

Chapter 1

Long baseline observations with LOFAR

Observations using international LOFAR baselines have obtained science quality images with resolution $0.3''$ and rms noise $0.15 \text{ mJy beam}^{-1}$ at 154 MHz, see for example [2]. In this chapter we will describe the similarities and differences in the observations and subsequent processing as compared to LOFAR imaging using shorter (NL) baselines. This chapter is meant to serve as a reference for you who want to plan observations or calibrate and image LOFAR data using the longest LOFAR baselines.¹

1.1 Long baseline interferometry

The prime reason to use long baselines is to obtain very high-resolution images. Using the longest LOFAR baselines, subarcsecond imaging is possible in the HBA band and the upper part of the LBA band, see Table 1.1. However, the wide separation of stations means that each station sees a (very) different atmosphere, which means that visibility phases are generally less well behaved than on shorter baselines looking through a more similar patch of the atmosphere. Furthermore, the international stations cannot share the same clock (as the core stations do) and any offsets and drifts of the clocks will introduce delay errors between the stations. Finally, geophysical and Earth orientation effects are more important.

In addition, the field of view is at long baselines not limited by the primary beam of the largest station. Rather, the field of view is limited by the time and frequency resolution of the data. Since correlators output a discrete set of visibilities (i.e. samples in time and frequency), averaging is to some extent always done on interferometric data. We may also average the data further after correlation to reduce the computational resources needed for calibration and imaging. Any averaging must however be done with care. Averaging a range of samples in time and frequency together corresponds to averaging over a small parallelogram in Fourier space. This means some information is lost, and one has to take care to not lose information that could affect the scientific results. This effect is however not only challenging, it also makes calibration of long baseline data simpler.

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Freq. (MHz)	λ (m)	Int. station beam FWHM (deg)	Int. synthesized PSF FWHM ($''$)
15	20.0	19.39	3.30
30	10.0	9.70	1.65
45	6.67	6.46	1.10
60	5.00	4.85	0.83
75	4.00	3.88	0.66
120	2.50	2.59	0.41
150	2.00	2.07	0.33
180	1.67	1.73	0.28
200	1.50	1.55	0.25
210	1.43	1.48	0.24
240	1.25	1.29	0.21

Table 1.1: Values from [3].

Because of these differences, a somewhat different calibration strategy is usually required when imaging long baseline data than what is commonly used for LOFAR observations with shorter baselines. This need is nothing fundamentally new for LOFAR, in fact we may borrow many tools and knowledge developed for decades for use in very long baseline interferometry (VLBI) at centimeter wavelengths.

1.1.1 Calibration of international LOFAR stations

Data on long baselines are fundamentally no different from data on short baselines: calibration means to correct any errors in the visibility amplitudes and phases which were not included in the model applied when the data were correlated (such as atmospheric effects). If your target is very bright, you may be able to calibrate your data using the target itself. However, to find amplitude and phase corrections for the international stations, the target must be sufficiently bright on the angular scales measured by the baselines to the international stations. Because of the high resolution, calibration needs to be done using either a very compact source so that a point source model is good enough, or we need a very detailed model of the source structure. A science target is usually both weak and potentially has complex structure (on subarcsecond scales), which makes it hard to use for calibration of the international stations. Therefore, a nearby bright (and preferably compact) sources is usually observed along with the target. The amplitude and phase errors are derived using the calibrator, and the corrections are then applied to the target before imaging. This is called phase-referencing, and in ordinary VLBI observations it is usually done by switching back and forth between target and calibrator since an ordinary dish can only point in a single direction at once. For ordinary VLBI observations this requires switching often enough so that the corrections derived for the calibrator is valid also when observing the target source, but since LOFAR provides multiple beams, we may observe the calibrator and target simultaneously, simplifying calibration compared to ordinary VLBI. However, the calibrator must also be close enough to the target for the corrections derived to be valid also in the direction of the target. Preliminary investigations indicate that the separation between calibrator and target should not be larger than 5° , preferably closer than 1° . From Chapter 29. in [1] the isoplanatic patch size is given as $3\text{-}4^\circ$ at 4 m wavelength.

Finding a strong, compact (or a subarcsecond resolution modelled) calibrator within 1° is challenging, mainly because the sky is largely unknown at LOFAR frequencies. Efforts are under way to

build catalogues of suitable sources at LOFAR frequencies, but often a good first guess can be found by looking at the VLBI catalogue at higher frequencies: <http://astrogeo.org/calib/search.html>. Often one has to settle for a calibrator which is compact and near the target but which is not bright enough to calibrate the phase and amplitude separately for each visibility (i.e. each channel/integration time). The obvious solution to increase the signal-to-noise (SNR) is to average the data. For shorter baselines, one may usually average several channels and time bins together, provided that the errors because of e.g. the atmosphere does not introduce phase or amplitude changes within the averaging interval. However, for long baselines the errors are more serious, for example because of the very different atmospheres above the stations. The ionosphere may introduce *delay* errors (phase slope vs. frequency) of several hundred nanoseconds, which means that the visibility phases will change several cycles within a few MHz of LOFAR data. Blindly averaging such data will severely reduce the amplitude of the calibrator signal. If the phase also changes with time there will be a phase slope vs. time as well, which is referred to as a *fringe rate*. This means that simple averaging cannot be done to increase the SNR. This is usually the case also in cm-VLBI, and to be able to use the weaker calibrators the VLBI community has developed a technique usually referred to as *fringe fitting*. Global fringe fitting solving for delays and rates is, when writing this, only available within the Astronomical Image Processing System (AIPS, see <http://www.aips.nrao.edu>). To read the data into AIPS, we first need to convert from the standard LOFAR format of Measurement sets in a linear (X,Y) polarisation basis to UVFITS-files in a circular (R,L) polarisation basis. This is done in two steps, first the conversion to circular and then the conversion to UVFITS.

1.1.2 Conversion to circular polarisation basis

Standard VLBI techniques like fringe fitting work in a circular (R,L) polarisation basis. In this basis, the ionospheric disturbances are transformed from coupled amplitude/phase effects (as in the linear X,Y basis) to phase only effects. Also, since differential Faraday rotation does not mix R and L polarisations we may calibrate RR and LL independently. Conversion to circular polarisation may be done using different tools. The M82 data [2] were converted from linear to circular using the tool *mscorpol* v1.6, developed by T. D. Carozzi. This tool includes corrections for dipole-projection effects as a function of the correlated sky position relative to all included LOFAR stations. After the conversion, the data are circularly polarised, with full (but approximated) parallactic angle correction.

1.1.3 The UV-FITS format

Since AIPS understands the UVFITS-format, but not Measurement Sets (MS) we need to convert the data from MS to UVFITS. There are several ways to do this:

- You may use the function *exportuvfits* in CASA.
- You may use the tool *ms2uvfits* available at the LOFAR cluster, as `ms2uvfits in=[input-MS] out=[output-FITS-file] writesyscal=False`

1.1.4 Loading the data into AIPS

The AIPS task FITLD can be used to load the data into AIPS. For LOFAR data, the parameters `digicor=-1` and `douvcomp=-1` should be used.

1.2 Fringe fitting

The procedure used to find and correct residual rates and delays is called *fringe fitting*. A fringe fit is nothing more than a self-calibration including not only phases and amplitudes, but also derivatives of the phase with respect to frequency and time. By doing this, more data can be included in the fitting process thereby increasing the signal-to-noise, which enables solutions to be found for weak sources and/or in noisy data. In AIPS the most commonly used task for this is called **FRING**. This task considers the first derivatives of phase vs. frequency and time, i.e. it assumes linear delays and rates within the selected bandwidth and solution interval.

As an example, let's inspect two minutes of data on a particular baseline (CS001HBA - DE601HBA) for the source J0958+6533, the source used to find and correct residual delays and rates by [2]. The raw-data is plotted using the AIPS task **POSSM** in Fig. 1.1(a). From this figure we can see by eye that the phase ϕ changes approximately $\Delta\phi = 1.5$ cycles (i.e. $1.5 \cdot 2\pi$ radians) over the full bandwidth of $\Delta\nu = 15.9$ MHz. Assuming a linear phase gradient we can estimate the delay as $\tau = \Delta\phi / \Delta\nu = 94$ ns at this particular time. Indeed, **FRING** finds a very similar value as can be seen around 22 UT in 1.2(a). These corrections were found using the default parameters of **FRING**, with the following manual changes: The search was restricted to baselines longer than $60\text{k}\lambda$ (**uvrange** = 60,0), a delay search window of 600 ns (**dparm**[2]=600), a rate search window of 30 mHz (**dparm**[3]=30), and a solution interval of 2 minutes (**solint**=2). Solutions were found separately for each IF and polarisation.

After applying the corrections from **FRING**, the phase is flat with respect to frequency, see (b), as it should be for a point source.

Inspect the solutions carefully with **SNPLT** after use of **FRING**. The solutions should be smoothly varying with time, and are typically a few tens of nanoseconds for most antennas. Large delays (microseconds or above) should be reported to the Observatory, particularly if they appear in more than one dataset or if there are sudden changes in the delay.

1.2.1 Applying the solutions

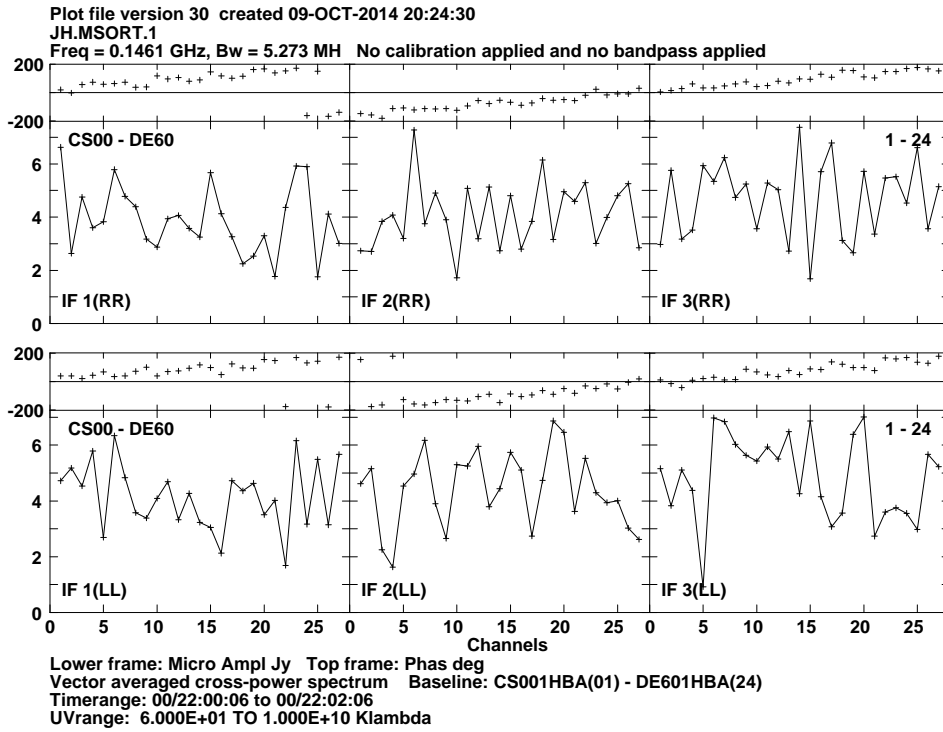
Describe optionally **SNSMO**, **CLCAL**.

1.2.2 Amplitude calibration

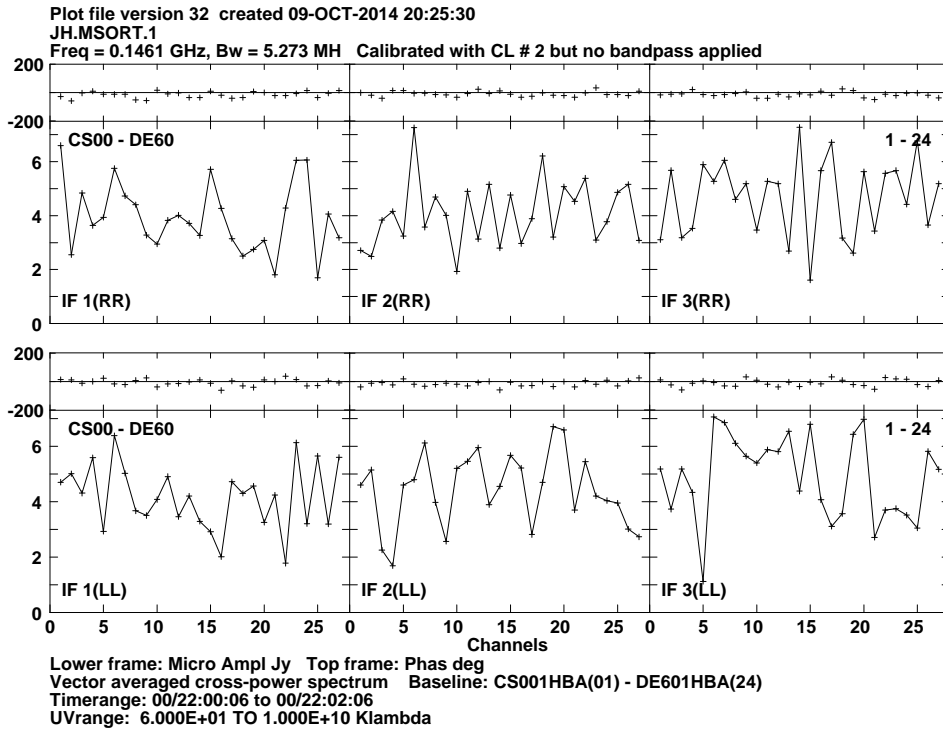
As described in Sect. X, the calibrator used for deriving delay, rate and phase corrections need to be close to the target and sufficiently compact to show enough signal on the longest baselines. This calibrator can in principle also be used for amplitude calibration of the long baselines, but again a good model is required. For fringe finding, the only requirement for good solutions is that the calibrator is bright enough and compact enough. But, for amplitude calibration, we must know the flux density of the calibrator. Usually the VLBI calibrators stay compact, but the flux density can vary more than a factor of two between observations due to intrinsic variability. Therefore they cannot be trusted to set the amplitude scale of the observation.

For the case of M82, the calibrator J0958 is bright and compact enough for amplitude calibration of the international baselines, but we did not know the correct flux density. Therefore, we included observations also of a known flux calibrator, 3C196. Now, the calibrator J0958 was used to track possible amplitude variations during the observation for all stations, and 3C196 was used to check the absolute amplitude scale, i.e. to find the flux density of J0958.

The amplitude corrections should be smooth, and will in most cases show a larger gain at the start and end of an experiment. This is because an observation is usually centered in time so that the target

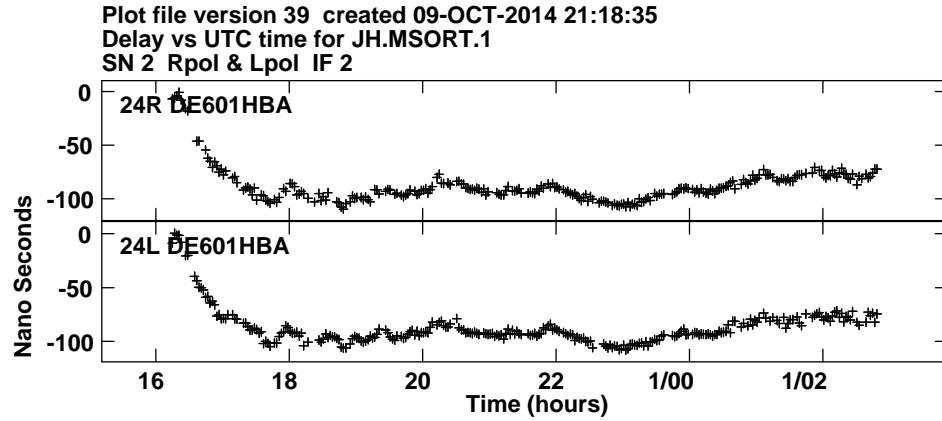


(a) Before fringe fitting

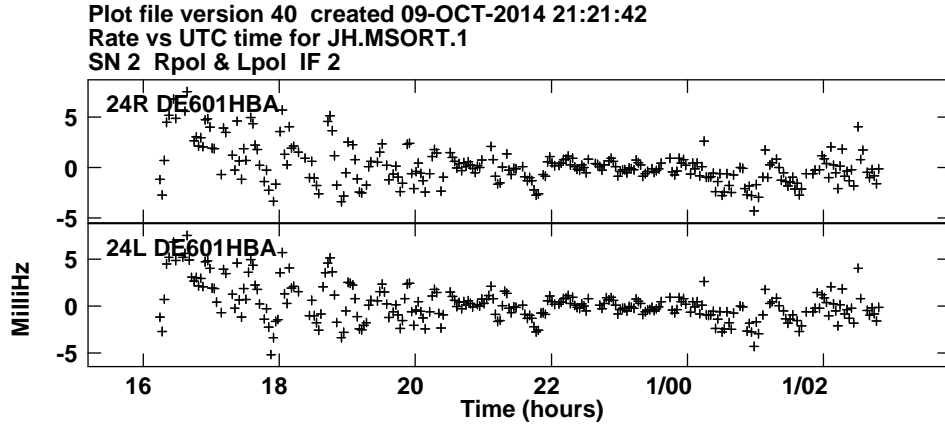


(b) After fringe fitting

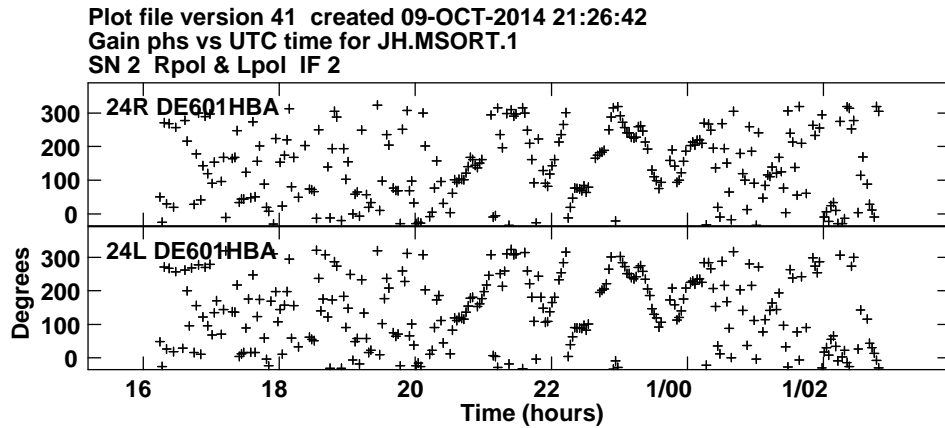
Figure 1.1: Two figures showing the effect of fringe fitting on two minutes of data on the baseline CS001HBA - DE601HBA. Both polarisations are shown, and the data are divided in three spectral windows (IFs in AIPS) of 5.3 MHz each. After applying the corrections from FRING, the phase is flat with respect to frequency, see (b), as it should be for a point source.



(a) Delay corrections for DE601HBA IF2



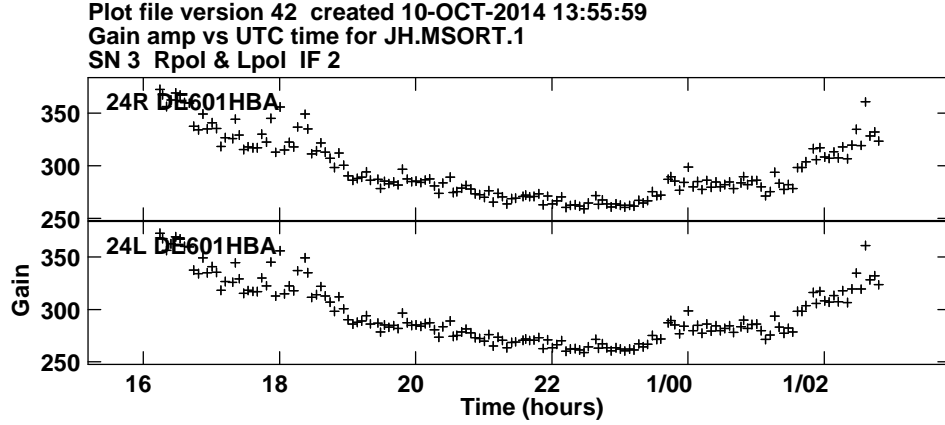
(b) Rate corrections for DE601HBA IF2



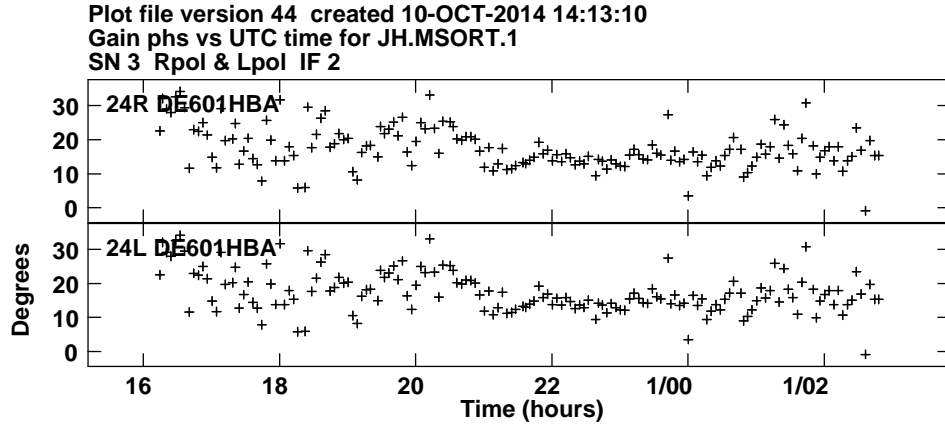
(c) Phase corrections for DE601HBA IF2

Figure 1.2: Delay ((a)), rate ((b)) and phase (c) corrections derived for the source J0958 at 154 MHz by FRING for antenna DE601HBA. These plots show the corrections derived for the whole 10 hour observation (the first segment of project LC0_026). It is clear from the rates and phases that phases changes rapidly during the first and last hours of the experiment. The delay solutions are more stable, although there is a large change in at the start. In general, the ionosphere is more stable during midnight than at sunset or sunrise.

will reach its peak elevation at the middle of the observation time. This means that it will be at lower elevation in the beginning and end of the observation, which means that the projected station area will be less at the start and end times. This in turn means that the sensitivity is lower at the start and end times, which means that the gain corrections need to be larger (and will be noisier) at these times. As an example, let us look at the gain corrections derived by CALIB in AIPS for DE601HBA on J0958, see Fig. 1.3. When running CALIB, we have decreased the number of free parameters compared to FRING, since we are now only solving for amplitude and phase. It is therefore possible to find minor phase corrections at this point which was not perfectly determined by FRING.



(a) Amplitude corrections for DE601HBA IF2



(b) Phase corrections for DE601HBA IF2

Figure 1.3: The amplitude and phase corrections derived by CALIB for the international LOFAR station DE601HBA during the first 10 hours of project LC0_026. We see larger, and more noisy, corrections at the beginning and end of the experiment, as expected from the smaller projected station area at these times relative to transit.

The final result of calibration for this baseline can be seen in Fig. 1.4.

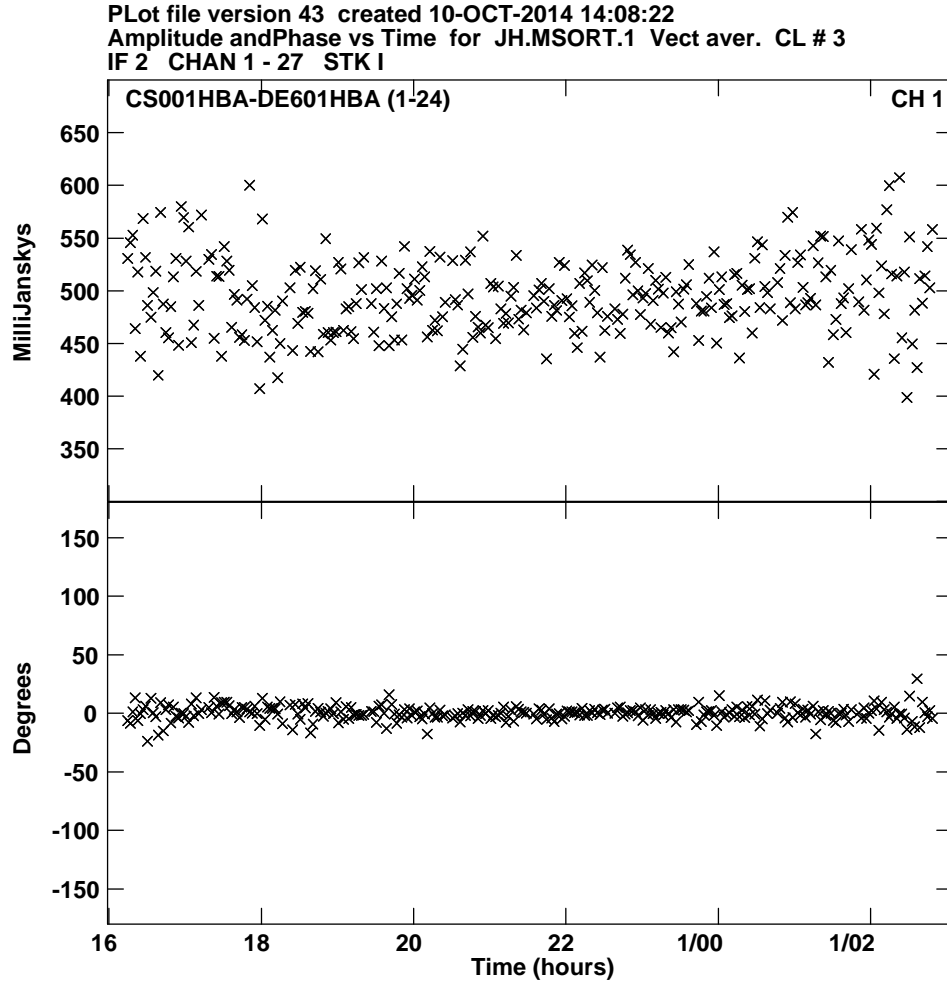


Figure 1.4: The final visibility amplitudes and phases on the DE601HBA-core baseline. We assumed this source to be a 0.5Jy point source, which means that we should now see two straight lines in this plot: one for the amplitude centered at 500mJy, and one for the phase centered at 0 degrees. This is also what we see using VPLOT in AIPS to inspect the data. Apart from noise, there are marginal changes differences to a point source. It is clear from [2] that this object has a weak extension to the south-west, and this should create minor deviations in the visibilities compared to those of a point source.

1.2.3 High-resolution imaging

Although AIPS can determine delays and rates, it is not the best option for imaging long baseline LOFAR data. Since we consider a small field of view, we do not need the beam models offered by AW-imager. However, at subarcsecond resolution we will may need to take into account any effects of a non-coplanar array, i.e. W-projection. The field of view θ_f possible to image without W-projection (i.e. using a single tangent plane) can be estimated as $\theta_f = \sqrt{\theta_b}/3$ (see 2-29 in [1]) where θ_b is the FWHM of the synthesized beam, both θ in radians. If your field of view is larger than this you need to perform deconvolution using W-projection, for example in CASA.

1.2.4 Combining the core into a single superstation

TODO: This section should include parset files, background info about strong calibrator and also plot of the station beam produced by the phased up core. Eskil's calculations at 154MHz suggest 5% amplitude loss at 30'' distance from phase center, which is the most serious of all effects mentioned in this document regarding field of view. Also, it is not clear to me if NDPPP phase-rotates the data properly when adding the beams in a specific direction, if using the shift-average approach in the coming pipeline.

Bibliography

- [1] Taylor, G. B. and Carilli, C. L. and Perley, R. A. *Synthesis Imaging in Radio Astronomy II*, ASPCS 180, 1999.
- [2] E. Varenus et al, *Subarcsecond international LOFAR radio images of the M82 nucleus at 118 MHz and 154 MHz*, submitted to A&A.
- [3] van Haarlem, M. P. et. al. *LOFAR: The LOw-Frequency ARray*, A&A 556A, 2V 2013