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THE LOFAR LONG-BASELINE CALIBRATOR SURVEY CLASSIFICATION

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Data manipulation of the LOFAR Long-Baseline Calibrator Survey (LBCS) and the Westerbork Northern Sky Survey (WENSS) catalogues are carried out in the present study. The aim of the study is to make calibrator classification statistics plots and estimations for further observations and upcoming stations. First, mean flux densities of LBCS calibrators against declination and observed station baseline length to the tied core station are plotted and the classified sources are marked. Second, we provide the designation – naming it the success rate – for the number of sources with the correlated signal against all the LBCS catalogue sources. Third, there is a trend in mean peak flux densities between stations – longer the baseline, higher mean peak flux density. Finally, estimations for upcoming and recent stations are made and some results are not encouraging.

Keywords: *catalogue manipulation, LBCS classification, LOFAR calibrators, statistical estimation*

1. INTRODUCTION

LOFAR, the LOw-Frequency ARray [1], is a new-generation radio interferometer constructed in the north of the Netherlands and across Europe. LOFAR covers the largely unexplored low-frequency range from 10–240 MHz and provides a number of unique observing capabilities. LOFAR is one of the first radio observatories to feature automated processing pipelines to deliver fully calibrated science products to its user community. New capabilities and techniques of LOFAR make it an important pathfinder for the Square Kilometre Array (SKA) [2].

One of the challenges in the design of the LOFAR radio telescope is calibration of the ionospheric effects as at low frequencies ionosphere is not uniform and can change within minutes [3]. Compensation for phase delays caused by Earth's atmosphere is very important for further radio interferometer data interpretation. To achieve it, a calibrator source near the target source must be observed. They should be close enough on the sky to be subject to approximately the same propagation effects. To perform calibration, delay and phase solutions are transferred from the calibrator to the target source. The aim of LOFAR LBCS [4] is to identify sources over a large part of the northern sky suitable for calibrating further observations. The survey includes sources with correlated flux densities starting from 50 mJy at frequencies around 110–190 MHz. Suitable sources are described as calibrator density over the sky. For the shortest international baselines, there is around one suitable calibrator source per square degree. For the longest baselines, there are significantly fewer suitable calibrators available. LBCS is an ongoing project and more than 24 000 sources have been observed and processed so far. LBCS database is formed using survey results. For each International LOFAR Telescope (ILT) [5] station, sources are classified into groups that are described if the source can be considered a suitable calibrator (marked as P-class) or there is insufficient correlated flux for calibration (marked as X-class). The LBCS source selection in the region north of 30°N uses three surveys. The first survey is the 74MHz VLSS [6], the second survey is the Multi-frequency Snapshot Sky Survey (MSSS) [7], and the third, the most used one, is the 325 MHz WENSS [8]. The LBCS database does not contain flux densities per beam for each source and the WENSS catalogue can be used to supplement the list. WENSS catalogue [9] sources are observed at frequency different from LBCS but still close enough for further calibrator classification statistics; therefore, estimations can be made.

2. CALIBRATOR CLASSIFICATION ESTIMATION

Automated Python scripts are used to manipulate WENSS and LBCS catalogues. As there are no unified source names in both catalogues, script recognises sources by their coordinates – right ascension and declination. There are 24 893 sources so far in the LBCS and 229 420 sources in the WENSS catalogue. ERI VIRAC high performance computing server cluster is used for execution of the scripts. In total, 18 447 sources overlaid in both catalogues and formed a new list containing LBCS database concatenated with peak flux densities from WENSS catalogue.

This chapter briefly explains catalogue manipulation and statistical methods used to acquire calibrator classification estimation.

Mean flux densities against declination are described in the following section. Peak flux densities are displayed as P-class or X-class source against declination. The script generates plots for every single station. Each source in the plot is displayed as P or X class source (for the specific station). Axes represent peak flux density in mJy/beam and declination in degrees. Range of Y-axis is limited to see only most of the points. Mean values are calculated for short intervals of 10 degrees by calculating all the specific class source peak flux densities in the interval and dividing by the count of sources. Mean values are connected to form a line. We chose to show the most extreme cases – the closest station DE605 (Jülich, 226 km) in Fig. 1 and the furthest station FR606 (Nançay, 700 km) in Fig. 2 to the tied core station at Exloo. Stations of Poland and Ireland were not included due to the lack of observed sources.

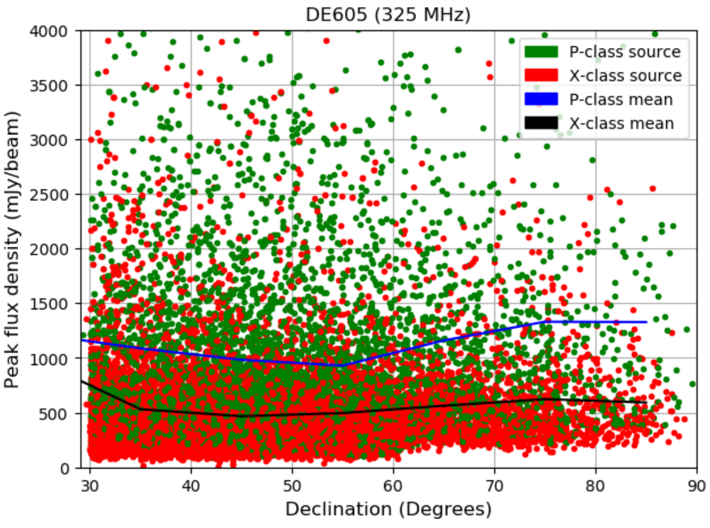

Fig. 1. DE605 peak flux densities and their mean values (classified as LBCS P or X sources) against declination – as the best case.

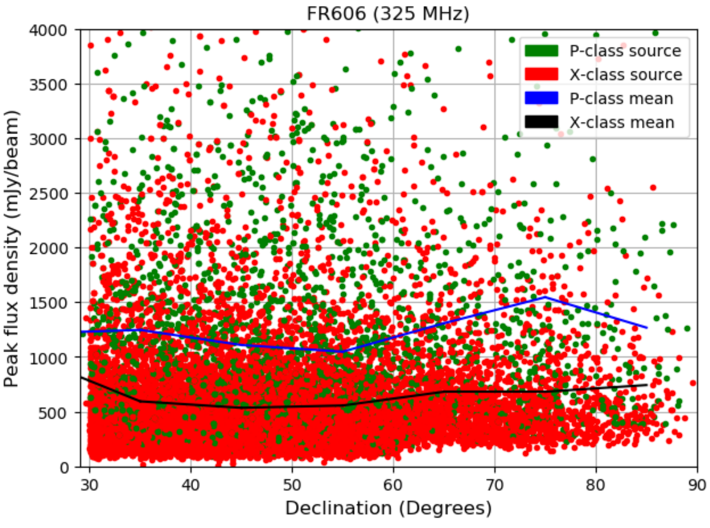

Fig. 2. FR606 peak flux densities and their mean values (classified as LBCS P or X sources) against declination – as the worst case.

Further data acquired on mean flux densities against baselines will be described. The script calculates and generates mean peak flux densities of the P or X class sources for each station. In Fig. 3, axes represent mean peak flux density in mJy/beam and station-to-core baseline length in km. The linear trendline is also marked for the P and X class source data as the points form a significant trend. The linear trendline equation is calculated using *polyfit()* and constructed using *poly1d()* function of *numpy* package.

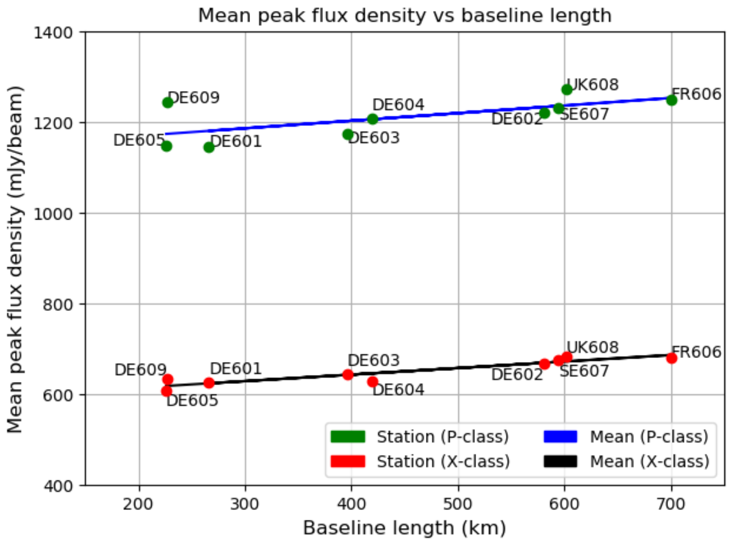

Fig. 3. Mean peak flux densities per station for P and X class sources.

3. RESULTS AND DISCUSSION

Results of mean peak flux densities against declination can be seen in Fig. 1, while Fig. 2 shows the distribution of P (as green dots) and X (as red dots) class sources on the plot. As we can see, there are more red dots at the bottom and occurrence of green dots increases if we move above. If plots were to be compared from different stations, then there would be obviously more red dots than green dots on longer baselines. The mean line on the plot shows mean peak flux density on a specific declination interval. Peak flux density decreases as we move further in declination till 60 degrees. Above 60 degrees there is a gap of sources at a lower limit of the plot. It results in an increase in mean values at the declination range. For all the stations used in the LBCS observations, the mean peak flux density trend is very similar. For longer baselines mean lines move up slightly.

In Fig. 3, we can see a significant trend for both P and X class source data. Mean values are about 1150 mJy/beam for the shortest baseline stations (DE605, DE601) of P-class source data. The last station in the plot (FR606) has the mean peak flux density around 1250 mJy/beam. A similar trend can also be observed for X-class source data – just above 600 mJy/beam and 700 mJy/beam, respectively. Resulting P-class source (1) and X-class source trendline equations (2) are as follows:

$$MPFD = 0.1672 \cdot BL + 1135.33 \quad (1)$$

$$MPFD = 0.1439 \cdot BL + 584.86 \quad (2)$$

where *MPFD* – mean peak flux density, mJy/beam;
BL – baseline length to the tied core station, km.

We can statistically estimate from trendlines what mean peak flux density is more likely to be from P or X class source for a certain baseline length. There are more recent international stations that are not included in Table 1. Knowing their baseline length to the tied core station, we can calculate what mean peak flux density sources are more likely to be suitable as calibrators. There are five international stations – PL610 (693 km), PL611 (999 km), PL612 (915 km), IE613 (989 km) –, and an upcoming station in Latvia LV614 (1079 km).

Table 1

Mean Peak Flux Density Estimation for Recent Stations

International station	Baseline length to the tied core station (km)[1]	Estimated mean P class source peak flux density (mJy/beam)	Estimated mean X class source peak flux density (mJy/beam)
PL610	693	1251	685
PL611	999	1302	729
PL612	915	1288	717
IE613	989	1301	727
LV614	1079	1316	740

4. CONCLUSIONS

Statistically, the mean peak flux density is lower for the sources on higher declination. It might be affected by the ionosphere because the layer of the ionosphere is thicker on lower elevation (and also declination). Another reason might be a man-made interference because observing at a lower declination station will detect manmade radio signals from the ground. Longer baselines statistically should have higher flux density to classify the source as P class.

In Fig. 3, there is just a small difference between the shortest and the longest baseline mean peak flux densities, but it is worth mentioning. Even the estimated data for the furthest station LV614 do not differ significantly. However, the change between baseline lengths may hold useful information about P and X class estimation.

The estimation of good calibrator sources (success rate) for baselines has also been performed. It has demonstrated that there is a huge contrast between stations when we compare the success rate. The designation reflects the number of LBCS calibrators that can be used to calibrate a baseline with a certain length. Unfortunately, the result is not encouraging for some recent or upcoming stations. The shortest baseline station (DE605) success is rated as high as 70 % but at the moment the longest baseline station (PL611) has only 3 %. It seems that there may not be any LBCS calibrator for upcoming station LV614. Therefore, we need solutions, such as another calibrator survey with more compact sources.

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LOFAR GARO BĀZES LĪNIJU KALIBRATORU SESIJAS KLASIFIKĀCIJA

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K o p s a v i l k u m s

Šajā dokumentā ir aprakstīta LOFAR garo bāzes līniju kalibratoru sesijas (LBCS) un Vesterborkas ziemeļu debess novērojumu (WENSS) sesiju datu apstrāde. Darba mērķis ir izveidot kalibratoru klasifikācijas grafikus un novērtējumus turpmākajiem novērojumiem un gaidāmajām stacijām. Pirmkārt, vidējie LBCS kalibratoru plūsmas blīvumi pret deklināciju un stacijas bāzeslīnijas garumu līdz tīkla centra stacijai ir attēloti un klasificētie avoti ir iezīmēti. Otrkārt, mēs piedāvājam apzīmējumu – pozitīvo rezultātu daudzums – kas ir novēroto avotu skaits, kuriem veidojas korelētais signāls attiecībā pret visiem LBCS kataloga avotiem. Treškārt, pastāv tendence vidējo pīķa plūsmas blīvumos starp stacijām - jo garāka bāzes līnija, jo augstāks vidējais pīķa plūsmas blīvums. Visbeidzot, tiek veikts gaidāmo un neseno staciju novērtējums, un daži rezultāti nav iepriecinoši.

Atslēgas vārdi: *LOFAR kalibratori, LBCS klasifikācija, statistiskie novērtējumi, katalogu manipulācija*