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Final implementation of algorithms for multiband and wideband fringe fitting and fringe fitting with dispersive delays

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## Dissemination Level

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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# 1 Introduction

Wide-band receivers are set to play an important role in the future of VLBI antennas, in both geodetic and astronomical contexts and this raises new challenges for the calibration of the resulting data. In particular, the BRAND EVN receiver is expected to cover a frequency range from 1.5 GHz to 15.5 GHz.

The calibration of residual instrumental and atmospheric delays (after a priori geometric model delays have been corrected at the correlator) is done as a part of the post-processing calibration process. For many years the "industry standard" method for this, in astronomical VLBI at the EVN and NRAO's VLBA, was the task FRING in the AIPS software package, but as part of the BlackHoleCam<sup>1</sup> project (2015-2018), similar functionality was implemented and added to NRAO's CASA package<sup>2</sup> in the fringe-fit task. The CASA implementation was modelled closely on the AIPS task, since it has proven to be robust and successful, and also because it was invaluable to be able to benchmark results against AIPS. This implementation is incorporated in the calibration pipeline rPICARD [ref:rpocard] developed and used as part of the Event Horizon Telescope (EHT) project<sup>3</sup>.

Now that CASA is fully capable of calibrating current VLBI data, it became an interesting project to develop the software further to handle the challenges of wide-band observation. For our purposes, there are two important issues:

## 1.1 Dispersion

The ionosphere introduces a dispersive delay proportional to  $1/(\text{frequency})^2$ , such that the phase across a subband includes a perturbation of the form  $1/\text{frequency}$  [ref:ion]. For typical VLBI experiments with observation frequencies of 1 GHz or above and small fractional bandwidths, this can be treated as a constant and removed using the standard FRING or fringe-fit tasks. For low frequencies – including the EVN's P band, at around 300 MHz, and even more strongly in the long baselines of international LOFAR data – the dispersive term needs to be fitted within single subbands, and for higher fractional bandwidths such as those of the BRAND<sup>4</sup> receiver we can expect to see dispersive effects at higher frequencies as well.

## 1.2 Wide bandwidth and sparse frequency coverage

The move to wider bandwidths means that more data will be collected by the next generation of radio astronomy receivers, but not all of it is useful. The considerable and growing problem of radio frequency interference (RFI) means that much of the radio spectrum is dominated by non-astronomical noise, so that the useable spectrum of a VLBI observation may consist of some "islands" of good data interspersed with gaps where the data is contaminated and has been excised. An objective of the RINGS project was to look at fringe-fitting algorithms tailored to this case.

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<sup>1</sup> <https://blackholecam.org>

<sup>2</sup> <https://casa.nrao.edu/>

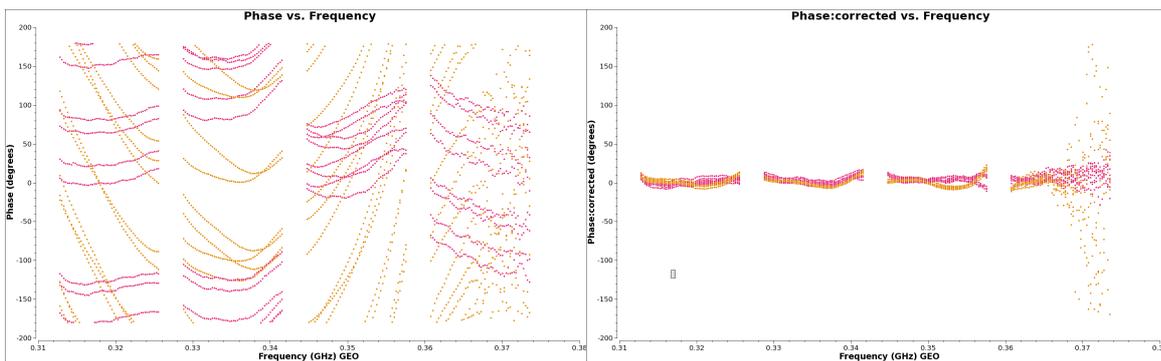
<sup>3</sup> <https://eventhorizontelescope.org/>

<sup>4</sup> <https://deki.mpifr-bonn.mpg.de/03RadioNet4/BRAND>

## 2 Implementation

Before discussing the implementation of either extension to the CASA fringe-fit task, it is handy to recap how the original FRING/fringe-fit algorithm works. There are two stages – a preliminary FFT-based stage that is used to find estimates of the calibration parameters (delay, rate and secular phase) – which are then used in a second stage as initial estimates for a least-squares best-fit algorithm based on the widely used Levenberg-Marquardt algorithm. The method can be used either on a single subband, if the data has a high enough signal-to-noise ratio to permit this, or if the phases have been aligned between subbands (which is often done via single-band fits on a bright calibrator) then the bands can be combined into a "multi-band" fringe-fit.

### Dispersive case



Fringe fitting results of EVN P band data with dispersive model – the algorithm correctly takes out the prominent 1/frequency curvature at the lowest bands and the linear terms at the higher frequencies.

For the dispersive case, it is possible to modify the FFT stage to include additional dimensions to accommodate new parameters – O. Wucknitz (MPG) provided the RINGS team with an unpublished research note on this strategy – but while this was implemented in a Python prototype during the project, it has not been incorporated into the C++ production version in CASA, since in the cases we have studied (less demanding than those of interest to Wucknitz) it has so far proved adequate to use a non-dispersive FFT stage and incorporate the dispersive term at the least squares stage starting with an estimate of zero.

To fit the model we fit an additional term for the dispersive delay but rather than use the simple form

$\Delta \phi = 1/f$  we first subtract the linear part of this expression across the band, so that the term fits only the deviation from a straight line (which of course corresponds to a constant delay, for which we are also solving). This idea (and the equation for it) were provided by Ivan Martí-Vidal, who used such a form with his UVMULTIFIT [ref:uvmultifit] software; the residual dispersive phase at a frequency  $f$  in a band between  $f_0$  and  $f_1$  is given by

$$\phi_{disp} = s \pi k \left( \frac{1}{f} + \frac{f - f_0 - f_1}{f_0 f_1} \right),$$

where  $k$  is the parameter for the strength of the dispersive effect. The code for this adaptation to the CASA fringe-fit task source file FringeJones.cc is currently in a separate branch (12365) of the CASA code<sup>5</sup>.

<sup>5</sup> <https://open-bitbucket.nrao.edu/projects/CASA/repos/casa6/browse/casa5/code/synthesis/MeasurementComponents/FringeJones.cc?at=refs%2Fheads%2FCAS-12365>

## Wideband case

In the wideband case by contrast, there is no need to modify the least squares algorithm - the model fitting algorithm uses only the frequencies and times for which data is available and is entirely unaffected by gaps. The concern is rather that the preliminary FFT stage could end up calculating the transform of large stretches of zeros, which could become a bottleneck for very wide bands. It is common in the FFT stage to pad the band with zeros at one end, as a simple way of getting an interpolated estimate from the data, because FFTs are cheap, but at some point it may become prohibitively expensive to do this if the observed bandwidth or number of spectral channels becomes large in absolute sense.

With this in mind we developed a new method for combining FFTs computed for individual subbands such that we can (a) calculate a way of adding them coherently and simultaneously (b) get a finer grained estimate of the calibration parameters and (c) also a better estimate of the SNR for the combined dataset. This algorithm was developed in Python using Jupyter notebooks and has been implemented in C++ for CASA. CASA packages containing this functionality are available from the NRAO website, but we do not anticipate integrating it into the mainline release until it has been further tested with and, if necessary, improved to handle test data from a wide band receiver.

The code for this adaptation to the CASA fringe fit task source file `FringeJones.cc` is currently in another separate branch (12765) of the CASA code<sup>6</sup>.

Both fringe fit branches are under active test and should be merged into future CASA releases.

## 3 Bibliography

[ref:rpicard] M. Janssen et al., *rPICARD: A CASA-based calibration pipeline for VLBI data. Calibration and imaging of 7 mm VLBA observations of the AGN jet in M87*, A&A, 2019

[ref:ion] F. de Gasperin et al., *The effect of the ionosphere on ultra-low-frequency radio-interferometric observations*, A&A, 2018

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<sup>6</sup> <https://open-bitbucket.nrao.edu/projects/CASA/repos/casa6/browse/casa5/code/synthesis/MeasurementComponents/FringeJones.cc?at=refs%2Fheads%2FCAS-12765>

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