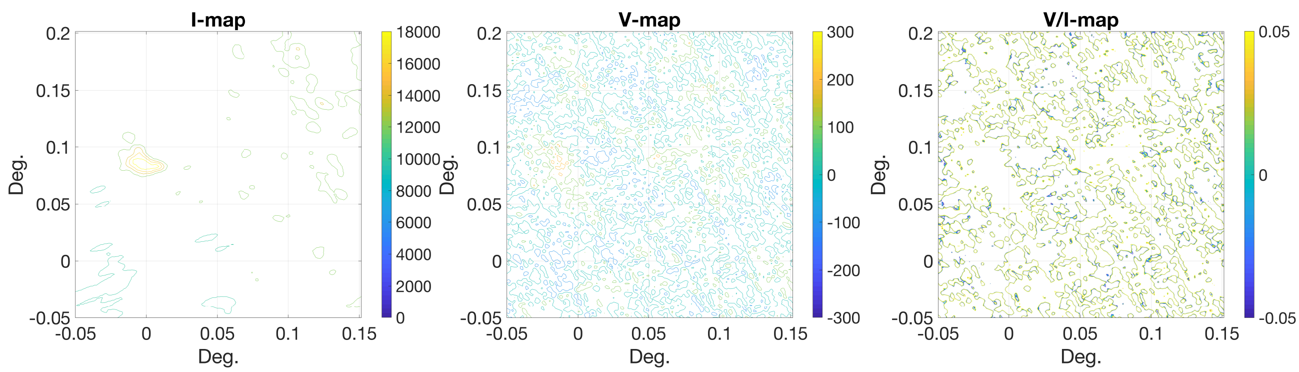

FIGURE 7 NoRH maps taken on 4 Apr 2019. In the left the Stokes I-map (intensity is in temperature, K), in the middle Stokes *V*-map, and in the right the degree of polarization.

that, observations would not be so sensitive to compromised or changing weather conditions.

6 | CONCLUSIONS

This is the first time that 3 mm (86 GHz) and 13 mm (22 GHz) solar polarization observations were made with the same radio telescope. We got confirmation that our 3 mm (86 GHz) receiver originally designed for VLBI observations, along with our other instrumentation, produces reasonably good-quality solar maps and also that the polarization capabilities can be exploited to create solar polarization maps. The amount of data so far is very limited, but new sessions will be scheduled soon.

The dynamic range of our system is large enough to make both solar and lunar observations. This was confirmed with observations presented here, where we provisionally determined the QSL brightess temperature at 3 mm (86 GHz) to be 6310 K.

MRO is well-known for its very long-term and dense 8 mm (37 GHz) solar observation data sets. 3 (86 GHz) and 13 mm (22 GHz) observations, including polarization, will complement the data and add to the understanding of the structure and evolution of solar radio brightenings. The improved angular resolution of the 3 mm (86 GHz) observations, when compared to 8 mm (37 GHz), makes it possible to study details of limb brightenings and polar area brightenings (such as polar faculae and pores) with better spatial resolution.

7 | ACKNOWLEDGEMENT

This publication makes use of data obtained at the Metsahovi Radio Observatory, operated by the Aalto University.

Nobeyama Radioheliograph is operated by the International Consortium for the Continued Operation of Nobeyama Radioheliograph (ICCON). ICCON consists of ISEE/Nagoya University, NAOC, KASI, NICT, and GSFC/NASA.

Helioviewer.org is an open-source project for the visualization of solar and heliospheric data. The project is funded by ESA and NASA.

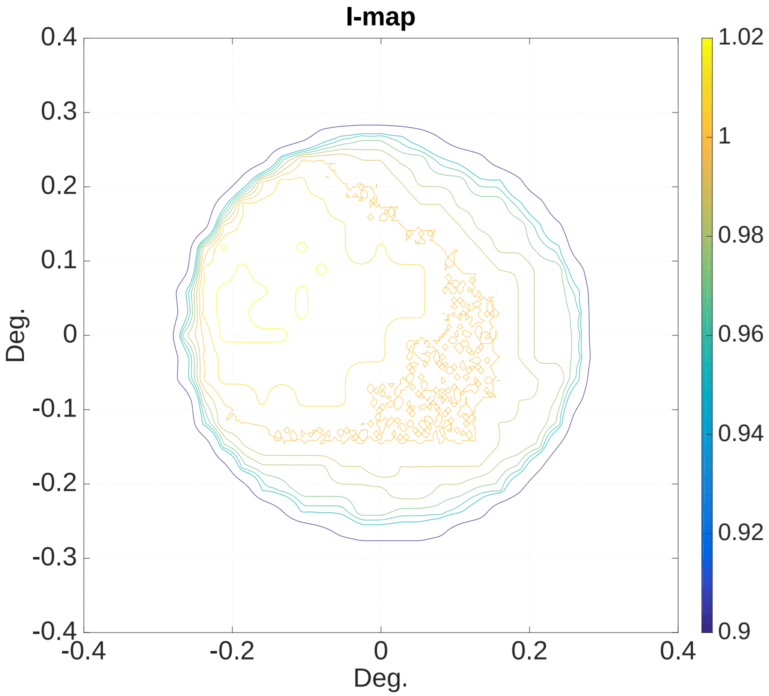

FIGURE 8 A lunar radio map at 3 mm (*I*-map) taken on 4 Apr 2019. The intensity is given relative to the quiet Moon level (QML).

REFERENCES

Bogod, V. M., Stupishin, A. G., & Yasnov, L. V. 2012, Sol. Phys., 276, 61

Hafez, Y. A., Trojan, L., Albaqami, F. H., et al. 2014, MNRAS, 439, 2271

Iwai, K., Shimojo, M., Asayama, S., et al. 2017, Sol. Phys., 292, 22

Kallunki, J., Tornikoski, M., Tammi, J., et al. 2018, Astronomische Nachrichten, 339, 204

Kallunki, J., & Tornikoski, M. 2018, Sol. Phys., 293, 156

Miyawaki, S., iwai, K., Shibasaki, K., Shiota, D., & Nozawa, S. 2016, ApJ, 818, 8

Mouner, A., Shaltout, A. M. K., Beheary, M. M., Gadallah, K. A. K., & Edris, K. A. 2018, Journal of Astrobiology Outreach, vol. 6, issue 01, id.160, 6, 160

Nakajima, H., Nishio, M., Enome, S., et. al. 1994, IEEE Proceedings 82, 705.

Pohjolainen, S., Portier-Fozzani, F., & Ragaigne, D. 2000, A&AS, 143, 227

Pohjolainen, S. 2000, A&A, 361, 349

Riehokainen, A., Urpo, S., Valtaoja, E., et al. 2001, A&A, 366, 676

How cite this article: Kallunki J., M. Tornikoski, E. Oinaskallio, P. Kirves J. Aatrokoski A. Mujunen, and J. Tammi (2019), Solar polarization observations at 3 and 13 mm

How cite this article: Kallunki J., M. Tornikoski, E. Oinaskallio, P. Kirves J. Aatrokoski A. Mujunen, and J. Tammi (2019), Solar polarization observations at 3 and 13 mm

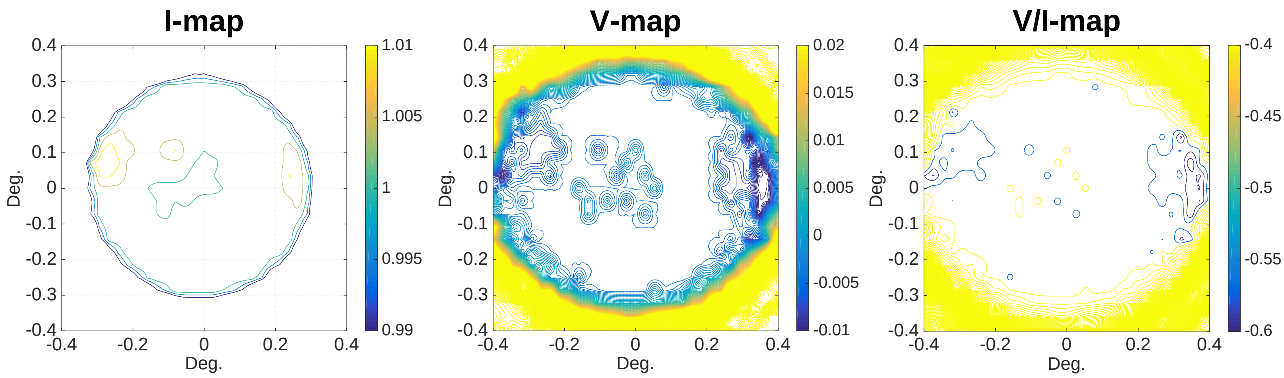

FIGURE 9 MRO 13 mm (22 GHz) maps taken on 9 May 2019. In the left Stokes I-map (intensity is relative to QSL), in the middle Stokes V-map, and in the right the degree of polarization.

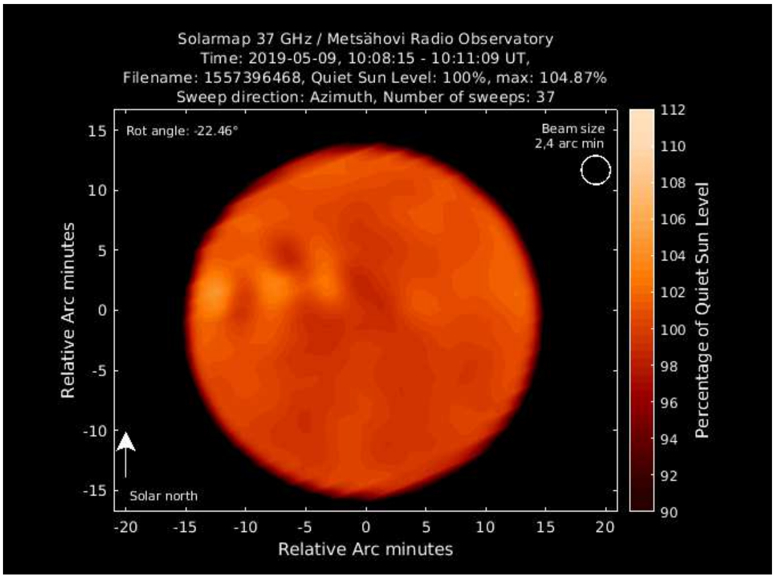

FIGURE 10 Solar radio map at 8 mm (37 GHz) observed at 9 May 2019.