Proceedings of the 7th European VLBI Network Symposium
Bachiller, R. Colomer, F., Desmurs, J.F., de Vicente, P. (eds.)
October 12th-15th 2004, Toledo, Spain

A Review of VLBI Instrumentation

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Abstract. The history of VLBI is summarized with emphasis on the technical aspects. A summary of VLBI systems which are in use is given, and an outlook to the future of VLBI instrumentation.

1. Introduction

1.1. On the Way to VLBI

Due to the length of radio waves the resolution of filled aperture telescopes is much more limited in radio astronomy than in the optical domain. Early on it was realized that in the radio higher resolution could be achieved by using interferometers.

Michelson or phase-sensitive interferometers need relative phase-stability between the two receiving elements. Initially radio interferometers used a common frequency-standard, whose signal had to be transported to each interferometer element by cable, waveguide or micro-wave link. This meant that the separation of the receiving elements could not be expanded beyond about 100 km, as the atmospheric conditions prevent longer phase-linked baselines via micro-wave transmission.

In the fifties of the last century in addition to conventional Michelson interferometers so-called intensity interferometers were developed, in which the intensity fluctuations of the incident radiation received at widely separated antennas were cross-correlated. Due to the low requirements for phase-stability independent local oscillators could be used and therefore longer baselines were possible. The data could be recorded at each telescope and correlated later. The disadvantage of this incoherent form of interferometry is its low sensitivity and the lack of phase information which makes it difficult to obtain images (Kellermann & Moran 2001).

In the early sixties the Jodrell Bank radio linked interferometer had reached a baseline length of up to 127 km with a resolution of better than $1''$ at 21 cm (Anderson et al. 1965). These and other observations showed that some radio sources were still unresolved. Longer baselines were needed.

Discussions about the feasibility of interferometry with very long baselines were also begun in the early sixties (Matveenko et al. 1965), the main problems being the need for independent local oscillators and the necessity to record the data at each antenna prior to correlation. The local oscillators had to have sufficient time stability, so that the phase relationship between the elements of a VLB Interferometer remained constant for some time and would allow the integration of the correlated signals. A data recorder should allow data-rates as high as possible while being still affordable for astronomers.

Technical developments in the middle of the sixties led to new frequency standards like Rubidium frequency standards and Hydrogen masers with stabilities of 10^{-11} and 10^{-14} respectively, good enough for VLBI observations at cm wavelengths. Relatively cheap tape recorders for television and computers appeared on the market, too. This led several groups to think about developing Very Long Baseline Interferometry systems.

1.2. VLBI-Specific Features

A general feature of tape recording interferometers is that the data has to be marked with the time of its arrival at the antenna. The time marks are best written together with the data onto the recording medium. This will allow to recover the arrival time of the data at the correlator. Before correlation, the clock offsets have to be determined as precisely as possible with the help of radio timing signals (Loran C before GPS became available) or with traveling high-precision clocks.

A VLBI specific problem is the “detection” of the fringes. They can only be found if signals from the same wavefront are correlated with each other. The width of the fringes, or the relative time delay between two played-back recordings which gives a detectable interference signal, is proportional to the reciprocal bandwidth. This means in general that the two playbacks have to be synchronized to much better than a microsecond, in contrast to the geometrical delays of up to several milliseconds which have to be taken into account as well, and which are due to the figure of the earth and its motion, and the position of the radio emitting object. All this is aggravated by the fact that the clocks at the two antennas are independent and their relative offsets are not known a priori. As a result correlation has to be done at several “trial” delays around the expected value to make VLBI possible at all.

Another difference to local interferometers is the high rate of the fringes which can be understood as the Doppler shift between the widely separated antennas (or the rate of change of the delay), which is introduced by the earth’s rotation. In an early paper (Matveenko et al. 1965) the authors had erroneously concluded that this “natural” fringe-rate would reduce the integration time to less than a fringe period. A solution is to either remove this Doppler shift at the stations or determine and remove the “natural” fringe-rate at the correlator.

The last peculiarity is the determination of the precise delay and delay-rate of the interference maximum after the correlation with the so-called “fringe fitting”.

2. Historic VLBI systems

In 1965 efforts to design and build a VLBI system were started by different groups. First fringes were found in 1967 after considerable effort.

2.1. The Canadian Analog VLBI System

The system used hydrogen masers as frequency standards, and studio TV recorders to record analog a 4 MHz band. To allow synchronization at playback 1-second ticks and spoken time marks were used. A single 2″ tape lasted for about 3 hours. Fringe rotation and phase-tracking correction was done at the time of recording; adjustments were done manually.

For correlation the tapes had to be aligned manually with the help of the audio time information. The assumption of the Canadian group that the stability of the recorders was good enough to maintain synchronization did not prove to be valid. Nevertheless fringes on a 3000 km baseline were found in spring 1967 (Broten 1988).

2.2. The MK I Digital VLBI System

A NRAO-Cornell group designed a digital VLBI system based on modified computer tape drives. The 7-track tape units could record a 330 kHz band, 1-bit sampled at a total bit-rate of 720 kbits/s. 1-bit sampling was chosen as it gives the highest SNR in a bit-rate limited environment. For spectral line observations where the width of the line may be small compared to the total recordable bandwidth, 1-bit sampling is not optimal though.

A single computer tape lasted for about 150 seconds, so that 20 tapes were needed per site and hour. The data were correlated with a general purpose computer. To correlate one pair of tapes initially took about one hour of computer time. The data could easily be synchronized in the computer, and the exact time of each bit could be recovered as long as the bit count was not lost. First fringes were found in spring 1967 (Bare et al. 1967).

At about the same time a group at MIT-Haystack built a compatible recording system and successfully observed OH masers with VLBI (Moran et al. 1967). Due to the narrow line width and relative strength, OH masers have the advantage that the precision for the time synchronization is only a few hundred microseconds compared with the microsecond accuracy needed for continuum sources.

Already in early 1968 the first intercontinental (global) VLBI observation with 3 antennas (Green Bank, Haystack, Onsala) was performed. In 1970 the maximum baseline length achievable on earth of more than 10000 km was reached. At the same time the observing frequencies were increased from initially 610 MHz to 10.6 GHz (Cohen 2000; Kellermann & Moran 2001).

Geodetic VLBI observations were started in 1969. The frequency synthesis technique was introduced to significantly increase the precision of the delay observable – the primary geodetic measurand. Already at that time phase-referencing was discussed as a possibility to extend the coherent integration time.

More multi-baseline observations were performed, and in 1971 superluminal motion was discovered (Whitney et al. 1971). The bottleneck in VLBI observing with the MK I system was the correlation. It had to be done on fairly expensive general purpose mainframe computers.

2.3. The MK II VLBI system

In about 1971 NRAO introduced the MK II VLBI system (Clark et al. 1972) which used AMPEX 2″ video recorders, modified to record digitized signals. The recorded bandwidth was 2 MHz at a bit-rate of 4 Mb/s. The correlator was implemented in hardware. The fringe rotation was done now at the correlator because the higher observing frequencies, longer baselines, and longer integration times required a continuous, precise, and reliable tracking of the effects of the earth's motion. Another major argument for this change in concept was to keep the recording site as simple as possible: correlation can be repeated, observing not unless all stations re-observe.

By the middle of the seventies the 1-baseline correlator had been expanded to two and three stations. In addition the number of correlation lags had been increased from 32 to 512, which was important for spectroscopy. Initially it was very difficult to mechanically align recording and playback machines such that the data could be played back with reasonably low error rates. The situation improved when 1″ IVC recorders were introduced.

A copy of the NRAO 3-station correlator was installed at the MPIfR in Bonn in 1978. The correlator situation further improved when Caltech built a 5 station MK II correlator. Later Caltech built a 16-station correlator which was then enhanced to correlate MK III data.

The MK II system became a very convenient and cheap VLBI system when at the end of the seventies VCRs replaced the IVC studio video recorders. In 1979 the first 7-station global VLBI experiment was observed (Romney et al. 1982). At about the same time the last 2″ Ampex recorders were taken out of operation.

2.4. The MK III VLBI system

The MK III VLBI system (Rogers et al. 1983) was developed by MIT Haystack Observatory in the late seventies. Instrumentation tape recorders with 28 tracks were used to record 1-bit digitized data on 1″ wide tape stored on 14″ open reels. As each single track could record up to 8 Mb/s the maximally recordable bandwidth was a factor 56 and the sensitivity a factor of about 7.4 larger than that of the MK II system. Different recording modes with lower bit-rates were possible.

Due to its 14 independently tunable baseband converters the MK III system was well suited for geodetic VLBI observations in which bandwidth synthesis is used to increase the spanned bandwidth, improving the precision of the measured delay (Rogers et al. 1983; Whitney 1988). The a priori unknown phase of the individual channels can be calibrated with the phase calibration signals. A comb of sharp pulses with a separation of 1μs are injected in the signal path, preferentially as close to the receiving horn as possible. In the frequency domain these pulses correspond to sine-waves at every MHz. The injection point of the phase-cal is also the reference point for the wide-band or multiband delay, and thus the reference point for geodetic VLBI measurements.

In 1979 a 1-baseline correlator became operational which was soon extended so that 3 or 6 baselines could be correlated simultaneously depending on the recording mode. A copy of this correlator was installed at the MPIfR in Bonn in 1982. A new and more powerful version called MK IIIA with 6/12 baselines capacity was developed at the end of the eighties and installed at Haystack, USNO, and MPIfR. All MK III correlators models had a baseline-based architecture. In 2000 they were finally replaced by MK IV correlators.

In 20 years of MK III operation 3 different kinds of tape material were used. The error rates of the original instrumentation tapes was not very good. It was replaced when video tape on 14″ reels became available on the market. The tapes were 9000 feet long and could hold about 10 GB of data, and lasted 6.5 minutes at the highest recording speed with a bitrate of 112 Mb/s. MK III recording was very expensive untill the introduction of movable record/playback heads with narrow tracks (55μm wide) increased the tape capacity by a factor of 12 (MK IIIA system). The need for 24 hours of unattended recording at the VLBA forced the introduction of the so-called thin tapes – a metal particle tape – which has a length of 17600 feet and allows a higher bit density. The capacity of the thin tapes is nearly 600 GB.

2.5. The Canadian S2 System

In Canada a first report on a VCR based VLBI system with a recording bit-rate of 12 Mb/s was published in 1988 (Yen et al. 1988). Later the S2 system was realized with professional-model VCRs recording at 16 Mb/s. By using 8 VCRs in parallel a total bit-rate of 128 Mb/s can be recorded. A lag-based modular and station-based correlator for the S2 system was developed (Carlson et al. 1999) for supporting both the S2-based space VLBI observations in the Japanese-led VSOP mission and the Canadian Geodetic VLBI program. The S2 VLBI system found widespread use also in Australia.

2.6. Japanese VLBI Systems

In Japan the development of VLBI systems began with the K-1 in 1976. In the eighties the K-2, K-3, and K-4 systems followed. The K-3 system which was developed in 1983 was fully compatible with the MK III system, and it included a 1-baseline correlator. The K-4 system is based on a commercial cassette-based helical scan recorder from Sony Corporation. The initial version used only 1-bit sampling. It was later enhanced to multi-bit sampling and purely digital filtering. The system can be configured for various recording modes of which many are compatible to MK III and VLBA modes with bit-rates up to 256 Mb/s (Kiuchi et al. 1997). Together with a 10 station FX correlator it supported the VSOP mission.

2.7. Other Early VLBI developments

2.7.1. Real-time VLBI

Already in 1976 a real-time link via a satellite was used to provide a communication channel between radio telescopes in West Virginia and Ontario. This system allowed instantaneous correlation of the data as well as a sensitivity substantially better than that of earlier VLBI systems, because a broader observational bandwidth could be used. Yen et al. (1977) showed that with the use of a geostationary communications satellite it was possible to eliminate the tape recorders and to do real-time correlation of a VLB interferometer. As a further possibility they mention the development of a phase-coherent VLB interferometer.

2.7.2. Multi-view VLBI

Hemenway (1974) used four antennas at 2 sites for astrometric and geodetic VLBI measurements. His interferometer had 2 simultaneous beams on the sky which helps to eliminate the unknown contributions to the signal paths caused by the ionosphere and troposphere. This observing method was later successfully used also with 3 antenna sites and 3 to 4 telescopes per site and the MK III recording system (Rioja et al. 2002; Porcas et al. 2003).

The advantages of multi-beam VLBI have also been realized by the geodetic community. By having multiple beams in different directions, parameter correlations could be reduced and parameters of interest could be determined more quickly and accurately (Petrachenko et al. 2002).

2.7.3. LO Transfer via Satellite

In 1982 a satellite was used to transfer the LO signal in a phase coherent way between remote stations of a transcontinental VLB interferometer (Knowles et al. 1982). Phase-degrading effects of the atmosphere were mostly canceled out with a dual-tone transmission method. A stability of 10^{-13} was achieved over a 1-hour period with indications that the link was truly phase stable at frequencies of less than 1 GHz.

2.7.4. Near Real-time Fringe Verification

With the MK III system it was possible to extract about 1 Mbit of data in the MK III decoder of the record terminals. This data could be transfered to one of the correlation centers at Haystack or Bonn by modem, where it could be correlated in software to verify the presence of fringes. As modems were very slow in the early eighties this method was not used very much and was given up later, as it was realized that careful checkout of the VLBI equipment before an observations was more likely to guarantee the success of an observation.

3. Today's VLBI systems

3.1. *The VLBA system*

As a dedicated VLBI array with 10 equal antennas the VLBA offers reliable performance with good amplitude calibration and easy data reduction. The VLBA correlator can handle up to 20 stations in parallel with high spectral resolution of up to 1024 spectral points. The VLBA system has 8 frequency channels and can record either 1-bit or 2-bit sampled data. These differences to the MK III system reflect the primary drivers for the development of each system: geodesy in the MK III case (bandwidth synthesis) and astronomy for the VLBA (2-bit data for spectroscopy and no need for many channels). The correlator architecture is of an FX type; unlike most other VLBI correlators the data is first Fourier transformed and then cross multiplied. In particular at the time of its design the FX approach had some advantages over the XF correlator design (Romney 1999). The correlator can do pulsar gating. The maximum total bit-rate per station is 256 Mb/s.

The VLBA recording/playback system is based on the MK IIIA recorder, but with completely redesigned control and record/playback electronics to improve its reliability. 32 tracks plus 4 so-called system tracks can be written in 14 passes onto a thin tape. In order to make the system less sensitive to individual lost tracks there is no fixed assignment between bitstream and tape track. The assignment is changed in a round-robin fashion called barrel-rolling. At the standard VLBA recording bit-rate of 128 Mb/s a tape lasts nearly 12 hours, making unattended operation possible as each VLBA station is equipped with 2 recorders. The maximum bit-rate of 256 Mb/s which used to be only marginally higher than that of the MK III system can now be increased to 512 Mb/s if the 2 recorders of each VLBA telescope are scheduled to record data in parallel.

3.2. *The MK IV data acquisition system*

The MK IV data acquisition system is mostly an upgrade to make MK III more compatible with the VLBA system. The MK III baseband converters were equipped with 8 and 16 MHz filters, the formatter was replaced by a MK IV formatter which can sample the data with 1 or 2 bits, and the recorder was modified to read and write 32 tracks with or without barrel-rolling. Beyond those compatibility modifications it was envisaged that the system should be able to record 512 and even 1024 Mb/s. The recorders have a 2nd write head for this purpose, but they were not capable of recording reliably at 320 ips, as required for 1024 Mb/s. Recordings at 512 Mb/s have been done in the European VLBI Network, but the 2-head recording mode needed for 512 Mb/s is prone to failures.

Four MK IV correlators became operational at the turn of the millenium. They had been developed by a consortium of several institutions in the USA and Europe. The correlator is of an XF architecture. It has inputs for up to 16 stations with a maximum of 16 channels per station. The correlator is software configurable. Cross- and auto-correlations from 32 to more than 1024 lags can be chosen, serving both continuum and spectral-line needs.

The 3 correlators in Haystack, Washington, and Bonn operate with software developed by Haystack Observatory. They are either exclusively dedicated to geodetic observations like the correlator at USNO, or are used for both astronomical and geodetic data. The correlator of the European VLBI Network at the Joint Institute for VLBI in Europe has twice the correlator capacity of the other MK IV correlators. It operates with software originally developed by Jodrell Bank personnel. It is dedicated to the correlation of astronomical data.

A new development at the EVN correlator allows data dumps as short as 0.25 s. Together with many spectral channels a much wider area of the primary beam of the single telescopes can be mapped. The aim is to map the full usable beam-width of the Effelsberg telescope. The resulting enormous amount of raw correlated data requires new parallel data reduction paths which are presently being implemented.

3.3. *The Japanese Gbit VLBI System*

The first observations with the giga-bit VLBI system were performed in 1999. The system consists of a sampler, a data recording system, and a data correlator. The observed data are sampled with 4-bits at a rate of 1024 Msps, but only one bit is extracted. The data recording system consists of a modified commercially available high definition broadcasting recorder which records the data at a rate of 1024 Mb/s. The correlator system was initially developed as the real-time correlator for the Nobeyama Millimeter Array of National Astronomical Observatory. The systems were used in a series of geodetic and astronomical VLBI sessions. (Koyama 2002)

A second generation system utilizes a VLBI Standard Interface (VSI) compliant interface. The new correlator can process two data streams at a data rate of 1024 Mbps.

3.4. *VLBI Standard Interface*

VLBI by its inherently international nature requires compatibility of recording and playback equipment all over the world. With more and more VLBI systems being developed which are not compatible with each other, the need for a standard interface arose. In 1999 a draft for a VLBI Standard Interface was formulated which was finalized in 2000 (http://web.haystack.edu/vsi/).

The purpose of VSI is to define a standard interface to and from a VLBI Data Transmission System (DTS) that allows heterogeneous DTS's to be interfaced to both data-acquisition and correlator systems with a minimum of effort. The definition meanwhile has three parts: 1) a hardware definition: VSI-H 2) a software definition: VSI-S and 3) a definition which should help transferring VLBI via networks: VSI-E. The latter was deemed necessary if VLBI data is transferred between different VLBI equipment at telescope and correlator via Internet. It is still under development.

4. Ongoing Developments

Multi-station correlators are the most complex part of a digital VLBI system; the data acquisition systems are kept as simple as possible to increase their reliability. Except for the very first system all multi-station correlators have been realized in hardware. As a consequence the development cycle is many years and the investment of both manpower and capital is very substantial. A consequence is that correlators live much longer than general purpose computers. Some MK II correlators were operational for about 20 years. The MK III correlators were operated from about 1980 to 2000. The VLBA correlator has been operational for about 10 years. It is expected that the MK IV correlators will not be switched off before the year 2010, even though its design dates from the nineteen-nineties.

Rapid developments in data acquisition, transmission, and storage in the last few years, mostly driven by the computer industry, can make VLBI cheaper and more sensitive. Unfortunately compatibility with existing (hardware) correlators often leads to compromises.

4.1. Disk Recording

In early discussions about an "off the shelf" replacement for the MK IV recorders at the end of the previous decade people considered computer cassette tapes as a probably best choice (Whitney 2000). It was soon realized that the prices for computer hard disks (IDE/ATA) were dropping much more rapidly than those of tape-based computer storage systems (see Whitney 2003).

4.1.1. The Mark 5 System

In early 2001 a disk-based demonstration VLBI recording system was developed and demonstrated within 3 months. With support from several international institutions the Mark 5 system has been developed. The Mark 5 systems are based on a server grade PC with a special PCI I/O card from Conduant Corporation. This so-called Streamstor card writes to all disks in parallel in a round-robin fashion. The data is not kept in a normal file system, and failure of single disks does not corrupt the data on the remaining disks. The VLBI data is fed to the Streamstor card via a FPDP bus from/to a custom design Mark 5 I/O card, and not via the PCI bus. (Whitney 2003)

An initial prototype unit called Mark 5p was deployed by summer 2002. It was limited to 512 Mb/s. Up to 16 disks were housed in individual carriers. The Mark 5A version capable of 1024 Mb/s (with a MK IV formatter) followed in late 2002. Both versions were meant to be a full replacement for a MK IV or VLBA tape drive. For the end of 2004 the Mark 5B model has been announced which will have a VSI compatible interface. It will make the formatter obsolete, and will take digitized data directly from the samplers of a VLBI terminal. It will allow the VLBA to go to 1024 Mb/s recording. In addition to a VSI output the Mark 5B can also play back data in VLBA format. It will have phase-cal extraction capability and for MK IV correlators a replacement station unit which can handle the station-based part of the correlation. Both the Mark 5A and 5B systems can hold 2 '8-pack' disk carriers in 2 banks. Each 8-pack carries 8 disks. Recording or playback is to/from a single 8-pack at a time. The system can record uninterrupted by switching between the two 8-packs. Idle 8-packs can be hot-swapped. Compatibility between Mark 5A and 5B will only be realized in one direction. Mark 5A systems will be upgraded to playback 5B recordings in VLBA format.

The Mark 5 system was chosen as the next generation VLBI recording system by the EVN, large parts of the geodetic community, and the VLBA. The EVN and IVS are in the process of switching to Mark 5. The VLBA will migrate to Mark 5B in 2005/2006. The EVN has officially announced the opportunity of network observations with 1024 Mb/s, and the first astronomical gigabit observations are scheduled for the October 2004 observing session.

4.1.2. The PC-EVN System

In 2001 Mujunen and Ritakari from Metshovi Observatory presented their plan for a disk-based VLBI recording system totally built from commodity PC computer parts. In the original design a master PC would control 4 PCs each recording data in parallel (RAID level 0) onto 8 removable ATA disks connected to the PCI bus; in this configuration a recording bit-rate of 1024 Mb/s could be reached. The data is stored on a standard Linux file system (Parsley et al. 2003). VSI-compatible setups with single PCs are still being used for instance in Australia for bit-rates of 256 and even 512 Mb/s.

4.1.3. The Japanese K5 System

A somewhat similar setup was chosen for the K5 system. A single PC will record 4 channels. The complete system with 4 PCs is compatible with the Keystone Project Terminal and will record 16 channels (Kondo et al. 2003).

4.2. Near Real-time Network Monitoring

Near real-time fringe verification was successfully tried in the early eighties (see chapter 2.7.4). With the introduction of Mark 5 and tests of e-VLBI it has been realized that the reliability of the EVN can be greatly enhanced if the performance of the network is checked during the observing sessions by regularly transmitting small fractions of the data from all participating antennas to the correlation center. In the course of 2003 'ftp fringe-tests' were introduced in the EVN. The short-time goal is to transfer a short scan of the first observation at each frequency. Later a scan of every observation should be transfered. At present the data is transmitted by ftp and correlated at JIVE with a copy of the Japanese software correlator (see chapter 5.2).

4.3. Tied Array or Real-time VLBI

It is clear that when telescopes are connected to the Internet with a sufficiently large bandwidth that all the data can be transferred to the correlator directly. The cost for this transfer has to balanced against the cost of disk storage and shipment. As long as not all telescopes have this connectivity the data has to be recorded at the correlator so that not much is saved. At present the development of e-VLBI activities is being pushed mostly in Japan, where e-VLBI was first developed (see below), the European VLBI Network and MIT Haystack Observatory.

Most research networks like e-VLBI as an application which exercises the high-speed national and international networks which are not fully used at present. In particular the long-term requirements for simultaneous Gb/s data streams from antennas worldwide converging in a single processing center are challenging. As a result e-VLBI efforts are financially supported by national network organizations or government funding agencies. A big stumbling block is still the 'last mile problem'. Most telescopes are in remote places and are not connected to high-speed networks, for which optical fibers are a pre-condition. In some countries it is required that services are bought from a network provider which is typically very expensive, at least more expensive than lighting a dark fiber.

From a scientist's point of view there is hardly any advantage in e-VLBI except that the data could become available sooner after the observation. Unfortunately some auxiliary information and measurements like that of system temperatures and atmospheric conditions might not be available in real-time.

An exception is the UT1 campaign of the geodesists where efforts are underway to provide UT1 within 24 hours of the observation. At present the transfer is still of the ftp-type. As only 1 hour of observation at 2 telescopes at a bit-rate of 112 Mb/s is involved, no special technical problems have to be solved, and with the availability of a sufficiently fast Internet connection at affordable annual costs the UT1 intensive observations could be changed to real-time VLBI.

Advantages of e-VLBI are mostly in savings at the logistical level and probably in reliability after all processes will have been sufficiently automated; manpower at antennas and correlators could be reduced, weekends and night shifts fully utilized.

4.3.1. Japanese Real-time VLBI Projects

The dominant activity in e-VLBI has been in Japan where at about 1995 the Keystone project was started linking 4 antennas in real-time at 256 Mb/s (Kondo et al. 2003). Recently a 1 Gb/s network inside Japan is being developed (Kondo et al. 2002).

4.3.2. E-VLBI at MIT Haystack Observatory

Haystack demonstrated e-VLBI between Haystack and NASA/GSFC where 788 Mb/s were reached on a 700 km baseline in 2002. Also in 2002 real-time VLBI was demonstrated at 256 Mb/s between Haystack and GGAO. E-VLBI test observations were successfully conducted between Haystack and Kashima, and real-time VLBI between Haystack and Onsala. The group is actively involved in defining the VSI-E standard for electronic data transport for which a final definition is expected towards the end of 2004. Research on IP protocols like RTP for VLBI data transfer is being done.

4.3.3. E-VLBI activities in the EVN

The EVN has an active collaboration with several national academic network organizations and the European network Dante/Géant. The immediate aim is to demonstrate e-VLBI at 512 Mb/s with 4 or 5 telescopes at the end of 2004. The initial aim of 1 Gb/s had to be dropped because the channelization of VLBI data in steps of powers of 2 does not match the steps of network capacity well. So two 1 Gbit connections would be needed to transfer 1 Gb/s VLBI data without loss. Another problem is that the speed of the present computer main boards used in the Mark 5 systems is insufficient for dumping 1 Gb/s of data to an ethernet. Newer main board with two 1 Gbit ethernet ports and more advanced internal architecture might solve this problem.

In 2004 a map was made from a 3 station observation which had been observed and correlated in real time. The bit-rate was 32 Mb/s per station and no disk buffering was used.

4.4. Satellite VLBI

Ideas about satellite VLBI – earth-space interferometers – date back nearly to the beginnings of VLBI. Several projects were proposed in the course of time, but none were realized until 1997 when the Japanese VLBI satellite HALCA was launched. A first successful experiment was conducted however in 1986 using a 4.9-m antenna on NASA's Tracking and Data Relay Satellite System (TDRSS).

The HALCA satellite with a 10-m antenna had 3 receivers working at 1.3, 6, and 18 cm on board. The apogee of 21,400 km and perigee of 560 km above the Earth's surface were chosen to optimize the uv-coverage. Regular observations were performed at 6 and 18 cm in combination with the EVN, VLBA, and Australian radio telescopes. As the 1.3-cm receiver failed to operate properly the maximum resolution at 6 cm of earth-space baselines is only comparable to the VLBA alone at 2 cm, but with considerably less sensitivity.

5. Future Developments

In February of 2004 in the last general meeting of the IVS with the topic: "Today's Results and Tomorrow's Vision" several papers with an outlook to the year 2010 and beyond were presented. The EVN board of directors has started a similar discussion.

A key sentence for this chapter could be the beginning of an article by Whitney et al. (2004): "In contrast to the first ~30 years of VLBI development, where highly specialized equipment for VLBI data acquisition was designed and built at great cost, the last few years are being driven more and more by taking advantage of rapidly developing technology in the computer and networking industry. This trend is only likely to accelerate, and VLBI must position itself to take maximum advantage of these technologies."

In addition new and bigger telescopes as well as better receivers would help to satisfy the astronomers' demand for more sensitivity. To equip telescopes with VLBI data acquisition is becoming cheaper – except for the obligatory H-maser, so that additional telescopes might join the EVN. The possibility to increase the data-rates is limited by the limited bandwidths at cm wavelengths; mm-VLBI could profit here most.

5.1. Data Acquisition and Transport

In the six years between 2004 and 2010 the infrastructure in computing and data communications will change dramatically. If the present trend continues, in 2010 we will have 66 GHz processors with 60 GB main memory and 20 TB hard disks. Networks will work at 100 Gb/s speeds. Global connectivity will be available at 660 Gb/s. It is immediately obvious from those numbers that the data-rate and volume problem of VLBI will have vanished. We must accept that at least one generation (possibly two) of VLBI equipment will become totally obsolete before we reach 2010 (Mujunen & Ritakari 2004). Two, four, and eight Gb/s of recording bit-rate seems possible before 2010, both with disks and e-VLBI.

In the VLBA and MK IV data acquisition racks analog baseband converters (BBC) are being used for splitting the radio band into manageable pieces, which are then digitized and recorded. For 'digital radio' frequency conversion techniques have been developed, which encourages the design of digital BBCs, which can offer greatly improved performance and reliability, as well as larger bandwidths than the maximum 16 MHz of the present BBCs. The EVN has started a Digital BBC project. The aim is to build 4 prototypes within 2 years followed by series production. The aim is to develop a programmable, expandable and therefore flexible converter. Initially the BBCs would be a straight forward replacement for MK IV and VLBA BBCs, later larger bandwidths could be added, RFI suppression (e.g. Kesteven 2003), or even fringe rotation and phase-tracking might be brought back to the antennas. It should be mentioned that at some point in the future it might even be possible to design a pure software baseband converter. In Japan a first simple software BBC with limited capabilities has already been realized.

5.2. Correlators

The correlator of the MK I system had been realized as a program in a general purpose computer, and in 1990 a prototype software correlator for MK II pulsar VLBI was devised by Petit et al. (1990). The advances of computer industry seem to make it possible that after more than 30 years of hardware correlators for VLBI software correlators become again competitive. A very attractive feature of software correlators is that the enormous effort in manpower for a new design of the hardware does not exist; the correlator program can simply be compiled on the latest, fast machine and voilà a new correlator. A disadvantage is that at least at present hundreds and thousands of PCs would be needed to replace a MK IV correlator. A software correlator has been developed by Kondo et al. (2003) and is also being used at JIVE for the ftp network monitoring.

For large VLBI arrays, large bandwidths, many spectral channels, and more than 1 beam, hard/firmware correlators are probably the only realistic solution for the near and intermediate future (see for example Carlson & Dewdney 2003). Future correlators will produce very large data-sets which will allow mapping of a large part of the primary beam. The postprocessing software will take over the role of stearing the delay/rate beam to the area of interest on the sky.

5.3. MM-VLBI

Higher resolution can be achieved in VLBI either by going into space to increase the baseline length, or by going to higher observing frequencies. At present mm-VLBI can achieve the highest spatial resolutions, and the reduced opacity at the higher frequencies might allow probing the cores of AGNs deeper towards the event horizons of the central black holes.

At wavelengths of less than 1 cm the sensitivity of VLBI observations is reduced because the telescopes are fewer and smaller, sources are often weaker, receivers are noisier, and the maximum coherent integration time is shorter. As a result the number of observable sources is still limited. Nevertheless regular mm-network observing is performed at 86 GHz with good success (Krichbaum et al., Pagels et al., these proceedings).

Increasing the bit-rate is one of the keys to more sensitivity at mm-wavelengths. For instance a proposal by Haystack Observatory which amongst other things asked for money for developing 4 Gb/s VLBI recording for mm-VLBI has just been accepted by NSF.

The limited coherence time could be lengthened if attempts to measure the path-length fluctuations in the atmosphere with water vapor radiometers are successful (see Roy et al. these proceedings). Dual frequency receivers can be used to calibrate the phase fluctuations at the high frequency with the lower frequency. This technique has successfully been used in VLBI (Middelberg et al. 2002) and is also being used in the Vera project (see Kobayashi these proceedings)

VLBI at higher frequencies is still in an experimental stage, but first transatlantic fringes have been found even at 1.3 mm wavelength. The situation will improve as more mm-telescopes become available at 2 and 1 mm wavelength. (see Krichbaum et al. these proceedings)

5.4. E-VLA, New Mexico Array, and E-MERLIN

When VLBI moves away from recording interferometry to become ethernet-based the differences between VLBI and large local arrays like MERLIN will become smaller. The difference that will (probably) remain is the use of independent local oscillators for VLBI, while local arrays have a central LO which is disptributed to the antennas.

Projects like E-VLA, the New Mexico Array, and E-MERLIN with EVN extensions demonstrate that a closer connection between VLBI on one side and the VLA and MERLIN on the other side will develop in the future. It is even conceivable that the VLA and the VLBA will merge into one huge array (Walker 2004). E-MERLIN may expand to include Westerbork or Effelsberg on demand at up to 30 Gb/s. In the far future a full integration of MERLIN and EVN might be possible.

5.5. Square Kilometer Array and VLBI

The SKA will bring a major breakthrough in sensitivity in radio astronomy at cm wavelengths. Its angular resolution though will be limited to less than what is available today. Global VLBI with the SKA and in particular a combination of SKA, global VLBI, and space VLBI will open a new, totally unexplored area in the "sensitivity – angular resolution" plane (Gurvits 2003). It should be noted that SKA and space VLBI alone would not provide an appropriate coverage of the UV-plane and as a result would compromise the gain in sensitivity by degradation in the image quality. Telescopes paticipating in global VLBI with the SKA will feed the data to the SKA correlator via fibres with very high data-rates.

Acknowledgements. The author would like to thank D. A. Graham for critical suggestions and corrections.

References

Anderson, B., Donaldson, W., Palmer, H. P., & Rowson, B. 1965, Nature, 205, 375

Bare, C. B., Clark, B. G., Kellerman, K. I., Cohen, M. H., & Jauncey, D. L. 1967, Science, 157, 189

Broten, N. W. 1988, JRASC, 82, 233

Carlson, B. R. & Dewdney, P. E. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 271

Carlson, B. R., Dewdney, P. E., Burgess, T. A., et al. 1999, PASP, 111, 1025

Clark, B. G., Weimer, R., & Weinreb, S. 1972, NRAO Report 118

Cohen, M. H. 2000, in Radio interferometry : the saga and the science, 173

Gurvits, L. I. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 303

Hemenway, P. D. 1974, PhD thesis

Kellermann, K. I. & Moran, J. M. 2001, ARA&A, 39, 457

Kesteven, M. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 93

Kiuchi, H., Amagai, J., Hama, S., & Imae, M. 1997, PASJ, 49, 699

Knowles, S. H., Waltman, W. B., Yen, J. L., et al. 1982, Radio Science, 17, 1661

Kondo, T., Koyama, Y., Nakajima, J., et al. 2002, in International VLBI Service for Geodesy and Astrometry, 142

Kondo, T., Koyama, Y., Nakajima, J., Sekido, M., & Osaki, H. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 205

Koyama, Y. 2002, in International VLBI Service for Geodesy and Astrometry, 55

Matveenko, L. I., Kardashev, N. S., & Sholomitskii, G. B. 1965, Soviet Radiophys., 8, 461

Middelberg, E., Roy, A. L., Walker, R. C., Falcke, H., & Krichbaum, T. P. 2002, in Proceedings of the 6th EVN Symposium, 61

Moran, J. M., Crowther, P. P., Burke, B. F., et al. 1967, Science, 157, 676

Mujunen, A. & Ritakari, J. 2004, in International VLBI Service for Geodesy and Astrometry, 56

Parsley, S., Pogrebenko, S., Mujunen, A., & Ritakari, J. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 145

Petit, G., Fayard, T., & Lestrade, J.-F. 1990, A&A, 231, 581

Petrachenko, W. T., Klatt, C., & Ward, V. 2002, in International VLBI Service for Geodesy and Astrometry, 162

Porcas, R. W., Alef, W., Rioja, M.-J., et al. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific., 39

Rioja, M. J., Porcas, R. W., Desmurs, J.-F., et al. 2002, in Proceedings of the 6th EVN Symposium, 57

Rogers, A. E. E., Cappalo, R. J., Hinteregger, H. F., et al. 1983, Science, 219, 51

Romney, J., Alef, W., Pauliny-Toth, I., Preuss, E., & Kellermann, K. 1982, in IAU Symp. 97: Extragalactic Radio Sources, 291

Romney, J. D. 1999, in ASP Conf. Ser. 180: Synthesis Imaging in Radio Astronomy II, 57

Walker, R. C. 2004, in International VLBI Service for Geodesy and Astrometry, 100

Whitney, A. R. 1988, in IAU Symp. 128: The Earth's Rotation and Reference Frames for Geodesy and Geodynamics, 429

Whitney, A. R. 2000, in Proceedings of the 5th european VLBI Network Symposium. Eds.: J.E. Conway, A.G. Polatidis, R.S. Booth and Y.M. Pihlström, published Onsala Space Observatory, 233

Whitney, A. R. 2003, in New technologies in VLBI. Edited by Y.C. Minh. ASP Conference Series, Vol. 306. San Francisco, CA: Astronomical Society of the Pacific, 123

Whitney, A. R., Hinteregger, H. F., Kondo, T., & Koyama, Y. 2004, in International VLBI Service for Geodesy and Astrometry, 85

Whitney, A. R., Shapiro, I. I., Rogers, A. E. E., et al. 1971, Science, 173, 225

Yen, J. L., Kellermann, K. I., Rayhrer, B., et al. 1977, Science, 198, 289

Yen, J. L., Leone, L., Watson, G. A., et al. 1988, in IAU Symp. 129: The Impact of VLBI on Astrophysics and Geophysics, ed. M. J. Reid & J. M. Moran (Dordrecht, The Netherlands: Kluwer), 489