

## **LOFAR and HDF5: Toward a New Radio Data Standard**

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**Abstract.** For decades now, scientific data volumes have experienced relentless, exponential growth. As a result, legacy astronomical data formats are straining under a burden not conceived of when these formats were first introduced. With future astronomical projects ensuring this trend, ASTRON and the LOFAR project are exploring the use of the Hierarchical Data Format version 5 (HDF5) for LOFAR radio data encapsulation. Most of LOFAR’s standard data products will be stored natively using the HDF5 format. In addition, HDF5 analogues for traditional radio data structures such as visibility data and spectral image cubes are also being developed. The HDF5 libraries allow for the construction of potentially distributed, entirely unbound files. The nature of the HDF5 format further provides the ability to custom design a data encapsulation format. The LOFAR project has designed several data formats that will accommodate all LOFAR data products, examples of which are presented in this paper. With proper development and support, it is hoped that these data formats will be adopted by other astronomical projects as they, too, attempt to grapple with a future filled with mountains of data.

### **1. Introduction**

The commencement of the operational phase of The LOw Frequency ARray (LOFAR) telescope holds forth both great scientific potential and challenges to current and legacy information technologies: volume and complexity of the data will continue to push the envelope of commonly used data protocols.

Recognizing that this envelope is already strained, the LOFAR project has embarked on an ambitious project to design and define a set of radio data standard formats that are capable of encapsulating the full spectrum of not just LOFAR data products, but astronomical radio data in general.

It is with this ambition in mind that the LOFAR data formats group has been developing these format specifications and associated software infrastructure, an ongoing, two year effort to date. It was determined that HDF5 would be a robust, viable data framework capable of handling the size, scope, diversity, and parallel processing requirements of LOFAR data (Wise et al. 2011). This work certainly has potential use beyond the radio community. New large scale optical telescopes, such as the LSST, are also investigating the viability of using HDF5. Furthermore, the 20 year history of HDF and its continuing use by NASA, the NOAA, and other agencies, ensure broad use and long term support.

In addition to the format descriptions themselves, the LOFAR project is currently developing a set of software tools for creating and working with these formats. The Data Access

Library (DAL) in C++, along with an associated Python interface (pyDAL), are designed to allow for the easy construction and manipulation of these data formats. There are also a number of tools already available to read and visualize HDF5 files, such as: HDFView,<sup>1</sup> VisIt<sup>2</sup> + plugin, PyTables,<sup>3</sup> h5py,<sup>4</sup> MATLAB<sup>5</sup> and IDL.<sup>6</sup> Additionally, the LOFAR project has started work on an HDF5 plugin for VisIt, a visualization tool specializing in handling large datasets. Initial communication has been opened with William Joye regarding implementation of DS9 compatibility with LOFAR Sky Image Cubes.

## 2. The LOFAR Radio Telescope

LOFAR is nearing the end of construction in The Netherlands and throughout Europe. There are currently 30 Dutch stations and 5 other European stations actively observing commissioning proposals. Once LOFAR is completed, there will be 40 stations in The Netherlands and at least 8 additional European/International stations. LOFAR's Low Band Antenna (LBA) functions in the range of 30-80 MHz and High Band Antenna (HBA) is in the 120-240 MHz range; the telescope bandwidth is 48MHz. LOFAR can create 8 (possibly more) simultaneous beams, has a spectral resolution of 0.76 kHz (1 sec) and a time resolution of 5.1 nano-seconds.

The features of LOFAR that point to massive data volumes: 30,000 networked, passive phased-array antennae in The Netherlands; international baselines to 1500 km; 6 Gb/s Data Rate, correlated by Blue Gene/P supercomputer, Groningen, NL; Ability to form 8 (and possibly more) concurrent digital beams.

## 3. LOFAR Data: Variety, Complexity, Volume

Datasets produced by LOFAR observations will vary tremendously in size and complexity. Images, Beam-formed (BF) data, Transient Buffer board time-series data are expected to produce large files, with some observations potentially creating files of several tens of terabytes (see Table 1).

LOFAR's observational modes are capable of producing highly complex, large volume datasets. Legacy protocols fall short of being able to describe or store these data. This looming predicament is especially germane to the SKA pathfinder LOFAR project, wherein certain operational modes will be capable of generating datasets comprising hundreds of gigabytes to tens of terabytes. Therefore, the LOFAR project has been driven to consider viable alternatives to "standard" astronomical data formats, such as FITS and CASA Tables. For more detailed discussion of LOFAR data rates, volume, complexity, and HDF5, see Wise et al. (2011).

## 4. LOFAR Data Format Specifications

A viable solution was needed for potentially massive LOFAR data products. HDF5 provides a framework allowing users to essentially design their own files to appropriately accommodate a known variety of datatypes (Wise et al. 2011). The LOFAR project has been engaged in

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<sup>1</sup>HDFView: <http://www.hdfgroup.org/hdf-java-html/hdfview/>

<sup>2</sup>VisIt: <https://wci.llnl.gov/codes/visit/>

<sup>3</sup>PyTables: <http://www.pytables.org/moin>

<sup>4</sup>h5py: <http://code.google.com/p/h5py/>

<sup>5</sup>MATLAB: <http://www.mathworks.com/products/matlab/>

<sup>6</sup>IDL: <http://www.itervis.com/ProductServices/IDL.aspx>

EXPOSURE TIME	NUMBER OF SUBBANDS	NUMBER OF STATIONS	FILE SIZE KNOWN MODE	FILE SIZE SEARCH MODE
1 min	248	20	11.2GB	244GB
10 min	248	30	112GB	3.3TB
1 hr	248	10	672GB	6.7TB
1 hr	248	20	672GB	13.4TB
1 hr	248	30	672GB	26.8TB
2 hr	248	5	1.3TB	6.7TB
12 hr	248	5	8.0TB	40.3TB
12 hr	248	15	24.0TB	120.1TB

Table 1. Sample, LOFAR BF dataset sizes for different observation times and number of stations used. The difference between Known and Search Mode is that data are saved per station for searching, as opposed to combined when observing a known object (to increase signal-to-noise and save disk space).

developing and designing a complete set of specifications for all LOFAR observational data. This has necessarily required differing file designs for differing data, with a certain structural parallelism maintained across all file designs.

These Interface Control Documents (ICD)<sup>7</sup> provide detailed descriptions of a range of expected LOFAR Data Products, including Radio Sky Images, Transient Time Series data, Beam-Formed data, Dynamic Spectra, UV Visibility, Rotation Measure Synthesis, Near-field Imaging. By way of example, structures of a LOFAR Radio Sky Image and a Dynamic Spectra file are outlined in Figures 1 and 2.

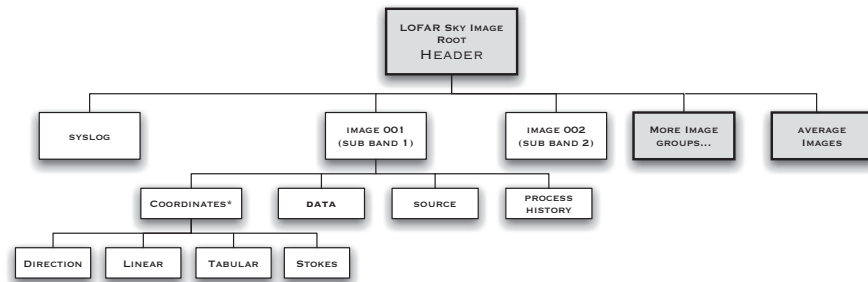


Figure 1. LOFAR Radio Sky Image Data Structure.

The LOFAR ICD team has also produced a document describing the coordinate system for the file structure; these coordinates are closely related to the WCS for FITS. It is not the intention of the project to redo decades of WCS work which is already in place, but to map the LOFAR coordinates to standard WCS.

## 5. Summary and Future Considerations

In order for the adoption of LOFAR data formats to prove useful in the real world, the LOFAR project is committing resources to help develop the next generation of astronomical tools for LOFAR data. A major effort of the LOFAR project has been the development of the Data Access Library (DAL), which ultimately will provide interfaces through FITS, the CASA/AIPS++

<sup>7</sup>[http://usg.lofar.org/wiki/doku.php?id=documents:lofar\\_data\\_products](http://usg.lofar.org/wiki/doku.php?id=documents:lofar_data_products)

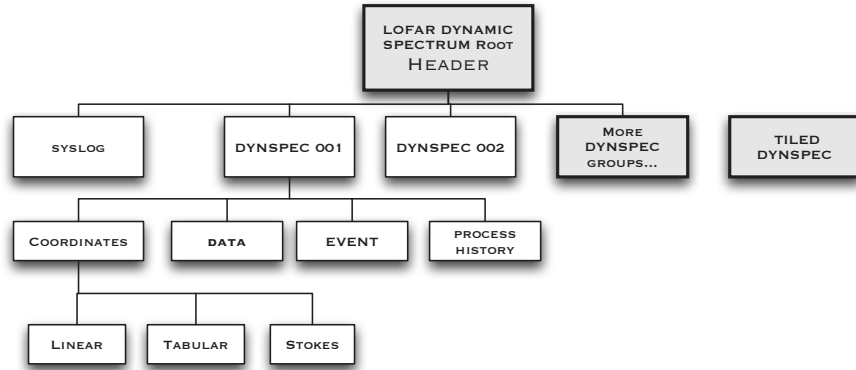


Figure 2. LOFAR Dynamic Spectra Data Structure.

Measurement Sets and HDF5. All LOFAR products will be accessible through DAL tools, which are part of the LOFAR User Software (LUS)<sup>8</sup> repository.

The LOFAR project has set up a moderated majordomo email list, called **nextgen-astro-data@astron.nl**. Interested parties are encouraged to sign up via **majordomo@astron.nl** with “**subscribe nextgen-astrodata**” as the only text in the body of the message. Ultimately we would like to see these formats grow into a true set of standards for radio data that can meet the demands of the next generation of radio observatories. Such standards are sorely lacking in the radio community at present and are clearly needed as radio astronomy moves into the SKA era.

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## References

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<sup>8</sup>LOFAR User Software Repository: [http://usg.lofar.org/wiki/doku.php?id=development:getting\\_started](http://usg.lofar.org/wiki/doku.php?id=development:getting_started)