Science & Technology Facilities Council

The Role of Technology in the Development of Very Long Baseline Interferometry

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EUROPEAN vlbi NETWORK

JIVE
JOINT INSTITUTE FOR VLBI IN EUROPE

Proud to be part of MANCHESTER 1824 The University of Manchester | unesco | Heritage Fund

SKAO

MANCHESTER 1824
The University of Manchester

e-MERLIN

Discovery of Quasars in Early 1960's

- Compact radio sources, < 1 arc sec
- High resolution needed to study
- A radio telescope 100 km in diameter? Impractical
- Use interferometers. Pioneered at Cambridge and Jodrell in 1950's
- Palmer developed use of microwave links
- Phase rotator essential (high fringe rate)

250' MkI telescope

25' remote telescope at Pocklington Lincolnshire

Mon. Not. R. astr. Soc. (1967) **137,** 81–94.

OBSERVATIONS OF TWELVE RADIO SOURCES AT A WAVELENGTH OF 0·73 m WITH A TRACKING INTERFEROMETER HAVING A BASELINE OF 180,000 WAVELENGTHS

B. Anderson and W. Donaldson

(Communicated by the Director, Nuffield Radio Astronomy Laboratories)

(Received 1967 March 3)

OBSERVATIONS OF 384 RADIO SOURCES AT A FREQUENCY OF 158 Mc/s WITH A LONG BASELINE INTERFEROMETER

L. R. Allen, B. Anderson, R. G. Conway, H. P. Palmer, V. C. Reddish and B. Rowson

(Received 1962 July 12)*

New Limits to the Angular Sizes of Some Quasars

21-cm

R. L. Adgie
H. Gent
O. B. Slee *

Royal Radar Establishment,
Great Malvern,

A. D. Frost †
H. P. Palmer
B. Rowson

University of Manchester,
Nuffield Radio Astronomy Laboratories,
Jodrell Bank.

NATURE, FEBRUARY 25, 1967

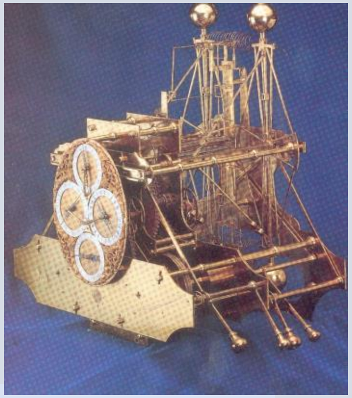
11 an 6 -cm

LETTERS TO THE EDITOR

ASTRONOMY

Radio Diameter Measurements with Interferometer Baselines of One Million and Two Million Wavelengths

VLBI Requirements and the solution



- Science driver --- compact radio sources. Intercontinental baselines needed; direct interconnection not feasible.
- Funding
- Sensitivity:
  - Large radio telescopes
  - Low noise receivers
  - Wide bandwidth
  - Integration time > 10 sec
- Coherence
  - Stable frequency source
  - Accurate clock
- Recording system
- See discussion in B. Lovell 'Out of the Zenith' OUP 1973 Ch 6

- The Solution:
- 1963 Lovell in discussion with Shklovsky in Crimea
- 1965 availability of high-speed tape recorders, stimulated by TV industry
- Crystal oscillators not good enough – advent of Rubidium atomic clocks at reasonable cost
- Timing by LORAN C
- 1-bit sampling van Vleck 1943
- 1965 and onwards experiments proposed
- 1967 Hectic Spring!

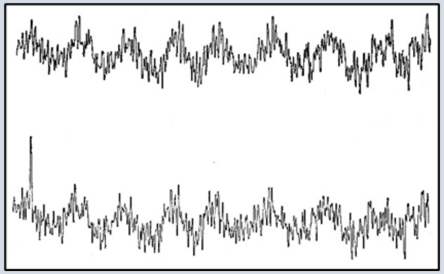
The Early Experiments Spring 1967

- The Canadian system:
  - April 1967, Broten et al., Nature, July 1, 1967
  - Algonquin – Penticton; 448 MHz, 3074 km, res = 0.04”
  - Analog recording bw1 MHz, Rb clock
- NRAO/Cornell system:
  - May 1967,Bare et al., Science, July 14, 1967

  Green Bank – Maryland Point; 610 MHz, 220 km, res = 0.5”
  - Mk1 Digital system (1 bit/sample); bw = 360 KHz
- MIT Group
  - June 1967, Moran et al., Science, August 11, 1967
  - Green Bank – Haystack; 1665 MHz, 845 km, res =0.045”
  - Modified Mk1 (5 and 120 KHz bw)

Thanks to J. Moran slides URSI GA Montreal 2017

3C274



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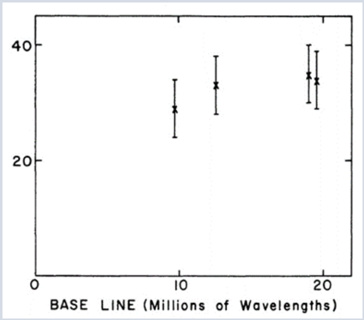
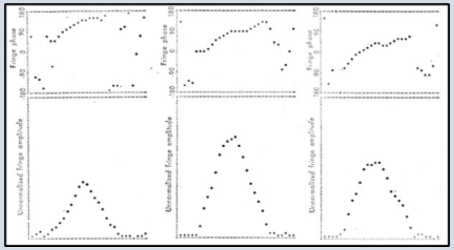


W3(OH)



IEEE Milestone

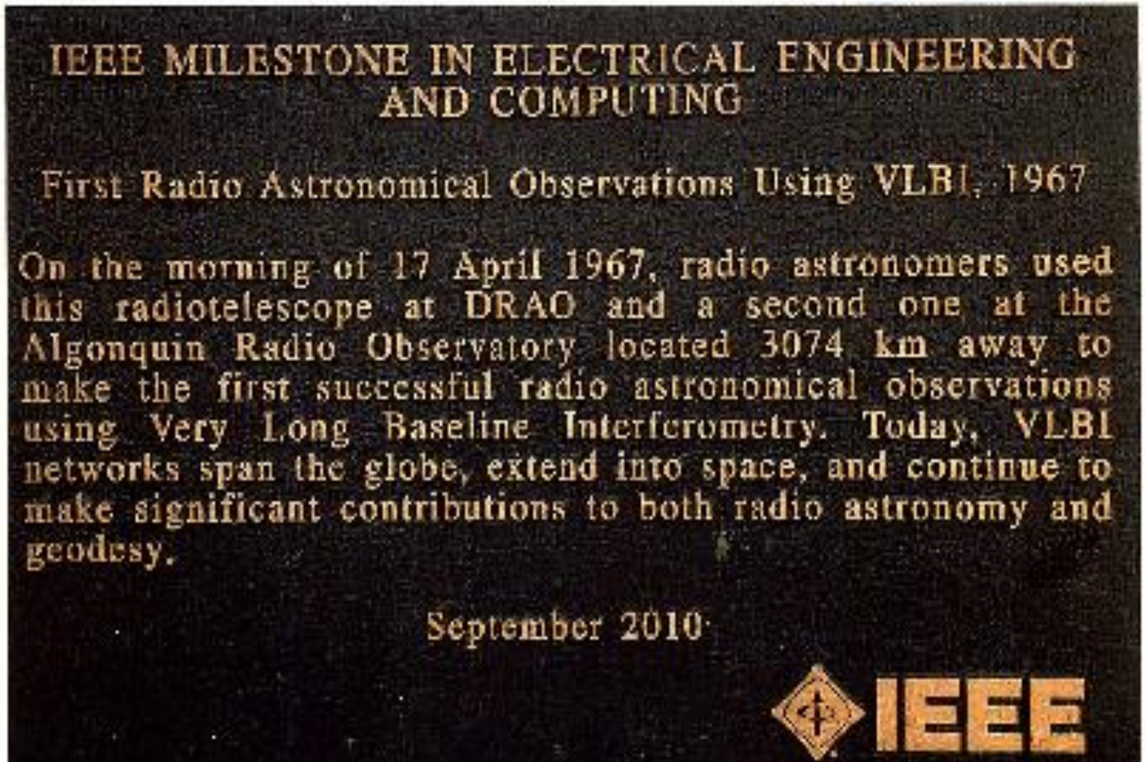


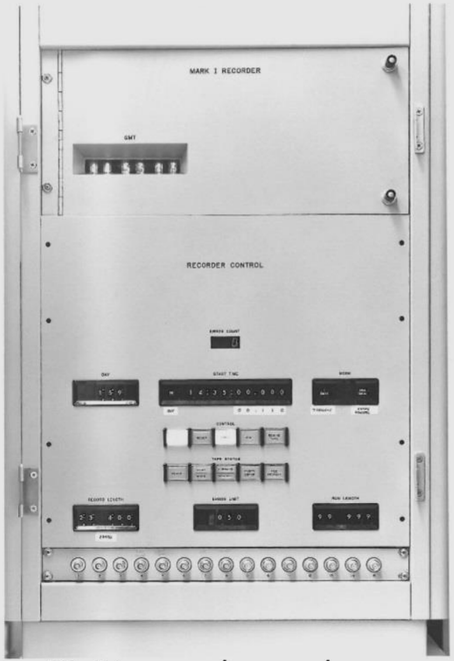
Figure 1: The Dominion Radio Astrophysical Observatory (D.R.A.O) in Canada bears a plaque, which states that the first radio astronomical observations using VLBI occurred here on 17 April 1967.

VLBI Equipment Used at Haystack for First Fringes 8 June 1967 MkI

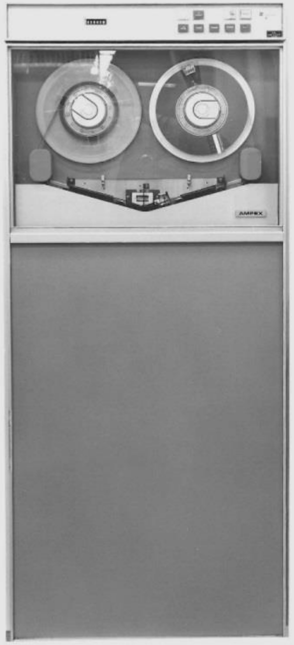
Video converter

Hewett-Packard 5065A
Rubidium clock

Varian H-10 hydrogen maser



Digitizer and recorder
controller

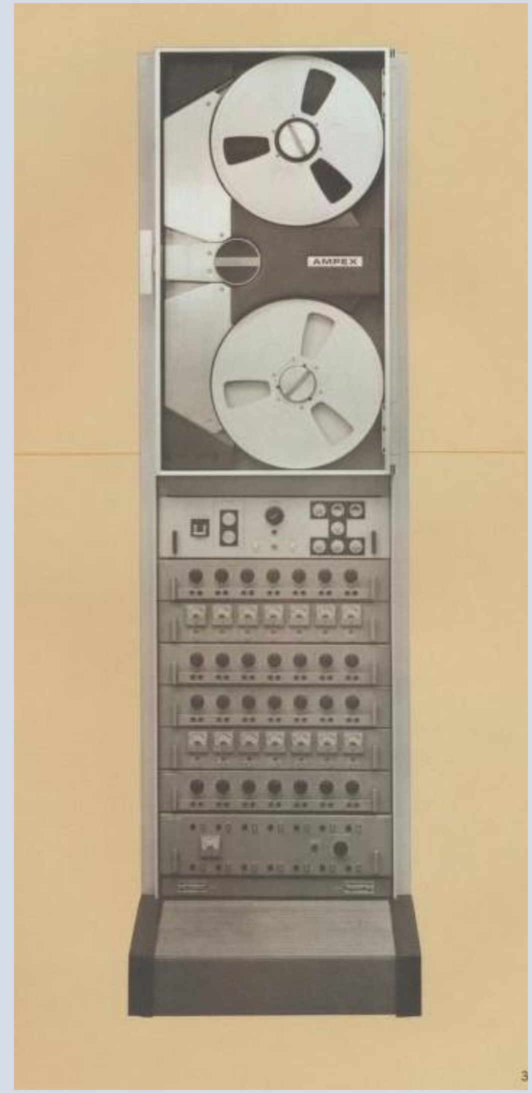


Recorder

Moran 2017

The Jodrell Bank Story

- 1965 Estimated cost for 2 recorders and 2 Rb clocks was £50000 (total JB budget £60,000==£1.5 M 2023). (Lovell 1973)
- 1965 Rb clock bought, Extra funding for recorders sought.
- 1966 Ampex FR1800 recorder bought £12.5k, electronics being built in house
- Linear scan analogue recording
- December 1968 local test
- March 1969 Jodrell Bank- Arecibo, 610MHz. 1 MHz bw , failed.
- December 1969 JB-Arecibo SUCCESS
- Full story in C. Game PhD Thesis Manchester 1972
- Bryan Anderson and 2 students!



Canadian Analog and NRAO Digital Mk 2 Systems
Ampex VR660 Television Recorder (3 x 10^10 bits) 2" tape

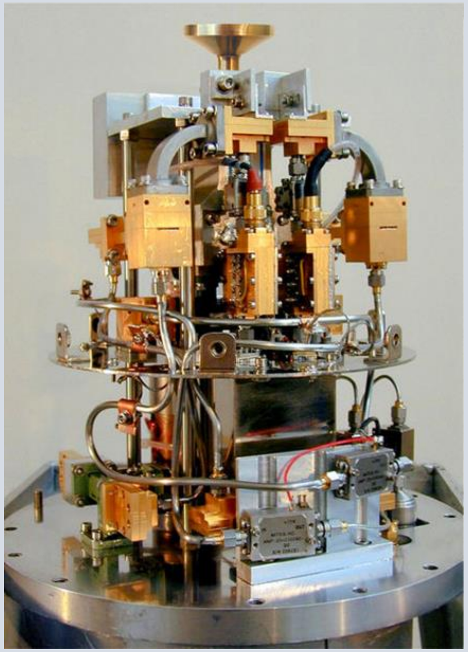
1965 cost: $25K (see Broten, JRASC , 1988) $195K (2017 dollars)

MkII formatter 1970's

1970's IVC recorder, Mk2 system
digital recording 1" tape
2 MHz bw

Receiver Development

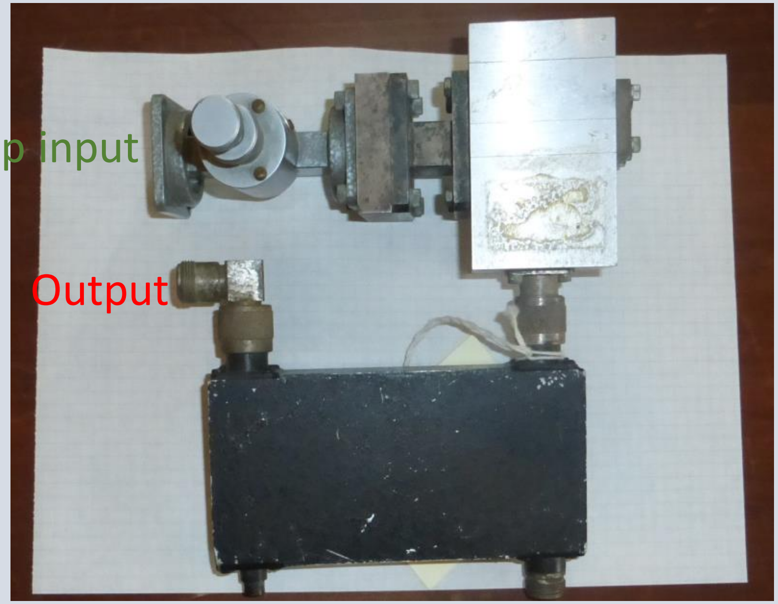
JBO 22GHz Rx 2000’s



Ferranti 1420 MHz Paramp 200K 1967

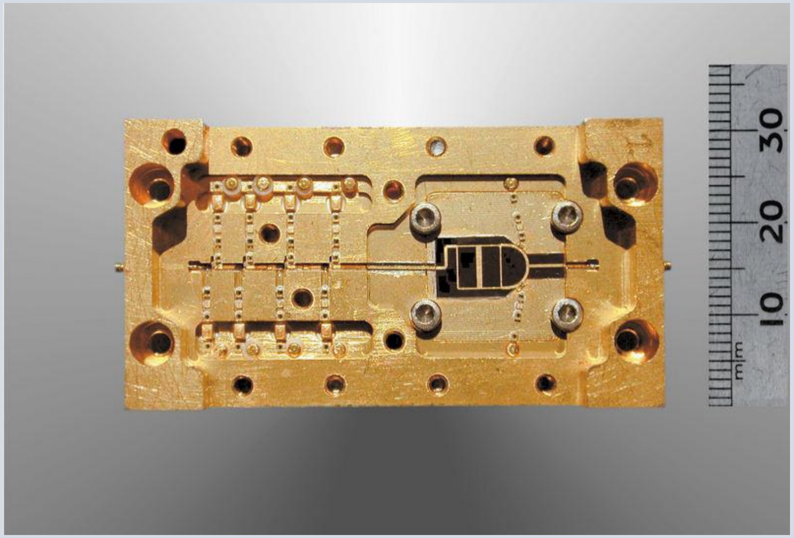
X- ba***nd*** pump input

Output



1420 MHz input

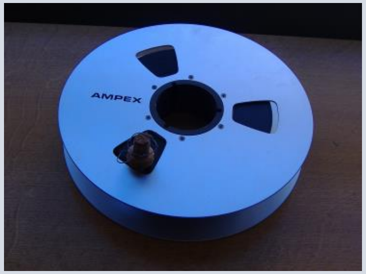
30 GHz Planck LNA 20K
Davis+2009
InP HEMTs



Tape recording 1970's onwards

Mk1
1967

Mk2
1970



VCRs cheap, reliable 1976

Mk3/4
1980's

Clocks

- Timing and synchronisation
- Count down from standard frequency (5 MHz)
- Which second?
- TIM!
- WWV or Loran C: UTC second
- Now GPS
- Frequency stability

JBO Sigma-Tau Maser 1992

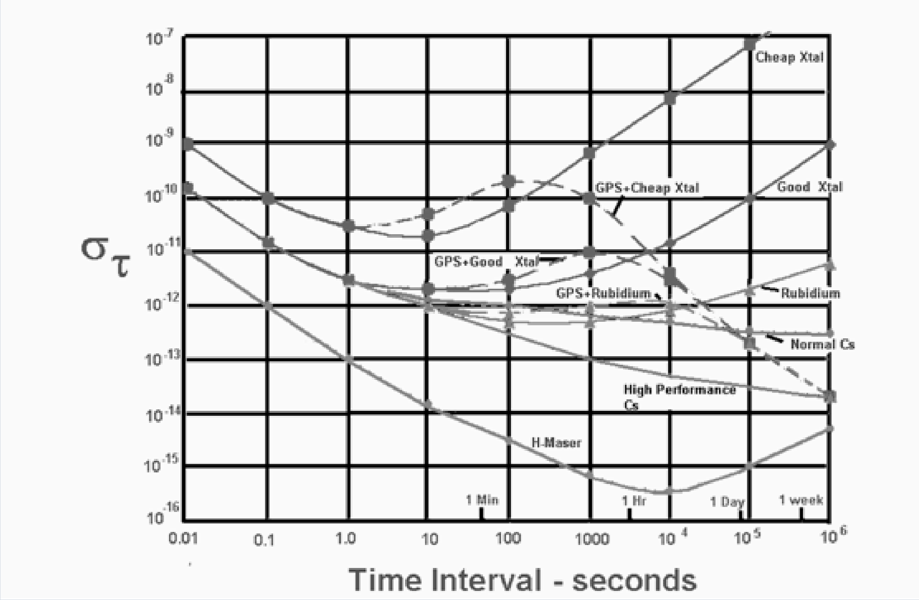


Table 3 Coherence Time at 3 GHz and 10 GHz, and Allan deviation

Standard	Tau_C at 3 GHz	Tau_C at 10 GHz	σ_τ at 1 sec	σ_τ at 10 sec	σ_τ at 100 sec	σ_τ at 1000 sec
Cheap Xtal	3 sec	0.4 sec	3.10^{-11}	2.10^{-11}	8.10^{-11}	8.10^{-10}
Good Xtal	30 sec	10 sec	3.10^{-12}	2.10^{-12}	2.10^{-12}	4.10^{-12}
GPS+Rb	60 sec	20 sec	3.10^{-12}	3.10^{-12}	7.10^{-13}	1.10^{-12}
Cesium	200 sec	30 sec	3.10^{-12}	1.10^{-12}	3.10^{-13}	1.10^{-13}
Passive H maser	1500 sec	300 sec	8.10^{-13}	3.10^{-13}	7.10^{-14}	3.10^{-14}
H maser	1 day	8.3 hrs	1.10^{-13}	$1.2.10^{-14}$	3.10^{-15}	7.10^{-16}

MK3/Mk4

- 1970's Need for higher bandwidth and multiple bands for geodesy led to Mk3
- Linear tape recording 14 tracks on 1" tape: 56 MHz. 18000 ' Tape lasted 13 min (cf 4hrs with Mk2 VCRs)
- Mk3a – narrow heads multiple passes on the tape x 14 (cf JB system 1960's)
- Mk4 MIT/NASA -- EMU 1996
- Mk4 compatible with VLBA and space VLBI 32 Mb/s per track

EMU China April 2000

Chopo, Gino, Michael, Les, Ralph, Ed

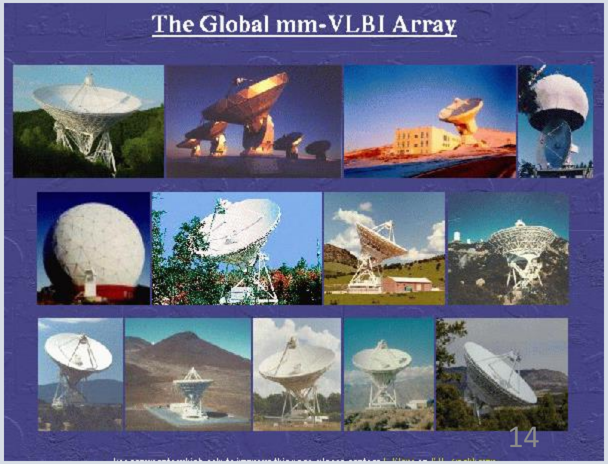
		Mark IIIA		Mark IV		Standard VLBA#		Augmented VLBA$*	
		#chans	Mb/s	#chans	Mb/s	#chans	Mb/s	#chans	Mb/s
4 Msample/sec	1 bit	14x2	112	16x2	128	8x2	64	14x2	112
	2 bit	-	-	16x2	256	8x2	128	*	*
8 Msample/sec	1 bit	14x2	224	16x2	256	8x2	128	14x2	224
	2 bit	-	-	16x2	512	8x2	256	*	*
16 Msample/sec	1 bit	-	-	16x2	512	8x2	256	14x1	224
	2 bit	-	-	16x2	1024	8x2	512	*	*
32 Msample/sec	1 bit	-	-	16x1%	1024	8x2	512	8x1	256
	2 bit	-	-	16x2+	2048	8x1	512	*	*

Alan Whtney in

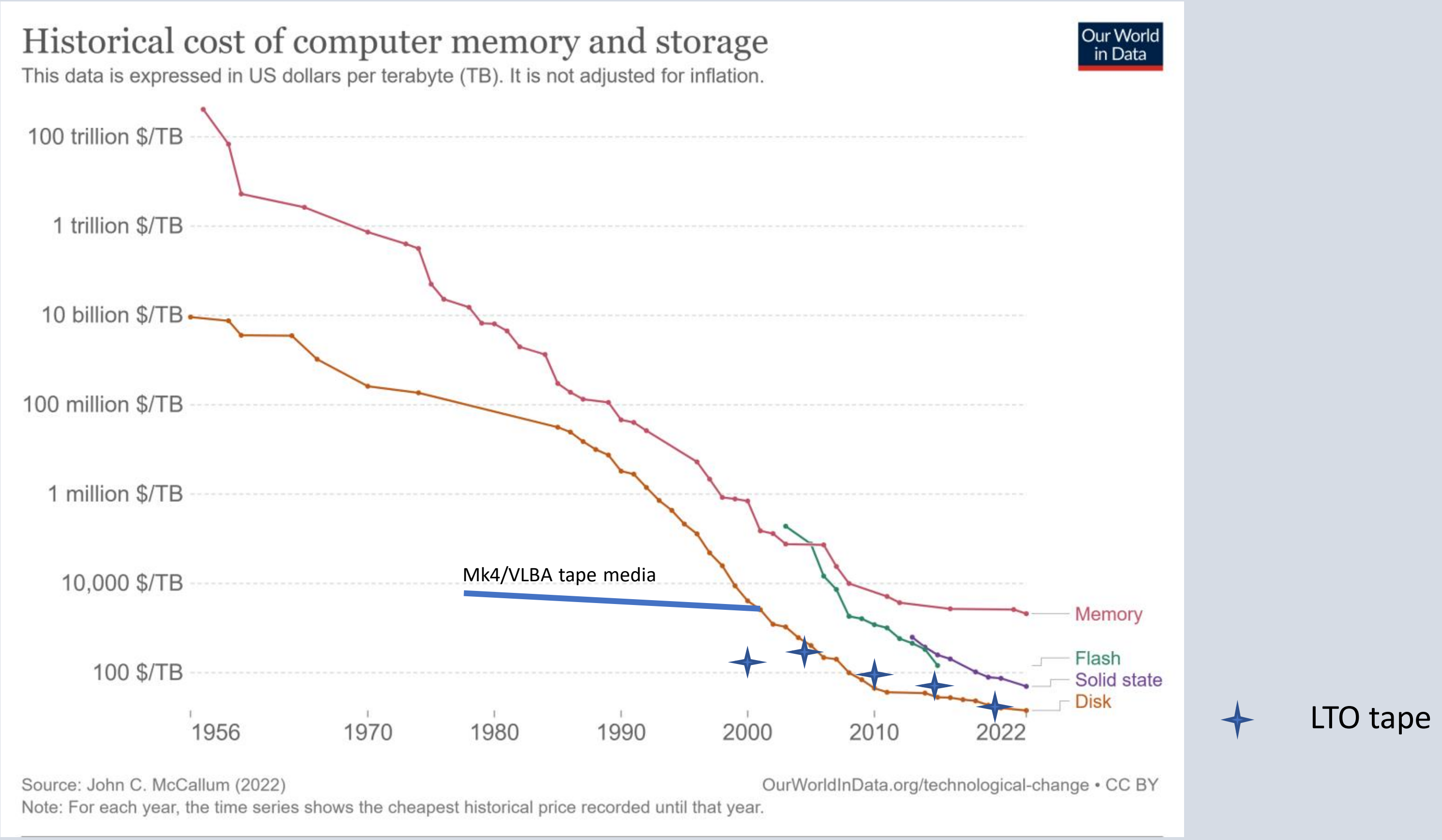
I.I. Mueller and B. Kołaczek (eds.),
Developments in Astrometry and Their Impact on Astrophysics and Geodynamics, 151–157.

The Networks

- 1970's
- US Network: Haystack, Green Bank, Vermillion River, North Liberty, Fort Davis, Hat Creek, Owens Valley.
- Europe: JODE experiment, later JB, Onsala, Westerbork, Effelsberg, Medicina, Wetzel, Metsahovi .
- VLBA USA 1980's
- EVN – 1980's
- Now:
  - EVN 18 telescopes including China, VLBA 10 telescopes, Canada, Asian – Pacific (China Japan VERA Korea KVA Australia), GMVA, EHT



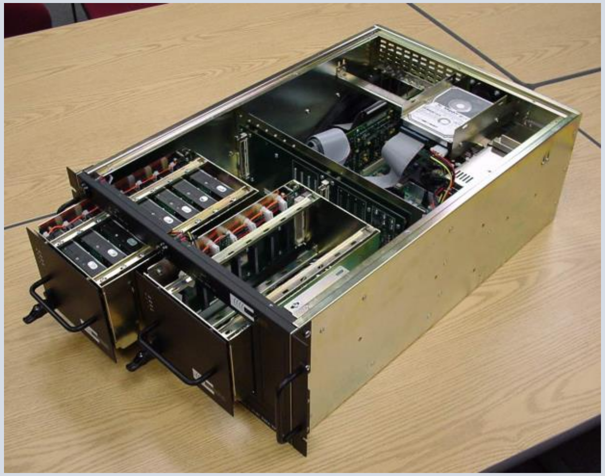
Transition to disks….



https://ourworldindata.org/grapher/historical-cost-of-computer-memory-and-storage

2000's Mk5

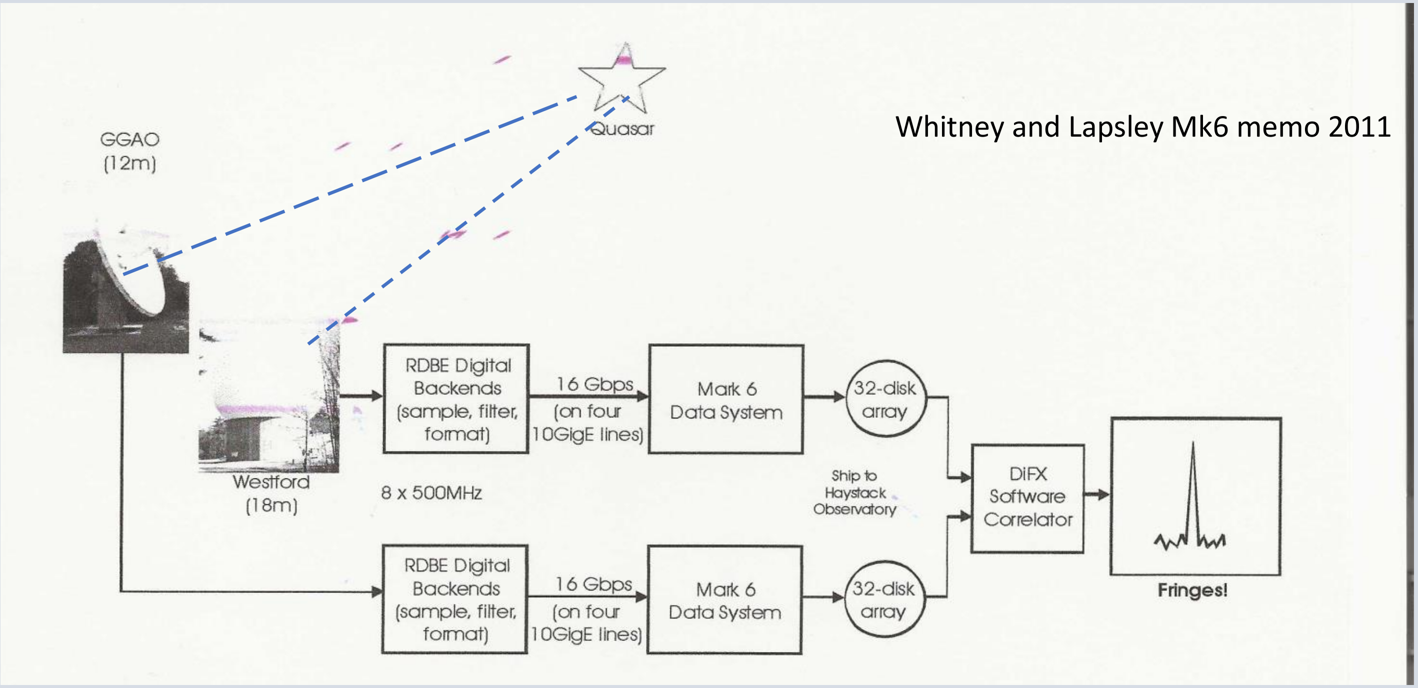
- Developed at MIT Haystack Observatory
- Uses low cost PC based components
- With ATA exchangeable disk packs
- Up to 2048 Mb/s
- Support for Mark 5 development was provided by BKG, EVN, KVN, MPI, NASA, NRAO and USNO.



Mk6

Mk 6 Module with 8 x 4 = 32 Terabytes on disks (2 x 10^14 bits)

- 16 Gbps continuous recording
- Using COTS tech
- Use 4 disk packs in parallel



Whitney and Lapsley Mk6 memo 2011

e-VLBI

- 1st e-VLBI meeting Haystack April 2002
- *i*Grid 2002 (Sept) showed sustained transmission across academic networks, JANET, GEANT, SURFnet at 500 Mb/s possible
- 2005 regular e-VLBI runs in EVN using Mk5 systems
- 2006– ESLEA project
- iGrid 2006 Transatlantic flows from EVN telescopes at 512 Mb/s to US
- Now routine real time VLBI

High data rate transmission in high resolution radio astronomy—vlbiGRID

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Abstract

Mon. Not. R. Astron. Soc. **374,** L47–L50 (2007) doi:10.1111/j.1745-3933.2006.00262.x

First e-VLBI observations of GRS1915+105

A. Rushton,[1] R. E. Spencer,[1] M. Strong,[1] R. M. Campbell,[2] S. Casey,[1] R. P. Fender,[3,4] M. A. Garrett,[2] J. C. A. Miller-Jones,[4] G. G. Pooley,[5] C. Reynolds,[2] A. Szomoru,[2] V. Tudose[4,6] and Z. Paragi[2]

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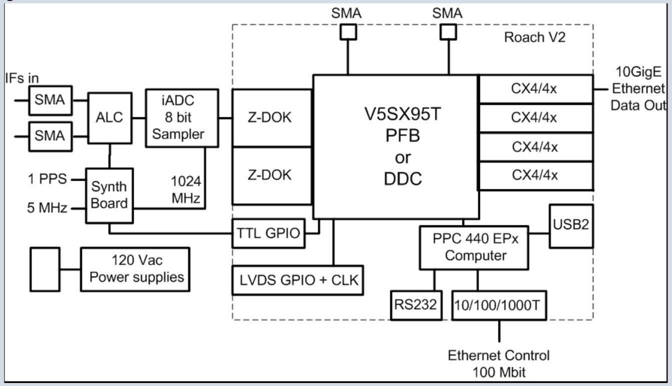
Accepted 2006 October 25. Received 2006 October 25; in original form 2006 October 6

ABSTRACT

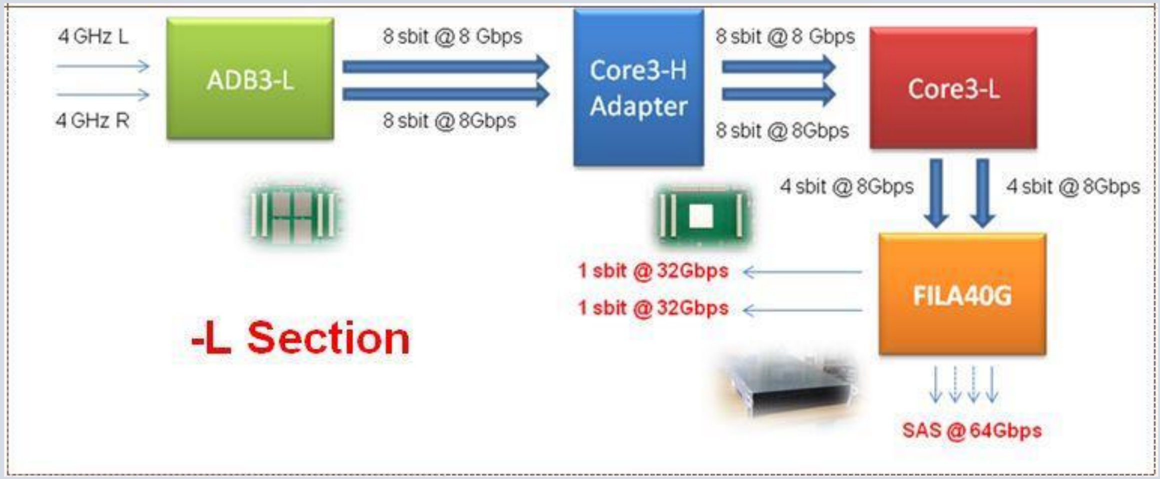
FPGA revolution: Digital backends: RDBE DBBC and Flexbuff 4 Gb/s and beyond

- RDBE Roach



Whitney 2011

- DBBC



Tuccari+2014

- Flexbuff - flexible data buffering

Takes data from Mk5 or DBBC, Can store several days at 1 Gbps.
Sent at ease to correlator after the observations

Lundquist and Szomoru 2014

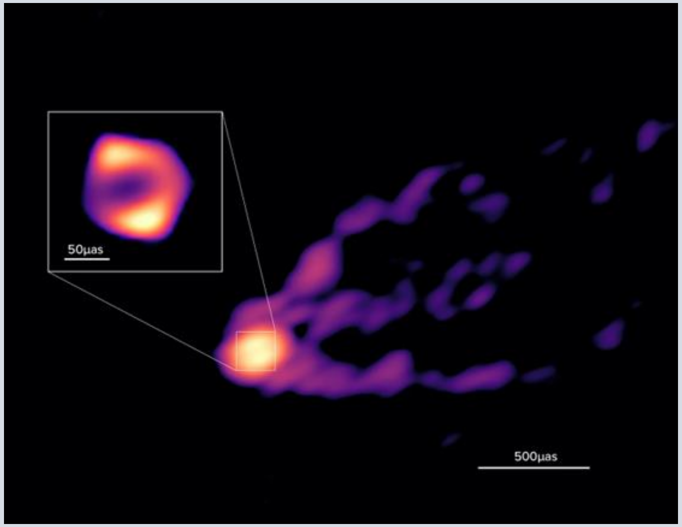
Comparison:

Feature	RDBE	DBBC2	R2DBE	DBBC3
Total RF MHz	2x512	2x1024	2x2048	4x4096
Sampling Rate Msps	1024	2048	4096	8192
O/P data rate Gbps	2	8	16	64
Xilinx FPGA	V 5	V5	V6	V6
O/P format	Mk5b	VDIF	VDIF	VDIF

Vertatstchitsch+2015

Summary

- Continuing changes in VLBI kit as tech. develops
- Mk5 in common use, e-VLBI increasing
- EHT and VGOS (geodesy) use high bandwidth Mk6
- Digital backends now common – RDBE (Mk6) DBBC (EVN)
- Heavy use of FPGAs
- EVN using “Flexbuff” data recording on disk, transmitted to the correlator over the internet afterwards



EHT and GMVA/ALMA image of M87
MPIfR R. Lu et al. Nature 2023

Main Conclusion:

Technological developments are an essential part of VLBI!