Holography for LOFAR

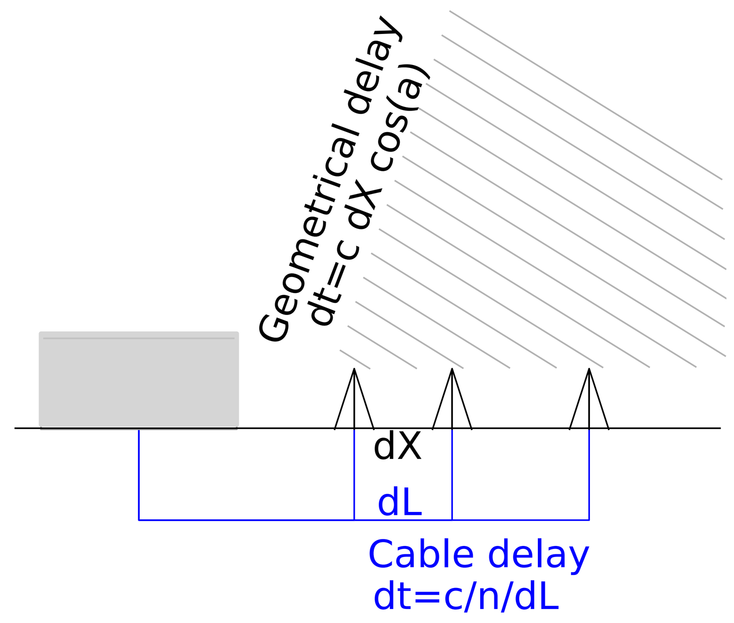
Calibration of a phased array radio telescope using holography: the LOFAR case

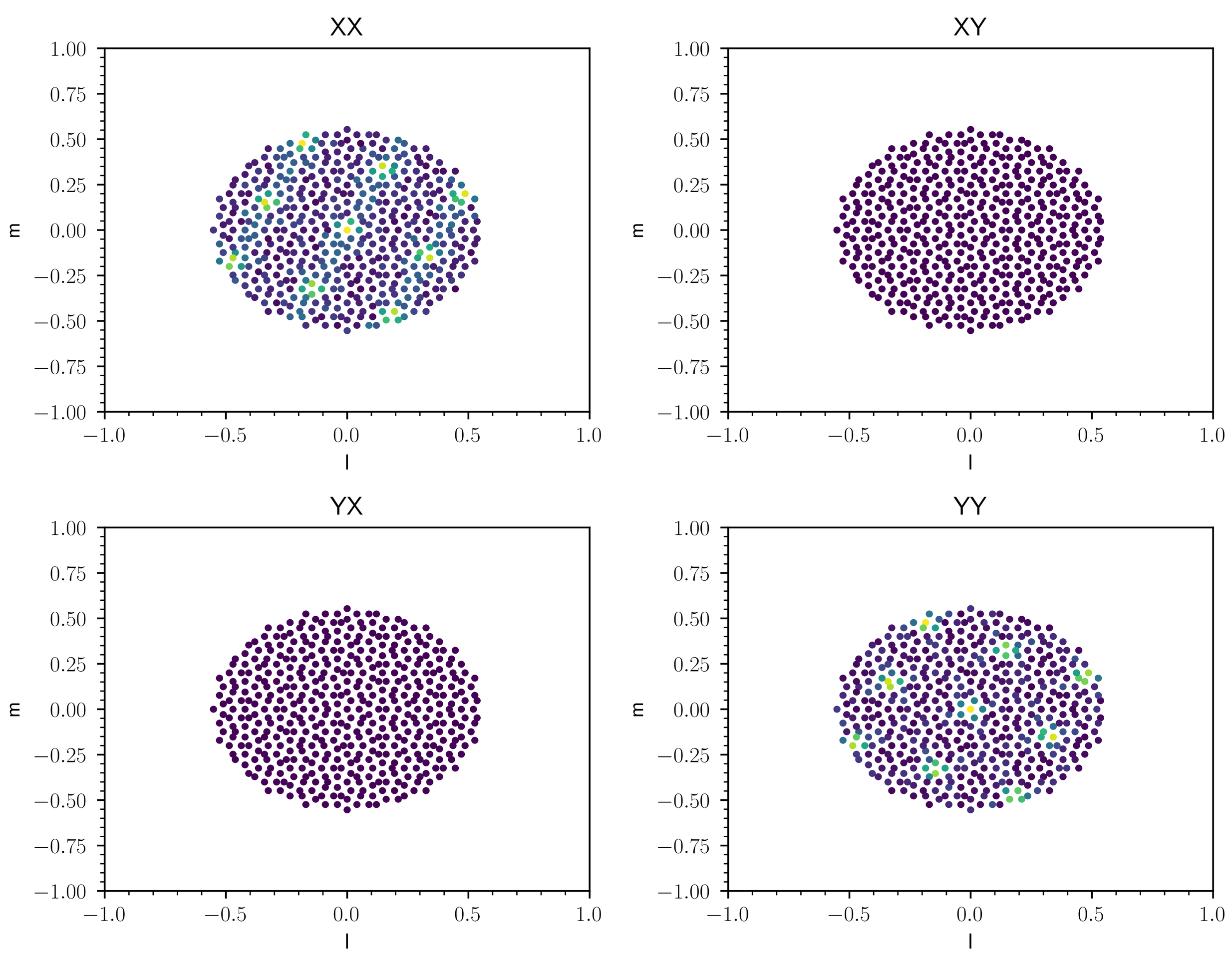
The LOFAR telescope

The LOFAR telescope is a radio telescope composed of 52 stations spread across Europe with the majority in Northern Netherlands. Each station has a field with 96 Low Band Antennas (LBA, 10-90 MHz) and one or two fields with 24, 48 or 96 tiles, each consisting of 16 High Band Antenna (HBA, 110-250 MHz). Such a configuration is called a phased array. At the station the signal of a field is beamformed in one or more directions. The stations are then cross correlated to make sky images or beamformed for high time resolution studies of for example pulsars and solar flares. To point the telescope in the right direction we need to calibrate it to correct for delays in the signal path caused by different length cables and the station electronics. We have adopted the holography calibration method, used traditionally to calibrate radio dishes, for a phased array.

A LOFAR station

Beamforming



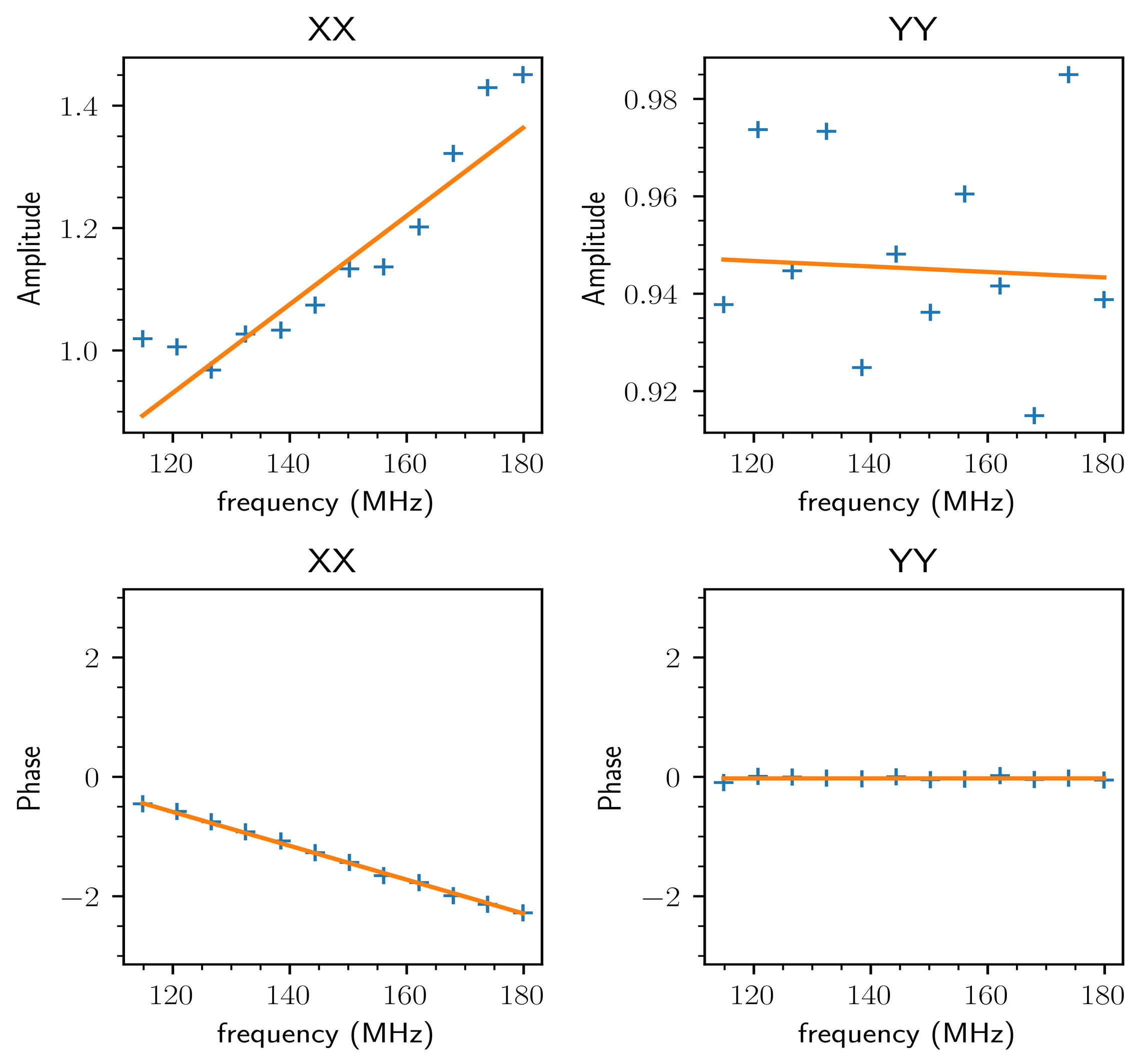


Analysis

The goal of holography is to solve for the gains G of each antenna by solving the matrix equation:
V = M * G
where V is the measured signal (left figure), M is the matrix used for beam forming that depends on the coordinates of the antennas and the positions of the beams, and is like a fast fourier transform, and G are the unknown gains of each antenna. We solve for this using a least square method, implemented in numpy.

The image below shows a 2-D fast fourier transform from the beam coordinates (l,m) to the ground coordinates (x,y). This is a first guess of the solution G. The signal strength is intenstiy, while the color indicates phase. Cyan is phase 0, green is negative phase and blue is positive phase. The 9 antennas that had an artificial delay introduced clearly stand out in the X polarisation only.

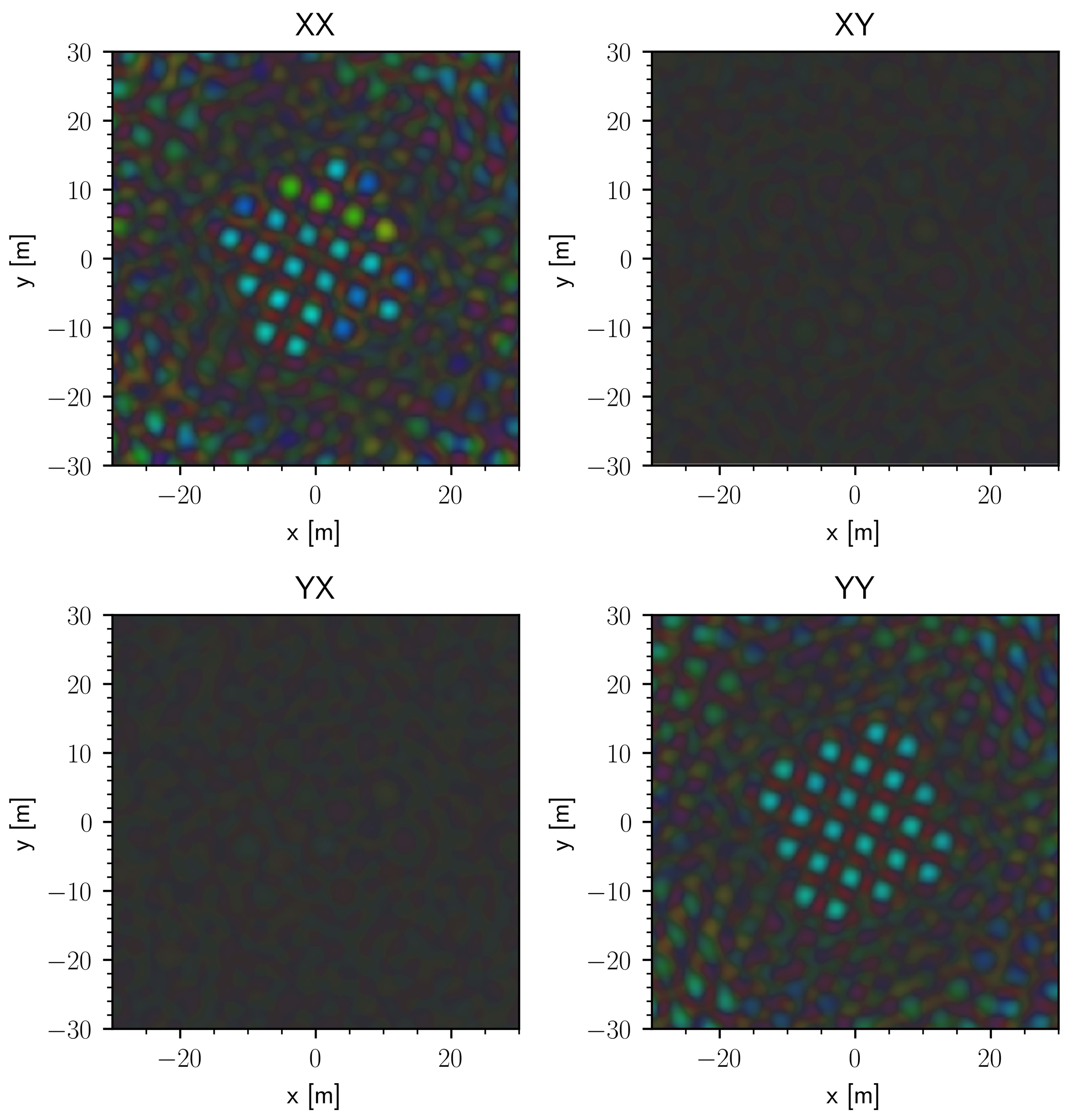
The image on the right shows the phase solution for all 12 frequencies of the antenna at x=10m, y=5m. The slope in XX is caused by the added delay of -4.5 ns



Observations

- 481 beams are pointed in a grid around a calibrator source.
-12 frequencies of 195 kHz bandwidth are recorded to sample the full band
- The beams are cross correlated with a reference station that is pointed at the calibrator source for each pair of the two polarisations X and Y.
- To check the software delays were introduced in 9 antennas of the X polarisation

The image shows the signal at 162 MHz
- The YY shows the expected response pattern with a central beam and 8 sidelobes near the edge caused by the regular outlay of the antennas on the ground.
- XY and YX show no signal. Signal propagation can change the polarisation at different sides, but by multiplying with the inverse visibility of the central beam, such propogation effects are completely removed.
- XX shows additional signal in stripes. This is caused by the delays that were introduced.



Implementation

The Holography software is developed in Python. The software stores each step into a Holography DataSet (HDS) in an additive way. In such a way, it is always possible to analyse and debug every single step. Furthermore, the first step in the processing consists in generating an HDS from the recorded data and the observation specification. The HDS is sufficient to perform the holography and it is stored in HDF5 file format. The Holography software makes use of very standard libraries, in particular:
- Astropy for the coordinate conversion;
- python-casacore to read the MeasurementSet;
- Docker to deploy and execute the software;
- matplotlib to produce the inspection plots.
- Numba to accelerate the inspection plots;
- h5py to manage, store and load from hdf5;
- numpy to manipulate and process the data;

Conclusion

We are finishing the implementation of holography for LOFAR. It can almost be used to calibrate the LOFAR HBA antennas. For the LBAs we need to apply changes to the beamformer to create enough independent beams for this method to work. The main benefits of the holography method are the robustness against local radio frequency interference (because of correlation with remote stations) and robustness against effets of the ionosphere and interstellar medium that can deflect sources or change the polarisation of the signal. In addition, the inspection plots can show us in one view if any station needs an update or if it shows any problems what would reduce the sensitivity, that are difficult to notice thus far. The generic analysis once the Holography DataSet has been created allows the method to be easily adapted to other phased arrays.

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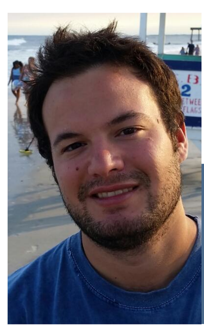

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