Work package number [9]	WP7	**Lead beneficiary** [10]	2 - ASTRON
Work package title	RINGS		
Start month	1	**End month**	42

Objectives

The main objective for 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:

- 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,

- Deliver routines that allow robust self-calibration for low signal-to-noise-ratio sources,

- The functionality delivered by RINGS will be incorporated in the CASA CORE software package,

- Ensure continuity in the support of the software by incorporating the software in CASA (moving away from legacy software packages like HOPS-Haystack Observatory Post-processing System and AIPS),

- As a joint objective with the WP6: 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.

- Support the WP3 Training to provide a training workshop for radio astronomers in the use of the RINGS functionality,

- Organize interaction with the Radar and Seismic Imaging industry to exchange algorithmic approaches for phase calibration and enhance cross fertilization between these domains,

- The envisaged RINGS results are expected to lead to further valorisation. The open-source S/W for antenna pattern description is likely to have benefits for industry and academia.

Description of work and role of partners

WP7 - RINGS [Months: 1-42]
ASTRON, MPG, JIV-ERIC, UMAN, OSO, DIAS
WP7.1 Methodology and approach [ASTRON, UMAN OSO, JIV-ERIC, MPG, DIAS]

Work package 7.1 organises the common aspects for WP7. It organises a review of the state of the art, sets up a common framework and methodology for development. After the first phase of implementation, WP7.1 will harmonize the various approaches into a single strategy for WP7. This will ensure a coherent approach in the final implementation phase of WP7.

WP7.2 Polarimetry Conversion [OSO, DIAS]

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 depolarization 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.

WP7.2 will develop and test advanced algorithms for the polarization calibration of wide-band and long-baseline interferometric observations at both low frequencies (the case of LOFAR) and high frequencies (the case of mm-VLBI and ALMA). Additionally it is planned to implement full-polarization beam-modelling algorithms in our wide-band calibration software, for a high dynamic-range interferometric calibration. Currently there is a need in wide-field imaging for a proper mathematical framework for polarimetric beam models. The 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.

WP7.3: Multiband and Wide Band Fringe Fitting [JIV-ERIC, DIAS, MPG]

This task will handle the non-dispersive delays, phases and delay rates. Fringe fitting corrects an observation for atmospheric errors, which prevent the averaging of data in time and frequency, and therefore limit the sensitivity of a radio telescope. 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 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.

The joint objective with BRAND will be implemented in the final stage of WP7.3. The RINGS software will be used to fringe fit a wideband dataset taken with a BRAND receiver. This will be the verification of the joint capability provided by JRA's BRAND and RINGS.

WP7.4: Fringe Fitting with dispersive delays [UMAN, ASTRON, DIAS, MPG]

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 any simple gradient-descent optimisation techniques inevitably become caught in local minima.

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 results of this task are also essential to achieve the maximum sensitivity in any radio telescope using the receiver to be developed by the WP6 BRAND.

Task 7.5: Advanced calibration algorithms for full-polarization interferometry data [OSO, DIAS]

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.

The WP7 will be managed by ASTRON leading the technical coordination and UMAN leading the scientific coordination. RINGS will use RadioNet pages for daily management of the ongoing work; the access will be public. The stakeholders for all the relevant facilities are well known, and therefore, direct communication of results to them and their involvement where necessary will be organised using an email distribution list. In particular, RINGS will

- organize with the WP3 a workshop on instructions on the application of the RINGS results,

- invite industry partners from geodesy, seismic imaging and radar imaging at the end of project to share the results for exploitation in industry at a workshop organised under WP2 Dissemination,

- seek close interaction with the CASA team at NRAO for alignment of the activities to ensure maximum uptake of the results on all facilities,

- actively communicate the activity mission and progress within and outside projects for instance the US (NRAO for the VLA, MIT Haystack), South Africa (SKA and the MeerKAT Observatory), China (University of Shanghai), Australia (Murchison Wide Field Array) and Korea (KVN).

Participation per Partner

Partner number and short name	WP7 effort
1 - MPG	5.00
2 - ASTRON	13.00
5 - JIV-ERIC	14.00
6 - UMAN	13.00
7 - OSO	13.00
16 - DIAS	18.00
Total	76.00

List of deliverables

Deliverable Number[14]	Deliverable Title	Lead beneficiary	Type[15]	Dissemination level[16]	Due Date (in months)[17]
D7.1	Report State of the Art and Common Framework for Development	2 - ASTRON	Report	Public	6
D7.2	Report on the strategies to combine results of first phase of tasks 7.2-7.5	2 - ASTRON	Report	Public	24
D7.3	Final implementation of algorithms for polarimetry conversion	7 - OSO	Other	Public	30
D7.4	Final implementation of algorithms for multiband and wideband fringe fitting	5 - JIV-ERIC	Other	Public	30
D7.5	Final Implementation of algorithms for fringe fitting with dispersive delays	6 - UMAN	Other	Public	30
D7.6	Final implementation of advanced calibration algorithms	7 - OSO	Other	Public	30
D7.7	Verification of RINGS software on BRAND dataset	1 - MPG	Other	Public	36
D7.8	RINGS Final Report	2 - ASTRON	Report	Public	42

Description of deliverables

Reporst state of the art and common framework for development and on the strategies to combine results of first phase of tasks 7.2–7.5.
Final implementation of algorithms for polarimetry conversion and for multiband and wideband fringe fitting.
Verification of RINGS software on BRAND dataset. Final implementation of algorithms for fringe fitting with dispersive delays and of advanced calibration algorithms.

D7.1 : Report State of the Art and Common Framework for Development [6]

Report State of the Art and Common Framework for Development

D7.2 : Report on the strategies to combine results of first phase of tasks 7.2-7.5 [24]
Report on the strategies to combine results of first phase of tasks 7.2-7.5

D7.3 : Final implementation of algorithms for polarimetry conversion [30]
Final implementation of algorithms for polarimetry conversion

D7.4 : Final implementation of algorithms for multiband and wideband fringe fitting [30]
Final implementation of algorithms for multiband and wideband fringe fitting

D7.5 : Final Implementation of algorithms for fringe fitting with dispersive delays [30]
Final Implementation of algorithms for fringe fitting with dispersive delays

D7.6 : Final implementation of advanced calibration algorithms [30]
Final implementation of advanced calibration algorithms

D7.7 : Verification of RINGS software on BRAND dataset [36]
Verification of RINGS software on BRAND dataset

D7.8 : RINGS Final Report [42]
Final Report

Schedule of relevant Milestones

Milestone number[18]	**Milestone title**	**Lead beneficiary**	**Due Date (in months)**	**Means of verification**
MS47	End of RINGS preparatory phase	2 - ASTRON	6	Report complete
MS48	First implementations of RINGS algorithms in Python	6 - UMAN	18	Test report
MS49	Strategy for single calibration approach	6 - UMAN	24	Minutes of the meeting
MS50	Final Implementation of algorithms in CASA	2 - ASTRON	30	Released and validated
MS51	Final report and publication	2 - ASTRON	36	Final report and publication submitted.