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Report State of the Art and Common Framework for Development

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Dissemination Level

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
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Index

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1 Introduction

The main objective for WP7 RINGS (Radio Interferometry Next Generation Software) is to deliver advanced calibration algorithms for the next generation of radio astronomy facilities, characterized by a high sensitivity, a high bandwidth and long baselines:

The algorithms to be delivered by RINGS will allow the correct calibration of existing and upcoming high-sensitivity, wide-bandwidth, long-baseline radio interferometers, by extending existing fringe-fitting routines that solve for non-dispersive station-based delays. Furthermore, additional routines focus on robust self-calibration for low signal-to-noise-ratio sources,

The functionality delivered by RINGS will be incorporated in the CASACORE software package. Continuity in the support of the software is ensured by incorporating the software in CASA (moving away from legacy software packages like HOPS-Haystack Observatory Post-processing System and AIPS).

This deliverable contains an overview of

- the joint approach taken by all the RINGS tasks for software development (section 2),
- the state of the art in the various research topics on which the work in RINGS will build.

The deliverable serves to:

- organize the work in RINGS efficiently,
- create a shared understanding of the work carried out in the various tasks,
- maximize the uptake of the results after the lifetime of the project,
- allow external partners to collaborate with RINGS.

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2 Engineering approach

During the RINGS kick off (Dwingeloo, 9 January 2017), it has been agreed to develop in RINGS according to the CASA/CASACORE methodology (see Figure 1 for an overview).

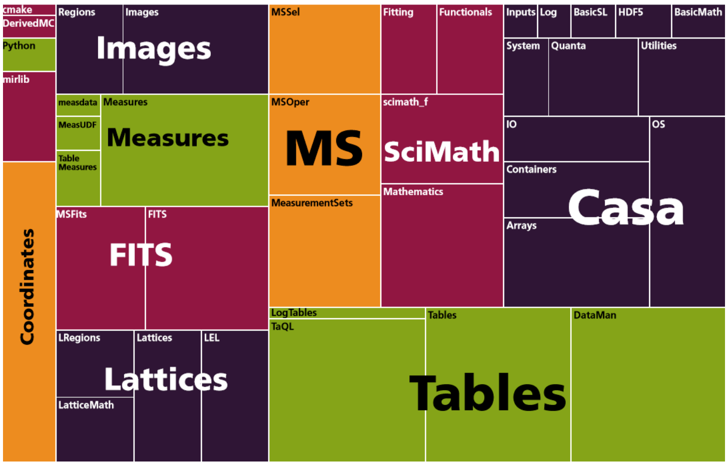

Figure 1: overview of CASACORE

RINGS will adhere to the CASACORE development style

- Development in github on a CASACORE fork
- Proper unit testing will be done using the CASACORE testing system
- Good documentation shall be provided in the form of doxygen, CASACORE note

Technical aspects of development methodology:

- RINGS results will be delivered as part of the CASA/CASACORE suite. RINGS results have to go in both. Algorithms in CASACORE, wrapping layer in CASA. Some facilities rely on CASA, whereas CASACORE provides a better structure and reusability. A clear interface/boundary what should go where etc. can't be given at this stage and needs further consideration
- Developers should in general strive for as few as possible external dependencies (not fewer)
- Unit tests will be performed using the CASACORE test framework
- RINGS will use the CASACORE
  - namespace
  - file structure
  - build system
- RINGS will use the CASACORE data structures where applicable.

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3 Polarimetry Conversion

Current interferometric observations are performed at very high data rates (several Gbps, at least) using wide fractional bandwidths. Hence, linear-polarization receivers will have to be used over such wide bands, because using quarter- wave plates to convert to circular polarisation would yield unacceptably large polarisation leakage. Algorithms for an optimum calibration of the polarization response of wide-band receivers still need to be developed. This is especially true for very low frequencies, where Faraday rotation and depolarisation must be taken into account, together with the receiver's leakage, and for long baselines, where the parallactic angles of the antennas are different, making it difficult to calibrate the phase delays and rates from observations on a linear-polarization basis.

The starting point for Post-Correlation Polarization Conversion of this work is Roy et al. (2013). APP (ALMA Phasing Project) polarization White Paper. The strategy outlined in this approach is:

- Record X/Y phased-up streams at ALMA.
- Record RCP/LCP streams at the other stations.
- Cross-correlate all polarization products (i.e., visibilities in mixed-polarization basis): X/R, X/L, Y/R, Y/L
- Convert to pure circular basis (RR, LL, RL, LR) after correlation.

The conversion is done with the PolConvert program (Martí-Vidal et al. 2015, A&A, 587, 143). PolConvert calibrates the VLBI mixed-pol fringes using the tables from the ALMA-only calibration:

$$V'_{\odot\odot} = C_{\odot+} \times G \times V_{+\odot} \quad (3.1)$$

However, we assume that G calibrates V perfectly. A wrong G can a□ect the Pol. Conversion.

We are converting:

$$V'_{\odot\odot} \propto \begin{pmatrix} 1 & j \\ 1 & j \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} \times \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix} \quad (3.2)$$

where ρ is the Y/X ratio of the residual gains at ALMA (i.e., not properly calibrated with CASA).

We can re-write:

$$V'_{\odot\odot} \propto \begin{pmatrix} 1 & D \\ D & 1 \end{pmatrix} \times V_{\odot\odot} \quad (3.3)$$

where $D = (1-\rho)/(1+\rho)$

If $\rho \sim 1$, we can use ordinary pol. calibration to correct for this effect

This approach has been verified using two epochs of APP-VLBI to perform a proper full-pol. calibration:

- B3 (86GHz): April 10, 2016 (with FD, KP, LA, MK, and OV), lasting 4.2h. ALMA used 11+6 antennas. Very low elevations at ALMA for some calibrator scans. Shadowing problems.

- B6 (230GHz): April 8, 2016 (with SMA and LMT), lasting 4.5h. ALMA used 37+10 antennas. Not many VLBI stations. Weather not optimum.

Effect of ρ on the RL/LR bias

$$LR = (Q - I - V - jU)\rho + I + Q + V - jU \quad (3.4)$$

$$RL = (Q - I + V + jU)\rho + I + Q - V + jU \quad (3.5)$$

Current Status

- We calibrated the SV intra-ALMA APP observations (using an ad-hoc QA2 script) and successfully used them with PolConvert, computing the ALMA-VLBI fringes in circular basis.
- A fraction of the B3 data (pol. calibrator scans) was taken at low elevations (and were affected by shadowing). The APP software does not account for shadowing.
- There are artifacts in the estimates of the X-Y phase for the B3 data. This may be related to a recent CASA bug correction and is under investigation.
- A good X-Y phase (and good X/Y ratio) calibration are critical to ensure a good conversion (a few degrees and 5% amplitude, for a residual post-conversion leakage of 3%).
- BUT, if there are small residual X-Y calibration e□ects after PolConvert, these can be corrected with an ordinary VLBI polarization calibration (though this might not be the optimum solution).

Since PolConvert is only commissioned for Phased-ALMA continuum observations, future work should address the following

- Proper commissioning of spectral-line VLBI (especially, Stokes V for, e.g., Zeeman splitting).
- Proper commissioning of phase-referencing mode (up to now, only self-solutions are applied).
- Proper implementation of single-telescope VLBI station (up to now, we derive the calibration from the intra-ALMA visibilities, so we need a phased array for an optimum calibration).
- For single telescopes, we need to derive D from the VLBI visibilities alone. Up to now, PolConvert can estimate D, but the approach is not optimum (e.g., missing solution globalization to all baselines).
- Testing and commissioning at other (non-ALMA) bands. The case of wide fractional bandwidths (e.g., BRAND).

PolConvert is now a CASA Task. May need to adapt it to pure CASACORE in the frame of RINGS.

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4 Full-polarisation beam-modelling algorithms

This work builds on the Measurement Set Correct Polarization (MSCORPOL) project and work of the LOFAR Long Baseline Working Group as well as Polconvert (part of APP), which is software for the calibration/conversion of the ALMA mm-VLBI visibilities. There is a clear need for better telescope beam models & a common S/W system for handling them. DreamBeam is a Software Package for Radio Telescope Beam Models and will be the basis for this work.

All telescopes have a tapered field-of-view i.e. beampattern: For wide FoV, knowledge of beam pattern - also polarimetric – would increase fidelity of final image

Aperture Telescopes e.g. LOFAR, MWA, SKA-LOW

- have large variation in gain pattern with pointing due to fix mount & digital pointing compared to mechanical pointing
- This can lead to difficulties in gain calibration –LongBaseline workgroup has found that transfer of gain solutions using LOFAR beam model over more than 10 degrees is ”dangerous”
- Improving beam models could mitigate this

Unfortunately there is no established way of publishing & sharing beam models. Would be furthered by pipeline independent repositories and S/W to handle them

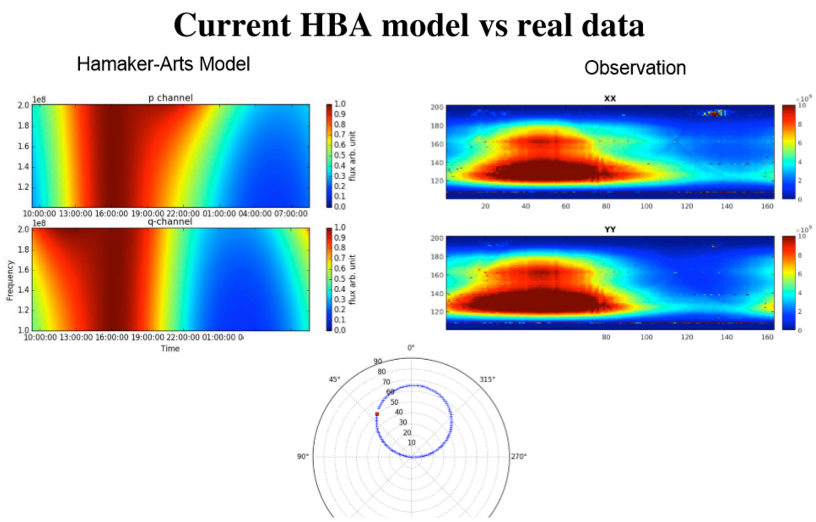

Figure 2: comparison of beam models with actual observations for LOFAR HBA

DreamBeam (dBe)

- is a S/W package for beam models
- Provides a uniform application programming interface (API) for generic telescopes
- Implements a variety of mathematical representations of antenna patterns
  - Wide field: – Vector Spherical Harmonics – Tabulated spherical grids – Hamaker’s representation
  - Narrow field: – Bessel functions – Shapelets

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- Representations can be ingested from
  - EM simulators
    - FEKO
    - NEC2
    - CST
  - Observations
    - Anechonic chamber
    - Holography
    - Light curves

Actually antenna radiation patterns are handled by a package called AntPat. dBe handles interferometric measurement equations:

- Written in python
- Utilizes CASACORE

Will have

- LOFAR based on FEKO
- VLA (FEKO)
- SKA Band 1 (CST)

Dreambeam is available on github: – https://github.com/2baOrNot2ba/dreamBeam.git

It has the LOFAR default pipeline model (Hamaker-Arts). The FEKO based model will be available soon whereas the VLA model is being developed

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5 Multiband and Wide Band Fringe Fitting

This task will handle the non-dispersive delays, phases and delay rates. Fringe fitting corrects an observation for instrumental and atmospheric phase errors, which prevent the averaging of data in time and frequency, and therefore limit the sensitivity of a radio telescope. It also corrects for clock errors, which can be distinguished from atmospheric errors by a different wavelength dependence. Multiband fringe fitting deals with datasets where the frequency coverage is cut into multiple bands with a (large) gap between them. Wideband fringe fitting handles datasets with continuous frequency coverage, where the bandwidth is of the same order as, or larger than, the observing frequency. WP7.2 is complementary to the BlackHoleCam project (ERC-2013-SyG, Grant Agreement no. 610058) and will build on the approach and prototype code delivered by that project. Both cases require the inclusion of a frequency dependent sky model, handling of non-linear frequency dependence of delays, and ingestion of large volumes of data for a single processing step.

Only CASA allows us to combine this functionality in a single software package. It enables the scripting required for pipeline development. In the longer term it will be sustainable and easier accessible than AIPS or equivalent software packages, also because it is based on the Measurement Set data format. Finally, the observations for BlackHoleCam include ALMA, which relies on CASA software for data processing. This work is also particularly important for International LOFAR array.

The development of the CASA components is guided by the current EVN pipeline, which runs under AIPS ParselTongue. An overview of the steps is shown in Figure 3. Polarisation calibration is handled in another work package, and therefore not included in our development.

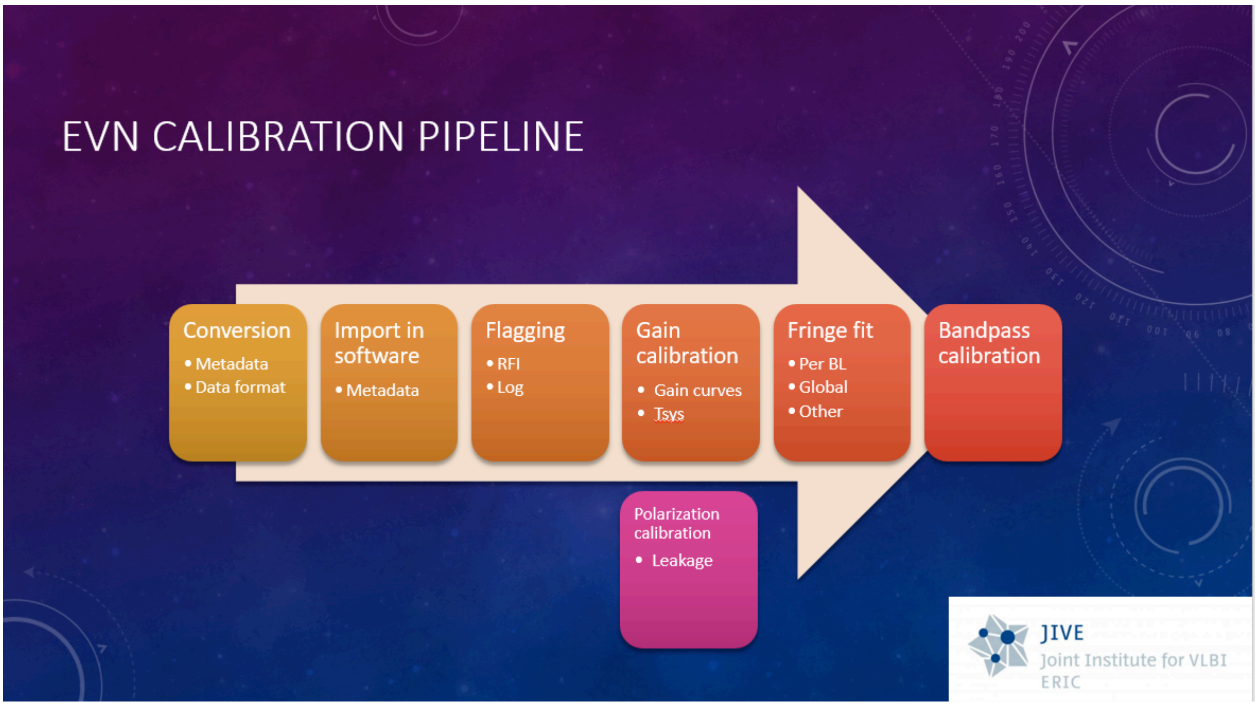

Figure 3: EVN Calibration pipeline

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Within CASA several tasks need adjustment to handle generic VLBI data. These include the importing of FITS-IDI data, definition of metadata required for calibration (system temperature, gain curve), and several tasks involved in applying corrections for specific types of correlators. The majority of the work on this has been done. CASA has no task for fringe fitting, which is being implemented based on the AIPS FRING task. A working prototype is available, production code is in progress. Adjustments to the lower level CASA infrastructure have been made by the NRAO team.

A comparison using simulated data shows that the new CASA fringecal task performs equally well as the AIPS FRING task. Small scale differences are at the level of numerical noise. In data with simulated delay and rate offsets the CASA and AIPS processing recover identical solutions. A known issue with CASA is processing speed. This is known to the team, but the priority is on functionality first. The testing of new CASA tasks continues with EVN observations of bright sources. In discussion with our RINGS partners we also plan to include tests on non-imaging and geodesy observations.

Discussions with astronomers have resulted in a detailed list of possible improvements, which include handling of the data weights, including a source model, and averaging over frequency or time. This will be further discussed as part of a small RadioNet workshop in October, where ~10 VLBI experts will bring their own data to JIVE to exercise the new CASA tasks.

Within the RINGS project there are close ties between this team and the team developing the dispersive fringe fitter. For wide bands dispersion becomes a problem even at higher frequencies. There is also a collaboration with the team developing polconvert to ensure that its output is handled well by the CASA routines.

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6 Fringe Fitting with dispersive delays

A dispersive delay (such as is caused by the Earth's ionosphere) leads to an additional phase change inversely proportional to frequency. Because of this inverse relationship, dispersive delays typically only become noticeable at low frequencies, especially below 1 GHz where instruments such as LOFAR operate. Over a sufficiently narrow bandwidth, the phase dependence on frequency can be approximated linearly, allowing a dispersive delay to be corrected with a traditional (non-dispersive delay only) solution, but this approximation breaks down when wide bandwidths are used. In this case (wide bandwidths, low frequency, such as for LOFAR) dispersive delay must be solved for; however, the problem space becomes exceedingly large, and simple gradient-descent optimisation techniques inevitably become caught in local minima.

AIPS dispersive fringe fitting are "not well tested" and certainly not able to do dispersive + non-dispersive correctly. The approach taken by RINGS builds on ongoing work in the LOFAR Long Baseline Working Group (LLBWG) and will use traditional techniques to constrain the solution space and 'guide' the overall phase solution (non-dispersive + dispersive delays) to the global minimum.

The general formula for the overall signal delay is:

$$\tau = \tau_{geom} + \tau_{source} + \tau_{troposphere} + \tau_{ionosphere} + \tau_{instyrumental} + \varepsilon \qquad (6.1)$$

In which

$$\tau_{ionosphere} = \frac{c^2 r_e}{2\pi\upsilon^2} \times TEC \qquad (6.2)$$

The TEC is time and location dependent TEC place and time. A typical example of the location dependency is given in Figure 4.

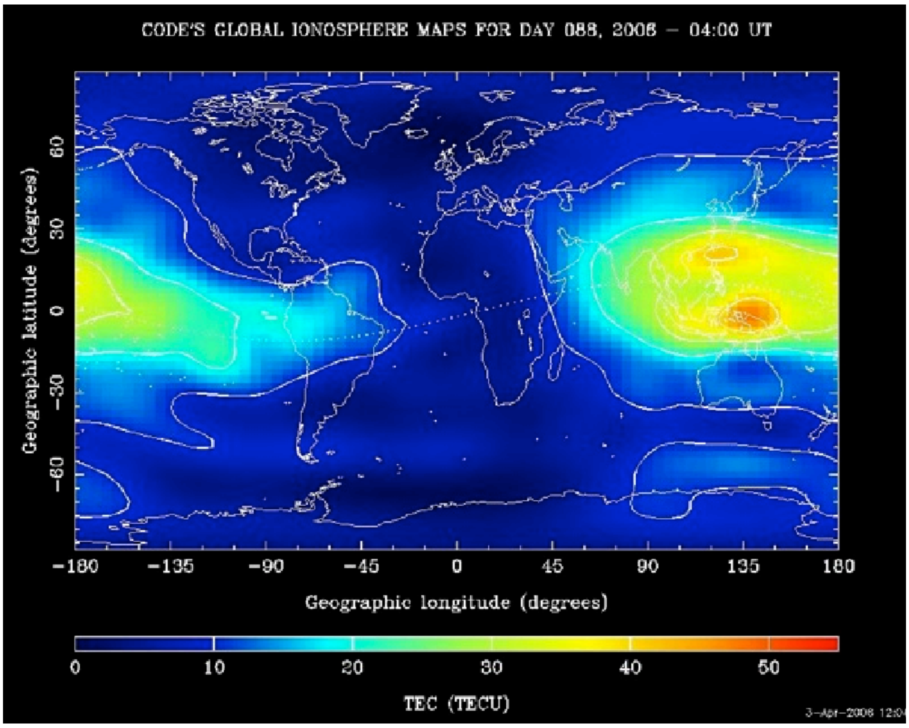

Figure 4: A typical TEC map

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The ionospheric delay is then:

$$\phi = 2\pi[\upsilon\tau(t) + K(t)/\upsilon] \quad (6.3)$$

Where K(t) is determined by the ionosphere

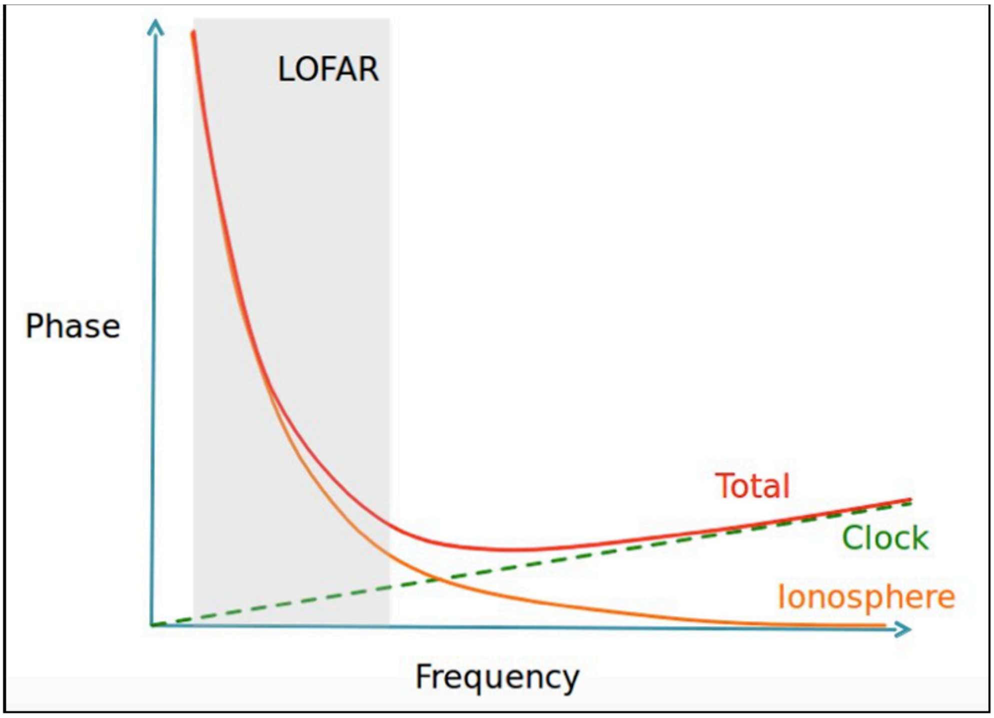

Figure 5: Phase delays as a function of frequency for LOFAR (credits: J.Moldón)

To account for curvature, we need a second Taylor term:

$$\ddot{\phi}(\upsilon - \upsilon_0)^2 \quad (6.5)$$

which results in convolution in delay space.

The effect of the dispersive ionospheric delay is:

- to smear the peak of the function in delay space.
- This makes it more difficult to estimate the true delay parameters.
- Furthermore, over a narrow-ish frequency band there will be degenerate solutions between the dispersive and non-dispersive delay values.

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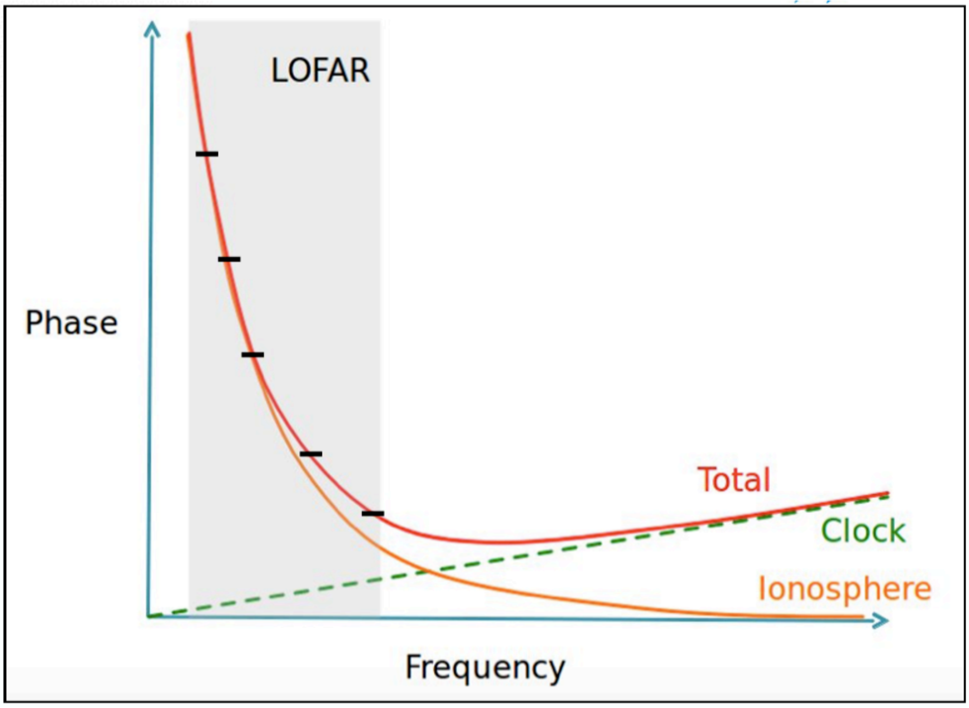

Figure 6: narrow-band approach to fringe fitting (credits J.Moldón)

A zero order model for K(T) can be obtained using GPS TEC data:

$$K(t) = K_{GPS}(t) + \delta K(t) \quad (6.6)$$

Fringe fitting in existing software

- AIPS (Greisen/Cotton/Schwab): Fits delay, rates. Option for dispersion. APARM(10), but not directly fitted.
- ALBiUS (Stewart/Bourke/Moellenbrock): KTest() 2DFFT method. Prototyping. FFT implemented, LSQ?
- CASA/Blackhole Cam (van Bemmel/Small/Kettenis): Fits delay, rates. KTest() function?
- Re-gridding Method (Wucknitz)

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7 Advanced calibration algorithms for full-polarisation interferometry data

Self-calibration is one of the most important calibration techniques in interferometry. It allows one to overcome dynamic-range limitations due mainly to atmospheric fluctuations, thereby decreasing the image noise to the theoretical limits. However, this technique is known to be problematic for low-SNR observations, due to the high probability of false detections. To date, there is no self-calibration algorithm able to deal with low-SNR data in a statistically robust way. WP7.5 will develop a robust, full-polarisation self-calibration algorithm incorporating direction dependent effects (WP7.2) and dispersive frequency dependent effects (WP7.4). This will be especially important for wide-field LOFAR images, as well as for ALMA mosaics and observations of extended polarized structures. The work in this task builds on previous work on UVMULTIFIT, a versatile library for fitting visibility data, implemented in a Python-based framework. UVMULTIFIT does simultaneous fitting of multiple source components to visibility data.

In its current version, the program UVMULTIFIT (https://launchpad.net/uvmultifit) is able to fit complex parametric model structures to any set of visibilities, accounting for primary-beam effects (as long as the individual model components are small, compared to the antenna beam), w-term projection, mosaic observations and multi-frequency synthesis. There is also an experimental modeling mode where a parameterized antenna-gain evolution (in amplitude and phase) can be fitted simultaneously to the source structure. More advanced data analysis (e.g., sparse-modelling deconvolution and Markov-chain exploration of the parametric space) are currently being developed.

In the frame of RINGS, the simultaneous modeling of antenna gains and source structures has to be further studied and improved. The use of Kalman filters to model the time evolution of the gains has to be studied, optimized and implemented. Modeling of dispersive gain effects in the multi-frequency synthesis of UVMULTIFIT has to be studied and implemented. In addition, development of metrics for the assessment of the gain calibration (using, e.g., Markov-chain Monte Carlo exploration of the antenna-gain parameter space) and reliability (e.g., assessment of eventual spurious effects on low dynamic-range observations) has to be developed.

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