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udpPacketManager: An International LOFAR Station Data (Pre-)Processor

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Summary

International LOFAR stations are powerful radio telescopes, however they are delivered without the tooling nessasary to convert their raw data stream into standard data formats that can be used by common processing pipelines, or science-ready data products.

`udpPacketManager` is a `C` and `C++` library that was developed with the intent of providing a faster-than-realtime software package for converting raw data into arbitrary data formats based on the needs of observers working with the Irish LOFAR station (I-LOFAR), and stations across Europe. It currently offers an open-source solution for both offline and online (pre-)processing of telescope data into a wide variety of formats.

Statement of need

International LOFAR stations (van Haarlem et al., 2013) produce a 3 Gbps stream of UDP packets, split across 4 separate ports. Each packet contains a standard header with basic time and telescope hardware information, typically followed by 7808 bytes of time-major beamformed voltage data, with 2 complex samples per antenna polarisation, for 16 time samples across a variable number of frequency samples (Virtanen, 2018, Table 6). In order to convert these data into a usable format, the 4 ports must be combined, data integrity issues (such as packet loss) must be identified and mitigated, and the beamformed samples must be unpacked and reordered following a set specification in order to be processed efficiently.

Previous work in this regard includes the LOFAR und MPIfR Pulsare (`LuMP`) Software (Anderson, 2013), an open-source recorder that saves data to a PUMA2-derived data format that can be parsed using the DSPSR (van Straten & Bailes, 2011) ecosystem, and the ARTEMIS system (Serylak et al., 2012), a hardware-software package for online transient observations derived from the source-available `PELICAN` LOFAR backend (Mort et al., 2021). These were found not to be sufficiently flexible to account for peculiar ways of utilising the telescope hardware, such as supporting multi-mode observations (McKay-Bukowski, 2013), nor work within some constraints of the REALTA compute cluster (Murphy et al., 2021). Consequently, `udpPacketManager` was built to better facilitate observations with the telescope.

The software has supported ongoing observations of the Sun, Pulsars and Rotating Radio Transients (McKenna et al., 2023; Murphy et al., 2021) in Ireland since early 2020, alongside multi-site work with Breakthrough Listen in the search for extraterrestrial life (SETI) in coordination with the Sweedish LOFAR station at Onsala since 2021 (Johnson et al., in prep.) and observations of Jupiter in coordination with the French LOFAR station and one of the German LOFAR stations, at Postdam, in 2022 (Louis et al., 2022).

Inputs, Outputs and Metadata

udpPacketManager contains a flexible interface for handling multiple different data sources and sinks in a semi-transparent manner, allowing for data to be read and written out through normal files, FIFO named pipes, zstandard (Collet & Kucherawy, 2021) compressed files (which allow for a greater than two times space-saving when handling raw voltages from LOFAR stations), PSRDADA ringbuffers for online processing (van Straten et al., 2021), and write-only to HDF5 files that conform to LOFAR ICD003 (Alexov et al., 2012). These interfaces were also used to create the associated ILTDada project (McKenna, 2023), a UDP packet capture software that writes data to a PSRDADA ringbuffer for immediate processing with this software.

Given that the header attached to the data itself contains minimal metadata outside the start time of the data block, metadata is parsed from an associated file that contains one or more commands to control the telescope (beamctl (Virtanen, 2018, Appendix A.2)) and minimal other metadata, such as observer and project identifiers. This is then processed to generate a chosen output header, which can follow the GUPPI RAW (Lebofsky et al., 2019), SIGPROC (Lorimer, 2011), PSRDADA, or ICD003 specifications.

The library can reform the data to a number of output formats. For raw voltages outputs, standard time-major and beamlet-major orders, which can also be additionally split by antenna polarisation and complex sample components are available. Partial or full Stokes parameters are also generated in similar formats, with temporal downsampling up to a factor of 16 available in the library itself. All of these outputs can be calibrated to correct for interferometric beam issues by applying, or generating for external use, Jones matrices generated by dreamBeam (Carozzi, 2016-).

Two command-line-interfaces are provided alongside the library. The first, lofar_udp_extractor, offers an easy interface for accessing the normal functionality of the library for observers, while the second, lofar_stokes_extractor, utilises the output voltages to perform additional processing for science-ready outputs, such as channelisation of Stokes parameters through the FFTW library (Frigo & Johnson, 2005) and additional temporal downsampling beyond the library's factor of 16 limit. Both of these interfaces act further act as examples of how to further utilise the library and its outputs.

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