Proceedings of the 6th European VLBI Network Symposium
Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)
June 25th-28th 2002, Bonn, Germany

The Beginnings of VLBI at the 100-m Radio Telescope

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Abstract. This will be an informal review of the beginnings of VLBI at the 100-m telescope in Bad Münstereifel–Effelsberg. It will include short remarks on the organizational, technical and scientific aspects, the people involved and the main areas of application.

1. Introduction

The following is a summary in tabular form of a talk to be given at the beginning of a guided tour to the 100-m radio telescope for interested participants of the EVN Symposium 2002. This write-up is also intended to serve as a guide to the literature covering the development of Very Long Baseline Interferometry from its beginnings in the Sixties until the early Eighties (of last century). The chronology in sect. 2 lists a number of milestones of a technical, organizational and scientific nature, with special emphasis on events where the 100-m telescope was involved. For a full account of the early days of 'independent-oscillator tape-recording interferometry' see Kellermann & Cohen (1988), Locke ed. (1988), Lovell (1973), and Moran (1998) and references therein. For a complete VLBI bibliography up to mid-1980 see the report by Cohen (1980). For the technical status of VLBI at certain epochs see Findlay (1970), Special Issue of Proc. IEEE (1973), and Thompson, Moran & Swenson (2001).

From the very beginning the scientific motivation for the development of VLBI has come from astrophysics (quasars, radio galaxies, active galactic nuclei, interstellar masers), geophysics (Earth rotation parameters, crustal motion, tides of the solid Earth), and gravitational physics (light ray bending). When MPIfR scientists got involved in VLBI observations with the 100-m telescope in 1973 the exciting achievements (see section 2) of a 6-year pioneering phase had already received world-wide attention. To mention just a few points:

– there was the by no means trivial demonstration that the VLBI method worked, even on intercontinental baselines and
– that the angular diameters of several compact sources are on the scale of milliarcseconds;
– indications for multiple-component or complex structure of these sources inferred from spot measurements;
– the successful line VLBI observations of water masers; and
– the exciting discovery of superluminal motion in 3C279.

Nevertheless, it was obvious that a number of challenges were ahead of us. There was the problem of the corrupted visibility phase which seemed to render proper imaging impossible. Similarly the phase fluctuations induced by the wet atmosphere seemed to shatter the hopes of geodesists for cm accuracy in measuring intercontinental distances. There were enough skeptics in the academic establishment who predicted that these problems could never be overcome. Fortunately they were refuted by the progress of the following decade.

VLBI imaging: After the rediscovery of "phase-closure" by Rogers et al. (1974) and the invention of the CLEAN method by Högbom (1974) came the decisive breakthrough between 1977 and 1981 of "hybrid mapping"; see the review article by Pearson & Readhead (1984), the paper by Ekers (1983) and the original contributions by Readhead & Wilkinson (1978), Gull & Daniell (1978), Walker (1978), Wilkinson et al. (1979), Cotton (1979), Schwab (1980), Cornwell & Wilkinson (1981). For a list of all 52 objects known to have been mapped by VLBI at the time of writing, see Preuss (1983). But note: the weak cores of only eight double-lobed radio galaxies had been mapped by 1986.

Astrometric / geodetic VLBI: See Shapiro et al. (1974) and the review article by Sovers, Fanselow and Jacobs (1998).

Physical modeling of compact sources in quasars and radio galaxies: In the 1970s it became obvious that the model of an adiabatically expanding source of synchrotron emission —which was pretty successful when applied to variable sources (Pauliny-Toth & Kellermann 1966)— cannot explain the energy supply required in the luminous extended radio galaxies. That was the time when the models of continuous collimated outflow (also called 'beam' or later 'jet') took shape. This development was inspired by the maps coming out of observations with the 5-km interferometer in Cambridge, UK, especially by the map of Cygnus A by Hargrave & Ryle (1974). The early VLBI experiments already provided valuable circumstantial evidence in support of jet models: the cores of milliarcsecond scale size, their linear structure, and the close relation of their source axes to the directions of larger scale features. The following selection of important papers may mark this line of theoretical development: Rees (1971); Longair, Ryle & Scheuer (1973); Blandford & Rees (1974); Scheuer (1974); Scheuer & Readhead (1979); Blandford & Königl (1979). But note the paper by Saslaw, Valtonen & Aarseth (1974) on the gravitational slingshot model.

2. VLBI Chronology 1967 – 1984

1967 May: The NRAO-Cornell VLBI system Mark-I (360 kHz bandwidth) begins operations (Kellermann & Cohen 1988); correlation is done on a general purpose computer.
First successful VLBI experiments in Canada at 75 cm and in the USA at 50 cm wavelength (Broten et al. 1967, Bare et al. 1967); 15 experiments altogether performed in the USA and Canada in 1967.

1968 January: First successful transatlantic experiment involving Green Bank (West Virginia), Haystack (Massachusetts), and Onsala (Sweden) at 6 cm wavelength, in October also at 3 cm.
VLBI observations of water masers (Burke et al. 1972)

1969 October: angular resolution record on the baseline Green Bank (West Virginia) – Simeiz (Crimea) of 8035 km length or 286 million wavelengths 2.8 cm.

1970 April 13–15: First VLBI Symposium at the National Radio Astronomy Observatory, Charlottesville, Virginia (Findlay ed. 1970).
First bandwidth-synthesis interferometer for astrometric and geodetic VLBI designed and built by A. Rogers (1970).
October: Irwin Shapiro and the MIT/GSFC/Haystack group study gravitational ray bending. From alternating observations of 3C 279 and 3C 273 they infer double structure for both sources from visibility curves for the Goldstone-Haystack baseline (Knight et al. 1971). Follow up observations lead to the discovery of *superluminal motion* (Whitney et al. 1971, Cohen et al. 1971).

1971 May 12: Official commissioning of the 100-m telescope; initiator and leader of the telescope project: Otto Hachenberg, Bonn University and MPIfR.
NRAO Mark-II VLBI system in operation, bandwidth: 2 MHz (Clark 1973); 2-station correlator at NRAO, Charlottesville, upgrade to 3-station capability 1975, end of operation 1993.

1972 August 1: Start of regular astronomical observations with 100-m telescope at 11 cm wavelength.

1973 June 18–21: First VLBI observation including the 100-m telescope at 13 cm wavelength; VLBI terminal: NRAO Mark-II; frequency standard: Rubidium, stability about 10^{-12}; receiver: 300 K uncooled paramp; array: Effelsberg, NRAO 140 ft and DSN 26 m antenna 'Venus', Goldstone, California.
Objects: strong compact extragalactic sources: 3C 84, 3C 120, 3C 273, 3C 279, 3C 345, 3C 454.3, CTA 21, 0742+10, 1633+38, and 2134+004; correlation at NRAO, Charlottesville.
Investigators at MPIfR: A.T. Moffet (on leave from Caltech), D.A. Graham, I.I.K. Pauliny-Toth, E. Preuss, A. Witzel; 'non-MPI' investigators (1973–1975) include: M.H. Cohen, K.I. Kellermann, G.H. Purcell, J.D. Romney, R.T, Schilizzi, D.B. Shaffer, D.L. Jones, G.W. Swenson, and J.L. Yen.
July: Second VLBI observation, first at 2.8 cm: Effelsberg - Green Bank (failed) - Fort Davis – OVRO.
August: Third VLBI observation, second at 13 cm: Effelsberg - Johannesburg, South Africa.
Friendly contact established between the ad hoc VLBI group at the MPIfR and James Campbell and his colleagues from the Geodetic Institute of the University of Bonn. The geodesists use the data from astronomical Mark-II observations and soon achieve a delay accuracy of about 3 nanosecond (1 m) and after a while about 1 nanosecond (30 cm).

1974 January: First 6 cm VLBI observation: Effelsberg - Onsala - Green Bank - Ford Davis - OVRO.
Rediscovery of the phase-closure condition by Rogers et al. (1974).
Introduction of the CLEAN algorithm by Högbom (1974).
February 4–6: Second VLBI Symposium at the California Institute of Technology, Pasadena (no proceedings);
Geodetic VLBI: tides of the solid Earth visible in delay residuals (Irwin Shapiro).
'Imaging' of continuum sources: 2- or 3-component models of about a dozen strong sources.
Febr. 7: meeting in Marshall Cohen's office on upcoming international observing campaigns; special 'operational goal' for a full-track 5-station experiment: 'map' 3C 84 at 2.8 cm! Slogan: no data is better than bad data! 'Mission control center' for this observation at Caltech (just to give a taste of the way VLBI worked at that time !) Observations had to be organized on the basis of ad hoc collaborations and each observatory had to approve every single proposal.
Beginning of the planning stage for the US *Network of Existing Telescopes* and a *Dedicated VLB Array*.
June 27–July 3: VLBI observations of 12 sources with a multi-baseline array (Bonn, Green Bank, Fort Davis, Owens Valley) at 2.8 cm. The detection threshold for correlated flux density ranges from about 0.1 to 0.8 Jy. The technical aspects of these long-track observations (such as sensitivity, calibration and model-fitting) and of experiments which were to follow, are described by Cohen et al. (1975).
Good or useful data from all 10 baselines of the 4-station array are obtained for 3C 84. Never before in astronomy had so much direct structural information been obtained from such a small patch of the sky. Nobody managed to obtain a satisfying fit with the nice model-fitting program written by George Purcell (1973). We found that the the visibility amplitudes are reproduced by a complex source structure consisting of point sources on a regular grid. Advantage of such a 'gridfit' procedure over model-fitting programs is: it does not get stuck in local minima while iterating and can therefore yield amplitude solutions even for com-

plicated brightness distributions. (Pauliny-Toth, et al. 1976).

1975 April 7, Cafeteria MPIfR: initial discussion by I. Pauliny-Toth, E. Preuss, R. Booth (on leave from Jodrell Bank), and G. Miley (visiting from Leiden) on the possibility of organizing a *European VLBI Network* of existing telescopes; decision to invite colleagues from European observatories to discuss the matter.
September 26: first informal meeting on VLBI in Europe at the MPIfR with about 20 participants, secretary: Roy Booth.

1976 March 5: Second informal European VLBI Meeting in Bonn.
March and May: First observations under the framework of the US VLBI Network comprising seven telescopes.
October: First 18 cm VLBI continuum and line observations with the array Effelsberg - Onsala - Dwingeloo; objects observed include: the nucleus of the giant radio galaxy 3C236 and the OH-IR star NML Cygnus.
October 22: Third 'EURO–VLBI' Meeting in Onsala; first time participants include James Campbell (Univ. Bonn) and Richard Schilizzi (NFRA).
November 19-21: First successful 1.35 cm continuum VLBI observations including the 100-m telescope; array: Effelsberg - Crimea - Haystack; sufficient S/N for NRAO 150, 3C 84, and 3C 345.
Total number of VLBI observing projects including the 100-m telescope from 1973 through 1976: about 20; failure of one station in 7 of these projects.
December: first space VLBI proposal submitted to NASA by Burke, Clark, Cohen, Kellermann, Moran, Rogers and Shapiro; although not funded the project was an important initiative in the development of Orbital VLBI.

1977 Hydrogen maser in operation as frequency standard at the 100-m telescope.
September: Informal European VLBI meeting at Jodrell Bank.
November: K.I. Kellermann and R.W. Porcas, coming from NRAO, join the MPIfR; K.I. Kellermann becomes director of the extragalactic/VLBI group, succeeding O. Hachenberg.
Mapping of water masers using spectral phase referencing (Walker et al. 1978).

1978 January: 4-station European 18cm experiment ("JODE") with Effelsberg, Jodrell Bank, Onsala and Dwingeloo, employing polarisation switching, and destined to become the "pilot" experiment for the MPIfR Mark-II processor.
Around June: 3-Station Mark-II processor at MPIfR, Bonn, in operation. (Switched off and dismantled in June 1992.)
Jon Romney, coming from Caltech, Pasadena, joins the VLBI group and stays until 1983; he will be head of the correlator group and provide a SELFCAL software package.
August 10–12: IAU/URSI Colloquium 'Formation of Images from Spatial Coherence Functions in Astronomy', Groningen, The Netherlands (proceedings: Schooneveld ed. 1979).
August 13–18: Third VLBI Symposium in Heidelberg, Germany (no proceedings).
Haystack Mark-III system in operation, bandwidth: 56 MHz (Rogers et al. 1983); correlator at Haystack Observatory.

1979 June: Scientific staff of the VLBI group: Walter Alef (student), Anne Downes, Barry Geldzahler, David Graham, Ken Kellermann (director), Ivan Pauliny-Toth, Richard Porcas, Eugen Preuss, Jon Romney, Kurt Weiler, Arno Witzel, secretary: Rosel Bock.
About 50 VLBI projects scheduled within last 15 months; VLBI share of observing time on the 100-m telescope: 17 %.
Beginning of absentee observing in Effelsberg; MPIfR associate member of the US University Consortium for VLBI.
November: Start of Mark-III data recording at the 100-m telescope with help from Alan Whitney and Brian Corey, Haystack Observatory, and first geodetic Mark-III VLBI experiment at 3.8 cm including the 100-m telescope. A series of four additional campaigns for measuring 'Continental Drift' and 'Monitoring of the Earth Rotation (MERIT)' follows up to October 1980; principal investigator on the German side: J. Campbell, Bonn. With the introduction of the Mark-III system the accuracy of the delay measurement improves dramatically to about 0.03 nanosecond or 1 cm.
VLBI Workshop held at MPIfR, Bonn.

1980 Beginning of the year: K.I. Kellermann leaves the MPIfR and returns to NRAO as originally planned; I.I.K. Pauliny-Toth head of the VLBI group.
European VLBI Network (EVN) formed by a consortium of five observatories: MPIfR, Jodrell Bank, Bologna, Onsala, and NFRA; beginning of coordinated scheduling in common observing periods spaced at regular intervals; reviewing of observing proposals by EVN Program Committee, first chairman: I.I.K. Pauliny-Toth (MPIfR).

1981 Superluminal motion found in the weak core of 3C 179, a quasar exhibiting extended, double-lobed emission (Porcas 1981).

1982 December 3–Station Mark-III correlator, a replica of the Haystack machine, operational at MPIfR, Bonn; financial support from Sonderforschungsbereich 78 *Satellitengeodäsie* which is financed by the German Science Foundation (DFG) (J. Campbell, these proceedings).
QUASAT proposal submitted to ESA by R.T. Schilizzi on behalf of a group of European, American and Australian radio astronomers; mission concept: a radio telescope in Earth orbit observing compact radio sources in conjunction with ground-based VLBI networks, a project to be studied as as a joined ESA/NASA project (Schilizzi & Burke, ed., 1984). Members of the ESA study team:

B. Anderson, J.E.B. Ponsonby and P.N. Wilkinson (Manchester, UK), A. von Ardenne and R.T. Schilizzi (Dwingeloo, NL), A. Boischot (Paris, F), R.S. Booth and B. Rönnäng (Onsala, S), D.A. Graham and E. Preuss (Bonn, D), G. Tofani (Firenze, I); although the project did not materialize in the end it was an important step in the development of Space VLBI.

1983 JUNE: Geodesists start using the new high-precision 20-m antenna in Wettzell, Bavaria, for monitoring work; the first successful experiment is done with Onsala, Sweden. The correlation on the MPIfR processor and the complete data reduction is done by the VLBI group of the Geodetic Institute of the University Bonn; staff members: James Campbell (head), Arno Müskens, Axel Nothnagel, and Harald Schuh. See J. Campbell (these proceedings), for the development of geodetic VLBI in Europe.

June 27–July 1: Fourth VLBI symposium = IAU Symposium No. 110 in Bologna (Fanti, Kellermann & Setti 1984). High-dynamic range, VLA map of Cygnus A presented by R. Perley (NRAO).

1984 June: 'Consortium of European Radio Astronomy Institutes for Very Long Baseline Interferometry' formally established during the QUASAT workshop held in Gross Enzersdorf near Vienna (Schilizzi & Burke ed. 1984).

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