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Breaking the Milliarcsecond Resolution Barrier

K. I. Kellermann
National Radio Astronomy Observatory[1]
520 Edgemont Rd., Charlottesville, VA, 22903, USA
E-mail: `kkellerm@nrao.edu`

Using the MK I VLBI system in a series of experiments of increasing baseline length and angular resolution, the milliarcsecond barrier was passed within two years of the first successful VLBI observations. The MK II VLBI system gave more portability, increased bandwidth, and longer observing time, but was plagued by poor data quality until the adoption of consumer VHS TV recorders.

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1. Background

Following the recognition of discrete radio sources, it was generally thought that the radio emission originated in stars. Hence, they were called *radio stars,* and so they were thought to have angular dimensions of the order of a milliarcsecsecond or less, and that interferometer baselines of thousands of miles would be needed to resolve the discrete radio sources.

Building a conventional interferometer with such long baselines was clearly beyond the state of the art in the 1950s. Hanbury-Brown and Twiss [1] developed their famous intensity, or post detection, interferometer with the aim of implementing the transatlantic baselines though to be needed to resolve radio stars. In spite of broad skepticism that their proposed technique was theoretically feasible, they successfully demonstrated that their post-detection interferometer actually works.[2] However, it was soon recognized that the discrete radio sources were actually extragalactic. Radio linked interferometry at Jodrell Bank [2] showed that that few radio sources had angular dimensions under one arcsecond.[3] So there was little motivation to pursue post-detection interferometry to obtain high angular resolution in radio astronomy

Hanbury-Brown and Twiss went on to successfully develop the intensity interferometer technique at optical wavelengths, where they were able to measure the diameter of a number of stars, and also revolutionized our understanding of fundamental physics of waves and particles.

Nevertheless, the first successful long baseline observations at radio wavelengths using unconnected antenna elements were made using post detection correlation interferometers. In 1965 a group at the University of Florida used simple audio tape recorders and independent crystal oscillators to study the size of the decametric Jupiter bursts at 18 MHz over a 55 km baseline (3300 λ) [3]. Later Gubbay et al. used an intensity interferometer at 13 cm over a 1,170 km (9 x 10^6 λ) baseline between two stations in Australia and were able to show that the quasar 3C 273 had angular dimensions less than 0.01 arcsec [4].

The first discussions of coherent independent-oscillator-tape-recording-interferometry were by Matveenko et al. [5][4] and Slysh [6]. Although there were some discussions between Russian and British radio astronomers about implementing a VLBI system between Russia and Jodrell Bank, the required precision frequency standards and high speed tape recorders were not then readily available in Russia or the UK. However, in 1965, motivated by the observed high synchrotron self absorption spectral cutoff frequencies as well as the reported variability and evidence for interplanetary scintillations, both Canadian and American teams independently began the development of VLBI systems. The Canadians used hydrogen masers as frequency standards and analogue studio TV recorders to record a 1 MHz IF band at 448 MHz [7,8.9.10.11],

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[2] I remember when Hanbury-Brown came to Caltech, I think in 1961, and gave a Physics Department colloquium. As was their tradition, the professors all sat up front in the first row. Richard Fineman, as was his usual practice, hecked the speaker and informed him, that post detection interferometry is theoretically impossible. Hanbury responded, “Yes, I know. But, we built it anyway, and it worked.”

[3] Of course if the radio-linked interferometry had been done at centimeter wavelengths, they would have discovered the existence of compact flat spectrum radio sources, and history might have been very different.

[4] The intrigues of the Russian paper are given in a separate publication in this volume by Matveyenko.

while two U.S, teams elected to record digital data and used much less expensive Rubidium frequency standards.

2. MK-I

The NRAO-Cornell *MK I* VLBI system was initially conceived over a pitcher or two of beer by Marshall Cohen and the author, but it was mostly Barry Clark who made it happen. We were soon joined by Dave Jauncey who had just arrived at Cornell with a strong background in experimental cosmic ray physics and by Claude Bare who designed much of the digital hardware. The *MK I* concept was more conservative than the more ambitious Canadian plan. Following Sandy Weinreb's development of the one- bit digital autocorrelation spectrometer, we recorded only one-bit data. Each bit was recorded at a precisely define time, so we did not have to worry about timing inaccuracies introduced by deformation of the magnetic tape. However, we paid a big price in sensitivity for this since the only digital recording system available to us was a standard narrow-band computer tape drive. We were able to record only a 330 KHz bandwidth with a Nyquist sampling rate. Including overhead, we recorded at 720 kbps. A standard 10 ½ inch reel of half inch computer tape lasted for only 200 seconds. It was an adventure to rewind and dismount each tape, mount a new one, and be ready for the next observation. With practice, one learned to complete the cycle in seven minutes, but a ten minute cycle was a bit more typical. A two day run could fill up several hundred tapes which then had to be shipped for correlation.

Correlation was done in a general purpose computer initially using a program written by Barry Clark. This was 40 years before the present generation of software correlators [12, 13]. Correlation of a pair of three minute tapes took almost an hour with the NRAO IBM 360/50 machine in Charlottesville, but only ten minutes on a model 360/75. Marshall Cohen managed to get some funny money to use the Caltech IBM 360/75, provided we worked only at night when no one else was using the computer. I recall many nights at the Caltech computing center with Marshall working through cartons containing hundreds of tapes.

Since we could not afford Hydrogen masers, our local oscillator system was based on HP Rubidium frequency standards. The 5 MHz output of the frequency standard was multiplied by a factor of 122 to obtain our 610 MHz local oscillator. Since we were concerned about coherence, we were conservative in choosing an initial operating frequency of 610 MHz which was still a somewhat higher frequency than the 448 MHz used by the Canadian group. Later, on order to minimize the short term phase noise, we sometimes tried to lock a commercial high quality crystal oscillator to the 5 MHz output from the HP Rubidium standard using a variety of time constants. Time synchrozation was obtained by transporting clocks, or by using the 100 khz Loran-C transmissions which were available throughout the North Atlantic region.

With such a narrow bandwidth and an integration time limited by coherence we anticipated that we would need all the collecting area we could get, so we planned to start with the baseline between the Green Bank 140-ft and Arecibo 1000-ft radio telescopes. In late 1966 we shipped several thousand pounds of equipment and tapes to Puerto Rico, but the shipment somehow got lost on the way. After locating everything in a Pan American Airlines warehouse in Baltimore, it was all shipped on. But, there were no fringes, so everything was sent back to NRAO, inspected, and returned to

Arecibo. Again there were no fringes, so it was clear that we needed to start with a less ambitious baseline. On the night of March 6/7 1967 a local test of our independent-oscillator-tape-recording interferometer using short baseline between the 140-ft and one of the Green Bank interferometer 85-ft antennas was successful. On March 8, an interferometer between Green Bank and the NRL Maryland Point 85 ft antenna was successfully implemented over a 220 km (450,000 λ) baseline [14]. Meanwhile an MIT group had developed a compatible VLBI system to observe maser sources. The NRAO-Cornell and MIT groups teamed up to observe at 18 cm using an 845 km ($5 \times 10^6 \lambda$) baseline between the 140-ft and Haystack antennas. The NRAO-Cornell group observed quasars [15] and the MIT group OH masers [16]. The resolution was ~0.01 arcsec, and confirmed the small angular dimensions predicted by the spectral cutoff and variability which had been observed in many quasars. We quickly improved the resolution by using the Hat Creek 85-ft antenna along with the 140-ft; a baseline of 3500 km, ($20 \times 10^6 \lambda$) so that we were able to resolve sources bigger than about 0.01 arcsec [17]. The Canadian group stayed with 448 MHz, so never approached the mas barrier.

Regrettably I managed to miss all of the excitement, as I went to Europe after the first unsuccessful Arecibo run for a six month leave of absence. We never did figure out what went wrong with the 610 MHz Arecibo observations, although we suspected the phase lock system in the local oscillator chain. However, in August and November, 1968 we successfully ran the Green Bank to Arecibo baseline, but using a more conventional local oscillator set–up [18].

3. International Adventures

Even on the transcontinental baseline, some sources remained unresolved. We anticipated that by going to shorter wavelengths and higher resolution, that we could find even smaller structure that was too weak to observe at the longer wavelengths due to synchrotron self absorption. But where could we find a suitably distant antenna that would be available. Coincidently, at this time, we became aware that the radio astronomy group at the Onsala Space Observatory, led by Olaf Rydbeck, was keen on getting involved in VLBI. With Rydbeck's support at the Observatory and in getting our stuff through Swedish customs, in only a few months we organized the first transatlantic VLBI which was carried out in January, 1968. We observed at both 6 and 18 cm using the 140-ft together with the Onsala Observatory 85-ft antenna over a baseline of 6319 km ($105 \times 10^6 \lambda$ at 6 cm) to detect structure as small as 1 milliarcsecond [19]. In mid 1969, we also initiated observations between California and Australia [20].

The transatlantic and transpacific baselines are about the longest baselines that can be achieved from the surface of the earth. Somewhat longer physical baselines are possible, but at the expense of common visibility. It was clear that if we wanted to continue to improve the angular resolution, we would need to go to shorter wavelengths. At the time, the only antenna known to us outside the United States which could work at short centimeter wavelengths was the 22-m precision antenna located near Moscow in the USSR.

Marshall Cohen and I had each previously met Victor Vitkevitch who was the Director of the Soviet observatory. On somewhat of a lark, we wrote to him proposing a US –USSR VLBI observation at short centimeter wavelengths. At the time, we were unaware of the early paper by Matveenko et al., and certainly did not appreciate the immense logistical and political problems in both countries that would be involved in penetrating the iron curtain. We were not particularly surprised or disappointed when we initially received no response to our letter, but six months later we were very surprised to receive a telegram from Viketvich accepting our proposal, but he suggested that instead of the 22-m antenna near Moscow, that we use the 22-m antenna in Crimea.

The first of several experiments was run in October 1969 at 2.8 and 6 cm over a baseline of 8,000 km [21]. At 2.8 cm, the angular resolution was 0.4 mas. We had finally broken the milliarcsecond barrier. In working with the USSR in the 1969 we encountered enormous technical, logistical, and political challenges. But, in the end there was good-will and cooperation from both sides at all levels, from supporting staff to the Directors of NRAO and the Lebedev Physical Institute, and apparently at high military and government levels as well.

The collaboration established more than 40 years ago between the USSR and the United States has continued and expanded with now routine VLBI between Russia and other parts of Europe and Asia as well as with the U.S. A dedicated VLBI network, QUASAR, has been established in Russia, and after more than 3 decades of planning, RadioAstron has been successfully launched and is giving record breaking resolutions. A complete account of our adventures associated with the collaboration with the USSR was reported by Kellermann [22] and Matveenko gives more background information in his paper in this volume.

4. MK II

The *MK I* VLBI system was very effective and produced many exciting new results, not only by our AGN/quasar group, but also by the MIT group doing OH and H_2O maser studies, but there were many drawbacks. The bandwidth and thus the sensitivity was limited; the computer tapes were heavy and expensive to ship; tapes only lasted for a few minutes, and correlation was very slow in a general purpose computer, and very expensive if one had to pay real money for the computing time. We became aware of a broad band TV recorder, the Ampex VR 660C that looked suitable for VLBI and only cost about $6,000. Barry Clark built a hardware correlator, first with just two playback stations, but latter modified to handle three simultaneous inputs. When it worked well, playback was accomplished in real time. But that was infrequently.

Allen Yen, from Toronto, had warned us that the Canadian group had tried the VR 660C, but had experienced many problems. Since we planned to record digital data, we thought we would be immune to small tracking errors that plagued our Canadian colleagues. How wrong we were. The VR 660C was a transverse recorder using two inch wide tape. The tape moved relatively slowly, past a rapidly spinning wheel containing the record/playback heads which allowed us to record a 4 Mbps data stream which Nyquist sampled a 2 MHz bandwidth. However, playback of the data was very sensitive to the alignment of the tape and the record/playback head wheel, and it was necessary to carefully and frequently adjust multiple interdependent alignment screws to achieve satisfactory playback. To exacerbate the problem, we obtained hundreds of surplus magnetic tape at no cost, but we did not understand, until several years had passed, that these tapes were made for longitudinal not transverse recording, so their grains were misaligned and so the SNR was significantly degraded. Several thousand pounds of these tapes are still buried in Green Bank.

We later learned about a new transverse TV recorder was on the marker, the IVS 825 which used one inch tape. It worked much better than the Ampex machine. The real breakthrough came as a result of Allen Yen's innovative modification of inexpensive consumer type VHS TV recorders. Allen engineered this system during visits to Caltech, NRAO, and MPIfR during the 1970s. The VHS based *MK II* VLBI system was an instant success. For a few hundred dollars it was possible to have a VLBI recorder; tapes cost only a few dollars each. Dozens of VHS recorders were modified at Caltech and NRAO and became operational around the world. Multi-station correlators were built and operated at NRAO, Caltech, Bonn, and later in Sydney.

Richard Schilizzi arrived at Caltech in 1973 and immediately took an active role in the program which Marshall Cohen had organized to obtain milliarcsecond images of what are now called blazars, and to study their motions. We observed primarily at 2.8 cm mostly using the Green Bank 140-ft, the OVRO 130-ft, and the Harvard 85-ft antenna located near Fort Davis, Texas, but sometimes we also used the 150-ft antenna at the Algonquin Radio Observatory in Canada, and the MPIfR 100-m antenna in Germany. In spite of the record/playback problems discussed in the previous section, we obtained the first milliarcsecond resolution "images." The data were analyzed by looking at fringe visibility plots and locating the maxima and minima in the u,v plane to determine the basic structure and orientation in the sky. Guided by the location of the fringe visibility extrema we all learned to do simple qualitative Fourier transforms in our head, and we fit simple models to the data using only amplitudes and no phase information.

The results of this program were reported in three papers published in 1975. The first paper by Cohen et al. [23] described the techniques, and the second and third papers by Shaffer et al. [24] and Schilizzi et al. [25] reported on the results. Paper II concentrated on five sources with relatively simple structure. In Paper III, Richard tackled some of the more complex structures. He managed to come up with models of the highly variable source 3C 120, the quasar 3C 273 and GPS source Parkes 2134+004 which bear reasonable resemblance to current images of these sources. However, the structure of the radio galaxy 3C 84 (NGC 1275) was too complex for our limited data and these simple analysis techniques. After discussing the location of the various maxima and minima, Schilizzi et al. could only report that *no simple model could be found which fits all the data.* Soon after, Richard departed Caltech for the Netherlands, where he started VLBI, built up JIVE as its first Director, and took the first tentative steps toward space VLBI.

Further details of the development of the MK I and MK II VLBI systems and early observations have been given by Kellermann and Cohen [26].

5. Lessons Learned

Measure twice; cut once.[5] *A one element interferometer is like half a pair of scissors.*[6] Many of the earlier VLBI experiments did not give fringes due to timing errors as large

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[5] Unknown wise carpenter

as 1 second, unlocked or wrong local oscillator setting, or crossed polarization. In some cases the problem was never found. We would like to think that VLBI is now sufficiently mature that these things don't happen anymore; and mostly they don't. But, I am aware of at least one case of crossed polarization that occurred as recently as 2012.

Bad data is worse than no data. Good data is like the cool evening breeze.[7] It seems that invariably, one spends 90% or the time trying to save the 10% of the data that for one reason or another is of poor quality; and in the end usually the 'bad" data can't be used anyway.

You get what you pay for. We wasted a lot of time, effort and money trying to resurrect bad data especially from the recordings made on the surplus magnetic tape using VR660C machines. It would have been much easier if at the start we had invested in decent tape in high performance recorders.

Trust your data. We went into the VLBI business with the preconceived idea that compact radio sources could be described by circular Gaussians. Since poor coherence and experimental errors can only lead to reduced amplitudes, we ignored low visibility points. It wasn't until the highly redundant "Goldstack" [27] observations that we had any confidence in low points which indicated spatially separated components in 3C 273 and 3C 279.

Beware of bureaucrats and self appointed experts. While we were still planning the first *MK I* system, we had a visit to NRAO, by G. Winkler, the Director of the of the US Naval Observatory Time Division who told the Dave Heeschen, the NRAO director, that our proposed interferometer system would not work because even the best frequency standards were not sufficiently accurate. He did not understand that absolute accuracy was not an issue, and that only relative stability over a few minutes of time would be adequate. Fortunately, Dave Heeschen didn't listen to him. We also had problems with a referee of an early paper who complained that we did not describe how an interferometer works over a curved surface. I replied that the ends of the interferometer, like all pairs of points, defined a straight line.

Listen to advice: For years Alan Moffet would ask me, "Why don't you make use of phase closure." I knew about the famous paper by Jennison [28] but I did not understand how to actually use it to make images, until the papers by Readhead and Wilkinson [29] and Cotton [30] were published, so I sort of ignored Al's good advice.

Those early years were great fun. We got to travel a lot and made good friends around the world, although for decades the NRAO Director would ask me to explain why it was necessary for Marshall Cohen to come to Green Bank and I to Owens Valley to support a certain early experiment. We learned about making international phone calls, how to operate telex machines even those with non Latin character keyboards, and the intricacies of using air freight. We learned to distinguish between real LORAN

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[6] George Purcell, 1973, Caltech PhD Thesis

[7] Marshall Cohen, date unknown

signals and an unadvertised Soviet copy operating in the Baltic Sea. We also became experts on import/export regulations and tariffs. I recall one occasion when Marshall Cohen and I drove a truck to LAX to collect some tapes that had just arrived from an experiment with Australia. The customs officer wanted some huge amount of money, although we carefully explained that the tapes were ours – in fact the property of the U.S. government and we had only sent them to Australia a few weeks earlier. We even had the shipping bill with us. "No matter," he explained. "You sent out blank tapes and now they contain information and so are more valuable and you have to pay the tax." He went on to explain that this happens all the time with Hollywood when they send out blank film, they have to pay tax if they bring it back after filming a picture abroad. We tried to explain that our tapes only contained noise and no data, but realized that sounded pretty weak if we were going to through the process and expense of sending them out and back. Finally, he decided that he wasn't getting anywhere with us, and we did not have the same deep pockets as Hollywood producers. He asked us if our data was anything like oil exploration data for which they hadn't yet established a tariff. We agreed that it was, and he let us go with our tapes.

6. Acknowledgements

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