Advanced Technology Development in VLBI

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1. Where is VLBI data-acquisition headed?
2. Mark IV correlator

Where is VLBI Data-Acquisition Headed?

- Stay on tape?
- Disc?
- e-VLBI?

- VLBI is perhaps the world's single most voracious data-gathering activity in terms of collected **data-volume/day**!
- With the advent of Gb/sec recording systems, the near future foresees ~1000 Tb/day (that's a *Petabit*/day)
- In *most* cases, the single most significant driver is the **cost** of moving VLBI data from station to correlator.

Comparison of available 1 Gbit/sec VLBI recording systems

	Mark IV	**Toshiba D6**
Recorder type	Multi-track linear	Multi-head helical scan
Data rate	1.024 Gbit/sec (expandable to 2 Gbit/sec)	1.024 Gbit/sec
Recording capacity per reel/cassette	~5 x 10^3 Gbits (~1.1 hours at 1 Gbit/sec)	3.7 x 10^3 Gbits (~1 hour at 1 Gbit/sec)
Areal data density (not including overhead)	~23 Mbits/in^2	~95 Mbits/in^2
Error rate	<1 x 10^{-4}	<1 x 10^{-11} (error corrected)
Read while write	No	Yes
Cost per reel/cassette	~$1000	~$500
Media cost per Gbyte	~$0.5	~$0.12
Estimated hardware cost (recording system only)	~$250,000	~$500,000
Typical headstack life	~3000 hours	~1000 hours
Approx. headstack replacement cost	~$20K (2 headstacks)	~$30K (entire head array)

Disc vs. Tape? Magnetic vs. Optical?

Storage media cost only:

Tape –

Mark IV:

Now: ~30 Mb/in^2 at ~$0.50/GB
In 5 years: ~120 Mb/in^{2}at ~$0.12/GB

D-6:

Now: ~100 Mb/in^2 at ~$0.12/GB
In 5 years: Unclear

Magnetic Disc –

Now:~3 Gb/in^2 at ~$20/GB
In 5 years: ~15 Gb/in^2 at ~$5/GB
In 10 years: ~100 Gb/in^2 at ~$1/GB

Optical Disc –

CD: 0.7 Gb/in^2
DVD: 3.3 Gb/in^2
Problems: Low data rate
Relatively high costs

Optical Tape

- Terabit, Inc to announce 100 MB/sec at ~$0.50/GB, **but** WORM! (WORM='write once, read many')
- Whole optical tape market is struggling with magnetic competition
  magnetic

e-VLBI: The Rationale

- Improve overall system reliability by reducing dependence on tape recording systems in long term
- Automate stations; reduce operational station costs
- Monitor, test, debug stations in near real-time; improved data reliability
- Reduce processing turnaround time
- Will help to allow use of heterogeneous VLBI data-acquisition systems

Elements of Successful Wide-Area e-VLBI

1. Easy connection to any available network of any speed
2. Cross-compatibility between all VLBI DAS's
   (i.e. Mark IV, VLBA, K4, S2);
   standardized data-transmission format preferred
3. For forseeable future – asynchronous data transmission; implies significant local buffering at both DAS and correlator
   - Disc storage now ~$20/GB and *dropping rapidly*
   - Mark IV tape is ~600 GB.
4. Affordable network price structures

Note: In this model, the network connection need not be directly at the station!

Expt type	#stations	Total data	Data-transmission time (total)			Comments
			1 Mbps	100 Mbps	1 Gbps	
Station Checkout	2	2 Gb	30 min	20 sec	2 sec	Observe strong source; 30 sec at 32 Mbps
'Small' 24-hr expt	5	55 Tb	1.7 yrs	6 days	15 hrs	128 Mb/sec/stn
'Large' 24 –hr expt	15	1300 Tb	41 yrs	150 days	15 days	1 Gb/sec/stn

Potential e-VLBI applications

Sampling of Current Network Connection Costs

(based on telephone inquiries to several major communications companies in mid-1998)

MCI

Green Bank – Washington – Wettzel

T1 $12K/month (assumes availability in GB and Wettzel)

T3 ~$150K/month (but no current guarantee of availability)

Worldcom

Boston – London	T1	$28-30K/month
Boston – London	T3	$480K/month
Boston – Frankfurt	T1	$58K/month + $1.5K/month Euro access charges
Boston – Washington	T1	$4K/month + $1K/mo access charges
		(~32% discount on 3-year contract)
Boston – Washington	T3	$33K/month + $4.5K/mo/end site access charges
		(~25% discount for 3-year contract)

ATT

Wettzel – Westford	T1.5	$35K/month
	T3	Not available
Westford – Wash	T1.5	$5.8K/month
	T3	$65K/month
Green Bank – Wash	T1.5	$6.3K/month
	T3	$46K/month

Notes:

T1 is ~1.4 Mbps

T3 is ~45 Mbps

What is the future of e-VLBI?

- May be practical today for certain short, time-critical experiments, particularly over limited geographic range
- Practicality on global scale is primarily dependent on network costs
- Network backbone costs in U.S. are dropping faster than 'Moore's Law' (12-month doubling time vs. 18-month doubling time)
- Installed capacity U.S. coast-to-coast recently expanded by x5 when Qwest 'lit' 100 fibers carrying 100 Tb/sec!
- Improvement in wavelength-division multiplexing on optical fiber promises ~4 Tb/sec/fiber
- Direct optical amplification used for long hauls, though expensive
- One of biggest hurdles is high-speed, economical *local* connections

The Bottom Line!

- Despite amazing gains by the disc industry, tape is likely to be workhorse for most VLBI for at least 10 years, though disc may act as buffer storage for some e-VLBI data.
- VLBI can, and should(!), occasionally take advantage of the vast computer-industry R&D expenditures, most likely in a 'snapshot' mode, but may be expensive to adapt. VLBI will not be driver for industry.
- Global e-VLBI is not likely to be economical for some time, though e-VLBI will be practical in certain limited situations. Network prices are predicted to plummet in next few years as competition heats up, though local connections may remain a problem.
- Though e-VLBI is not practical now, the VLBI community would be well-advised to begin international collaboration to define standards. develop concensus, and lay the groundwork for e-VLBI ……'opportunity knocks for those who are prepared'.

The Mark IV Correlator Project

VLBI Correlators (USNO;Haystack;JIVE;BKG/MPI):

- 1 Gbit/sec/station (16 channels @ 32 Msamp/sec/channel max), expandable to 2 Gbit/sec/station
- Configurable to a variety of number of stations, up to 32 maximum
- Compatible with Mark IIIA, Mark IV and VLBA tape and channel formats

Westerbork CEI:

- Up to 16 stations in a variety of configurations, operating at 40 Msamp/sec/channel max, up to 1 GHz total bandwidth.

SMA CEI:

- Up to 10 stations in a variety of configurations, operating at 208 Msamp/sec/channel (multiplexed x4 and presented to correlator at 52 MHz), up to 4 GHz total bandwidth.

ALL USE SAME CORRELATOR BOARD AND CHIP!

Innovations

- First large-scale VLBI international cooperative development effort
- First large-scale 'station-based' XL correlator
- First full-custom VLSI chip for VLBI correlation
- High-speed serial data links (~1 Gbps on small coax) for data distribution
- Station model intermixed with data from each SU
- Highly innovative way of managing 'vernier-delay' and phase-rotation/shifting in correlator chip

Mark IV VLBI Correlator Features

- 1 Gbit/sec/station, expandable to 2 Gbits/sec/station
- Station-based architecture
- Scalable architecture allows up to 32 stations, 16 channels/station
- Full compatibility with Mark IIIA, Mark IV, VLBA
- 4X playback speedup compared to Mark IIIA correlator
- Efficient sub-netting
- Flexibility to exchange #baselines with spectral resolution
- Supports recirculation with 'Data Distributor' option
- Extensive use of VEX files for correlator operation/configuration
- HOPS post-correlation package

Division of Engineering Labor

- Haystack
  - Correlator chip and board
  - VLBI correlator data-interface boards
  - SMA correlator data-interface boards
  - High-speed serial data links
- JIVE/EVN
  - Station unit
  - Data distributor
  - Control board
- Attempt to balance US/European contributions
- Software being independently developed

VLSI Correlator Chip

- Developed as joint Haystack-UNM/NASA/SERC project
  - Functional specification, design, simulation at Haystack
  - Chip design at UMN/NASA/SERC under subcontract to Haystack
  - Fabrication at Hewlett-Packard foundry
- First packaged prototypes received Jan 95
- Commercial availability through UNM non-profit subsidiary
  ~10,000 chips have been fabricated

Correlator Board

Features

- 32 VLSI correlator chips/board
- Access to 64 2-bit data streams, configurable through 64x64 custom ASIC cross-point switch; up to 64 Msamples/sec data rate
- 16,384 lags/board, flexibly configurable to real/complex
- Up to 128 baselines/board
- Cross-polarization and auto-correlation modes supported
- 16 modules required for 16-station, 1 Gbit/sec/station, 32 lags/baseline VLBI correlator (64 modules for 32 stations)
- 48 modules required for 6-station, 4 GHz BW SMA correlator; 96 modules required for expanded 8-station SMA correlator

Status

- Has undergone exhaustive testing at Haystack, Dwingeloo
- Successfully tested to 70 MHz by CfA

1st static fringes - JIVE and Haystack - Aug 97

Tested following correlator aspects --

- data flow through SU
- static delay correct within SU
- serial link performance
- input board/FIFO working
- correlator-chip arithmetic and counters

1st VLBI fringes - Haystack Oct 97

Tested following correlator aspects --

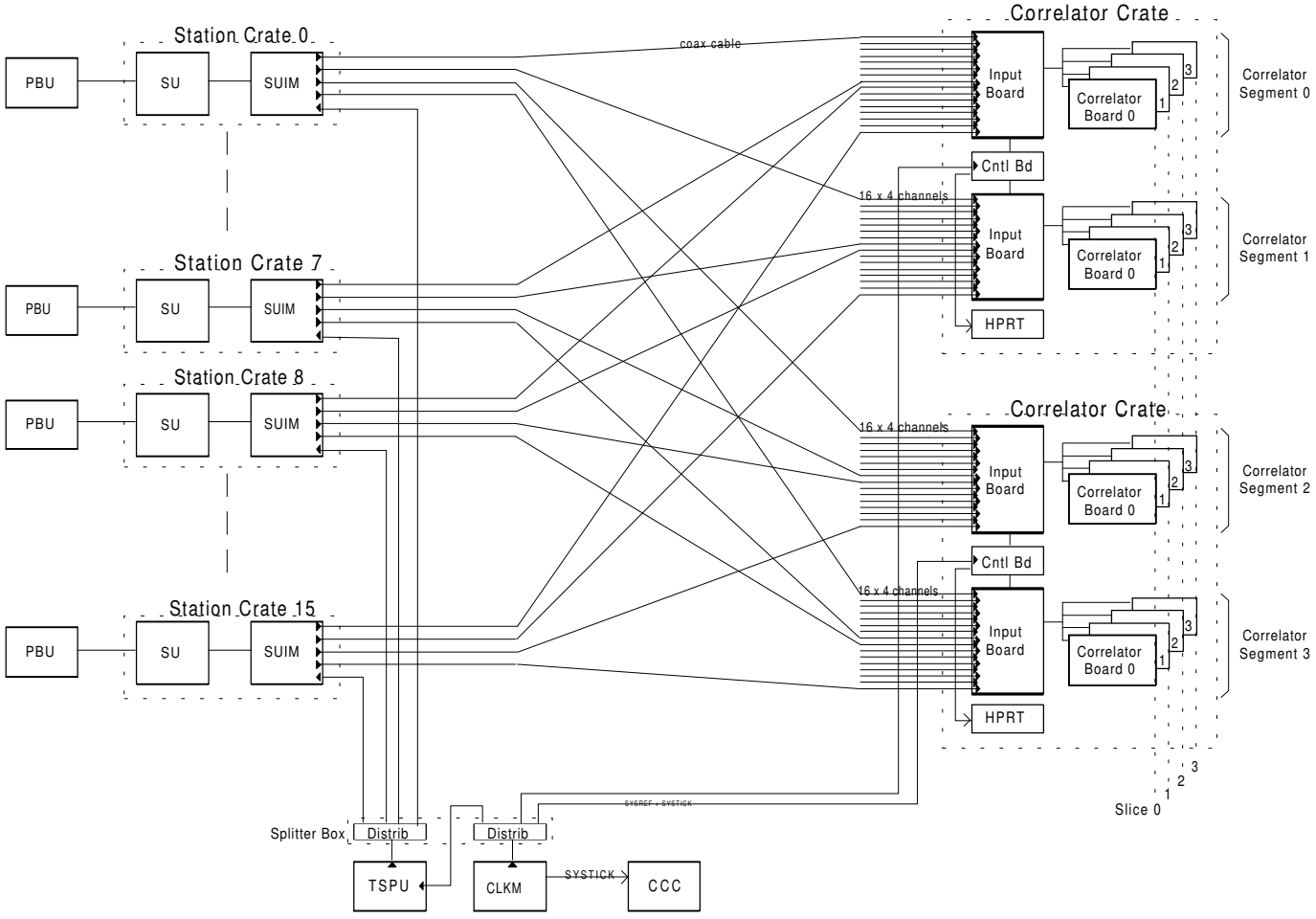
- CALC/genaroot spline model
- SU generation of correlator frame-header packets from splines
- correlator chip capture of header packets
- dynamic parameter calculations
- pipelining of parameters in SU and CU software
- correlator-chip delay trackers for both stations and baselines
- fringe rotation
- dynamic tap adjustment
- 90-deg phase shift on delay changes
- 2-tape-drive/2 SU fringes Feb 98 (JIVE) and April 98 (Haystack) after delivery of 2nd prototype Station Units

Software

- Correlator control entirely based on 'VEX' files, including 'observe' files and VEX-like files for correlator configuration; this approach offers ease and flexibility to adapt to special requirements
- Message-based process interactions
- Relatively small amount of critical real-time control is needed due to model generation by SU's and embedded station-parameter-passing in data stream.
- Post correlation software is an extension to the HOPS package already in use with Mark 3/3A.
- Plan easy data-migration path to AIPS and FITS.

Schedule

- Most hardware is ready except Station Units.
- Station Unit deliveries from Allied Signal expected March-April 99.
- Phase-cal modules in SU have lagged – problems are now believed to be corrected, but delivery of production units will not be until ~3Q99.
- Mark 4 correlator to be delivered to USNO in ~May 99 time frame with 'Mark IIIA capabilities', but without phase-cal capabilities.
- Mark 4 correlator to be delivered to BKG/MPI in ~July 99, without phase-cal capabilities.
- Software development is pacing initial deliveries.
- Additional software development will continue to support full capabilities, to be completed in 18-24 months following initial deliveries.



Mark IV Correlator Interconnection Block Diagram
(16 stations, 1 Gbit/station))