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LOFAR PL610 STATION DATA PRODUCT SPECIFICATION

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ABSTRACT. Since 2017, the Space Research Centre of the Polish Academy of Sciences in Warsaw, Poland, has measured and gathered over 35,000 hours of observations with the use of the LOw Frequency ARray (LOFAR) radio telescope. This paper outlines the Standard Data Product acquired from the LOFAR PL610 station located in Borówiec, Poland. Within this context, we detail the data products that are accessible, provide metadata descriptions for them, and include an example of the data under both quiet and disturbed ionospheric conditions.

Keywords: ionosphere, LOFAR, scintillation, ionospheric data

1. INTRODUCTION

1.1. LOFAR Radio Telescope

LOw Frequency ARray (LOFAR) for Radio Astronomy is an international network of radio telescopes distributed across Europe (Haarlem et al.,2013). It consists of 52 separate stations: 38 in the Netherlands, 6 in Germany, 3 in Poland, 1 per country in France, Sweden, United Kingdom, Ireland, Latvia, and one soon to be constructed in Italy. LOFAR was designed and constructed by ASTRON – the Netherlands Institute for Radio Astronomy (Heald et al., 2013). It operates at frequencies between 10 MHz and 240 MHz. Multiple LOFAR stations can be used together as an international interferometer in the International LOFAR Telescope mode (ILT mode). However, each station can operate separately in the so-called single station mode. This means a single LOFAR station can be used as a radio telescope operating with limited parameters (Pożoga et al., 2021).

1.2. LOFAR PL610 station

The PL610 LOFAR station located in Borówiec, Poland ($52°16'32.7"$N, $17°04'25.5"$E), is an international LOFAR station. It consists of two antenna fields – Low-Band Antenna (LBA)

and High-Band Antenna (HBA) fields, and the data processing unit located inside a container (Figure 1). Both antenna fields have 96 antennas each. In the case of LBA, the covered frequency range is 10-90 MHz. The HBA antenna field operates at frequencies between 110 and 240 MHz. Additionally, the station is equipped with 100 Hz Global Navigation Satellite System (GNSS) scintillation receivers, as well as a riometer, and a radio receiver (Rothkaehl et al., 2018).

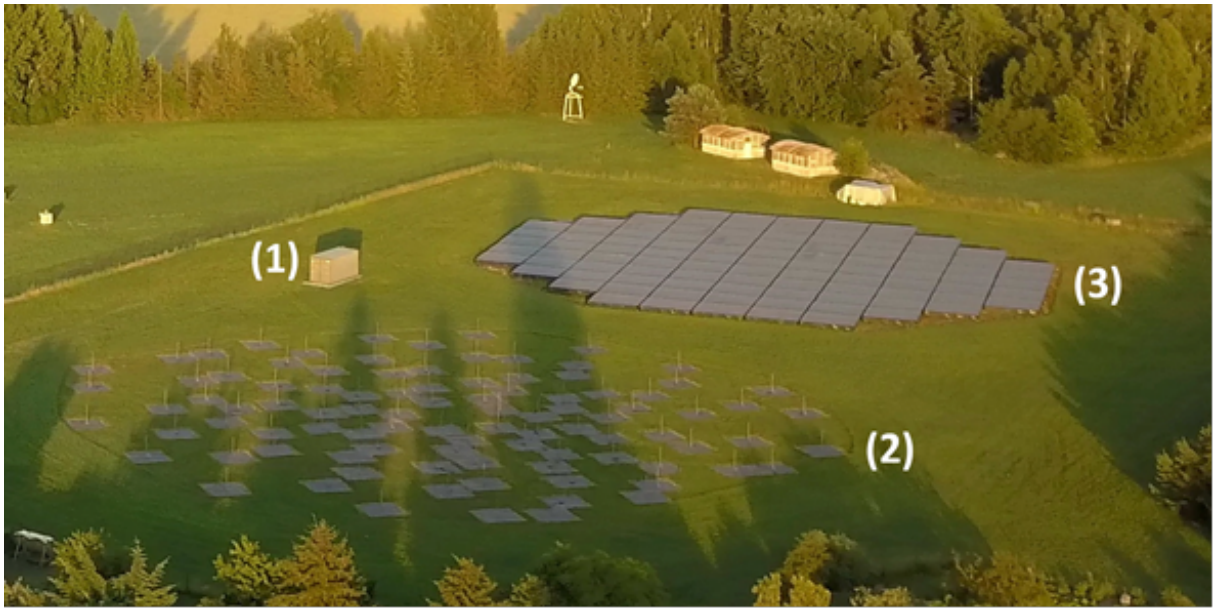

Figure 1. The Space Research Centre, PAS, LOFAR PL610 Station in Borówiec, Poland.
(1) Container with electronic equipment; (2) Low Band Antenna Field;
(3) High Band Antenna Field (Pożoga et al., 2021)

An LBA antenna consists of two perpendicular dipoles used for measurements of two horizontal linear polarizations. The signal from each described dipole is transmitted to a nearby building where the data processing unit is located. The signal is later recorded and digitized (at 200 MHz, with 12-bit resolution) and then utilized for beamforming (Droszcz et al., 2021; Pożoga et al., 2021). The station beam is fully digitally steered. This allows for a quick and easy selection of the direction of the observation.

The operating frequency and flexibility of the LOFAR instrument, including the LOFAR PL610 station, allow it to be used as a near-Earth space research and monitoring tool. The station enables observations of the Earth's ionosphere and space weather phenomena. In addition, the observation of radiation from other objects in the solar system (e.g., Jupiter) can be carried out (Pożoga et al., 2018a; Pożoga et al., 2018b; Rothkaehl et al., 2018).

1.3. LOFAR Observations

The available LOFAR observations described in this paper are carried out in the local mode, using a single (PL610) station (also referred to as a single station mode).

The typical observations performed with the LOFAR PL610 station include the measurements of ionospheric scintillation using the four strongest natural radio sources. In LOFAR nomenclature, they are called A-Team radio sources. The group consists of CasA, CygA, TauA, and VirA (Pożoga et al., 2021). In addition to data related to these objects, the available ones include the measurements carried out for Jupiter and the Sun (Rothkaehl et al., 2018). The beam-formed data

include the dynamic spectra of observed radio sources (A-Team sources, Sun, Jupiter) and the S_4 index measurements – available only for the strongest A-Team radio sources. Additionally, the all-sky observations of astronomical radio sources may be performed. However, this kind of studies is not a part of the routine.

Within the framework of the observation, the Space Research Centre of the Polish Academy of Sciences (SRC PAS), in collaboration with the Warsaw University of Technology, uses the PL610 LOFAR station as a passive radar to observe LEO satellites, utilizing signals from DAB+ and DVB-T as illuminators (Jedrzejewski et al., 2023).

The influence of the ionosphere on the angle of incidence of the strong radio sources (such as CasA and CygA) is also a matter of the studies conducted by SRC PAS. In order to do that, we use cross-statistics recorded as a side product of the scintillation observation (Pożoga et al., 2019).

The data available in the database comes from the period starting on June 23, 2017, and onwards. The database contains NetCDF (.nc) files, the contents of which are described further in this paper. The typical NetCDF file contains an hour of observational data. However, the files may be shorter if measurements do not start at the full hour.

2. DATA PRODUCT DESCRIPTION

To facilitate the utilization of LOFAR-obtained data for its users, we describe the metadata contained in our standard product. This detailed metadata description aims to enhance the understanding and accessibility of the data. We discuss the projects within which the PL610 LOFAR data are (or will be soon) available, as well as a procedure for obtaining the data on individual requests.

2.1. Metadata Description

In the following subsection, we present the metadata of the standard product along with the description of each attribute, its format, and specification (Table 1). Table 1 includes the name of each attribute that can be found within the standard data product, along with its definition.

The data are available in a NetCDF format. The values assigned to the attributes in the metadata may vary slightly due to the development of the measurements throughout the years of observation and carried out measurements.

For the purpose of projects, such as VESPA (further described within this paper), the metadata is generated. This metadata allows searching the products provided by SRC PAS. They are designed to match the fields required by the specific platform. In the future, the same thing will apply to the PITHIA-NRF project (further discussed in this paper).

Table 1. The metadata of the standardized LOFAR PL610 data product

Name of the attribute	Attribute description
StartTime	timestamp marking the beginning of the observation given in ISO 8601 datetime YYYY-MM-DDTHH:mm:ss(.SSSSSS) format
StopTime	timestamp marking the end of the observation given in ISO 8601 datetime YYYY-MM-DDTHH:mm:ss(.SSSSSS) format
Lane	technical parameters defining which lane was used during measurements. It is a numerical value (e.g., 1, 2, 3 or 4)
Target	the radio source used for the observations (e.g., CasA, TauA, CygA, VirA, Sun, Jupiter)
Digdir	the right ascension, declination, and epoch (J2000 for the available data)
Anadir	the right ascension, declination, and the epoch (J2000 for the available data) for HBA analogue beam forming
Band	the bands on which the observations were carried out (e.g., 10_90, 110_190, 210_270) given in MHz
SoftRev	Software Revision; it includes the name of the computer
Datatype	the type of the data
Observatory	the LOFAR station from which the observations were carried out. In the case of the described data sets – PL610 station
Bitmode	source data bit resolution 4/8/16 bits
FFTLength	the additional subband division using FFT (e.g. 1, 16). 1 – no division, spectral resolution: 195.0 kHz; 16 – spectrum resolution increase to 12.2 kHz
TimeLength	the time of the observation given in seconds [s] and multiplied by 100 Hz; the number of samples measured per second
SubbandNo	the number of observed frequencies
dimensions(sizes)	Time(TimeLength), Subband(SubbandNo)
variables(dimensions)	the variables including Stokes parameters (I, U, V, Q) given as float32 variables: I(Subband,Time), U(Subband,Time), V(Subband,Time), Q(Subband,Time), N(Time) – int64 – the number of samples, and Subband – given as float32 Subband(Subband)

2.2. PITHIA Data Product

The Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access Services: a Network of Research Facilities (PITHIA-NRF) is a project aiming to build a network of research infrastructures distributed across Europe. It integrates the observing facilities, data processing tools, and prediction models dedicated to the research on the ionosphere, thermosphere, and plasmasphere (PITHIA-NRF Research Infrastructure, 2021).

Within the PITHIA-NRF project, the Space Research Centre of the Polish Academy of Sciences provides observational data from various instruments dedicated to the investigation and monitoring of ionospheric conditions. The measurements performed by the PL610 LOFAR station in Borówiec, Poland, are the products distributed within the framework of the PITHIA project. The data can be found in the project PITHIA e-Science Centre[1].

[1]PITHIA-NRF, 2024, *PITHIA e-Science Centre*, Access date: August 14, 2024; available under <https://esc.pithia.eu/>

The PITHIA data product is going to include ionospheric data, such as LOFAR S_4 index (Pożoga et al., 2021) calculated using the signal measured from the A-Team radio sources (see section 1.3, mostly CasA and CygA; however, the VirA and TauA will also be available). The S_4 datasets will be processed by a specialized semi-automatic pipeline developed at SRC PAS.

Currently, dynamic spectra of four Stokes parameters are also available for the mentioned sources. Moreover, the dynamic spectra for Jupiter and the Sun are also available. The observations are discontinuous, meaning they are carried out for selected days in which the PL610 LOFAR station will operate in the local mode (see section 1.3). The dynamic spectra-related data can be accessed via PITHIA e-Science Center website[2]. The data can be accessed using the Astronomical Data Query Language (ADQL) request in the dedicated query form (link is provided on the website).

The external teams can work on their own projects and access the data through the Trans-National Access (TNA) programme. As one of the nodes, SRC PAS offers access and the possibility to lead a measurement campaign with the use of the LOFAR station in Borówiec.

2.3. VESPA Data Product

Virtual European Solar and Planetary Access (VESPA) is a project that aims to build a Virtual Observatory (VO) for Solar System science. It adapts the VO techniques and develops new tools and standards designed for planetary science-related data (Europlanet Society, 2020).

The LOFAR data available within the framework of the VESPA project is Jupiter observations carried out on the PL610 LOFAR station in Borówiec, Poland, and can be found on VESPA Datacentre[3].

All data available in VESPA VO is prepared to match the standard of LOFAR PL610 data. The observation can be accessed online via the VESPA Query Interface and allows the search of the data by minimal and maximal time of observation. As of now, the available target of observations that can be accessed at VESPA servers is Jupiter. More detailed information on how to access the data and related tutorials can be found on the website of the VESPA project.

2.4. Data on Request

In case the data not being available on any server mentioned before, it can also be requested by an individual. Such a situation may occur in case of new data from a period of one year back, some archival data that were not processed but measurements have been performed or the dates when observations of specific events/projects were carried out. Such observations can still be accessed upon contact with SRC PAS.

Moreover, it is possible to ask for data from observations with LOFAR in both – the ILT mode and the local mode. In case of the special needs of the user, the request on specific observations and/or data can be submitted directly to the Space Research Centre, PAS.

Such data will be made available in case of observations carried out in agreement with Space Research Centre PAS. It applies to the international or national projects in which the PL610 LOFAR station has been used to gather the observational data. It is made available after earlier agreements on the terms and conditions.

[2]PITHIA-NRF, 2024, *PL610 LOFAR station data*, Access date: August 14, 2024, available under <https://esc.pithia.eu/data-collections/DataCollection_PL610_LOFAR_Station>

[3]VESPA: A community-driven Virtual Observatory in Planetary Science, 2024, *VESPA*, Access date: August 14, 2024, <http://www.europlanet-vespa.eu/index.shtml>

Users can access the data already available within the online platforms without any previous/ongoing involvement in the SRC PAS projects – they are open access. However, when published, proper acknowledgements and/or citations must be included.

In order to request the data, contact one of the authors of this paper.

3. EXAMPLES OF THE AVAILABLE DATA PRODUCT

To present the sample of the data product, we examined the examples in which the LOFAR PL610 station data have been used. We present the observations carried out during quiet conditions, as well as during a recovery phase of a geomagnetic storm. The presented cases belong to the data available on request. We show the product processed with the S_4 pipeline and plots based on observations led under various states of the ionosphere.

3.1. Example 1: Quiet conditions

To show the available product, a sample of data recorded in quiet ionospheric conditions has been shown (Figure 3). In the following example, we present the data from the 9th of June, 2021. The analysed time window was selected based on the Dst index value (close to 0 nT, Figure 2) and PL610 data availability for this period.

The presented example is data recorded for the CasA radio source and processed by the developed S_4 pipeline (Pożoga et al., 2021).

3.2. Example 2: Moderate geomagnetic storm

In the following example, we present the data available on request. The example is related to observations made during disturbed ionospheric conditions after the geomagnetic storm that occurred on March 13, 2022. The data presented was recorded on March 15th, 2022, during the storm recovery phase, when the ionospheric conditions were still not so quiet. The Dst index is shown in Figure 4, and data can be seen in Figure 5.

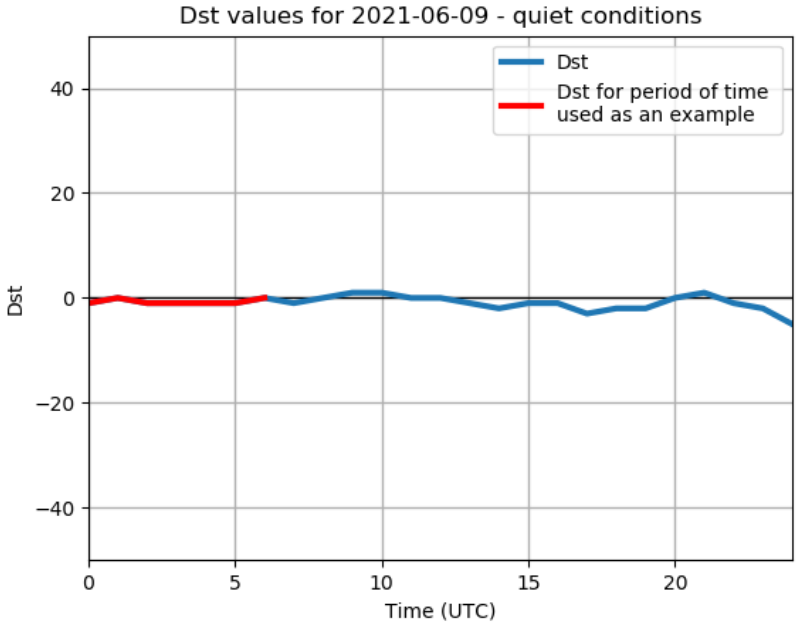

Figure 2. The Dst index for 9th of June, 2021

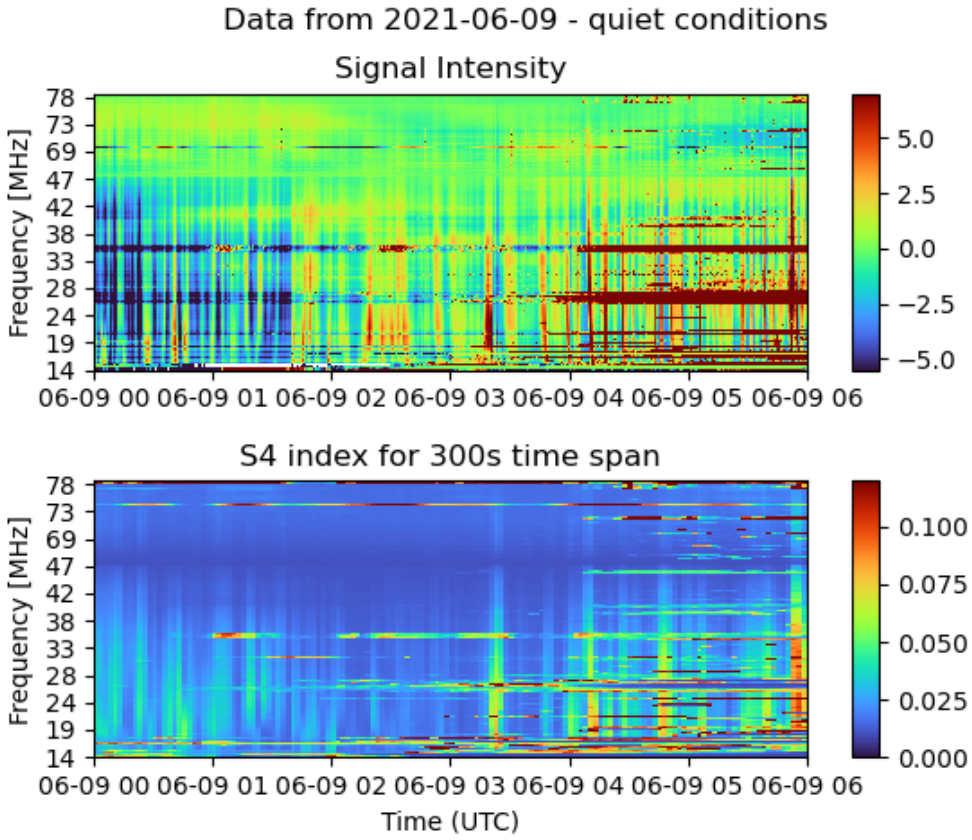

Figure 3. The I Signal Intensity (top) and the S_4 index for 300-second time window (bottom) plots of the recovery phase after the geomagnetic storm for CasA radio source

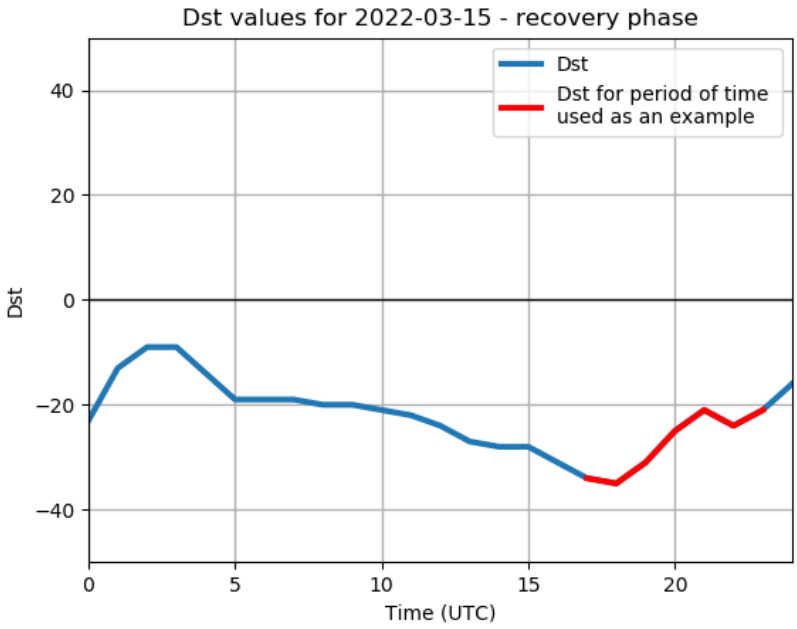

Figure 4. The Dst index for March 15th, 2022

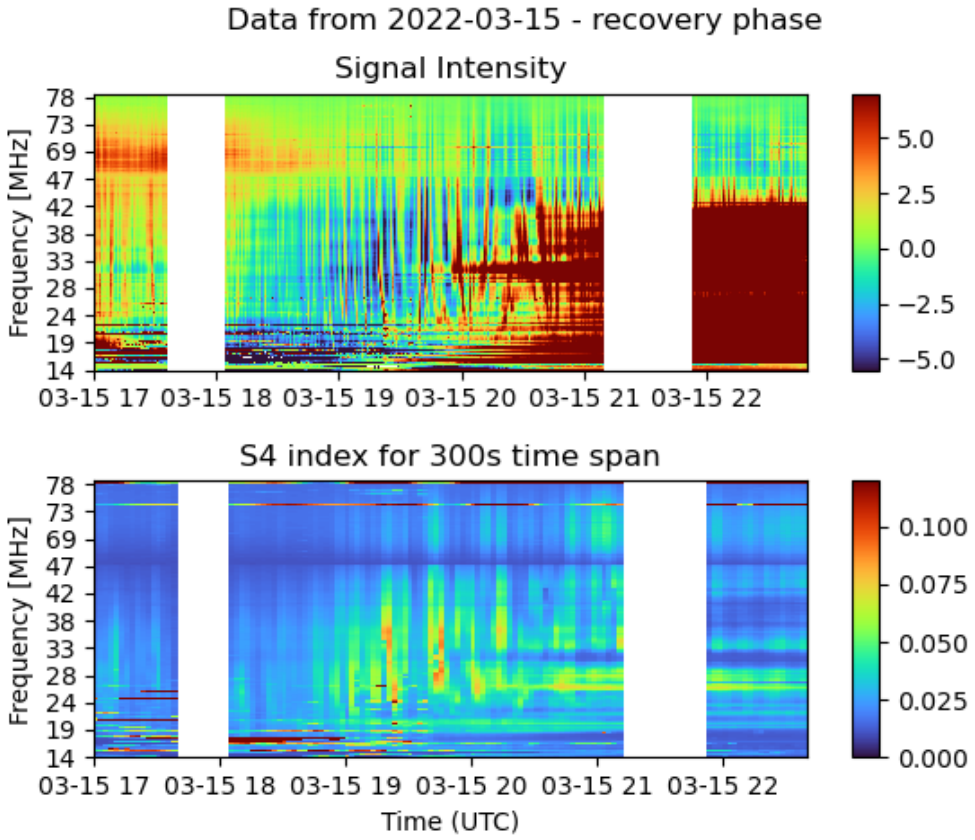

Figure 5. The I Signal Intensity (top) and the S_4 index for 300 second time window (bottom) plots of the recovery phase after the geomagnetic storm for the CasA radio source

4. SUMMARY

The LOFAR PL610 data are a product standardized for implementation on various platforms used as online databases. VESPA and PITHIA are examples of such data access platforms. The aim of standardizing the product is to keep the common format of standard LOFAR data that can be adjusted for upload to diverse individual search engines.

The available data contains the measurements carried out on PL610 LOFAR station in Borówiec, Poland, directed towards the near-Earth environment, Solar and Jupiter observations. The near-Earth environment observations include ionospheric studies and computational data processed using the special semi-automatic pipeline.

Currently, the selected data products can be accessed via the PITHIA-NRF Platform and VESPA VO. Moreover, some data can also be requested directly from the Space Research Centre, PAS, Warsaw, Poland, by emailing the authors of this work.

When using the data in a publication, the user is expected to write an acknowledgment for the SRC PAS Group and/or cite this work. An example of an acknowledgment formula could be: "We acknowledge the Space Research Centre of the Polish Academy of Sciences and Plasma Physics Group for providing the LOFAR PL610 data."

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REFERENCES

Droszcz, A., Jedrzejewski, K., Klos, J., Kulpa, K., Pozoga, M., (2021), Beamforming of LOFAR Radio-Telescope for Passive Radiolocation Purposes, *Remote Sensing*, vol. 13, issue 4, p. 810

Europlanet Society, (2020), VESPA – Europlanet Society, *European Union's Horizon 2020*, accessed 06.06.2023 <https://www.europlanet-society.org/europlanet-2024-ri/vespa/>

Haarlem, M., Wise, M., Gunst, A., Heald, G., McKean, J., Hessels, J., de Bruyn, A., Nijboer, R., Swinbank, J., Fallows, R., Brentjens, M., Nelles, A., Beck, R., Falcke, H., Fender, R., Horandel, J., Koopmans, L., Mann, G., Miley, G., Zwieten, J., (2013), LOFAR: The low-frequency array, *Astronomy and Astrophysics*, 2013, doi: 10.1051/0004-6361/201220873.

Heald, G., McKean, J., Pizzo, R., (2018), Low Frequency Radio Astronomy and the LOFAR Observatory, [online] available: https://doi.org/10.1007/978-3-319-23434-2.

Jędrzejewski, K., Malanowski, M., Płotka, M., Pożoga, M., Kulpa, K., (2023), Passive Multistatic Localization of Space Objects using LOFAR Radio Telescope, *2023 IEEE International Radar Conference (RADAR)*, Sydney, Australia, 2023, pp. 1-6, doi: 10.1109/RADAR54928.2023.10371124.

PITHIA-NRF Research Infrastructure, (2021), The PITHIA-NRF Project – PITHIA-NRF Research Infrastructure, *European Union's Horizon 2020*, accessed 06.06.2023, <https://pithia-nrf.eu/>

Pożoga, M., Ciechowska, H., Grzesiak, M., Rothkaehl, H., Wronowski, R., Matyjasiak, B., Tomasik, Ł., Beser, K., "Ionospheric Scintillation Diagnostic on LOFAR ILT Network in Single Station Mode",*2021 Signal Processing Symposium (SPSympo)*, 2021, pp. 220-225, doi: 10.1109/SPSympo51155.2020.9593637.

Pożoga, M., Matyjasiak, B., Grzesiak, M., Rothkaehl1, H., Przepiórka, D., Wronowski, R., (2018a), Observations of the geomagnetic storm 27-28.05.2017 with LOFAR PL610, *PTA Proceedings*, vol. 7, p. 91-93

Pożoga, M., Matyjasiak, B., Rothkaehl, H., Przepiórka, D., Grzesiak, M., Wronowski, R., (2018b), Ionospheric scintillations over the polish LOFAR station PL610, *PTA Proceedings*, vol. 7, p. 94-96

Pożoga, M., Matyjasiak, B., Tomasik, Ł., (2019), Space weather usage of LOFAR PL610 station, Proceedings Volume 11176, *Symposium on Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments (WILGA) 2019*; doi: org/10.1117/12.2537373.

Rothkaehl, H., Pozoga, M., Morawski, M., Matyjasiak, B., Przepiorka, D., Grzesiak, M., Wronowski, R., (2018), Near Earth space monitoring with LOFAR PL610 station in Borowiec, *PTA Proceedings*, vol. 7, p. 48-54

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