IAU Colloquium 164: Radio Emission from Galactic and Extragalactic Compact Sources
ASP Conference Series, Vol. 144, 1998
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Thirty Years of VLBI: Early Days, Successes, and Future

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Abstract. The early days of VLBI are discussed, with emphasis on the fifteen experiments performed in the U.S. and Canada in 1967. Some key technical ideas are described that influenced the development of the technique, including digital fringe rotation, bandwidth synthesis, spectral phase referencing, phase closure and self-calibration, and water vapor radiometry.

1. Introduction

I am pleased to open this conference with a brief, rather idiosyncratic history of the early days of VLBI, with a few comments on future directions. People involved in VLBI have formed a remarkably cohesive community, with an urge to assemble at intervals of about four years. Table 1 lists these meetings, including the present one, the eighth in the series (the periodicity of the meetings is fairly good by human standards: the Allan standard deviation is about 0.1).

Table 1. VLBI Conferences[a]

Date	Ref [b]	Location
May 1970	1	Charlottesville, VA
Jan 1974		Pasadena, CA
Jun 1978		Heidelberg, Germany
Jun 1983	2	Bologna, Italy–IAU Symp. 110, VLBI and Compact Radio Sources
May 1987	3	Cambridge, MA—IAU Symp. 129, The Impact of VLBI on Astrophysics and Geophysics
Jul 1992	4	Manchester, England—Subarcsecond Radio Astronomy
Apr 1997	5	Socorro, NM—IAU Coll. 164, Radio Emission from Galactic and Extragalactic Radio Sources

Notes: [a]General astrophysical meetings; specialized meetings not listed. [b]Ref: 1: Findlay 1970; 2: Fanti, Kellermann, & Setti 1984; 3: Reid & Moran 1988; 4: Davis & Booth 1993; 5: This volume.

The early "pioneers" of VLBI, who received the Rumford Prize from the American Academy of Arts and Sciences for work done in 1967 on quasars and masers, are listed in Table 2. They belonged to three groups: Canadian, NRAO/Cornell and MIT, and were all rather young at the time. Thirty years later, eight of them are still actively employed in radio astronomy, six are retired, and five have died. The average age reflects the differences in the make-up of the groups. In 1967 the average age of the Canadian group was 43. Theirs was a group of mature researchers, some having served in WW II. In the NRAO/Cornell group the average age was 32; Cohen was the senior member, Clark, Jauncey and Kellermann were recent Ph.D. graduates, and Bare was the chief engineer. Among the MIT group the average age was only 30: Burke and Barrett were the senior members, and the others were graduate students (Ball, Rogers and I) or young engineers (Carter, Crowther and Hyde).

Acronyms have abounded in the VLBI community. The Canadians used the term Long Baseline Interferometry (LBI), while in the U.S. it was called Very

Table 2. 1971 AAAS Rumford Prize

NRAO/Cornell	Canadian	MIT
Bare (D)	Broten (R)	Ball (A)
Clark (A)	Chisholm (D)	Barrett (D)
Cohen (A)	Galt (R*)	*Burke* (A)
Jauncey (A)	Gush (R)	Carter (A)
Kellermann (A)	Legg (R*)	Crowther (C)
	Locke (R)	Hyde (R)
	McLeish (D)	*Moran* (A)
	Richards (R)	Rogers (A)
	Yen (D)	

Notes: A: active in radio astronomy; C: changed fields; D: deceased; R: retired; R*: retired but actively involved in research. Names of those present at this conference are in italics.

Long Baseline (VLB), which seemed to follow in alphabetical sequence from the Very Large Array (VLA). In the dark days of early 1967 when no fringes could be found on the Green Bank-Arecibo baseline, the project was referred to by some wags as the Very Large Disaster (VLD). The obvious deficiency of the acronym VLB led to the more complete one of VLBI (Very Long Baseline Interferometry), which gained universal acceptance rather slowly. Early experiments were named by concatenating pieces of station names, e. g., Greenstack (Green Bank-Haystack), Greenhat (Green Bank-Hat Creek), and Goldstack (Goldstone-Haystack). The first attempt to organize a systematic array employed telescopes at Fort Davis, Owens Valley and Green Bank, which became known as the FOG array. This led to the first loosely organized observer-based network called the Network Users Group (NUG). In 1982 a more formal consortium, the Very Long Baseline Network (VLBN), was formed. Other networks followed: the European VLBI Network (EVN), and the Southern HEmisphere VLBI Experiment (SHEVE). The first array constructed solely for VLBI was the Very Long Baseline Array (VLBA). Its early conceptual antecedents had names such as the Intercontinental VLBA (IVLBA) and the High Angular Resolution Telescope or HART ("You've got to have HART"). The Canadian array, which was never funded, was naturally called the Canadian Long Baseline Array (CLBA). Space VLBI has its own share of acronyms. The first generic term was S(pace)VLBI, but O(rbiting)VLBI soon came into general use. The first successful dedicated OVLBI mission started life as MUSE-B, then became VSOP (VLBI Space Observatory Program), and since launch has been called HALCA (Highly Advanced Laboratory for Communications and Astronomy).

2. 1967 and Beyond

The spring of 1967 was a time of frantic activity during the inception of VLBI. The experiments of this period are listed in Table 3. The excitement of the era is captured in a number of popular articles (e. g., Burke 1969a; Broten 1988; Cohen et al. 1968; Kellermann 1972; Kellermann 1992; Kellermann & Cohen 1988; Moran 1969; and Schilizzi 1986). The motivation for very high angular resolution observations of quasars and AGN was the failure to resolve these

Table 3. Early VLBI Experiments

Observ.[a] Date	Pub. Date	Ref [b]	Freq (MHz)	Station[c]	B (Km)	θ ($''$)	Type[d]	Sys[e]	Source[f]	Fate[g]
1964–65	1965	1,2	18	XY	55	62	I	F1	J	S
67/01/17	68/01	3,4	18	XZ	218	16	C	F2	J	S
67/01–02	1988	5	610	GP	2550	0.04	C	M1	Q	F
67/02	67/06/23	6	448	AA	0.2	690	C	C	Q	S
67/03/15	67/07/14	7	610	GG	0.7	145	C	M1	Q	S
67/04/13	67/07/01	8	448	AD	3074	0.04	C	C	Q	S
67/05/06	67/07/01	8	448	AO	250	0.6	C	C	Q	S
67/05/09	67/07/14	7	610	GN	226	0.4	C	M1	Q	S
67/06/08	68/09	9	1665	GK	845	0.04	C	M1	Q	S
67/06/08	67/08/11	10	1665	GK	845	0.04	C	M1*	M	S
67/06	67/09/09	11	2295	TW	110	0.2	I	A	Q	S
67/06/29			1665	GK	845	0.04	C	M1	Q	F
67/06/29	1968	12	1665	GK	845	0.04	C	M1*	M	F
67/07/22	>67/09	13–15	1665	GH	3506	0.01	C	M1	Q/M	S
67/07/29	67/10/07	16	448	AD	3074	0.04	C	C	Q	S
67/08/17	1968	12	1665	GJ	5870	0.006	I	J1	M	F
67/08	70/04	17	610	GP	2550	0.04	C	C	Q	S
67/10	1969	18	448	AD	3074	0.04	C	C	Q	S
68/01/27	1968	19	1665	GKHS	<7720	0.005	C	M1	Q/M	S
⋮										
68/06	1969	18	408	AJ	5127	0.03	C	C	Q	S
68/09		20	610	JP	6470	0.02	C	J2	Q	S

[a] First day of experiment (yr/mo/day).
[b] 1: Carr et al. 1965 2: Carr et al. 1970 3: Brown 1970 4: Brown, Carr, & Block 1968 5: Kellermann & Cohen 1988 6: Broten et al. 1967a 7: Bare et al. 1967 8: Broten et al. 1967b 9: Clark et al. 1968a 10: Moran et al. 1967a 11: Gubbay & Robertson 1967 12: Moran 1968 13: Moran et al. 1968 14: Clark, Cohen, & Jauncey 1967 15: Clark et al. 1968b 16: Broten et al. 1967c 17: Jauncey et al. 1970 18: Broten et al. 1969 19: Kellermann et al. 1968 20: Anderson, private communication.
[c] Station codes for baselines: A: Algonquin Park; D: DRAO, Penticton; G: NRAO, Green Bank; H: Hat Creek; J: Jodrell Bank; K: Haystack; N: Maryland Point; O: Ottawa; P: Arecibo; S: Onsala; T: Tidbinbilla; W: Woomera; X: Gainesville; Y: Ocala; Z: St. Petersburg.
[d] I: incoherent (post-detection); C: coherent (pre-detection).
[e] A: Australian (1 KHz); M1: NRAO/Cornell Mark I (360 KHz); M1*: M1 + Haystack (5 KHz & 120 KHz); J1: Jodrell Bank (10 KHz); J2: Jodrell Bank (720 KHz); C: Canadian (1 MHz); F1: Florida (1 KHz); F2: Florida (2 KHz).
[f] J: Jupiter; Q: quasars and AGN; M: OH masers.
[g] S: success; F: failure.

sources on the 127-km Jodrell Bank-Malvern microwave-linked interferometer. Interplanetary scintillation suggested small intrinsic source sizes, as did theoretical interpretation of sources with high turnover-frequencies and rapid time-variability (Cohen 1969). Lovell (1973) described his discussions with the Russians beginning in 1963, which resulted in a concept for a VLBI system linking telescopes at Jodrell Bank and Crimea at 700 MHz. For various reasons the project never got going, but the discussions may have facilitated U.S.-Russian experiments that began in 1969, and the belated development of the Jodrell recording system (see Table 3).

The earliest continuum VLBI observations were oriented toward measuring visibilities of many sources in order to deduce characteristic sizes. From these sizes, the turnover frequencies, and peak flux densities, the magnetic field strengths could be estimated. It gradually became apparent that visibilities varied with projected baseline and that source structures were complex. The relative success of the theory of adiabatically expanding synchrotron sources

(e. g., Shklovskii 1960, Pauliny-Toth & Kellermann 1966, and van der Laan 1966) helped to focus thinking on models of spherical sources or shells. The measurement of the full-track, well-sampled visibility curve of 3C 279 by Knight et al. (1971) showed a well-defined double source. These measurements were followed up and led immediately to discovery of superluminal motion (Whitney et al. 1971, Cohen et al. 1971). Concern lingered about the uniqueness of the models until the imaging results of Pearson et al. (1981).

The motivation for increased resolution in the study of OH masers was that the component "spots" of the masers were unresolved on connected interferometers in the U.S. and England, although those measurements showed that the spots were separated. The phase stability of the Agassiz-Millstone interferometer was so bad that I was well prepared to deal with the instabilities of VLBI. Increasingly more precise and sensitive VLBI maps of OH, H_2O, and later SiO masers were made in the 1970s. The spread in radial velocities suggested that comparable transverse velocities could be measured through proper motions. In the early 1970s, the logistical problems of VLBI, the complexity of the data processing, and the time variability of the masers all conspired to discourage the search for proper motions. However, Genzel et al. (1981) finally succeeded in measuring relative proper motions in the water masers in the nearby Orion Nebula (500 pc; 1 km s^{-1} = 0.4 mas yr^{-1}). Proper motions in OH sources were not detected reliably until much later (Bloemhof, Reid & Moran 1992; Migenes, Cohen & Brebner 1992). The most exciting extension of this work is the actual detection of the rotation of an accretion disk in NGC 4258 7 Mpc from the sun by the CfA/NRO/NRAO group (Herrnstein 1997).

Let me return once again to the activities of 1967. The Canadians and NRAO/Cornell groups felt their mutual competition keenly. After the Canadians succeeded in demonstrating their system on a 200-m baseline, they immediately moved to a 3074-km baseline, but could not find fringes. They then retreated to a 183-km baseline, only to discover a processing error in their long baseline data, which allowed them to recover the fringes. Meanwhile, the NRAO/Cornell group puzzled over their lack of fringes on the Green Bank-Arecibo baseline in early 1967, and regrouped to verify the viability of their system on the 700-m baseline formed by the NRAO 85-foot and 140-foot antennas.

The MIT group was competing with the Jodrell Bank group, which was developing the spectral line capability of the 127-km interferometer. The time allocation for the experiments in June 1967 was originally granted to the MIT group, but was then shared in a block by the MIT and NRAO/Cornell groups. Barry Clark and I divided up the time more or less gracefully along general "galactic" and "extra-galactic" sidereal times. This may be the origin of Clark's well-honed scheduling skills. The MIT group had an auxiliary 5-KHz filter to pick out one maser component and make delay-searching easy. The tapes were brought back to Haystack by Burke, and I processed them on the CDC3200 computer at Haystack. There was a sign error in the delay compensation, but fringes fleetingly poured out of the line printer when the delay went through zero. Not knowing whether these observations would be successful, a backup experiment had already been scheduled for late June. Most of the principals were rather tired, and when the 140-ft system was set up (by me!), the reference for the HP synthesizer was left on "internal". The fringes were splattered over a wide swath of fringe frequency and proved not to be very useful.

Meanwhile, Gubbay and coworkers implemented an incoherent VLBI system in Australia in 1967, which they later upgraded to a coherent recording system. The University of Florida group, which had studied Jupiter at 18 MHz with their incoherent VLBI system, conducted coherent VLBI experiments beginning in January 1967, but did not analyze and publish their results for almost a year. The first inclusion of a European telescope in VLBI was in January 1968, when Onsala Space Observatory, under the leadership of Olaf Rydbeck, participated in a MKI experiment with Green Bank, Haystack, and Hat Creek.

The success of VLBI raised anew the quantum paradox related to the Young two-slit interferometer, because the implementation of tape recorders suggested the possibility of identifying which antenna each photon arrived at while still preserving interference. Burke (1969b) noted that individual photons could never be tracked because of excess noise introduced in the amplifier by spontaneous emission.

The organizational complexity of arranging VLBI experiments (getting telescope schedulers to agree on a common time for observations, moving equipment around, staffing the observations, etc.) led to the concept of a network to facilitate operations. Marshall Cohen organized the NUG and I was the scheduler in the early years. Throughout the 1970s and 1980s, many NUG meetings and related discussions were held at the annual URSI meeting in Boulder, Colorado. The first network-sponsored observations took place in March and May of 1976, and included programs by Cohen et al. (3C 120, 3C 345, 3C 273, 3C 279, and 3C 84); Johnston et al. (astrometry), Readhead and Wilkinson (quasars), Shaffer and Kellermann (3C 286, 3C 147), and Burke et al. (W3(OH) and W75). Stations included Fort Davis, Hat Creek, NRL, Haystack, and Vermillion River, operating variously at 18 and 2.8 cm. The network soon expanded to include more stations, and routine sessions of about 14 days were scheduled every two months. The delegation of 43 days of time per year on the heavily oversubscribed 140-ft telescope represented a significant policy decision for NRAO. One of the early successes of the NUG was the standardization of operating frequencies. This might seem to be a simple step, but by the mid-1970s each group had its own preferred frequency and thought that change would jeopardize their long series of observations. The standard frequencies that were adopted were: 1663–1665 MHz, 4991–4993 MHz, 10650–10652 MHz, and 22229–22231 MHz. Another service of the network, provided by the SAO group for several years in the early 1980s, was to check for fringes at the beginning of each session. The real-time system developed by the MIT/NASA group was used (Levine & Whitney 1980, Rogers et al. 1983). At each station, 10^6 bits of data were stored in a buffer in the MK III system and sent by telephone to SAO, where fringes were searched for over an arbitrarily large delay range in a general-purpose computer. The data transmission at 1200 baud took about 20 minutes per station, and processing often took much longer. Instrumental delays were made available before the processing began. In January 1982 a more formal consortium was formed with a Memorandum of Understanding signed by the presidents of Cal Tech, MIT, Harvard/SAO, University of California, and University of Iowa. The consortium never received significant direct support from funding agencies, but accomplished a great deal through informal cooperation and initiatives of the individual observatories. Meanwhile, the directors of several European observatories (MPIfR, Jodrell Bank, Institute for Radio Astronomy (Bologna), Onsala Space Observatory, and the NFRA were the charter members) organized the European VLBI Network (EVN). This network has grown over the years to 16 telescopes. Its success led to the formation of the dedicated VLBI organization in Europe known as JIVE (Joint Institute for VLBI in Europe).

The first organized planning for a dedicated array took place at a workshop in Charlottesville in 1974. The results of studies begun there were summarized in a report, *VLBI Network Studies III: An Intercontinental Very Long Baseline Array* (Kellermann 1977). A table from that report showing a possible arrangement of telescopes is reproduced in Table 4. The cost of the proposed array was estimated to be $26M (1977 dollars). This study occurred well before the VLA came into operation, and the notion of a compact southwestern U.S. array emerged later. A great deal of effort was expended to justify the need for exactly 10 telescopes. In any event, the timescale from concept to completion of the VLBA was more than 20 years.

Table 4. An Early Configuration for the VLBA (Kellermann 1977)

Number	Location	Longitude	Latitude
1	Madrid, Spain	$3^\circ 11'$	$40^\circ 25'$
2	Maryland Point, Maryland	77 14	38 22
3	Green Bank, W. Virginia	79 50	38 26
4	South Central Ohio	$\sim$ 81 30	$\sim$ 38 30
5	South Central Indiana	$\sim$ 85 30	$\sim$ 38 30
6	South Central Illinois	$\sim$ 88 00	$\sim$ 38 30
7	Central Kansas	$\sim$ 99 30	$\sim$ 38 30
8	Central Utah	$\sim$111 00	$\sim$ 38 30
9	San Francisco, California	122 24	38 30
10	Mauna Kea, Hawaii	155 28	19 50

Plans for VLBI stations in space also began in the early 1970s. In the U.S. the first proposal was submitted to NASA in 1976 by Burke (PI), Clark, Cohen, Kellermann, Moran, Rogers and Shapiro for a shuttle-launched telescope (Burke et al. 1976). This proposal was not funded, but efforts were redoubled and many meetings and workshops ensued (e. g., Burke, Brown & Powell 1979). Much effort was put into developing the plan for the defunct QUASAT mission (e. g., Schilizzi & Burke 1984) and the yet-to-be-launched RADIOASTRON (Kardashev & Slysh 1988). The Japanese project began in 1987 with a proposal from an ISAS working group (Hirabayashi 1991). It was successfully launched on February 12, 1997, and the first fringes were detected, after some apprehension, on PKS 1519–273 at 1.6 GHz on May 7, 1997 (Hirabayashi & Edwards 1997). Hence VSOP was realized in 10 years, but it built upon 10 years of previous planning.

3. Some Clever Ideas

3.1. Digital Fringe Rotator

In the earliest version of the NRAO MKI processing program, fringe rate compensation was introduced by offsetting the synthesizers controlling the local oscillators. Barry Clark invented the remarkably efficient three-level fringe rotator, which was implemented in the hardware of the MKII system. In its operation it blanked the correlator output to achieve higher efficiency. I analyzed the performance of this rotator (see Thompson, Moran, & Swenson 1986), and found that it could be thought of as a phasor with a phase moving in steps of 45° and with an amplitude alternating between 1 and $\sqrt{2}$, as if it were tracing a box. Clark, of course, knew this all along.

3.2. Bandwidth Synthesis

The accuracy of interferometrically determined delays is on the order of $\Delta\tau \sim 1/B$, where B is the bandwidth, which for the early systems was only about 1 microsecond. By analogy with resolution depending on total spanned aperture, the delay resolution depends on the total spanned bandwidth, not the instantaneous bandwidth with its potential ambiguity problems. Rogers (1970) conceived of and built the first bandwidth-synthesis interferometer for astrometric and geodetic VLBI. The system was implemented by sequentially cycling the local oscillator among seven frequencies. Fortunately, the early HP synthesizer had the property that its signal remained coherent even after it was switched to another frequency and back. This system turned out to be very useful for masers, whose frequency spans often exceeded the bandwidths of the MKI and MKII systems. Time-multiplexed systems are obsolete now with the wide-bandwidth channelized systems like the MKIII and VLBA.

3.3. Spectral Phase Referencing

The concept of using the phase of a particular frequency component of a spectral line source as a reference was first applied to the OH maser data by Moran et al (1967b). For a long time in VLBI, this technique was used only to measure relative fringe rates to high accuracy. Full advantage of the technique was taken for water masers by Walker et al. (1978), and for OH masers by Reid et al. (1980). Although maser clusters have the advantage of providing reference features within $< 1''$, there are certain difficulties caused by the difference in frequency between the reference and referenced features that limit the ultimate accuracy of the technique (see Thompson, Moran, & Swenson 1986). This effect does not arise in continuum phase referencing.

3.4. Phase Closure and Self-Calibration

In the early 1970s continuum VLBI seemed to be at an impasse. With rather poor *uv* coverage and no phase information, the analyses were limited to non-unique solutions of multiple-component models. That situation changed dramatically in 1974 with the rediscovery of the phase-closure condition by Rogers et al. (1974) (originally used by Jennison 1958), and the introduction of the CLEAN algorithm by Högbom (1974). Thus began the steady development of image restoration techniques that continues today. A critical development was the introduction of iterative schemes variously called hybrid mapping or self-calibration, which made use of both amplitude and phase closure, CLEAN, and various image constraints (see Pearson & Readhead 1984). Recently these techniques have been adopted by some workers in optical interferometry.

3.5. Water Vapor Radiometry

The importance of water vapor to radio wave propagation through the atmosphere was dramatically illustrated by the failure of the MIT Radiation Lab's 1.3 cm radar during WW II (Kerr 1951, Buderi 1996). Subsequently, careful measurements of the 6_{16}–5_{23} water vapor line were made by Dicke et al. (1946), which they were later compared to the theoretical calculations of Van Vleck (1947). The observations were made with a load-switching gain stabilization technique now known as Dicke switching. Since then, a vast literature of both experiments and theory has appeared on this subject, but a full understanding of the physics has still not been achieved.

The basic concept of correction for atmospheric propagation is simple: by the Kramers-Kronig relation, the real and the imaginary parts of the index of refraction in any atomic or molecular transition are related by a Hilbert transform, so that absorption and phase shift are closely related. Water vapor in the lowest 2 km of the atmosphere is mainly responsible for the fluctuating component of phase shift. Unfortunately, the vertical distribution of water is highly variable. Hence, the correlation between phase shift and atmospheric emission is not perfect, due to pressure and temperature effects. Methods of the extraction of water vapor content from radiometer data were analyzed by Waters (1967) and Schaper, Staelin, & Waters (1970). However, the first attempts to measure a correlation between phase and water vapor content using the NRAO interferometer with two 22/19 GHz radiometers were disappointing (Waters 1971). Subsequently, substantial efforts were made by the geodetic VLBI community to make atmospheric-delay calibration corrections with radiometric measurements. The demonstrated accuracy based on global analysis is about 5 mm (Elgered et al. 1991).

There has been renewed interest in atmospheric calibration for extending the coherence of millimeter VLBI systems and for calibrating millimeter-wavelength connected-element interferometers. The efforts to correct the phases of millimeter interferometers with measurements made along the direction to the source being observed have met with considerable success. Three approaches have been pursued: 22 GHz water-line observations (OVRO); 183 GHz water-line JCMT; and continuum observations in atmospheric windows (BIMA, IRAM). Selected observations with fitted scale factors have led to rms phase correction over 1 hour to a level of 130 microns (Woody, private communication). Further development of these techniques are crucial to the success of such instruments as the SMA, MMA and millimeter VLBI systems.

4. The Future

Our technique has matured from its modest start of the quick hookup of existing telescopes at a cost of $\sim\$10^5$ to grand projects costing $>\$10^8$ and taking 20 years or more to bring to fruition (e. g., VLBA, OVLBI). The focus has moved from solely measuring fringe amplitudes to precise imaging and motion studies which rely principally on phase. One negative aspect is that, although in the early 1970s it seemed that a common recording technology was within our grasp, now commonality is farther off than ever. Perhaps the diversity of recording systems is in keeping with human nature.

In the future, receiver sensitivities will improve, approaching the quantum limit, bandwidths will increase, and coherence time will be lengthened. The maximum frequency is now 230 GHz, and that will undoubtedly move higher. The success of HALCA will lead to more ambitious instruments in space. One such project, ARISE, is already on the drawing boards. We shall hear about some of these developments at the next VLBI symposium 4 ± 0.4 years from now.

Acknowledgments. I thank Ken Kellermann for helpful discussions.

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