A Review of VLBI Instrumentation

EVN Symposium, Toledo 2004

Walter Alef

Max-Planck-Institute for Radioastronomy, Bonn

On the Way to VLBI

Early sixties:

Unresolved sources at longest baselines (127 km Jodrell)

Discussions about feasibility of VLBI

Middle of sixties:

Hydrogen masers and Rubidium frequency standards (stability: 10^{-14} and 10^{-11})

Tape recorders for television and computers

Development of VLBI systems started

VLBI-Specific Features

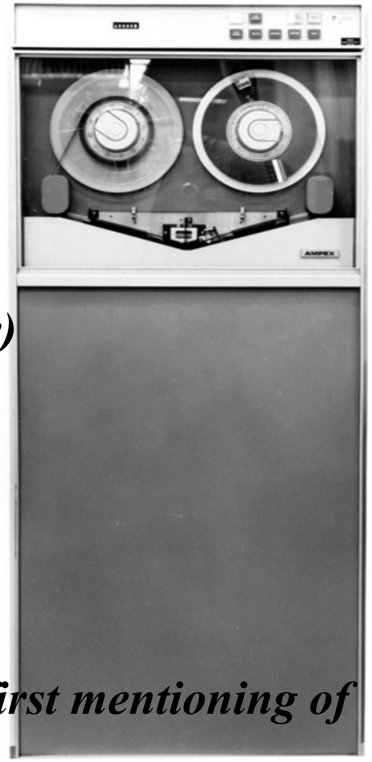
- *Independent local oscillators*
- *Data is recorded**
- *Delayed correlation**
- *Fringe detection/search*
- *High "natural" fringe-rate (up to kHz)*
- *Fringe fitting: determine exact delay and delay-rate*

Historic VLBI Systems

- ***The Canadian Analog VLBI System***
  - ***TV studio recorders, analog: 4 MHz BW***
  - ***Hydrogen Masers***
  - ***First fringes in spring 1967***
  - ***Stability of system insufficient***

Historic VLBI Systems (cont.)

- ***The MK I digital VLBI system (NRAO/Cornell)***
  - ***Modified 7-track computer tape units***
  - ***330 kHz BW @ 720 kbits/s, 1-bit sampling***
  - ***1 tape lasted about 150 s!***
  - ***Correlation on general purpose computer (software correlator)***
  - ***First fringes in spring 1967***
  - ***MIT-Haystack observed OH masers with compatible system***
  - ***1968: First global VLBI (Green Bank, Haystack, Onsala)***
  - ***1969: First geodetic VLBI observation (frequency synthesis; first mentioning of phase-referencing to extend coherent integration time)***
  - ***1970: 10000 km baseline and observing frequency 10.6 GHz reached***
  - ***1971: superluminal motion discovered***



Historic VLBI Systems (cont.)

- ***1971: The MK II VLBI system (NRAO)***
  - ***Ampex 2" video recorders (modified for digital recording; up to 3 hours per tape)***
  - ***Data-rate of 4 Mb/s 1-bit sampled from 2 MHz BW***
  - ***3-station hardware correlator***
  - ***Caltech 5-station correlator***
  - ***Caltech 16-station correlator (later enhanced for MK III)***
  - ***1978: Copy of NRAO 3-station correlator to Bonn***

MK II correlator at Bonn with 3 generations of recorders

Historic VLBI Systems (cont.)

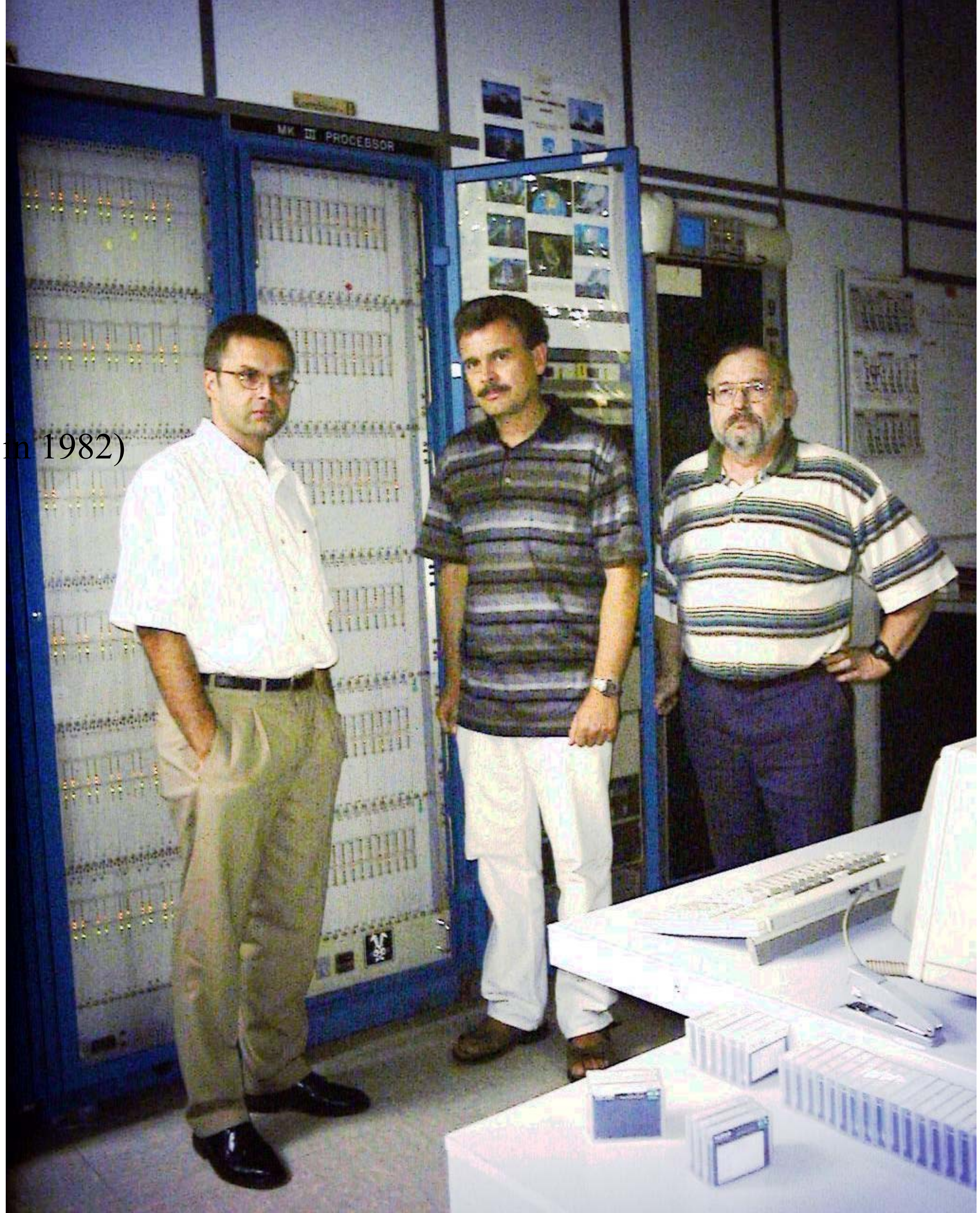
- The MK III VLBI system (Haystack)
  - Instrumentation tape recorders with 28 tracks (1" tape on 14" reels)
  - ~10 GB per tape
  - Different recording modes with different bit-rates
  - Each track could record up to 8 Mbits/s
  - Maximum bit-rate 224 Mbits/s (112 MHz BW, 1-bit digitized)
  - Sensitivity increase of up to about 7.4 over MK II
  - Due to 14 independently tunable BBCs well suited for geodesy
  - Phase-calibration system to align phases of BBCs; defines reference point for delay
  - 1982: MK III correlator at Bonn with 3 or 6 baselines

Historic VLBI Systems (cont.)

- The MK III VLBI system (cont.)
  - More powerful MK IIIA correlator at the end of the eighties (6/12 baselines) installed at Haystack, USNO, Bonn
  - Movable narrow tracks, tape capacity increase factor of 12 (~120 GB)
  - The MK III correlators were shut down in 2000

Last minute before the
MK III correlator in Bonn
was switched off in 1999.

Left: A. Zensus (director)
Middle: W. Alef (friend of correlator)
Right: H. Blaschke (assembled MKIII
correlator in 1982)



The Canadian S2 system

- Professional VCRs
- 16 Mbits/s per VCR
- 128 Mbits/s with 8 VCRs in parallel
- Lag-based correlator also for supporting VSOP

Japanese VLBI systems

- K-1 in 1976
- In the eighties K-2
- 1983: K-3 was fully compatible with MK III included a 1-baseline correlator
- K-4
  - commercial cassette-based helical scan recorder
  - 1-bit sampling, later multi-bit sampling + digital filtering
  - Various recording modes, compatible with MKIII/VLBA
  - Maximum bit-rate 256 Mbits/s
  - 10-station FX correlator
  - Support for VSOP

Other Early VLBI developments:
Real-time VLBI

- In 1976 a satellite link was used for data transfer between West Virginia & Ontario (Yen et al)
- Instantaneous correlation
- Better sensitivity because of broader bandwidth
- Yen et al. mention possibility of phase-coherent VLBI array

Other Early VLBI developments:
Multi-view VLBI

- In 1974 Hemmenway used 4 antennas at 2 sites
- 2 simultaneous beams on the sky
- Helps eliminate unknown ionosphere/troposphere
- Rioja et al. used 3 sites with 3 to 4 antennas in the nineties with MK III
- Advantages also for geodesy:
  - Parameter correlations can be reduced
  - Parameters can be determined more quickly

Other Early VLBI developments:
LO transfer via satellite

- 1982: LO transfer via satellite in phase-coherent way in transcontinental VLBI

Fringe verification with early eVLBI: 1984

courtesy of Richard Porcas

	(h:m)		(MHz)	(MHz)		Clock (usec)	(% of Ts)
215	22:00	3C273	10449.99	2.0	FO	-22.0	1.5
					KG	1.8	4.7
					GO	-10.8	1.4
					KO*		
					KF*		
					GF*		

* Fringes not found for KO,KF,GF - probably less than 1 percent

Derived Clocks (microseconds)

DAY	λ (cm)	K	G	F	O
215	2.8	3.7	5.5	16.7	-5.3**

** Assumed reference value.

Today's VLBI systems: VLBA

- 20-station FX correlator, up to 1024 spectral points
- 8 frequency channels
- 1-bit or 2-bit sampling
- Maximum total bit-rate 256 Mbits/s, 512 Mbits/s with 2 recorders in parallel
- Recorder based on MK III design, but:
  - 32 tracks
  - 14 passes
  - Barrel-role and data modulation
  - ~600 GB per thin tape

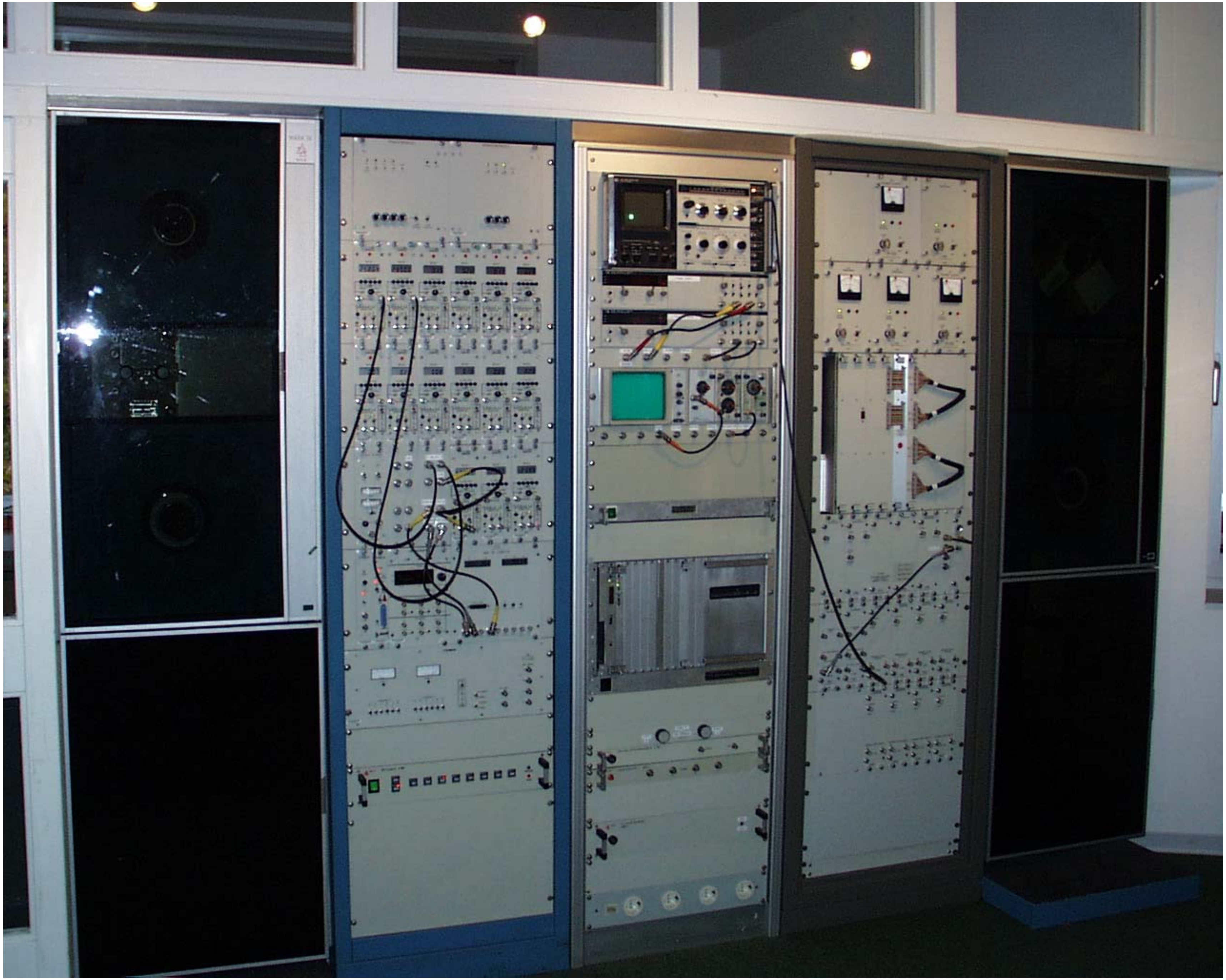
Today's VLBI systems: MK IV

- MK IV data acquisition is mostly an upgrade to make MK IIIA more compatible with the VLBA system
- Added 8 and 16 MHz filters to BBCs
- MK IV formatter

But also:

- 512 Mbits/s (1024 was planned) with 2 heads
- Lag-based MK IV correlators in about 1999
  - Up to 16 stations
  - 16 channels per station
  - Software configurable
  - 32 to more than 1024 lags

MK III/IV data acquisition system VLBA terminal



MK IV correlator at Bonn

Left rack: 2 crates with
8 correlator boards each
Middle: oscilloscope for
monitoring single track,
station unit,
Mark 5A
Right: Standard MK IV play-
back unit

Today's VLBI systems: Japanese Gbit VLBI system

- ***Consists of sampler, recording system, correlator***
- ***4-bit sampled at 1024 Ms/s, 1 bit used***
- ***Commercial HDTV recorder with 1024 Mbits/s***

VLBI Standard Interface (VSI)

Purpose: define a standard interface to and from a VLBI data Transmission System

- ***VSI-H: hardware definition***
- ***VSI-S: software definition***
- ***VSI-E: a standard for transport of VLBI data via networks***

Disk Recording: Mark 5

- *Uses special commercial Raid PCI card*
- *Data is fed to Raid card via separate bus from custom I/O card*
- *Non standard file system, can cope with disk loss*
- *Uninterrupted recording, hot swap capable*

- *2003 Mark 5A: 1024 Mb/s – MK IV, 2 8-packs*
- *2005 Mark 5B: VSI compatible, 1024 Mb/s – VLBA; includes formatter; phase-cal extraction; MK IV station unit*

Disk Recording: PC-EVN

- *Built from commodity PC parts (except I/O card)*
- *Original design had 4 PCs to reach 1024 Mb/s*
- *Raid Level 0, standard Linux file system*
- *8 removable disks*
- *VSI-compatible are still being used, e.g. in Australia with bit-rates of 256 and 512 Mb/s*

Disk Recording: K5

- *Japanese system similar to PC-EVN*
- *1 PC records 4 channels*
- *System with 4 PCs compatible with Keystone Project Terminal will record 16 channels*

Near Real-time Network Monitoring

- ***Mark 5 (and other disk based systems) allow easy data transfer via the Internet***
- ***In 2003 EVN has introduced 'ftp fringe-tests'***
- ***Oct/Nov 2004: a short scan of the first observation at each frequency***
- ***Later a scan of every observation should be transferred and checked***

Tied Array VLBI (e-VLBI)

- ***Probably increased reliability***
- ***Less manpower at telescopes***
- ***Cost has to be balanced against recording + shipping + media cost***
- ***Hardly any advantage for astronomers (gets data quicker)***
- ***Geodesists can deliver earth orientation more rapidly***
- ***"Last Mile" problem***
- ***Interesting for network people because high speed networks can be exercised***

Tied Array VLBI (e-VLBI)

- Japan:
  - 1995, Keystone project: 4 antennas, real-time, 256 Mb/s
  - Recently 1 Gb/s network is being developed
- Haystack
  - Test, real-time test, research in protocols
  - Rapid UT1 via e-VLBI
- EVN
  - Tests
  - Demonstration of 512 Mb/s with ~4 telescopes in 2004

Satellite VLBI

- 1986: TDRSS experiment successful (4.9 m dish)
- 1997: VSOP
  - First dedicated VLBI satellite
  - 10 m, 3 receivers: 1.3, 6 and 18 cm
  - Apogee 21,400 km, perigee 560 km
  - As 1.3 cm failed, maximum resolution only like VLBA at 2 cm, but less sensitivity
- Plans for VSOP2

Future Developments

- IVS 2010 vision paper
- Discussion in EVN about 2010 roadmap
- US VLBI future report
- More and bigger telescopes
- Better receivers
- More bandwidth (if possible)
- Higher bit-rates
- Cheaper hardware

Data Acquisition and Transport

- If present trend continues in 2010 we will have:
  - 66 GHz processors
  - 60 GB main memory
  - 20 TB hard disks
  - Networks at 100 Gb/s
  - Global connectivity at 660 Gb/s
- Digital BBCs: EVN project – 4 prototypes in 2006
  - Programmable
  - Wider bandwidths
  - Better reliability and performance
  - Possibly RFI suppression

Correlators

- ***Software correlators for small VLBI arrays***
- ***“Grid” correlation could be a future option***
- ***Hard-/firmware correlators for large VLBI arrays, many spectral channels, and more than 1 beam***
- ***Wide field of view (e.g. EVN correlator plans)***
  - Postprocessing software will steer delay/rate beam

mm-VLBI

- Highest spatial resolution, reduced opacity
  can get close to event horizons
- Reduced sensitivity
- Fewer and smaller telescopes
  - Weaker sources
  - Noisier receivers
  - Shorter coherent integration time
- ➔ Nevertheless quite successful!

mm-VLBI

What is needed:

- Increase bit-rate (have lots of BW)
- Water Vapor Radiometers (Roy)
- Rapid frequency switching e.g. 15/43/86 GHz
- Dual frequency receivers (Vera project)
- Alma, an other mm arrays for VLBI

E-VLA, New Mexico Array, E-MERLIN, SKA

Merging of VLBI with local arrays:

EVN + MERLIN telescopes

MERLIN + EVN telescopes

VLA + VLBA

SKA and VLBI: will open a new, totally unexplored area in the “sensitivity – angular resolution” plane