A short introduction to radio interferometric image reconstruction

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Abstract

We briefly introduce radio interferometry and review the image reconstruction methods developed for radio interferometers in the past half a century. We also summarise the similarities and the main differences between radio and optical/infrared interferometry.

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1 Introduction

The electromagnetic wavelengths in the radio regime range from kilometers down to millimeters. The upper edge of the atmospheric radio window is set by the ionospheric absorption and reflection which become dominant at freqencies below ~ 10 MHz. The other end, the boundary between the radio and sub-millimeter/far-infrared regimes is characterised by atmospheric molecular absorption bands. However, the Earth's atmosphere is transparent to a fairly broad range of radio wavelengths which are thus observable from the ground.

In terms of the diffraction-limited angular resolution, radio astronomy has a natural handicap because of the considerably (4 to 7 orders of magnitude)

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longer observing wavelengths compared to the optical. For example, the resolution of a large 100-m steerable parabolic reflector – about the maximum that can be built due to technical and financial constraints – at the wavelength of 6 cm is comparable to that of the human eye at the visible band. This is clearly insufficient since there exists a wealth of radio-emitting astronomical objects that are much more compact. Starting in the the 1940's, the interferometric technique was developed to overcome the limitation in angular resolution.

Here we give a short introduction to the history of radio interferometry, listing the most important and influential interferometer arrays of the past and present. We also mention some instruments that are being built or planned at the moment. These are likely to determine the main directions of the radio astronomical research for the coming decades. The next section of this review is devoted to an introduction to the image reconstruction methods, with emphasis on radio interferometry and practical considerations. At the end, we summarise the similarities and also the differences between radio and optical/infrared interferometry, which may be of special interest for the students of the summer school – and the readers of this volume.

Radio interferometry is a well-established discipline of which the basics are described in many excellent textbooks and review papers. Rather than giving all the details here, we will frequently refer to such resources. First of all, for those who are seriously interested in this technique, we recommend the book *Interferometry and Synthesis in Radio Astronomy* (Thompson et al., 2001). Much of the current scientific aspects of radio astronomy in general, as well as some historical reviews and future directions are covered in the book *Radio Astronomy from Karl Jansky to Microjansky* (Gurvits et al., 2005).

2 Radio interferometry: historical milestones

For the development of connected-element interferometry and aperture synthesis, that started after the second World War in Cambridge, Martin Ryle was awarded the Nobel Prize in physics in 1974. The subsequent work was done by different groups in the United Kingdom, the USA, the Netherlands and Australia. By the end of the 1970's, several interferometer arrays were built (see e.g. Jackson, 2008). They used a large number of different baselines between the pairs of interferometer elements, and the Earth rotation to better fill the aperture over a period of time. Some of these arrays and the years when they were completed:

- Jodrell Bank Interferometer (UK, 1958)
- One-Mile Telescope (Cambridge, UK, 1964)
- Green Bank Interferometer (GBI; USA, 1964)

- Westerbork Synthesis Radio Telescope (WSRT; the Netherlands, 1974)
- Very Large Array (VLA; USA, 1980)

The WSRT and the VLA are still in the forefront of radio astronomical research, being gradually upgraded to provide increased sensitivity, frequency coverage, bandwidth, etc. The six-telescope Multi-Element Radio Linked Interferometer Network (MERLIN) in the UK (1980) extended the baselines of the connected-element interferometers up to $\sim$ 200 km. The e-MERLIN that is being commissioned right now will provide a factor of 30 increase in sensitivity using a dedicated wide-band optical fibre network, new receivers and correlator. Other examples of major interferometers are the Australia Telescope Compact Array (ATCA; 1988), the Giant Meterwave Radio Telescope (GMRT; India, 1999), the Institut de Radioastronomie Millimétrique (IRAM; Plateau de Bure, France, 1988) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA; California, USA, 2007).

Investigation of radio sources with angular diameters smaller than the best resolution achievable with connected-element interferometers was the driving force behind the development of Very Long Baseline Interferometry (VLBI). With the advent of precise frequency standards needed for accurate timing, and the high-capacity magnetic tape recording, this development was done in the USA and in Canada in 1967. In the traditional VLBI, the data observed simultaneously at each individul telescope site are stored on magnetic tapes (nowadays on computer hard disks). By using local oscillators controlled by atomic clocks, it is possible to preserve the coherence of the signals for time intervals long enough to produce interference. The sky signals are converted down to lower frequencies and recorded. The tapes (disks) are brought together and later played back at a central computing facility called correlator. The actual interference is achieved here. In the last couple of years, advances in the broad-band optical fibre techology allowed to physically connect the correlator with even the most distant antennas (e-VLBI; e.g. Szomoru et al., 2006).

The ultimate limit for the ground-based VLBI baseline lengths is the Earth diameter. At 5 GHz, the corresponding resolution limit is about 1 milli-arcsecond (mas). However, many radio sources are unresolved by ground-based VLBI observations. The VLBI arrays could be extended beyond the Earth by placing an interferometer element into orbit. The first dedicated Space VLBI (SVLBI) satellite, the Japanese HALCA was launched in 1997 (Hirabayashi et al., 2000). Its successor (ASTRO-G) is planend for launch in 2013; the Russian RadioAstron SVLBI satellite is scheduled for a late 2009 launch.

Current radio interferometric instrumental developments include the Low Frequency Array (LOFAR) that is being built in Europe, centered in the Netherlands. This array will provide sensitive, high-resolution data with multiple beams, at radio frequencies below 250 MHz. The interferometer elements will consist of fields packed with dipole antennas. At the other end of the radio frequency regime (30–950 GHz), the Atacama Large Millimeter/Submillimeter Array (ALMA) is being constructed in Chile. The ALMA interferometer will consist of sixty-four 12-m paraboloid antennas with reconfigurable baselines, located on the Chajnantor plain in the Andes, at about 5 km elevation. The site provides excellent atmospheric transmission. It is currently the most ambitious project worldwide for building an international astronomical facility.

In a longer term, a major global endeavour is to construct a sensitive radio interferometer with a huge collecting area. The Square Kilometer Array (SKA) will be built in either Western Australia or South Africa by the end of the next decade. The planned frequency coverage is between the 100-MHz and $\sim$ 10-GHz range. More information and further references about the next-generation radio interferometers can be found in the review papers published in Gurvits et al. (2005). The overall picture is that radio interferometry is a vivid research field, driven by intriguing science goals such as studying the epoch of reionization by observing the redshifted neutral hydrogen line, surveying the faint and transient radio source population, investigating the close vicinity of supermassive black holes, studying the interstellar molecules and planet formation, cosmology, gravity, astrometry, and a lot more.

3 Radio interferometry: image reconstruction basics

Radio interferometers and synthesis arrays are used to make measurements of the fine details in the radio emission from the sky. These instruments are basically composed of two-element interferometers that measure the voltages induced by the electromagnetic radiation of cosmic sources (Thompson et al., 2001). With (radio) interferometric imaging, our goal is to restore the sky brightness distribution of the sources from the measured visibility data (e.g. Clark, 1995). The image is formed indirectly from the complex visibilities considering their errors and the geometry of the interferometer baselines. The image reconstruction process involves three major steps (e.g. Cornwell, 1995).

(1) The initial *dirty image* is formed from the visibility data via Fourier inversion. The quality of this image is hampered by the imperfect sampling of the aperture. A real example of the (u, v) plane coverage, i.e. the points corresponding to each interferometer baseline length obtained over a period of the observation, projected onto a plane perpendicular to the source direction, is shown in the top-left panel of Fig. 1. The so-called *dirty beam* is the response of the interferometer to a point-like radio source (i.e. the point spread function, PSF).

(2) The *deconvolution* corrects for the Fourier plane sampling effects. The lack of measurements at certain interferometer spacings means that in principle an infinite number of brightness distributions could be consistent with our visibility data. On the other hand, we may incorporate additional information to constrain our solutions. The most widely used deconvolution method is the CLEAN algorithm (Högbom, 1974; Schwarz, 1978). It assumes that the brightness distribution can be decomposed into a finite number of point sources, and that the rest of the sky around is practically "empty". These point sources have to be found in the dirty image and gradually removed in an iterative process. At the end, the point sources are smoothed (convolved with an "ideal" Gaussian-shaped beam instead of the dirty beam) and added to the residual image (noise) to form the CLEAN map.

(3) The visibility measurements are affected by e.g. atmospheric and instrumental errors, which cause phase – and sometimes amplitude – fluctuations. Realising that the phase errors are mostly antenna-based, Jennison (1958) introduced the closure phase. In a triangle of telescopes, the baseline errors cancel out in the sum of the phases. Four antennas are needed to define a similar closure quantity for amplitudes. The closure quantities are better observables of the source structure (Readhead & Wilkinson, 1978). Nowadays in practical radio interferometric imaging, the calibration errors are corrected with *self-calibration* (Cornwell & Wilkinson, 1981). Here the antenna-based errors are not eliminated but their values are estimated. Once derived, the phase error estimates can be applied to other, often much weaker nearby objects (phase-referencing; e.g. Beasley & Conway, 1995). The method can be extended to obtain phase derivatives with respect to time and frequency (global fringe fitting; Schwab & Cotton, 1983).

Image deconvolution and self-calibration are applied together in an iterative process called *hybrid mapping* (Cornwell, 1995). It starts with an initial source brightness distribution model (e.g. a point source). While the amplitudes are kept as observed, the model visibility phases are altered to be consistent with the observed closure phases. Then the antenna-based phase errors are determined in a least squares sense. This works well in arrays involving many antennas, since the $n-1$ antenna-based errors (one is a reference antenna) are constrained with $n(n-1)/2$ baseline-based measurements. The corrections are applied to the observed visibility phases. The next step is to obtain a better source model with e.g. CLEANing, based on the corrected visibilities. Then the previous steps are repeated until a convergence is reached. It is important to note that the deconvolution solutions are not unique. However, the hybrid mapping procedure results in reliable sky brightness distribution images within the uncertainties that should be well understood. For the hybrid mapping to work, the source has to be sufficiently strong to be detected within the atmospheric coherence time.

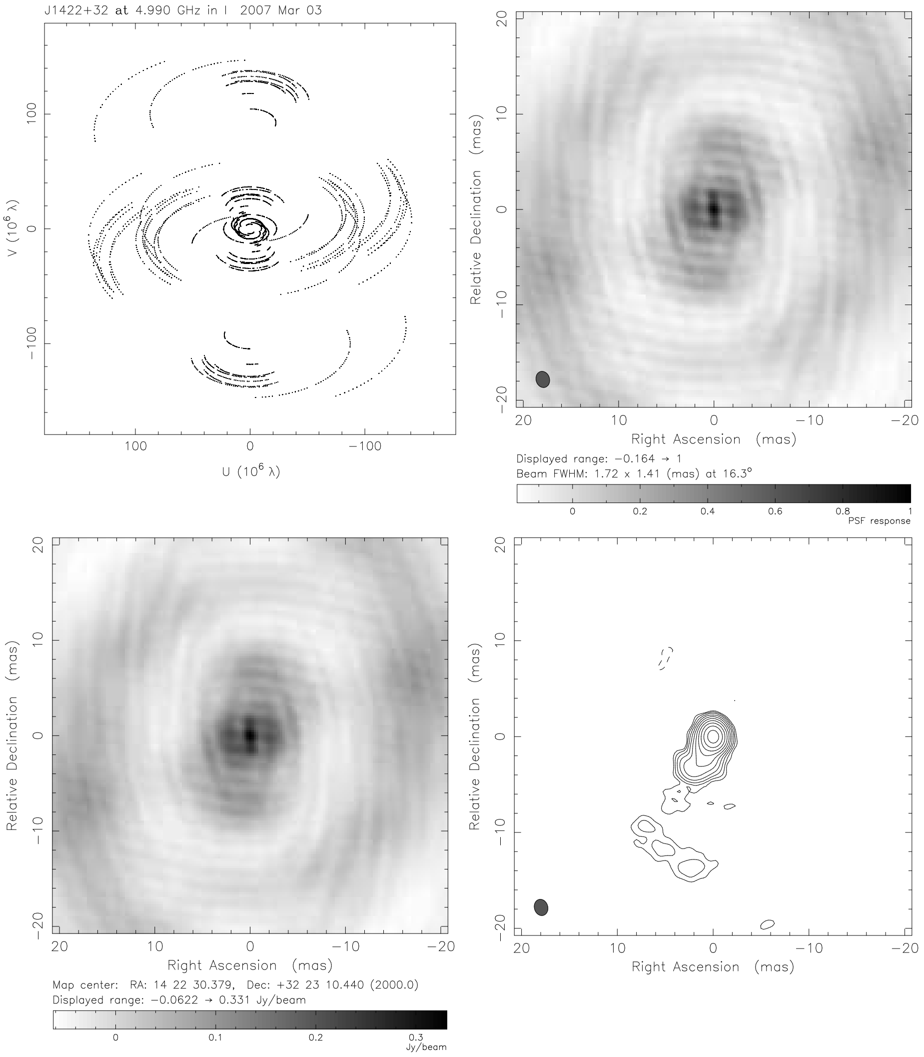

Fig. 1. An example of a (u,v) coverage *(top left)*, a dirty beam *(top right)*, a dirty image *(bottom left)* and a clean image resulted from several iterations of CLEANing and self-calibration *(bottom right)*. The 5-GHz data of the quasar J1422+3223 taken with 10 radio telescopes of the European VLBI Network (EVN) were used for this demonstration. In the (u,v) plot, the coordinate axes are scaled in the unit of 10^6 times the observing wavelength. In the clean image, the peak brightness is 307 mJy/beam, the first contours are drawn at ±0.4 mJy/beam. The positive contour levels increase by a factor of 2. The Gaussian restoring beam is shown in the bottom left corner. This quasar was used as a phase-reference calibrator for imaging a much fainter source, J1427+3312, the highest-redshift ($z = 6.12$) radio quasar known at present (Frey et al., 2008). The plots were prepared with the Difmap program (Shepherd, 1997).

The most widespread software of choice for calibrating and imaging radio interferometer data is the US National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System [1] (AIPS; Greisen, 2003). Image decon-

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[1] `http://www.aips.nrao.edu`

volution, self-calibration and brightness distribution model fitting can alternatively be performed with the Caltech difference mapping program[2] (Difmap; Shepherd, 1997).

4 A brief comparison of radio and optical interferometry

Finally, based on Cotton (2004) and Haniff (2005), we set radio interferometry against optical and infrared (IR) interferometry. (Note that by "radio" we usually mean centimeter wavelengths.) Although the principles of interferometry are the same in both branches, there are practical differences. First of all, the atmosphere has more severe effects in the optical/IR.

The atmospheric coherence sizes are $\sim 10-100$ cm in optical/IR. Since the telescopes are usually larger than these, one needs adaptive optics systems to utilise the whole surface of the aperture. There is no such need in the case of radio antennas[3], since even the largest ones are smaller than the corresponding $\sim 100-1000$-m coherence sizes in radio. The coherent integration times are a few milliseconds in the optical/IR, and some minutes in the radio.

The number of optical/IR photons detected in a single coherent integration time is very small, therefore the properties of the individual photons are important. Thus phase-sensitive detection in the optical/IR is impossible or very difficult because of the quantum effects. Radio observations are not affected this way. As a consequence, most optical/IR interferometers are of *direct* type: the incoming beams are combined, actually *added*. The signal detected – on an incoherent detector – only after the fringes are formed. Unfortunately, (variable) background terms can dominate the signal, making the fringe detection difficult. This problem can be overcome by forming a correlation interferometer, where the signals are not added but multiplied.

Radio interferometers work differently. The data are obtained/recorded at each antenna before the fringes are formed. The interference is achieved in the correlator from the sampled voltages. The signal processing includes *heterodyne* frequency conversion to a lower frequency, via mixing it with the local oscillator signal. At this "new" frequency, the signal can be easily and safely manipulated, e.g. amplified, digitized or even recorded for posterior correlation in the case of VLBI. Therefore it is simple to measure the correlation at different delay values and to determine which produces the maximum correlated output.

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[2] `http://www.astro.caltech.edu/~tjp/citvlb`

[3] However, because of the large size of the dishes, additional techniques/systems may be needed to preserve the correct shape of the antenna surface.

In the case of the adding interferometers, delay compensation must be applied to the beams directly. The delay (optical path difference) must be accurate to a small fraction of the observing wavelength for very short time periods, which makes this requirement fairly challenging.

In principle, radio signals from an *infinite* number of antennas with arbitrarily long baselines can be correlated. In practice, infinite means approximately 20 for the present arrays. In contrast, only a few telescopes ($n \approx 4-8$) can be used simultaneously for optical/IR interferometry. More telescopes cost e.g. more money, and the sensitivity is degraded because all the n beams must be splitted into $n-1$ parts for pairwise beam combination (Michelson interferometer). A direct interferometer can have very wide observing bandwidth which improves its sensitivity. Until now, radio interferometric observations used narrow (up to ∼GHz) bandwidths because of the limited computing power.

The maximum length of baselines achieved by radio interferometry was ∼ 10 000 km (space VLBI), while currently the longest baselines of optical/IR interferometers are shorter than 1 km. For practical reasons, more distant telescopes cannot be connected to form a direct interferometer. However, heterodyne interferometry might be possible in the optical/IR, by taking advantage of the frequency comb (Glindemann & Käufl, 2006).

The visibility amplitudes and closure phases (bispectra; e.g. Cornwell, 1987) are the good observables in optical/IR interferometry, and thus these are considered for the image reconstruction. For details, see Eric Thiébaut's paper in this volume or the *Image Reconstruction Beauty Contest* papers (e.g. Cotton, 2008, and references therein).

In the case of radio interferometry, one usually aims at determining the complex visibilities (see self-calibration above). Direct calibration of phases is possible if a calibrator source – which lies in the same isoplanatic patch – can also be observed within a coherent integration time. The phase solutions for the calibrator object can then be applied to the target data in order to remove the same phase errors. The relatively long radio coherence time allows the antennas to switch back and forth between the target and the calibrator (Beasley & Conway, 1995). In the optical/IR, both objects must be observed simultaneously. Such observations will soon be possible with PRIMA (Delplancke, this volume). Phase-referencing with a simultaneous dual-beam observing system is employed by the Japanese VERA (VLBI Exploration of Radio Astrometry) radio telescope network (Kawaguchi et al., 2000).

Despite some major differences mentioned above, there are many fundamental similarities in the two astronomical observing techniques. Lessons learned earlier from radio interferometric image reconstruction are being applied by optical/IR interferometry experts. It is likely that these two areas of astronomical interferometry will continue to benefit from the experience of each other.

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References

Beasley, A.J., & Conway, J.E., VLBI Phase-Referencing, *Very Long Baseline Interferometry and the VLBA*, ASP Conference Series, Vol. 82, eds. J.A. Zensus, P.J. Diamond, & P.J. Napier, Astronomical Society of the Pacific (San Francisco, 1995), 327-343

Clark, B.G., Interferometers and Coherence Theory, *Very Long Baseline Interferometry and the VLBA*, ASP Conference Series, Vol. 82, eds. J.A. Zensus, P.J. Diamond, & P.J. Napier, Astronomical Society of the Pacific (San Francisco, 1995), 3-16

Cornwell, T., Radio-interferometric imaging of weak objects in conditions of poor phase stability, 1987, A&A 180, 269-274

Cornwell, T., Imaging Concepts, *Very Long Baseline Interferometry and the VLBA*, ASP Conference Series, Vol. 82, eds. J.A. Zensus, P.J. Diamond, & P.J. Napier, Astronomical Society of the Pacific (San Francisco, 1995), 39-56

Cornwell, T., & Wilkinson, P.N., A new method for making maps with unstable radio interferometers, 1981, MNRAS 196, 1067-1086

Cotton, W.D., Radio and optical interferometry, *The Role of VLBI in Astrophysics, Astrometry and Geodesy*, NATO Science Series II., Vol. 135, eds. F. Mantovani, & A. Kus, Kluwer (Dordecht, 2004), 289-305

Cotton, W.D., 2008 Imaging Beauty Contest, *Optical and Infrared Interferometry*, Proceedings of the SPIE, Vol. 7013, eds. M. Schöller, W.C. Danchi, & F. Delplancke, SPIE–The International Society for Optical Engineering (Bellingham, 2008), 70131N.

Frey, S., Gurvits, L.I., Paragi, Z., & Gabányi, K.É., High-resolution double morphology of the most distant known radio quasar at $z = 6.12$, 2008, A&A 484, L39-L42

Glindemann, A. & Käufl, H.-U., Heterodyne interferometry with a frequency comb – The cornerstone of optical Very Long Baseline Interferometry? *Visions for Infrared Astronomy conference*, Paris, 20–22 March 2006, `http://www.lesia.obspm.fr/VIRA/absbook/node83.html`

Greisen, E.W., AIPS, the VLA, and the VLBA, *Information Handling in Astronomy - Historical Vistas*, Astrophysics and Space Science Library, Vol. 285, ed. A. Heck, Kluwer (Dordrecht, 2003), 109-125

Gurvits, L.I., Frey, S., & Rawlings, S. (eds.) *Radio Astronomy from Karl Jansky to Microjansky*, EAS Publications Series, Vol. 15, EDP Sciences (Les Ulis, 2005)

Haniff, C.A., The Future Development of Ground-based Optical/IR Interferometry, *Future Directions in High Resolution Astronomy: The 10th Anniversary of the VLBA*, ASP Conference Series, Vol. 340, eds. J. Romney, & M. Reid, Astronomical Society of the Pacific (San Francisco, 2005), 619-625

Hirabayashi, H., Hirosawa, H., Kobayashi, H. et al., The VLBI Space Observatory Programme and the Radio-Astronomical Satellite HALCA, 2000, PASJ 52, 955-965

Högbom, J.A., Aperture Synthesis with a Non-Regular Distribution of Interferometer Baselines, 1974, A&AS 15, 417-426

Jackson, N., Principles of Interferometry, *Jets from Young Stars II*, Lecture Notes in Physics, Vol. 724, eds. F. Bacciotti, E. Whelan, & L. Testi, Springer (Berlin, Heidelberg, 2008), 193-218

Jennison, R.C., A phase sensitive interferometer technique for the measurement of the Fourier transforms of spatial brightness distributions of small angular extent, 1958, MNRAS 118, 276-284

Kawaguchi, N., Sasao, T., & Manabe, S., Dual-beam VLBI techniques for precision astrometry of the VERA project, *Radio Telescopes*, Proceedings of the SPIE, Vol. 4015, ed. H.R. Butcher, SPIE–The International Society for Optical Engineering (Bellingham, 2000), 544-551

Readhead, A.C.S., & Wilkinson, P.N., The mapping of compact radio sources from VLBI data, 1978, ApJ 223, 25-36

Schwab, F.R., & Cotton, W.D., Global fringe search techniques for VLBI, 1983, AJ 88, 688-694

Schwarz, U.J., Mathematical-statistical Description of the Iterative Beam Removing Technique (Method CLEAN), 1978, A&A 65, 345-356

Shepherd, M.C., Difmap: An Interactive Program for Synthesis Imaging, *Astronomical Data Analysis Software and Systems VI*, ASP Conference Series, Vol. 125, eds. G. Hunt, & H.E. Payne, Astronomical Society of the Pacific (San Francisco, 1997), 77-84

Szomoru, A., van Langevelde, H.J., Verkouter, H., et al., VLBI in transition, *Ground-based and Airborne Telescopes*, Proceedings of the SPIE, Vol. 6267, ed. L.M. Stepp, SPIE–The International Society for Optical Engineering (Bellingham, 2006), 62673X

Thompson, A.R., Moran, J.M., & Swenson, G.W., Jr., *Interferometry and Synthesis in Radio Astronomy*, 2nd edition, Wiley (New York, 2001)