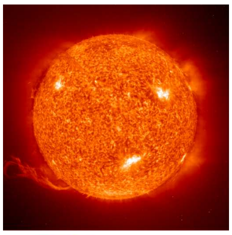

Definition of Solar Observing Modes with LOFAR

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Abstract

This document describes different modes suggested for solar observations with LOFAR. These modes include imaging of the radio Sun, both for studies of solar radio bursts with high time resolution, and monitoring of the long-term evolution of the radio Sun. Furthermore, a third mode is presented that uses LOFAR as a radio spectrometer. This mode makes use of only a single station or a small number of selected statations.

The observing modes described here make use of the LOFAR low (30 – 80 MHz) and high (120 – 240 MHz) band simultaneously. This requires a splitting of the antennaes of each station into two sub-arrays. If only a single band is available, or splitting is not possible, all observing frequencies have to be modified in order to fit into the available band.

This document is organized as follows: Each observing mode is discussed in a different section. Each section starts with a presentation of the general topic of the observing mode, as well as of the instrumental requirements. Then it is described in more detail how the observation should be performed, followd by some comments on data processing and the handling of data products. The table below provides a summariy of the observing modes:

Observing mode	Type of observation	Output data	Observation cadence	Number of 195 kHz sub-bands
Radio burst studies	Imaging	Complex visibilites	0.1 s	1 per obs. frequency
Solar monitoring	Imaging	Complex visibilites	1 min	1 per obs. frequency
Spectrometer mode	(Incoherent) Tied array	Dynamic spectra	0.01 s	all 165

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1 Solar Radio Burst Studies

1.1 General Instrument Settings

Solar radio burst studies comprise a rapid sequence of aperture synthesis images of the Sun that is initiated if a solar radio burst is detected. Such observations can be complementary to space missions like RHESSI, Hinode, or SDO, or they can be triggered by a “burst bell”, i.e. a radiospectrometer like the AIP’s Observatory for Solar Radioastronomy at Tremsdorf, that covers the frequency range of 40 – 800 MHz. The response time after such a trigger should be short, preferably less than 1 s. During dedicated observing campaigns, solar radio burst studies can be performed without the need for triggering.

The imaging sequence should be short, e.g. 0.1 s, in order to cover the dynamical evolution of the radio burst. The images should be taken on several, at least 4, frequencies, that include frequency pairs separated by a factor of two in order to detect radio radiation on the fundamental and first harmonic frequency. The bandwidth in each observed frequency should be small, of the order of 200 kHz. So a single 195 kHz sub-band can be used for each frequency. Solar burst radio radiation is chiefly plasma emission that is emitted on the local plasma frequency of the source region in the solar corona, or on its first harmonic. The plasma frequency is proportional to the square root of the electron number density, so different frequencies correspond to different electron densities, or in the gravitationally stratified solar atmosphere to different heights. For the adjustment of the frequencies during the burst, two possibilities exist. Since each frequency corresponds to a height in the solar corona, fixed frequencies enable studies of the spatial propagation of the burst. But for bursts that travel relatively slowly in the corona, and are detected first at frequencies above the LOFAR range, i.e. at lower height in the corona, the observed frequencies can follow the evolution of the solar radio burst. Radiospectrometric data can be used to guide the frequencies.

Solar radio burst are strong sources with typical intensities of several 10^6 Jy. This high intensity enables low bandwidths both for the observing frequency and the channel bandwidth. It also enables short integration times well below 0.1 s. The integration time should not exceed the characteristic time scales of 50 – 100 ms for radio bursts in the LOFAR frequency range.

Since the fundamental and harmonic frequencies might lie in the low and high band, respectively, it is reasonable to split the antennas of each station into two sub-arrays, with about half of the antennas in each band. The stations should be operated with the 200 MHz clock frequency in order to enable low-band observations. This excludes the frequency band 190 – 210 MHz, but this is the smaller restriction. The observed frequencies should include 40, 80, 160, and 240 MHz, but the inclusion of further frequencies, up to 10, is desirable.

At 240 MHz, the radio Sun typically has a diameter of 0.65°. The diameter increases to 0.72° at 120 MHz, and to 1.0° at 30 MHz. Thus, the radio Sun just fits into the primary beams of the LOFAR stations, and mosaicing is not needed. Imaging of the Sun also requires short baselines that are available in LOFAR’s central core. From experience with the Nançay Radioheliograph, baselines as short as 40-50 m are needed at 240 MHz.

The scattering of radio waves within the solar corona can limit the spatial resolution of solar images to a few 10”. Thus, at the beginning, the central core and the nearest remote stations will be needed, with baselines up to a few 10 km. Once the routine imaging of the Sun with these baselines has been established, it will be possible to investigate to what extent the inclusion of longer baselines does improve the images.

1.2 Observation

The proposed observation mode is taking aperture synthesis images of the Sun on at least 4 frequencies that are held fixed, or are directed by e.g. radiospectrograph data. For each frequency, one image is to be taken every 0.1 s for the duration of the solar radio burst. The integration time of each individual image does not exceed 50 ms. All images on the different frequencies should be taken simultaneously.

If LOFAR is operated with 8 independent observing beams, a total bandwidth of 4 MHz is available for each beam. This corresponds to 20 sub-bands of 195 kHz. So the concurrent observation of 10 frequencies, that each require only a single sub-band, is possible without the need for frequency switching. But if the observing frequencies are modified to follow the evolution of the radio burst, the necessary switching should be fast, i.e. within 1 – 10 ms.

The Sun moves less than 1" in the sky within 0.1 s. It's movement against the stellar background is 0.04" per second. So solar observations need a special phase center tracking. Given the expected limitations in spatial resolution for solar observations, the solar position in right ascension should be refreshed about each minute. Possibly, corrections may be applied off-line if a standard fringe stopping program, or hardware, must be used.

1.3 Data Processing

Channels of 195 kHz width (at each frequency) are convenient for solar physics. A narrow frequency channel (1 or 10 kHz) analysis in real time may be necessary at the lowest frequencies to remove interferences. In order to avoid problems with variable widths and shapes for the correlated frequency bands after interference mitigation, the correlations should be computed separately on small bands of 1 – 10 kHz, TBD, processed for interference mitigation, and then integrated over frequency in order to give a total band in the 100 – 200 kHz range. The outputs of the instrument are visibility functions, and interference must be removed in real time.

As mentioned above, solar observations will not require the longest baselines. However, for a rough estimate of the amount of calculations, and of the amount of data to handle, the full array with 77 stations and thus 2926 baselines is considered. The number of correlations per second can be determined taking into account:

- the number of narrow frequency channels needed for interference mitigation. For a 10 kHz analysis, the number of correlations for each baseline is 20.
- the speed of frequency switching: if the frequency is switched every 5 ms, the number of correlations to do is 200 per second. This means that for 4 frequencies, each frequency will be integrated 5 times after correlation in order to provide a 0.1 s time resolution.

Under these simple assumptions, to total number of correlations will be $\sim 1.2 \cdot 10^7$ per second. The total input data flow can be estimated under the same assumptions. For a bandwidth of 200 kHz, the sampling frequency should be 400 kHz, and the total input data flow will be

$$16\,(\text{bits}) \times 400\,(\text{kHz}) \times 4\,(\text{frequencies}) \times 2\,(\text{perpendicular dipoles}) \times 77\,(\text{stations}) = 4\,\text{Gbit/s}$$

The total output data flow is the number of words after processing. For 2926 baselines it will be:

$$2926 \times 2\,(\text{for complex}) \times 2\,(\text{I \& V}) \times 10\,(\text{time resolution}) \times 4\,(\text{frequencies}) = 468\,\text{kword/s}$$

Over a 195 kHz bandwidth, Faraday rotation is expected to wash out any linear polarization, and only Stokes parameter I and V correlations are needed.

The total data flow seems much smaller than the full BlueGene capabilities of 400 Gbits/s, mainly because we will use a very small bandwidth of 195 kHz. The size of the output words is not presently determined: it can be stated roughly that a 16 bits word size is sufficient in order to compute high dynamic images. But the dynamic of solar emissions is greater than 16 $\times$ 3dB. Therefore, the word size may be 32 bits, or a floating point format with e.g. 16 bits accuracy and 2 $\times$ 20 or more dynamic.

Outputs will be calibrated uv datasets, corrected for ionospheric disturbances, as much as possible. This is preferable to images, which can be later obtained through processing adapted to each specific study.

1.4 Off-line Data Processing

Solar observations need a special phase center tracking. Given the expected limitations in spatial resolution for solar observations, the solar position in right ascension should be refreshed about each minute. Possibly, corrections may be applied off-line if a standard fringe stopping program, or hardware, must be used.

1.5 Data Products Export

The data are to be exported to the Solar Science Data Center. After export, they can be deleted on the LOFAR storage cluster. The data volume is easily manageable by the Solar Science Data Center. A convenient access policy to the observations will be set up.

2 Solar Monitoring

2.1 General Instrument Settings

Routine monitoring of the Sun comprises aperture synthesis images of the Sun on selected frequencies both in the low and high bands, e.g. 40, 80, 160, and 240 MHz. The images on each of these frequencies should be taken shortly one after another, ideally at the same time. The imaging cadence is proposed to be 1 image per minute.

Since only the solar image at the respective frequency is of interest, the bandwidth at each observing frequency and the channel bandwidth can be small. Narrow bandwidths of the order 200 kHz are desirable since a small frequency interval covered by each observation better restricts the height range in the solar atmosphere that contributes to this image. So a single 195 kHz sub-band can be used for each frequency.

The Sun is a very bright radio source. At 40 MHz, the thermal radiation of the hot solar corona already has an intensity of about 2000 Jy. Solar radio bursts typically reach intensities of several 10^6 Jy. These high intensities enable the low bandwidths mentioned above, and would allow for short integration times of less than 0.1 s. But with one image per minute and frequency with short integration time, transient events between two images may be missed. An integration time of 1 minute per image avoids this and yields results that are more representative for the solar activity.

Since observations in both the low and high band are planned, a distribution of the antennas in two sub-arrays, with about half of the antennas in each band, is needed. The stations should be operated with the 200 MHz clock frequency in order to enable low-band observations. This excludes the frequency band 190 – 210 MHz, but this is the smaller restriction.

At 240 MHz, the radio Sun typically has a diameter of 0.65°. The diameter increases to 0.72° at 120 MHz, and to 1.0° at 30 MHz. Thus, the radio Sun just fits into the primary beams of the LOFAR stations, and mosaicing is not needed. Imaging of the Sun also requires short baselines that are available in LOFAR's central core. From experience with the Nançay Radioheliograph, baselines as short as 40-50 m are needed at 240 MHz.

The scattering of radio waves within the solar corona can limit the spatial resolution of solar images to a few 10". Thus, at the beginning, the central core and the nearest remote stations will be needed, with baselines up to a few 10 km. Once the routine imaging of the Sun with these baselines has been established, it will be possible to investigate to what extent the inclusion of longer baselines does improve the images.

2.2 Observation

The proposed observation mode is taking aperture synthesis images of the Sun on pre-defined frequencies. For each frequency, one image is to be taken per minute. This accommodates the image cadence of the Global H-α Patrol Network (*http://www.bbso.njit.edu/Research/Halpha/ha_site.html*). The total duration of the observations is about 8 h per day. The integration time of each individual image is 1 minute.

The Sun moves less than 1" in the sky within 0.1 s. It's movement against the stellar background is 0.04" per second. So solar observations need a special phase center tracking. Given the expected limitations in spatial resolution for solar observations, the solar position in right ascension should be refreshed about each minute. Possibly, corrections may be applied off-line if a standard fringe stopping program, or hardware, must be used.

2.3 Data Processing

In this observing mode, the imaging sequence is with 1 per minute and frequency much lower than in the solar radio burst mode, where 10 images are taken per second and frequency. Thus, both the number of correlations per second and the data rates are scaled down correspondingly, and stay well below any data transfer and BlueGene limitations.

Outputs will be calibrated uv datasets, corrected for ionospheric disturbances, as much as possible. This is preferable to images, which can be later obtained through processing adapted to each specific study.

2.4 Off-line Data Processing

Solar observations need a special phase center tracking. Given the expected limitations in spatial resolution for solar observations, the solar position in right ascension should be refreshed about each minute. Possibly, corrections may be applied off-line if a standard fringe stopping program, or hardware, must be used.

2.5 Data Products Export

The data are to be exported to the Solar Science Data Center. After export, they can be deleted on the LOFAR storage cluster. The data volume is easily manageable by the Solar Science Data Center. A convenient access policy to the observations will be set up.

3 Single station as spectrometer

3.1 General Instrument Settings

In this observing mode, a single LOFAR station is used as a pure solar radio spectrometer. Dynamic spectra of the radio flux from the whole Sun are recorded continuously, and imaging is not needed. The full bandwidth of 32 MHz should be used. The 165 sub-bands with 195 kHz each are evenly distributed over the low and high band, and placed on “quiet” frequencies with no RFI. The channel bandwidth should be small (1 kHz), in order to get a good spectral resolution.

The temporal resolution should be high enough to reveal short features on time scales of a few 10 ms. So an integration time of 10 ms is suggested. Since the Sun is a bright radio source with 2000 Jy thermal radiation at 40 MHz, and non-thermal radio bursts of several 10^6 Jy, the integration times can be this small.

These non-imaging observations correspond to the Tied Array mode. The use of more than one station opens further possibilities. If the data are simply combined, the Incoherent Tied Array mode should be used in order to retain the beam size of a single station that just covers the whole Sun. Stations at different locations can use different frequency band in order to avoid their local RFI sources, and to provide a more complete coverage of the whole LOFAR spectral range. Furthermore, concurrent observations at stations that are separated by several hundred kilometers enable the separation of intermittent ionospheric disturbances from temporal variations of the solar radio source.

Since observations in both the low and high band are planned, a distribution of the antennas in two sub-arrays, with about half of the antennas in each band, is needed. The station should be operated with the 200 MHz clock frequency in order to enable low-band observations. This excludes the frequency band 190 – 210 MHz, but this is the smaller restriction.

At 240 MHz, the radio Sun typically has a diameter of 0.65°. The diameter increases to 0.72° at 120 MHz, and to 1.0° at 30 MHz. Thus, the radio Sun just fits into the primary beams of the LOFAR stations, and this observing mode always covers the total radio flux from the Sun, irrespective of the source location on the solar disk.

3.2 Observation

The proposed observation mode is continuously recording spectra of the solar radio radiation in all 165 sub-bands, with 195 kHz each, on pre-defined frequencies. Only a single LOFAR station is to be used. For each spectrum, the integration time is 10 ms. The total duration of the observations is about 8 h per day.

During the integration time of each individual spectrum, a tracking of the Sun is not needed, but of course the observations have to follow the Sun during the day. The solar position in right ascension should be refreshed about each minute.

3.3 Data Processing

The tied-array beams need to be formed and Fourier-transformed in order to obtain the radio spectra. Since the full 32 MHz total bandwidth of the station is used, the 2 Gbit/s of the station data transfer will be exploited.

Since no imaging is involved, this observing mode will stay far below any BlueGene limitations. The final data product is spectral intensity of the solar radio radiation in the 32 MHz total frequency window, with a 1 kHz spectral resolution. The cadence for these spectra corresponds to the integration time of 10 ms.

3.4 Off-line Data Processing

After calibration (including ionospheric correction) and Fourier-transform, no further data processing is necessary.

3.5 Data Products Export

The data are to be exported to the Solar Science Data Center. After export, they can be deleted on the LOFAR storage cluster. The data volume is easily manageable by the Solar Science Data Center. A convenient access policy to the observations will be set up.