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1 Introduction

Radio Interferometry Next Generation Software (RINGS) was the third Joint Research Activity (JRA) and the seventh work package (WP7) of RadioNet. The aim of the project was to deliver advanced calibration algorithms for the next generation of radio astronomy facilities, which are characterized by a high sensitivity, a high bandwidth and long interferometric baselines. In particular, the project was focused on developing novel calibration procedures for RadioNet supported facilities (e.g., ALMA and LOFAR), which required determining station-based complex gains for both full-polarisation and dispersive delays. Also, RINGS delivered new methods for determining non-dispersive delays for the next generation of large bandwidth receivers, for example, the BRAND-EVN system, which was also part of RadioNet (WP6), and the ERC Grant (no 610058) BlackholeCam / EHT (Event Horizon Telescope).

The project ran from January 2017 until December 2020 and was a collaboration between 23 active researchers at 6 RadioNet partner institutions; namely, NWO-I and JIV-ERIC in the Netherlands, DIAS in Ireland, MPG in Germany, OSO in Sweden and UMAN in the United Kingdom.

RINGS was divided into five dedicated tasks or work packages (where the first institute was the lead institute):

WP7.1	Methodology and approach [NWO-I, UMAN, OSO, JIV-ERIC, MPG, DIAS]
WP7.2	Polarimetry conversion [OSO, DIAS]
WP7.3	Multi-band and wide band fringe fitting [JIV-ERIC, DIAS, MPG]
WP7.4	Fringe fitting with dispersive delays [JIV-ERIC, UMAN, ASTRON, DIAS, MPG]
WP7.5	Advanced calibration algorithms for full-polarisation interferometric data [OSO, DIAS]

The work was further quantified through realising eight deliverables:

D7.1	Report on state of the art and common framework for development
D7.2	Report on strategies to combine results of first phase of tasks 7.2–7.5
D7.3	Report on final implementation of algorithms for polarimetry conversion
D7.4	Report on final implementation of algorithms for multiband and wideband fringe fitting
D7.5	Report on verification of RINGS software on a BRAND dataset
D7.6	Report on final implementation of algorithms for fringe fitting with dispersive delays
D7.7	Report on final implementation of advanced calibration algorithms

In this final report (D7.8), the main results from RINGS are summarised; the interested reader is directed to the various individual reports for each of the tasks listed above, which were compiled during the course of the project[1]. This report is structured as follows. In Section 2, the main results, with respect to the objectives of the project are reviewed. As part of the project, the RINGS team held several networking activities to share ideas within the collaboration, but also to interact with interested members of the community. These activities are presented in Section 3. Finally, our main conclusions and future prospects are presented in Section 4.

2 Objectives and Results

RINGS had six main objectives, the results of which are summarised below.

- *Ensure continuity in the support of the software by incorporating the software in CASA (moving away from legacy software packages like HOPS and AIPS).*

[1] https://radiowiki.mpifr-bonn.mpg.de/doku.php?id=jra:rings

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The development of radio astronomy calibration and analysis packages had traditionally been facility based, where specific tasks were required depending on the nature of the single dish or interferometric array in question. This had the advantage of producing high quality algorithms that were tailor-made for a given facility, but had the disadvantage of increasing the number of packages that users would need to be trained in; this severely limited the accessibility of these facilities to the user base. Also, these algorithms were developed by a small group of software engineers, many of which were (close to) retiring. Therefore, the maintaining or future development of these software packages was not guaranteed.

A summary of the state-of-the-art calibration methods and algorithms for radio astronomy was presented in D7.1. In that report, a common framework for tackling the various tasks within RINGS was also presented. These two goals (state-of-the-art and common framework) covered areas related to polarisation conversion (as wide band receivers move to linear feeds to avoid significant leakage), full-polarisation beam modelling (to understand the response of each station as a function of position on the sky), multi-band non-dispersive and dispersive fringe fitting (to separate the effects of atmospheric and clock errors), and self-calibration methods for low signal-to-noise ratio data (tying many of the methods developed by RINGS together).

The next generation software package, the Common Astronomy Software Applications (CASA), has been adopted by many large facilities for data analysis (e.g. VLA, ALMA, e-MERLIN), and uses the industry standard MeasurementSet data format. For this reason, the algorithms developed during RINGS are either incorporated into CASA and distributed to the community via the bi-annual public releases, or can be imported to CASA as external tasks (available publicly via GITHUB).

• *The functionality delivered by RINGS will be incorporated in the CASA CORE software package.*

CASA CORE contains several core libraries that are the foundation of the tasks within the CASA software package. Also, as described above, it forms the basis of the MeasurementSet data format that many RadioNet facilities use (e.g. WSRT, LOFAR, e-MERLIN, ALMA). These libraries can be used to access and query multi-dimensional data arrays, provide functions for linear and non-linear fitting, and operate on astronomy specific metadata (such as reference frames and co-ordinate frames). By using CASA CORE libraries, the software developed by RINGS was written efficiently in a standardised form, provided a shared understanding between the various tasks, would maximise the uptake of the results after the project, and allowed external collaborators to contribute more easily to the project.

A discussion of the processes used within the CASA CORE environment was also reported in D7.1. Although much of the software developed by RINGS was incorporated into CASA CORE, during the project it became clear that this was not necessary for all tasks, or the additional coding required to achieve this goal would be redundant. Also, future developments of CASA (from version 6.0 onwards) were moving away from CASA CORE and instead were focusing on a python-based modular implementation of the software. Therefore, to maintain robustness against these changes, the software developed by RINGS was instead developed for inclusion into CASA directly (as part of official releases), or via stand-alone packages that could be imported into CASA. This decision and how the various tasks were linked together to form a joint approach are discussed in detail in report D7.2.

• *Deliver new functionality that allows 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.*

This objective was achieved through the development of new software that determined the change in the phase of the visibilities as a function of frequency (delay) and time (rate). This process is typically done through a process called fringe fitting, where the maximum signal in the delay-rate space is determined via a Fourier transform. The previous functionality of these processes within CASA was mainly developed to determine only the delay for wide-bandwidth instruments, like the VLA and ALMA, where dispersive effects were thought to be minimal. Also, this delay was determined for each station, relative to a single reference station, and therefore, only used a limited portion of the data in the fit, and did not take into account dispersive effects. The new software, developed as part of WP7.4 determined a so-called global fringe fit, using all of the station data together, while also solving for the rate. The algorithm solved for both the non-

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dispersive (related to errors in the station positions and clocks) and dispersive (related to the ionosphere) effects. The latter is particularly an issue at the low radio frequencies that LOFAR operates at. The algorithm was tested on EVN data taken at 327 MHz, and were incorporated into the FRINGEFIT task within CASA (further details are described in D7.5).

Also, the non-dispersive and dispersive effects can corrupt the data taken at higher frequencies with wide bandwidth receivers, severely limiting the sensitivity of, for example, the BRAND-EVN system that will operate between 1.5 and 15 GHz. The crucial issue is that such systems can have wide, but non-contiguous bandwidths due to data loss from intermittent radio frequency interference (RFI) or the choice of frequencies selected for observation due to persistent RFI. This can lead to issues in determining the correct delay and rate solutions, and although robust, applying a direct Fourier transform is computationally expensive. To overcome these issues, an algorithm that applies a fast Fourier transform on regularly gridded data was developed (see D.7.4 for further details). This software has been submitted for inclusion in the next available future release of CASA.

- *Provide the capability to fringe fit the ~13 GHz wide band covered by the BRAND receiver and be able to map the data with wide-band mapping software, including spectral corrections.*

One of the goals of RINGS was to test the fringe fitting software that was developed during the project to actual data from the BRAND-EVN system. Here, RINGS would provide the tools to test the response of the new BRAND receiver. However, due to delays in WP6 related to the Covid-19 pandemic, no working prototype BRAND receiver was produced. Therefore, the software that was developed during RINGS was instead successfully tested and verified on a BRAND-like dataset from the VGOS collaboration (see D7.7 for further details on these test observations). As no BRAND data was available, no mapping was carried out.

- *Deliver routines that allow robust self-calibration for low signal-to-noise data.*

Calibration routines are designed to remove the internal response of the instrument, and also the external contributions from atmospheric changes, which are imprinted in the data. Put simply, it results in the observed surface brightness having the correct absolute amplitude and position relative to some reference, independent of the measurement system that has been used. The typical method is to compare the response against a known source and derive calibration solutions that can be applied to the target of choice; this can limit the quality of the calibration, as these solutions are often determined at a different time and position on the sky, relative to the object of interest. This problem can be overcome by using a process of self-calibration, where the target itself is used as a calibration source, but this requires a sufficient signal-to-noise ratio in the data.

The wide bandwidth systems of the next generation interferometers, for example, LOFAR, have excellent sensitivity when the whole bandwidth is used together, which allows visibility phase errors to be corrected over shorter timescales. However, this can only be done when the dispersive phase errors have been accounted for over the entire band. As has been described above, such fringe fitting processes were developed during RINGS and are reported in D7.4 and D7.6.

However, self-calibration for interferometers with large fields-of-view can be limited be so called direction dependent effects, as the change in the visibility phase and amplitude is not constant across the field. This is because the total electron content of the ionosphere and the spatial-response of the station beam are not constant over the entire sky. This requires determining the station-based phase and amplitude solutions in multiple directions, and for all polarisations.

First, an algorithm was developed to convert the linear polarisation (X/Y) feed data to circular polarisation (R/L) data. This was done by solving for the Jones matrices in the linear regime and determining the polarisation leakage terms, as is standard. These calibration solutions were then applied to the visibility data, and the corrected linear polarisation baselines were then converted to a circular basis. The algorithm was released via CASA as the task POLCONVERT, and the details were reported in D7.3.

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Second, advanced software for polarimetric beam modelling was developed, with a particular focus on LOFAR, which has a very large field-of-view (several degrees at the highest frequencies). 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 therefore requires some knowledge of the station beam. The new beam modelling software is called DREAMBEAM, and is made available to the community via GITHUB. Further details on the algorithm developed for determining station beams for full-polarisation data is reported in D7.2.

Third, our ability to self-calibrate the data is also dependent on having an accurate model with which we can compare the data to derive the calibration solutions. In many cases, particularly when the source is complex, this model is not well known, which affects the quality of the calibration. Therefore, a new calibration strategy was investigated that uses a singular value decomposition of the visibilities. This method effectively phases up the station response in one specific direction from which the calibration solutions can be determined. This algorithm was tested with both simulations and actual observations from a LOFAR low band antenna array, and was found to be robust for complicated fields and in the low signal-to-noise regime. The algorithm is called ROBVISCAL, which is built using the CASA CORE libraries, and is publicly available via GITHUB. A report describing the implementation of the algorithm and the various tests that were done to determine the robustness is given in D7.6.

• *Provide a training workshop for radio astronomers in the use of the RINGS functionality.*

The principle fringe-fitting software, which is part of CASA, was presented to the community via two VLBI-CASA workshops held at the EVN Symposium (2018 in Granada) and at a dedicated training event (held online in 2020). In addition, the fringe-fitting software and elements of the UVMULTIFIT software were presented as part of the European Radio Interferometry School in 2017 and 2019. These two sets of training courses were targeted at experienced and novice users, respectively. As each of the work packages had a principle developer, they also served as the link to the community.

3 Management and Networking Activities

The active researchers from the partner institutes exchanged ideas during regular group telecons, the frequency of which was determined by the on-going work. At these telecons, progress was monitored and discussed, and new strategies for calibration were agreed on.

In addition, the whole team met once per year face-to-face to discuss progress and strategies. In total there were four face-to-face meetings (one was cancelled due to the Covid-19 pandemic):

RINGS Kick-off Meeting	Dwingeloo, the Netherlands	09 January 2017
RINGS Workshop	Dwingeloo, the Netherlands	11 September 2017
RINGS Workshop	Bonn, Germany	19 February 2018
RINGS Workshop	Dublin, Ireland	19 April 2019
RINGS Final Meeting	Cancelled due to Covid-19	

In addition to these networking activities within the collaboration, team members also attended the LOFAR long baseline working group workshops and telecons to share ideas and demonstrate the RINGS fringe fitting software for dispersive delays.

4 Conclusions and Future Work

Overall, RINGS has successfully delivered novel algorithms for the calibration of complex data from RadioNet supported facilities. These interferometers are characterised by large observing bandwidths and long baselines, which required new algorithms for dealing with linear-to-circular polarisation, and non-dispersive and dispersive delays to be developed. Also, such interferometers have wide fields-of-view, leading to direction dependent calibration affects that limited the imaging dynamic range. RINGS has mitigated many of these issues by delivering new algorithms for determining the station beams (for full polarisation) and for determining calibration solutions over large fields-of-view. These algorithms are publicly available as part of the latest releases of CASA, or via GITHUB.

In the future, we hope to connect with other industries and scientific areas of research (e.g., space-weather, radar and seismic), which can use the calibration software that has been developed during the RINGS project.

Members of the RINGS team discussing various calibration issues at the RINGS Workshop in Dublin, Ireland, 2019 © RadioNet.

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