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Report on the strategies to combine results of first phase of tasks 7.2-7.5

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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

The Joint Research Activity (JRA) Radio Interferometry Next Generation Software (RINGS) is work package (WP) 7 of RadioNet. The aim of JRA-RINGS is to deliver highly functional, maintainable and computationally efficient calibration software that addresses the challenges and opportunities posed by new and future wide bandwidth, long baseline radio interferometers. In particular, large bandwidth instruments are needed by the European radio astronomy community to improve the sensitivity of interferometric imaging by several factors, but these advances in hardware also require new functionality within the current calibration schemes to remove instrumental and atmospheric effects as a function of frequency, which are typically not a simple linear transformation. Crucial functional improvements provided by RINGS will be the development of algorithms for full service fringe fitting solutions, accurately encompassing dispersive delay (non-linear) and full polarisation. These routines will empower much more accurate, and thus, effective processing of data from radio astronomy facilities, such as the Atacama Large Millimetre Array (ALMA), the Low Frequency Array (LOFAR), the European Very Long Baseline Interferometry Network (EVN), the Multi-Element Remotely Linked Interferometry Network (e-MERLIN), the Event Horizon Telescope (EHT), the Global Millimetre VLBI Array (GMVA), the Karoo Array Telescope (MeerKAT), and the Square Kilometre Array (SKA).

In addition, JRA-RINGS will ensure that for the first time, all of the capabilities required to analyse data from radio interferometers at both high and low frequencies will exist in the same processing suite. This reduces the burden on users to gain expertise in multiple data processing packages and data formats when carrying out multi-wavelength experiments, eliminates the requirement to move large data volumes (several TB in some cases) between different processing systems, and makes the most sophisticated processing techniques available for all RadioNet interferometers. To achieve this goal, RINGS will apply state-of-the-art parallelisation techniques and integrate the results in the existing standard Common Astronomy Software Applications (CASA) package (<http://casa.nrao.edu/>), which is published under a GNU General Public License.

The JRA is organised through the activities of 5 separate WPs, where

- i) WP7.1 (Methodology and approach) will harmonise the various calibration approaches into a single, coherent strategy for implementation during the final phase of the JRA;
- ii) WP7.2 (Polarisation conversion) will develop and test advanced algorithms for the polarisation calibration of wide-band and long-baseline interferometry observations at both low frequencies (the case of LOFAR) and high frequencies (the case of mm-VLBI and ALMA);
- iii) WP7.3 (Multi-band and wide-band fringe fitting) will develop advanced calibration techniques that solve for the non-dispersive delays, phases and delay rates from instruments with a large bandwidth, such as from the BRAND instrument that is being developed within JRA-BRAND (RadioNet WP6);
- iv) WP7.4 (Fringe fitting with dispersive delays) will deliver an innovative calibration algorithm for solving the dispersive component to the phase as a function of frequency, which particularly affects long baseline observations at low frequencies with LOFAR, but also with wide bandwidth instruments operating at cm-wavelengths (e.g. BRAND); and
- v) WP7.5 (Advanced calibration algorithms for full-polarisation interferometry data) will develop a robust, full-polarisation self-calibration algorithm incorporating direction dependent effects (WP7.2) and dispersive frequency dependent effects (WP7.4), which will be especially important for wide-field LOFAR imaging, as well as for ALMA mosaics and observations of extended polarised structures.

This document provides a review of the activities within RINGS during the first phase of the project (see the RadioNet Periodic Report 1 for a detailed report) and provides a strategy for combining the various calibration algorithms that are being developed by each WP into a single, coherent implementation.

The main aim of the first phase of RINGS was to develop test algorithms for the different calibration elements. These strategies will form the basis for the second phase of RINGS, where the results from the different WPs will be developed into their final implementations and incorporated within a single calibration strategy. In Section 2, the status of the various calibration algorithms that are being developed within RINGS are reviewed, and in Section 3, the strategies for combining these algorithms, where applicable, are outlined.

## 2 Status of the various calibration algorithms

In this section, a short review of the different calibration algorithms that are being developed within RINGS is presented.

### 2.1 Polarimetric beam modelling of LOFAR

Within WP7.2, advanced software for polarimetric beam modelling has been developed, with a particular focus on LOFAR. Here, the separate dipole antennas of LOFAR do not have an isotropic response to the sky brightness distribution in full-polarisation, and this directivity results in a varying sensitivity of the instrument as a function of position on the sky. This overall response is typically called the beam. Calibrating the data from wide-field interferometric arrays of dipoles requires solving for so-called direction dependent effects, one of which is due to the varying beam. This research was done as a joint effort between OSO and DIAS, where OSO wrote the beam modelling and station operation software, and DIAS made the software to enable general-purpose comparisons between observational and model data.

The beam modelling software is called DREAMBEAM (<https://github.com/2baOrNot2ba/dreamBeam>) and is based on the previous package MSCORPOL (<https://github.com/2baOrNot2ba/mscorpol>), but considerably improves on the overall generality and extensibility. In line with the remit of RINGS, effort was put into making the code useful and extends the CASACORE package. The main focus of DREAMBEAM is to model the response of LOFAR as a function of position on the sky and frequency, whilst ensuring that the software could easily be extended to other radio telescopes in the future. DREAMBEAM is natively polarimetrically aware and written in python. This software enables the use of command line options to provide a highly flexible analysis and visualisation of the comparison between the predictions of beam models and the observed data across the full spectrum of LOFAR (see Section 2.3). Additionally, as a side effect to developing a system that can compare models with actual observations, it is also possible to use the software to analyse a single real observation, or to compare successive observations of the same target observed at different times to identify transient events. On-going work will expand DREAMBEAM to incorporate additional model options into the outputs, and thus enable comparisons between those models.

Also, additional development was done in producing a test package called BEAMMODELTESTER (<https://github.com/creaneroDIAS/beamModelTester>), which is designed to provide modular comparisons between the beam models supplied by DREAMBEAM and real observations of bright, non-variable sources. This comparison has the potential to allow for the evaluation of errors in the models, and also to allow for the comparison of new beam models with existing ones once they have been developed. The comparison is achieved by applying normalisations to the data as appropriate and selected by the user, and producing visualisations of source and model data, and of the differences between them, together with modular figures of merit indicating the quality of fit between model and source data. A useful side effect of the development of this module is that by producing visualisations of

the data, it also provides a useful visualisation tool for observing groups to evaluate spectra and temporal variation of sources. This package has been tested extensively with LOFAR data and a publication is in preparation to provide a public release. In addition, Interactive GUI and command line versions now exist, and a tutorial to introduce new users to the system has been developed.

In addition to this work, iLiSA, (international LOFAR in Stand-Alone mode; <https://github.com/2baOrNot2ba/iLiSA>) is a package that is used to make observations using the international stations of LOFAR in isolation. The types of observations include the standard operations of LOFAR (BST, SST, XST, ACC, TBB and BFS), but also three special observation modes. These are i) multi-band BST observations that allow for BST data to be recorded over multiple bands, that is, LBA, HBA-lo and HBA-h of LOFAR; ii) SEPTON, which allows the HBA of LOFAR to be used in an all-sky field-of-view; and iii) multi-sub-band XST, which records XST data over a defined sequence of sub-bands. From these observations, and with the iLiSA software, the user can extract data in a variety of formats, allowing further analysis using their own algorithms.

## 2.2 Fringe fitting (wideband and dispersive delays)

WP7.3 and WP7.4 of RINGS are focused on developing software for calibrating the phase of the visibility data from interferometers as a function of frequency. This particular form of calibration has two clear regimes: non-dispersive and dispersive effects, although further, higher order effects may become relevant in the future, particularly at very low frequencies and for very long (inter-continental) baselines. The source of these phase errors can be due to the individual stations having independent clocks and/or due to the differing path lengths to the individual stations arising from fluctuations within the total electron content of the ionosphere. The standard calibration scheme for solving for the delay and rate of the phase is through the process of fringe fitting. The main aim of WP7.3 is to solve for non-dispersive effects associated with wide bandwidth instruments at cm-wavelengths. This research was mainly done by JIV-ERIC, with additional input from MPG. WP7.4 focuses on dispersive processes that particularly effect low frequency observations, and initial test algorithms have been developed by JIV-ERIC and OSO, with additional input from UMAN.

The first component of WP7.3 was a full implementation of a CASA fringe-fitter in C++ (fringecal), which was developed within CASA's calibration framework. This implementation was based on an existing Python prototype developed as part of RINGS, which itself was based on the standard fring method within the Astronomical Image Processing System (AIPS). The fringe fitter was included in the public release CASA 5.3 in June 2018, and is now available for use by the astronomical community. In parallel, new CASA VLBI tools were made available, such as re-referencing and rate-aware interpolation of fringe calibration tables, improvements for VLBI amplitude calibration, and for importing VLBI data into CASA. These tools were validated using real and simulated data, in collaboration with BlackHoleCam partners from South Africa.

The on-going research is focused on fringe fitting schemes for wide bandwidth and multi-band instruments, such as BRAND receiver (1.5 to 15.5 GHz). The strategy that is currently being tested applies a Fast Fourier Transform (FFT) across the whole frequency band. This works in the case where the data are densely sampled, but is not very useful for data with a sparse frequency spacing. A regular spaced frequency grid is well understood, but is not fully implemented (uses nearest neighbour interpretation), and may be expensive/not optimal. Tests will be carried out using data from the Korean VLBI Network (KVN), where there is a small bandwidth that is sparsely sampled in frequency space. Additional BRAND receiver-like datasets from the VLBI Global Observing System (VGOS) will also be used for testing this calibration strategy.

The calibration strategy for WP7.4 involves a two-step process, where a standard 2 dimensional Fourier transform is used (fringecal) to find the delay, rate and a constant non-dispersive phase term, followed by a global least squares fit for the constant non-dispersive phase, the delay, the rate and a dispersive term. This python based algorithm has been tested on 327 MHz data from the EVN for a bright calibrator source, where the initial FFT obtains results that are sufficient for the least squares fit to

converge. Further testing on other data-types and data-quality (i.e. from LOFAR and VGOS) will be carried out over the next period, before the final implementation is done in C++.

### 2.3 Advanced polarimetric calibration

WP7.5 of RINGS concentrates on calibration algorithms for polarimetry using ALMA and LOFAR. In particular, this WP aims to combine the algorithms developed by WP7.2 and WP7.4 to implement a robust self-calibration procedure for low signal-to-noise ratio data, where the large fractional bandwidths provided by, for example LOFAR and BRAND receiver, will allow fainter sources to be used during the calibration process. This will require accounting for both direction dependent and dispersive effects in the data. This research is being carried out by OSO.

A full gain-calibration engine has been implemented in the UVMultiFit package. This calibration engine allows the use of generic equations for the amplitude and phase gains (and with any inter-relationship among them, which may be useful to calibrate direction-dependent effects for interferometers with short baselines, e.g. LOFAR). In addition to this, a Quinn-based estimator of the fringe peaks in delay-rate space has also been implemented, to help in optimising for the a-priori gain values (for the cases of rapidly-varying phases) as a first step before the  $\chi^2$  minimization. Preliminary results and tests of the calibration engine have been very successful.

In addition, given the remarkable versatility of UVMultiFit for the gain parameterisation, a simple global fringe fitter has also been implemented, which is being used for the comparison of basic calibration cases with the products from WP7.3 and WP7.4. The UVMultiFit global fringe fitter implementation outperforms on simulated VLBI data and provides good quality calibration to real observations. Current developments are focused on the output of standard CASA calibration tables. As it is, the solutions from UVMultiFit are applied to the data, producing new corrected visibility datasets, as opposed to the calibration being applied "on-the-fly". Outputting calibration tables would allow WP7.5 to be integrated with the other tasks being developed by RINGS and with those currently available within CASA.

## 3 Integrating various calibration algorithms

In this section, a review of the various strategies that can be used to integrate the calibration algorithms being developed by RINGS is presented.

The basic fringe fitter is already well integrated within CASA (FRINGEFIT task) since release CASA 5.3 and the intention is that the RINGS improvements to the fringe fitter, such as dispersive delay fitting and wide-band fringe fitting will be integrated in a future CASA release as well. This will ensure that the algorithms developed by RINGS are written to community standards, have sufficient documentation, and are independently verified, and that they are integrated within the standard data reduction software that is commonly used by the community. This provides familiarity for the end-user of the RINGS algorithms, which will be important for maximising the dissemination of the work done by the JRA. Providing that the complete data reduction flow is carried out within CASA, no further integration would be necessary. Also, with this integration strategy, the calibration can be done "on-the-fly" without writing out corrected visibilities between the various calibration steps. This will save both time and compute resources for the end-user.

An alternative example of an integration strategy is with the UVMULTIFIT task, which is available as a python package that can be seamlessly imported within CASA. It is not part of the standard CASA distribution, but has been developed independently, taking advantage of the functionality within CASA, and can be used by the end-user without needing to also install various dependencies. A disadvantage of this strategy is that it is not (currently) integrated within CASA's calibration framework, which means that "on-the-fly" calibration is not possible (although see Section 2.3 above). Therefore, corrected visibilities need to be written out

before running UVMULTIFIT, and the package writes out another set of calibrated visibilities. However, a calibration strategy that uses UVMULTIFIT can be done completely within CASA's iPython environment.

The FRINGEFIT task within CASA can also be used with other packages that use the MeasurementSet format as their data model. Examples of such packages are NDPPP, WSCLEAN, and AOFLAGGER, which are used by LOFAR, and MEQTREES, which is used by MeerKAT. As with UVMULTIFIT, the lack of a common calibration model requires the corrected visibilities to be written out between the calibration steps that use these different packages. These packages cannot be easily run from the iPython environment within CASA, and the other tasks within CASA cannot be easily run from a standard Python environment. A possible strategy is to create pipelines that integrate different MeasurementSet-based packages, for example in the case of STIMELA (<https://github.com/SpheMakh/Stimela>), which is used to build pipelines for the MeerKAT telescope. STIMELA uses container technology (DOCKER, SINGULARITY) and already provides support for WSCLEAN, AOFLAGGER, MEQTREES and CASA.

As stated above, the FRINGEFIT task is tightly integrated to the calibration framework of CASA, providing standard calibration tables that can be applied “on-the-fly”. While some of the fundamental fringe fitting code could be moved from CASA into CASACORE, this would require significant refactoring and is not our preferred option. To use this code, a non-trivial amount of additional code would have to be written to ingest visibility data in appropriate chunks and write out calibration tables and/or corrected visibilities.

Furthermore, NRAO (National Radio Astronomy Observatory) is currently working on converting CASA from Python 2 to Python 3. As part of this work, the structure of the Python code in CASA is being changed such that it can be easily imported as Python modules in a standard Python environment. At that point, it would be possible to integrate the various CASA tasks and functionality with other packages in a single Python script. CASA 6 will be released around mid-2019, which will provide another strategy for integrating the different calibration algorithms into a single integrated framework.

The polarimetric beam modelling that has been developed within the DREAMBEAM package needs to be incorporated with imaging algorithms, where the response of the beam across the sky can vary as a function of position and polarisation. Although such a package can also be developed further so that it can be imported within CASA for general use, having the beam prediction functionality within the imaging software that is currently being developed/used for the LOFAR total intensity and polarimetric imaging will better integrate this research with the user community. In this regard, integrating DREAMBEAM within NDPPP and WSCLEAN provides the best strategy for incorporating this algorithm within standard calibration/imaging software that is commonly used by the community.

Overall, our common calibration strategy is (in order of preference) to

- i) include the RINGS algorithms within a future release of CASA;
- ii) provide stand-alone packages that can be imported into a future release of CASA;
- iii) use scripting and pipelines to integrate the algorithms to relevant software.

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