LOW FREQUENCY SOLAR SCRUTINY WITH THE POLISH LOFAR STATIONS

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Abstract

The LOw–Frequency ARray (LOFAR) is a radio interferometer operating in the frequency range 10 – 240 MHz (corresponding to wavelengths of 30 – 1.2 m). Important issues of its broad scientific program are the solar and space weather investigations. We are expecting that the LOFAR telescope will bring interesting results in these fields. Three new LOFAR stations were built in Poland in 2015 and have been operating since the beginning of 2016. By including these stations to the ILT (International LOFAR Telescope), the resolution and sensitivity of the whole interferometer were improved and they are, for 240 MHz, 0.1 arcsec and 9.17 mJy/beam, respectively. Using a single LOFAR station, spectroscopic observations of the Sun can be performed; more stations allow us to obtain solar radio images.

1 Introduction

The LOFAR, LOw–Frequency ARray, science program is very broad, and it is organized in seven "Key Science Projects" (KSPs). They cover early universe research, pulsars, astroparticle physics, magnetic fields in the universe, solar physics, space weather and sky surveys [van Haarlem et al., 2013]. The calculations show that LOFAR will also be relevant in studying Jupiter–like planets and active moons.

In this paper we will focus on solar physics, and we will present the first test observations of the Sun taken by the LOFAR station in Bałdy (Poland).

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2 Solar observations by LOFAR

Solar radio observations are made at a large range of wavelengths from microwaves ($f >$ 3 GHz), up to hectometer/kilometer ($f <$ 3 MHz). Wild and McCready [1950] and Wild [1950a,b] distinguish five main types of solar radio bursts labeled as type I, II, III, IV and V (Figure 1). In the frequency range covered by LOFAR, we can observe all these bursts. Additionally, the LOFAR frequency range (10 – 240 MHz) corresponds to a radial distance between 1 and 3 solar radii in the corona [Mann et al., 1999].

The LOFAR telescope provides images and dynamic spectra of the Sun. Solar images require the use of core and remote stations. Dynamic spectra can be obtained by a single station. Observations of radio bursts require images over a broad frequency range. In addition, it is planned to participate in coordinated observation campaigns with other ground- and space-based instruments [Dąbrowski et al., 2016].

The solar and space weather KSP covers all manifestations of solar activity and also the Sun's influence on interplanetary space. For this purpose, images, dynamic spectra and measurements of interplanetary scintillation are taken [Vocks et al., 2016].

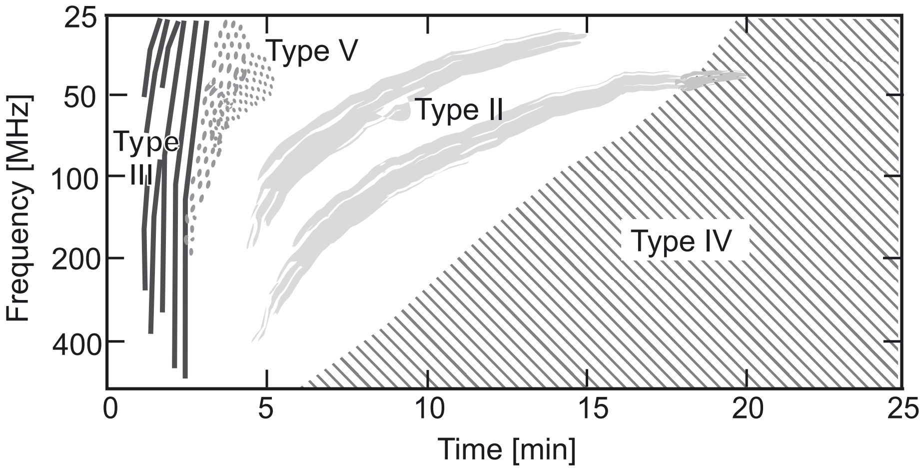

Figure 1: The schematic diagram shows the basic classification of solar radio bursts in the frequency range 25 – 500 MHz (based on Wild et al. [1963]).

The first interferometric solar observations with the LOFAR telescope were performed on March 17, 2011 (in the frequency range 115 – 162.5 MHz). This was part of the commissioning phase of the instrument, in order to test the telescope system for its capability to obtain radio images. During this observation, a weak radio burst was registered [Vocks et al., 2016].

On the other hand, Morosan et al. [2014] described the first tied–array beam solar observations with the LOFAR telescope in which images were shown simultaneously with their corresponding dynamic spectra. Type III bursts (Figure 2) were observed during the commissioning phase on February 28, 2013. Using one of the LOFAR beam formed modes (tied–array beams), high time and frequency resolution (83 ms, 12.5 kHz) dynamic

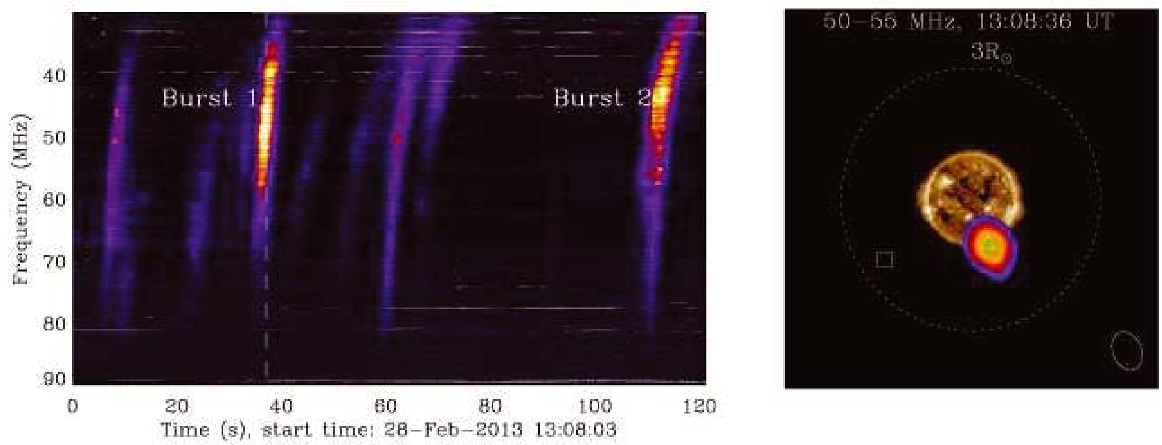

Figure 2: Dynamic spectrum (left) and solar radio image (right) of type III radio bursts observed on February 28, 2013 (see description in text) [Morosan et al., 2014].

spectra have been recorded at 126 spatial locations sampling the Sun. An example dynamic spectrum corresponding to a pointing on the south–western solar limb is shown in the left panel of Figure 2, and a few type III radio bursts can be identified. By combining the spatial and spectral information of tied–array beam observations, tied–array images of solar radio bursts were created as shown in the right panel of the Figure 2 (for more details see Morosan et al. [2014]). Here, a type III radio burst (burst 1 from the left panel) is overlaid on an Atmospheric Imaging Assembly 193 Å image of the Sun from NASA's Solar Dynamics Observatory.

3 The LOFAR telescope

The LOFAR telescope is a large radio interferometer that comprises 50 stations distributed throughout Europe. Each station contains two fields of dipole antennas: LBA (Low Band Antennas) and HBA (High Band Antennas) operating in the frequency range 10 – 90 MHz and 110 – 240 MHz, respectively. There are three types of stations: core, remote

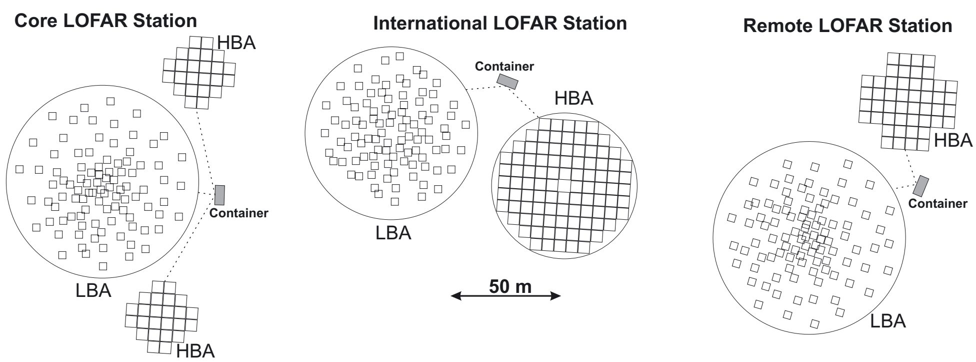

Figure 3: Types of the LOFAR stations (from left to right): core, international and remote (based on van Haarlem et al. [2013]).

and international stations. Each station has a different layout and number of LBA and HBA antennas (Figure 3). Most LOFAR stations are located in the Netherlands, where 24 are part of the core; 6 stations out of 24 were set on an "artificial island" with a diameter of about 350 m called Superterp. The remaining 14 stations called "remote" are located outside the core at a distance of up to 90 km [van Haarlem et al., 2013]. The 12 international stations are located in Germany (6 stations), Poland (3 stations), and one station each in France, Sweden, and the UK. In addition, a new Irish station in Birr is currently under construction (Figure 4). All LOFAR stations are connected by a broadband network with a data center in the Netherlands where the correlator is located.

4 POLFAR

The collaboration of the proposers from Poland was established in 2007 and organized in the Polish LOFAR Consortium – POLFAR. The agreement was signed by the representatives of the University of Warmia and Mazury (Bałdy station), the Jagiellonian University (Łazy station), the Space Research Center of the Polish Academy of Sciences (Borówiec station), the Nicolaus Copernicus University, the University of Zielona Góra, the Nicolaus Copernicus Astronomy Centre of the Polish Academy of Sciences, the University of Szczecin, the University of Environmental and Life Sciences, and the Poznań Supercomputing and Networking Center [Krankowski et al., 2014].

On June 11, 2014 the ceremony of signing the contract for construction of three new LOFAR stations in Poland between ASTRON and POLFAR took place at the University of Warmia and Mazury in Olsztyn. These stations were built in Bałdy, Borówiec, and

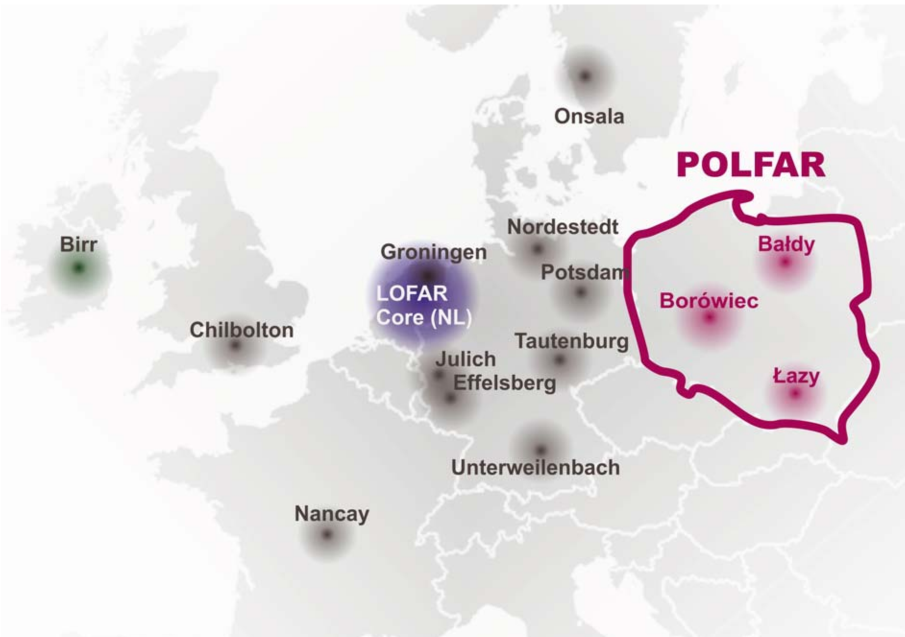

Figure 4: International LOFAR stations network in Europe. The Irish LOFAR station at Birr is under construction. POLFAR includes three stations: Bałdy, Borówiec, and Łazy.

Łazy. On December 9, 2015, the ILT (International LOFAR Telescope) board admitted POLFAR as a new member [Błaszkiewicz et al., 2016]. These stations allow the creation of an independent interferometer that can be used when they are not included in the LOFAR international mode of observations. POLFAR is improving the resolution and sensitivity of the whole LOFAR interferometer. For the longest baseline around 1550 km, which is situated between Chilbolton (UK) and Łazy the angular resolution of the instrument is 0.1 arcsec at 240 MHz (the highest frequency of LOFAR observations). The sensitivity of the instrument is 9.17 mJy/beam at 240 MHz, assuming that the integration time is 3600 seconds (based on LOFAR Image noise calculator: `https://support.astron.nl/ImageNoiseCalculator/sens.php`).

When it comes to the idea of a future interferometer made of three Polish stations only, the resolution and sensitivity at 240 MHz would be 0.5 arcsec and 92.52 mJy/beam (assuming that the integration time would be 3600 seconds), respectively. Taking the spectroscopic mode of observations, the time and frequency resolution would be 1 s and 0.195 MHz, respectively.

Figure 5: The LOFAR station in Bałdy under construction.

5 The LOFAR station in Bałdy

The LOFAR station in Bałdy is the first station in the system where the HBA tiles were assembled with the elements prefabricated on site, in a special tent. Preparation of the flattened field (81,8 m ×165 m) for the station construction started in summer 2014. It included alignment and drainage systems. This work was completed in the fall of 2014. In

Figure 6: The LOFAR station in Bałdy. LBA field (right), HBA field (left).

November 2014, we received prefabricated elements for the LBA and HBA. Their assembly was started in the beginning of June 2015 and was completed in 6 weeks (Figure 5). The commissioning phase occurred in the second half of August 2015. The inauguration of the LOFAR station in Bałdy took place on August 21, 2015 (Figure 6). At present, the station provides observations in both ILT and local modes.

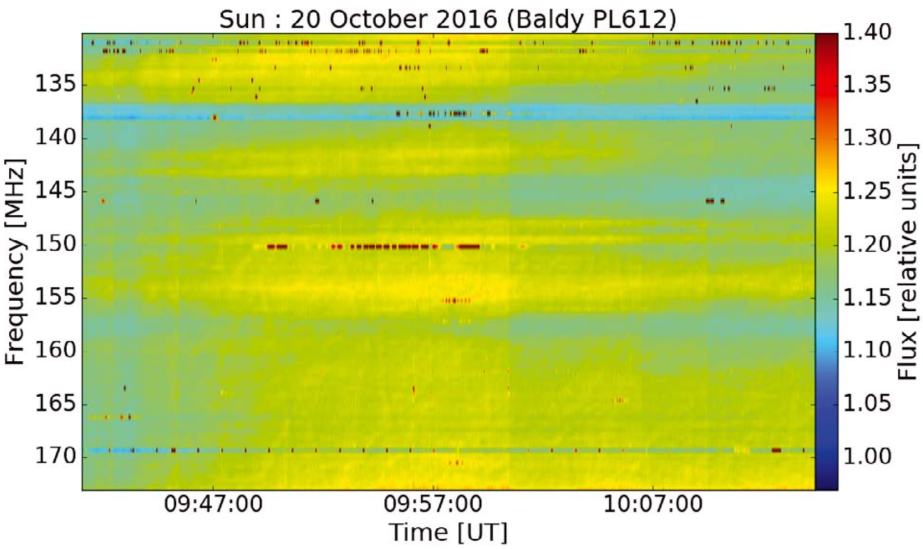

Figure 7: Quiet Sun dynamic spectrum recorded on October 20, 2016 between 09:41:02 and 10:14:22 UT in the frequency band 130.08 – 173.05 MHz.

6 Solar observations by Bałdy station

Bałdy LOFAR station is used for both ILT interferometric observations and local mode observations. One of the main observation goals of Bałdy stations in local mode are spectroscopic solar observations to obtain dynamic spectra of radio emissions from the Sun.

Dynamic spectra are time–frequency–intensity data. After corrections for the antenna response across the radio frequency pass–band and after removal of radio frequency interference (RFI) we can observe radio bursts occurring in the solar atmosphere.

The first test observations in Bałdy were made in October 2016. Unfortunately, we have not yet managed to observe radio bursts for the following reasons:

1. During the winter in Poland, the Sun is about 15° above the horizon at noon. So, LOFAR can follow the Sun only for a very short period of time around noon. For a single station, noises at elevation below 20° increase significantly.
2. Observation time in the local mode is only 3 days per week.
3. Currently, solar activity is very weak (forecasts indicate that a minimum of solar activity will be at 2020), and therefore the amount of radio events is very low now.

Figure 7 shows the example of a quiet Sun dynamic spectrum recorded on October 20, 2016 between 09:41:02 and 10:14:22 UT in the frequency band 130.08 − 173.05 MHz with a temporal resolution equal 1 s and a frequency resolution of 0.39 MHz with the LOFAR Bałdy station.

7 Concluding remarks

The first solar observations in ILT mode with the LOFAR telescope indicate that it is well suited for solar research at low frequencies. In the near future it will certainly bring some interesting observations and discoveries (see the paragraph 6).

First test solar observations were carried out in Bałdy and analyzed using special software developed by McKay–Bukowski and Fallows for the KAIRA instrument [McKay–Bukowski, 2013; McKay–Bukowski et al., 2015]. These observations did not bring any interesting results, due to point 3 in the previous paragraph.

However, it was important to verify that the telescope was fully operational in this field of observation. We are convinced that the single station observations will give a lot of interesting results soon.

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