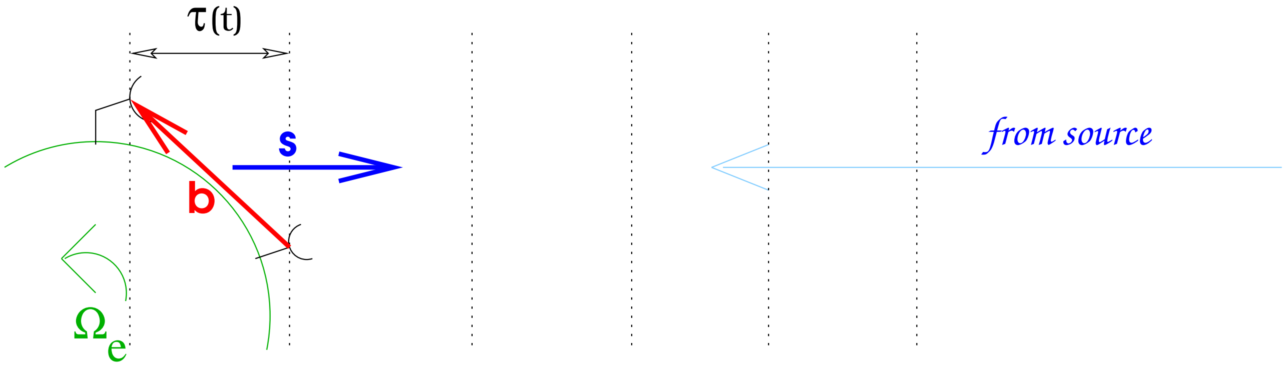
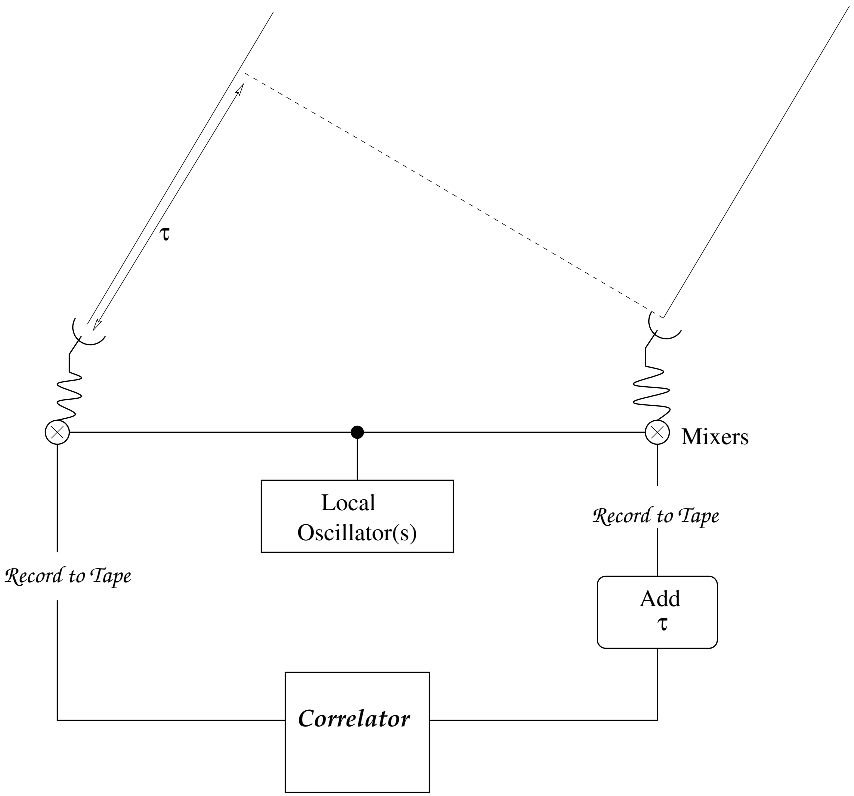
The EVN MkIV Data Processor at JIVE

Bob Campbell

— **JIVE** —

- Correlator Generalities
  - Pre-correlation
  - Correlation
  - Post-correlation
- Specifics of Downstairs
  - Playback & station units
  - Correlator



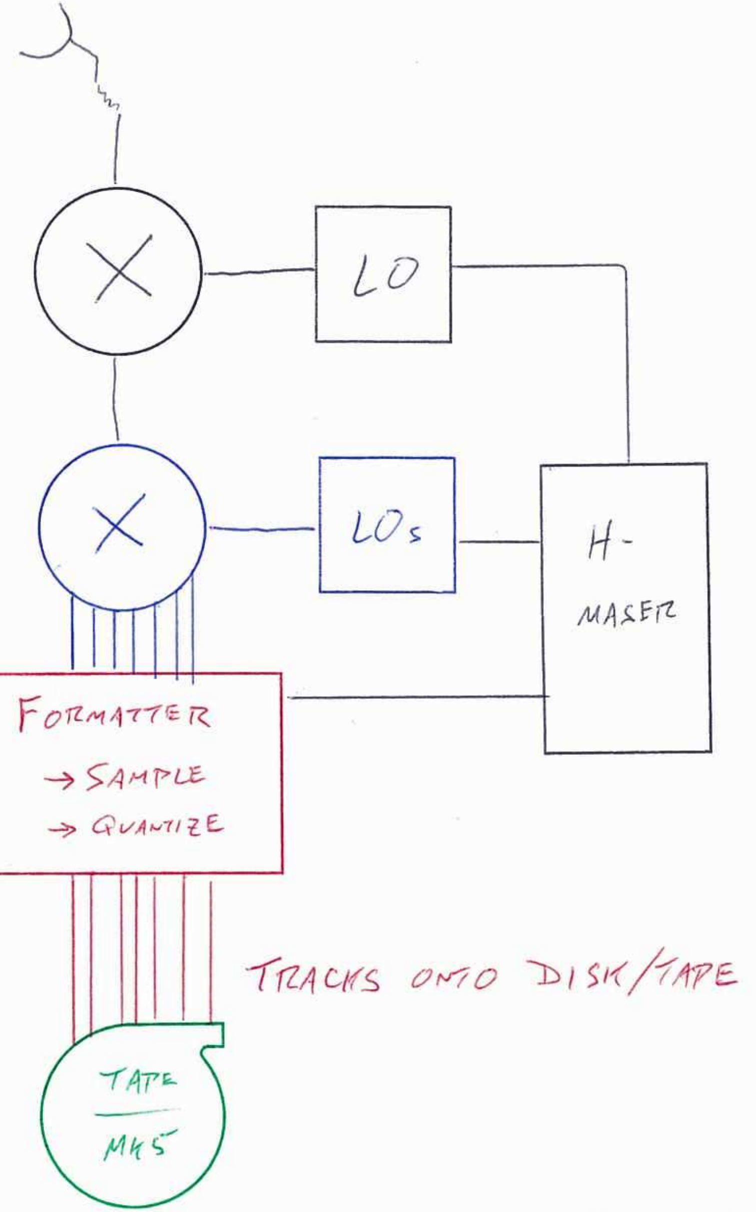


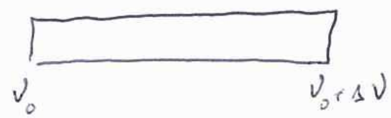
$$\tau(t) = -\frac{1}{c}\,\mathbf{B}(t) \cdot \hat{\mathbf{s}}$$

$$\varphi(t) = \nu\tau(t)$$

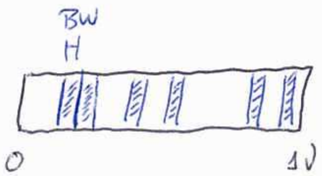
$$\tau_{\rm max} = 21.3\,\mathrm{ms} \quad (106\,\mathrm{M}\lambda)_{\rm C.band}$$

$$\dot{\tau}_{\rm max} = 1.55\,\mu\mathrm{s/s} \quad (7700\,\mathrm{cyc/s})_{\rm C.band}$$





FRONT-END



IF + VIDEO CHANNELS

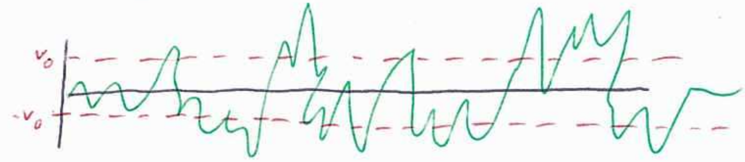
(BASE-BAND CHANNELS)

SAMPLING RATE: $\Delta t = \frac{1}{2BW}$ (NYQUIST)

2bit QUANTIZATION:

SIGN ($v \geq 0$)

MAG ($|v| \geq v_0$)



EACH VC: RATE $= \frac{1}{2BW}$ bps PER sgn/mag (≤ 32 Mbps)

FAN-OUT

MEDIUM MAY HAVE MAX TRACK RECORDING RATE (16 Mbps)

& MAX N_{TRACKS} (64)

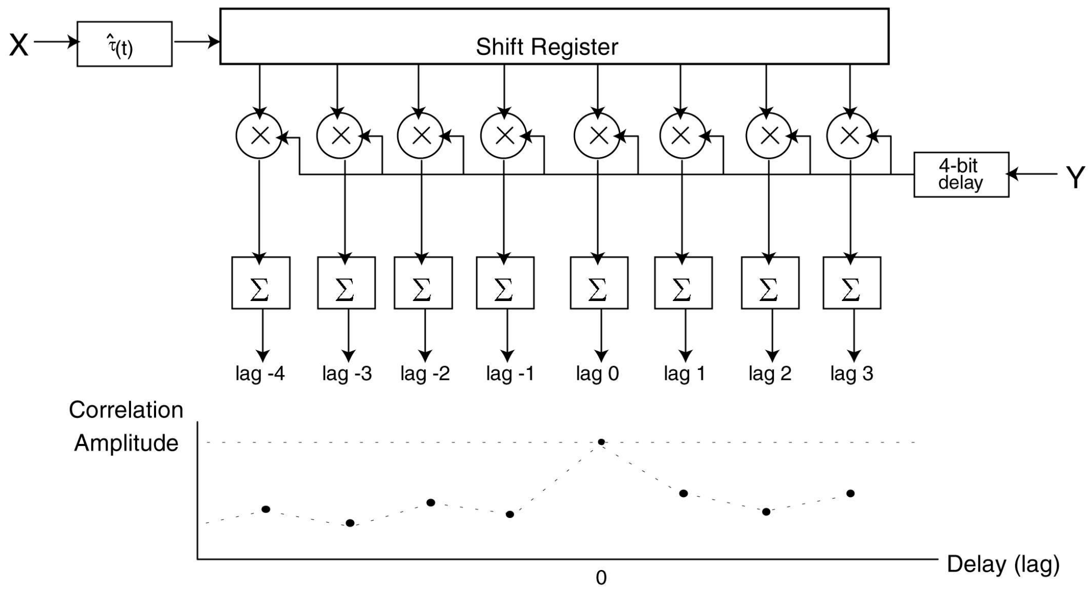
Pre-correlation tasks

- Provide aligned/conditioned bit streams to correlator
  - Undo recording complications: recover “scheduled” channels
  - Apply model to “stop” Earth under sky

Model Constituents (& approx. scales)

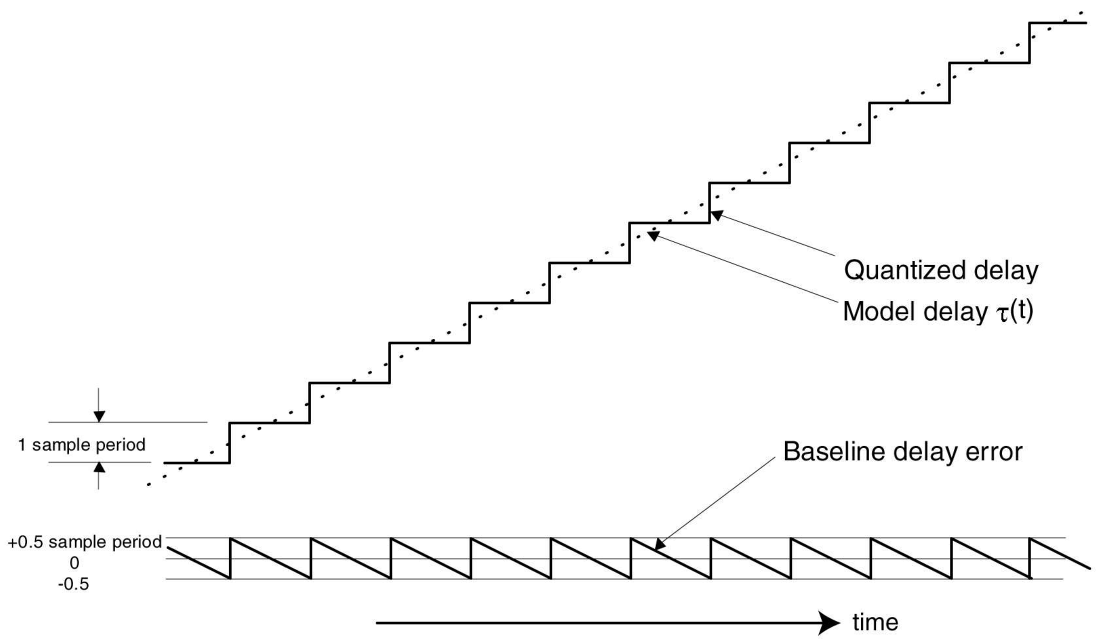
- Station / Source positions: different frames (ITRF, ICRF), motions
- Times: UTC, UT1, TT, TDB/TCB/TCG
- Orientation: Precession (50″/yr), Nutation (9.6″, 18yr), Polar Motion (0.6″, 1yr)
- Diurnal Spin: Oceanic friction (2ms/cy), CMB (5ms, dcds), AAM (2ms, yrs)
- Tides: Solid-earth (30cm), Pole (2cm)
- Loading: Ocean (2cm), Hydrologic (8mm), Atmospheric (2cm), PGR (mm's/yr)
- Antennas: Axis offset, Tilt, Thermal expansion
- Propagation: Troposphere (dry [7ns], wet [0.3ns]), Ionosphere
- Relativistic $\tau(t)$ calculation: Gravitational delay, Frame choice/consistency

Simplified Real Correlator



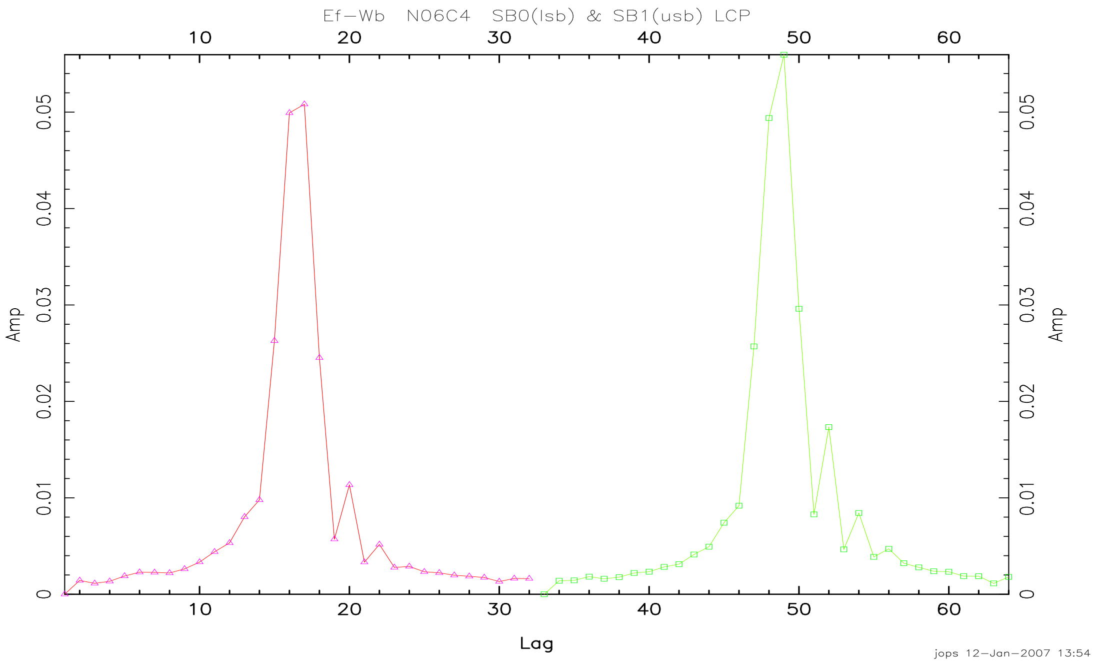
- Shifting signals from 2 stations by a series of 1-sample steps ($\equiv$ LAGS)
  - Each lag $=$ 1 sampling interval $= \frac{1}{2BW}$ (Nyquist)
- One signal has been delayed by τ (from $a\ priori$ model)
- This delay is constrained to be integral lags (drop/add a sample)

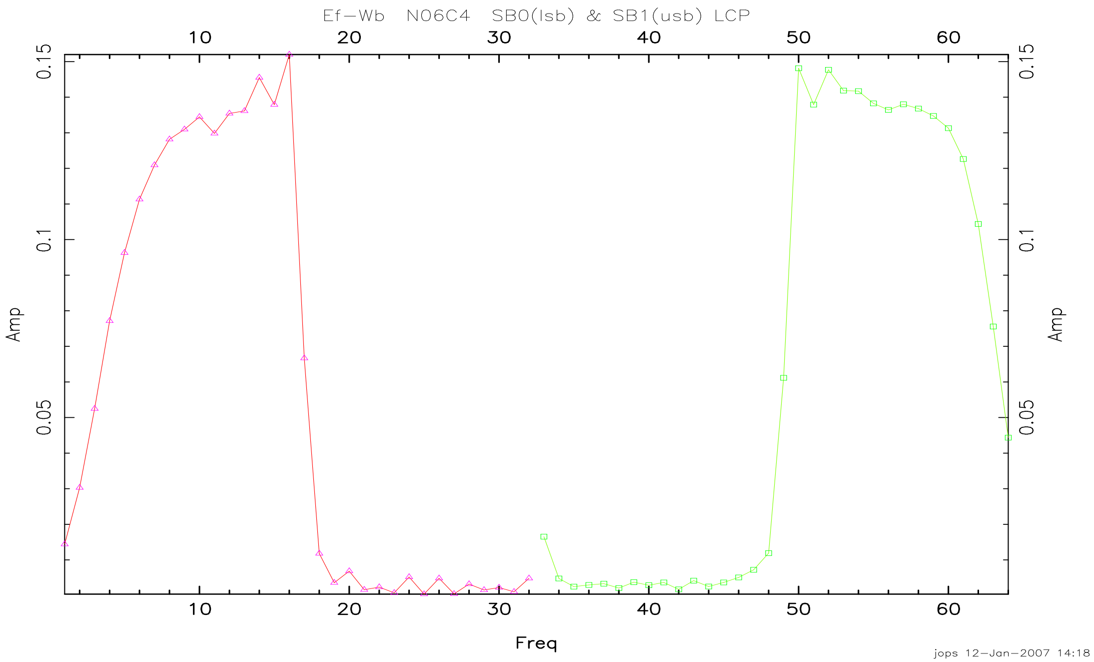
(Baseline) Delay Tracking



- Delay $\sim$ diurnal sinusoid
  - Amp $= B/c$; ~ 3.3 ms per 1000km of baseline
  - Delay steps $= \Delta_\tau = \frac{1}{2BW}$ (1 lag); $\sim 1/32 \rightarrow 1$ μs
- Sawtooth(y) delay error $|\delta_\tau| \leq 0.5$ lag $(\leq \frac{1}{4BW})$
- Adding/subtracting delay steps handled in bitstream

Correlation Functions *vs* lag, frequency

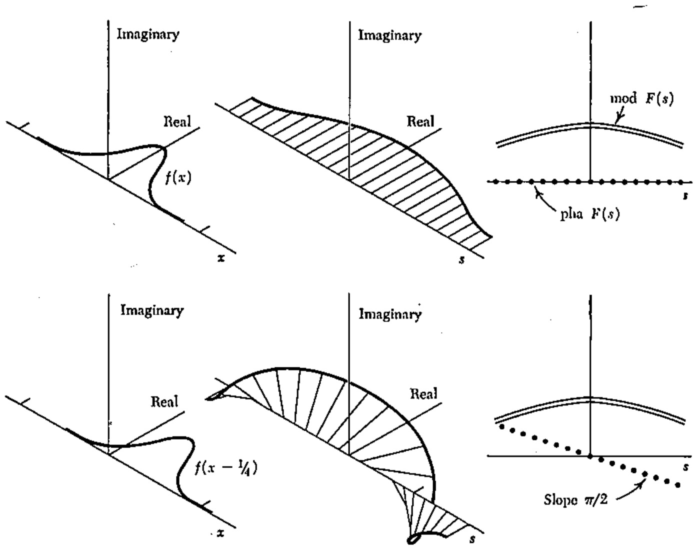




Delay Error $\rightleftharpoons$ Phase slope across band

- ⋆ Error = 1 lag $\longrightarrow$ 180° edge-to-edge phase slope across band

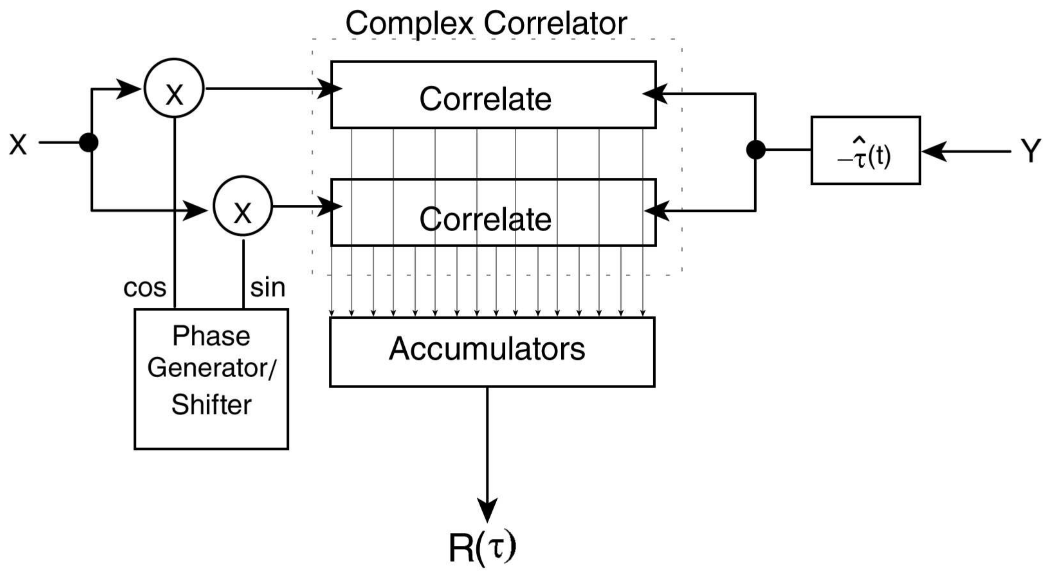
- Shift theorm: $f(t-\Delta) \rightleftharpoons e^{-i2\pi(\frac{\nu}{N_{\rm lag}})\Delta} F(\nu) \quad = \quad e^{-i\pi(\frac{\nu}{N_\nu})\Delta} F(\nu)$



- Can also derive via:
  - Tracing expression of fringe phase (TMS §9.3.i)
  - group-delay $= \frac{1}{c}\int \mu_g \, ds = \frac{1}{c}\int \frac{d}{d\omega}(\omega\mu_p)\, ds$

Baseline complex correlator

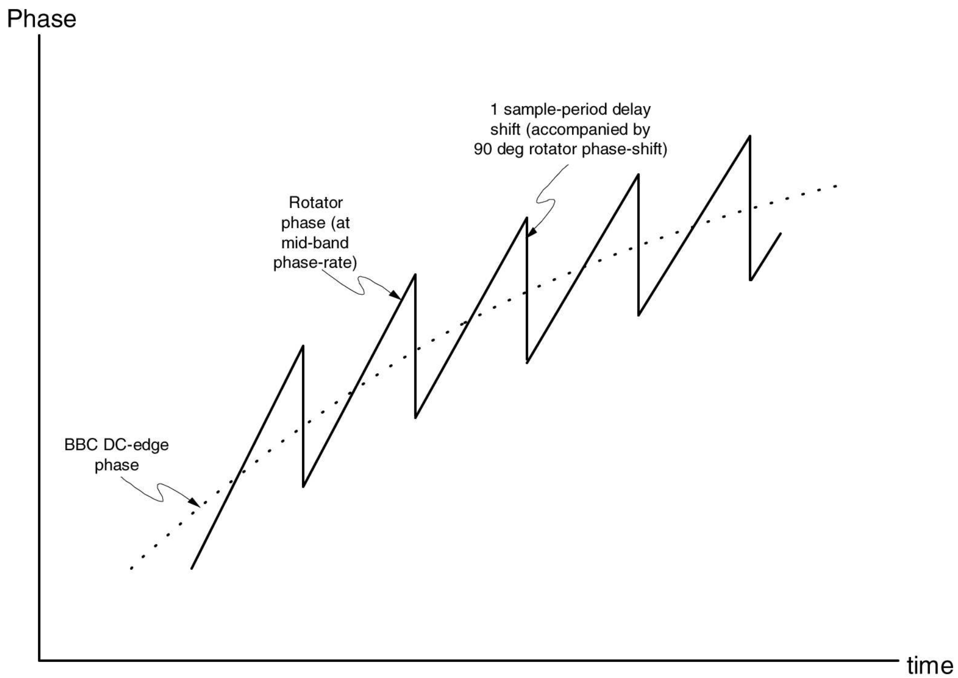
- Delay τ applied to one station
- Fringe rotation (rate $\dot{\tau}$) applied to the other
- cos/sin mixing of fringe rotation (Hilbert transforms: Bracewell Ch.12)
- output = one complex number per lag
- **XF**



Running the fringe rotation

- track φ at band center (minimize phase offsets at edges)
- DC edge $\rightarrow$ band center: φ_{FR} increment $= \pm 2\pi(\frac{BW}{2})\delta_\tau \; = \; \pm\pi BW\delta_\tau$
- Step fringe rotation $\pm 90^\circ$ at each instant delay shifted by $\pm\Delta_\tau$

$$\delta_\tau \rightarrow \delta_\tau \pm \Delta_\tau \; = \; \delta_\tau \pm \frac{1}{2BW}, \quad \varphi_{FR} \rightarrow \varphi_{FR} \pm \frac{\pi}{2}$$

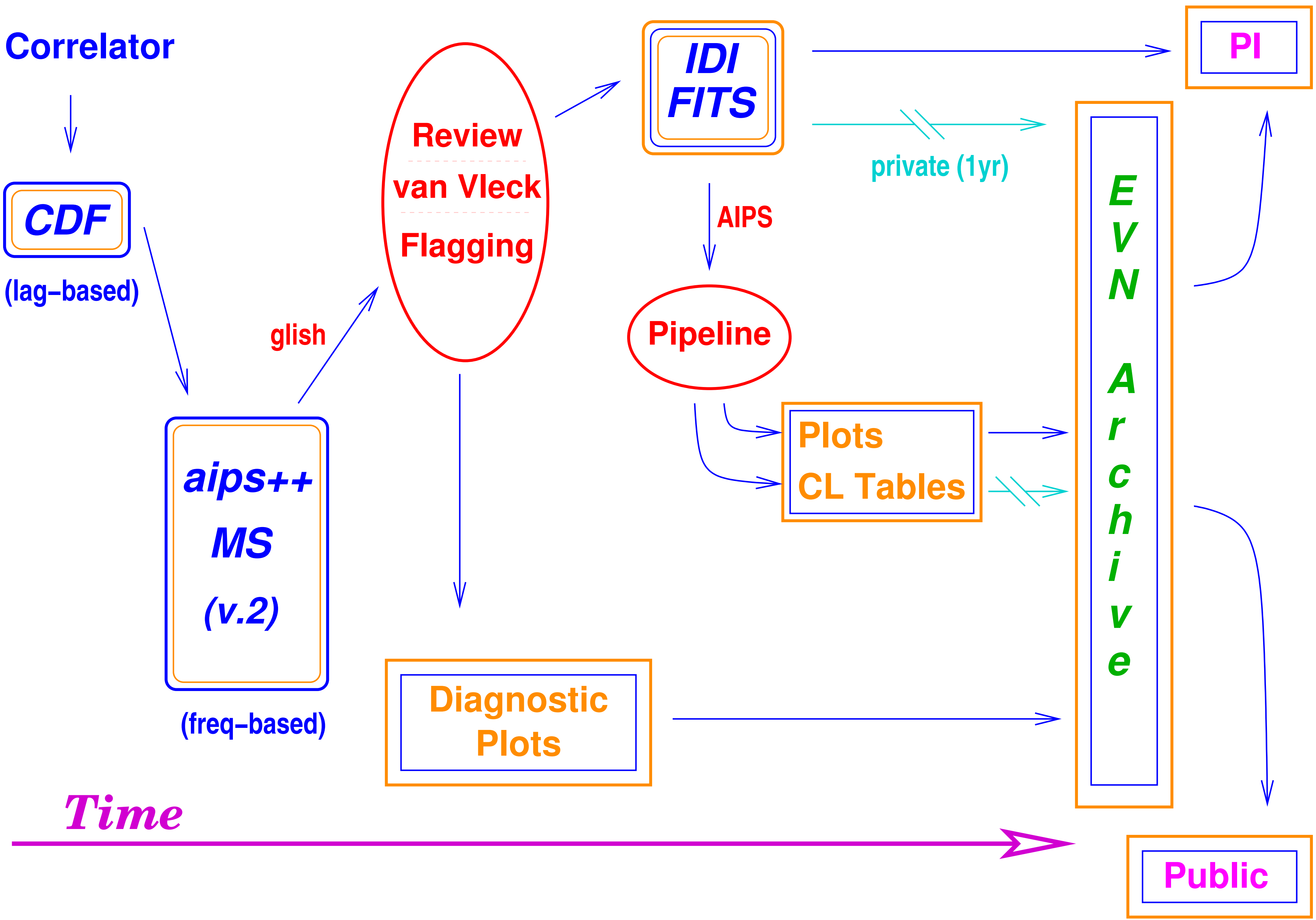


Baseline XF Correlator: Ops. Issues

- Reference epochs: UTC at "reference station"
- Scalability of implementing $N(N-1)/2$ delay elements
- The venerable Mk III (Haystack, Bonn, . . .)

$\hookrightarrow$ **Shortly: station-based XF**

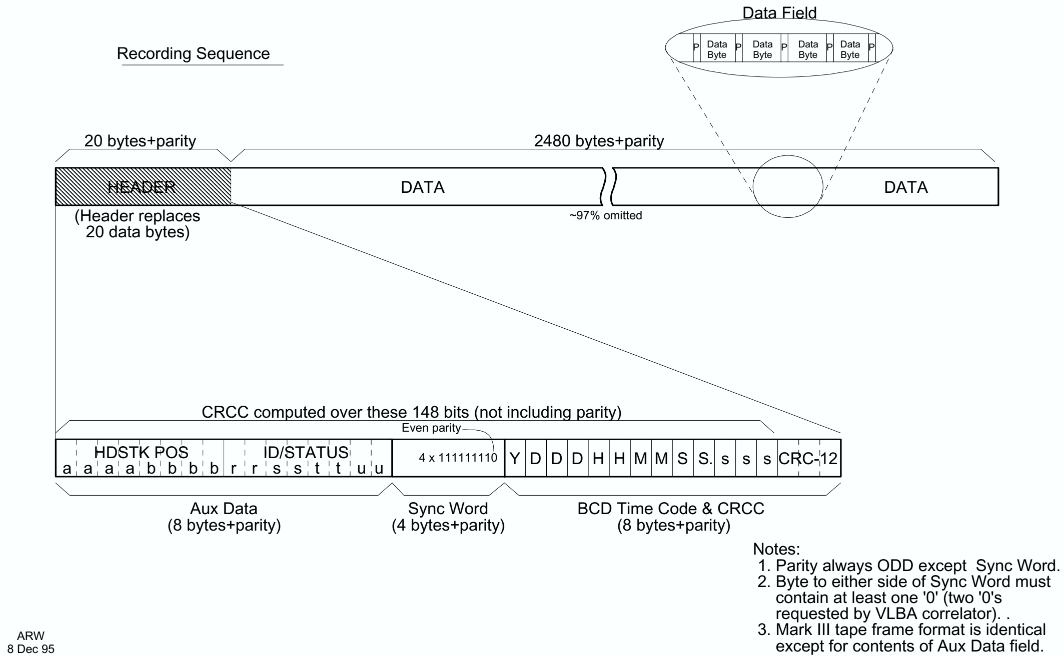
Post-Correlation Review/Distribution



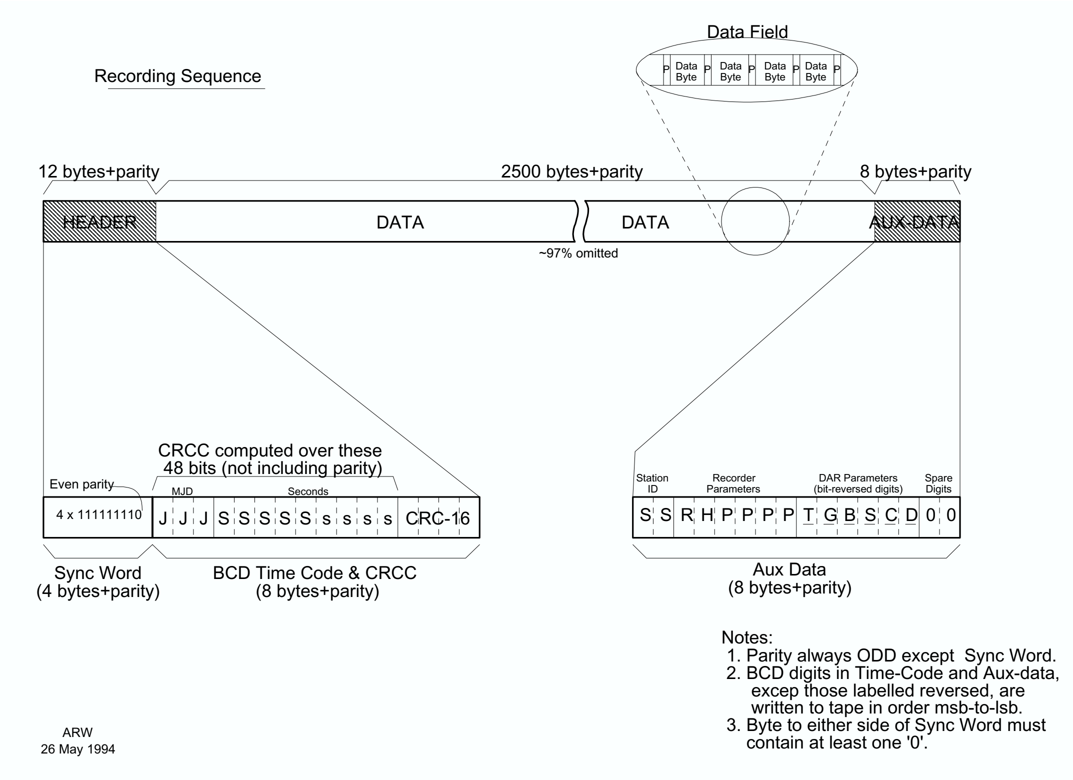
Data Playback

- Tape DPU
  - Heads: 2×32; $38\,\mu$m width; $17\,\mu$m guard band
  - 14 head positions $\rightarrow$ 448 tracks along $1''$-wide tape
  - Thin tape: capacity = 591 GB, cost $\sim$ \$1200
  - Playback speed: 80, 160 ips (4 or 8 Mbps/track)
  - Tension control: vacuum or tension arms
- Mark 5(A) Disk Packs
  - Goal = reproduce output of tape playback (tracks, fan-out . . .)
  - Capacity: 8 "normal" disks (3.2 TB packs now in regular use)
  - Random access
- Track data formats: Mark 4, VLBA

Track Formats



Mk4



VLBA

Frame Durations:

$8\,\mathrm{Mb/s} \rightarrow 2.5\,\mathrm{ms}$

$16\,\mathrm{Mb/s} \rightarrow 1.25\,\mathrm{ms}$

DIM / TRM

- DIM (Data Input Module)
  - Physical/logical track-assignment cross-bar switch
- TRM (Track Recover Module)
  - Read headers; seek special markers; read times
  - Align times (2.5 Mb buffer per track)
  - Flag bad data (validity bit)
  - TRM byte-slips
- Time distributed through system: ROT
  - Fundamental system clock-rate: 32×10^6 ticks per second

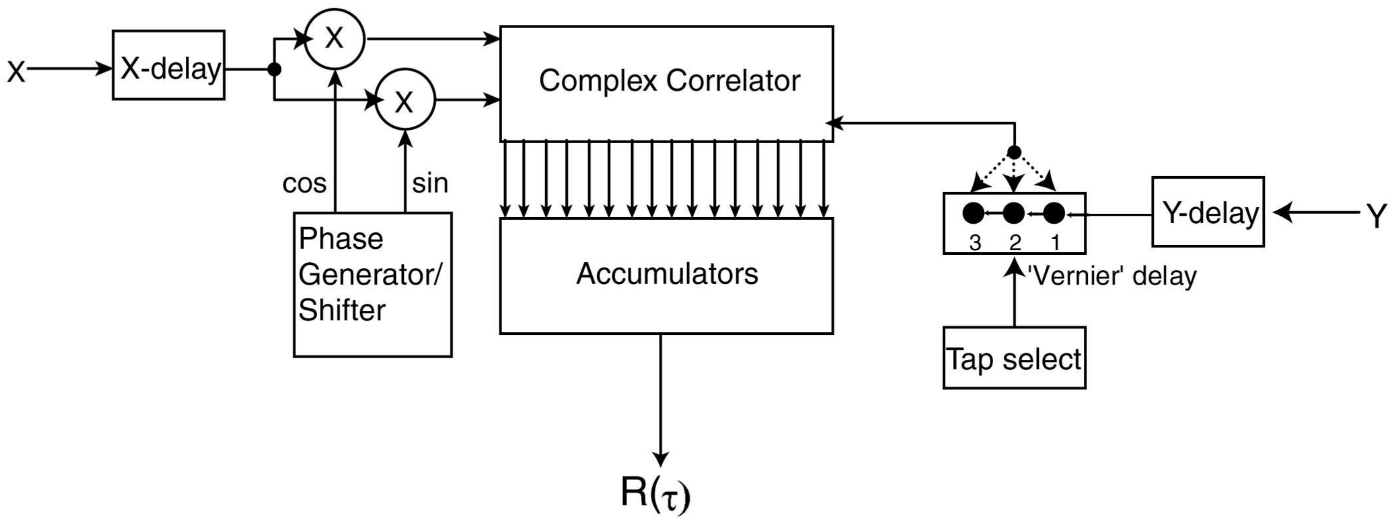
CRM / PCM

- CRM (Channel Recovery Module)
  - Undo fan-out to recover "scheduled" cahnnels
  - Max. 16 channels
  - Output = 3 bit-streams: Sign, Magnitude, Validity
  - CRM buffer jumps
- PCM (Phase-Cal Module)
  - Extract embedded calibration tones (at multiples of 1 MHz)

DCM & DMM

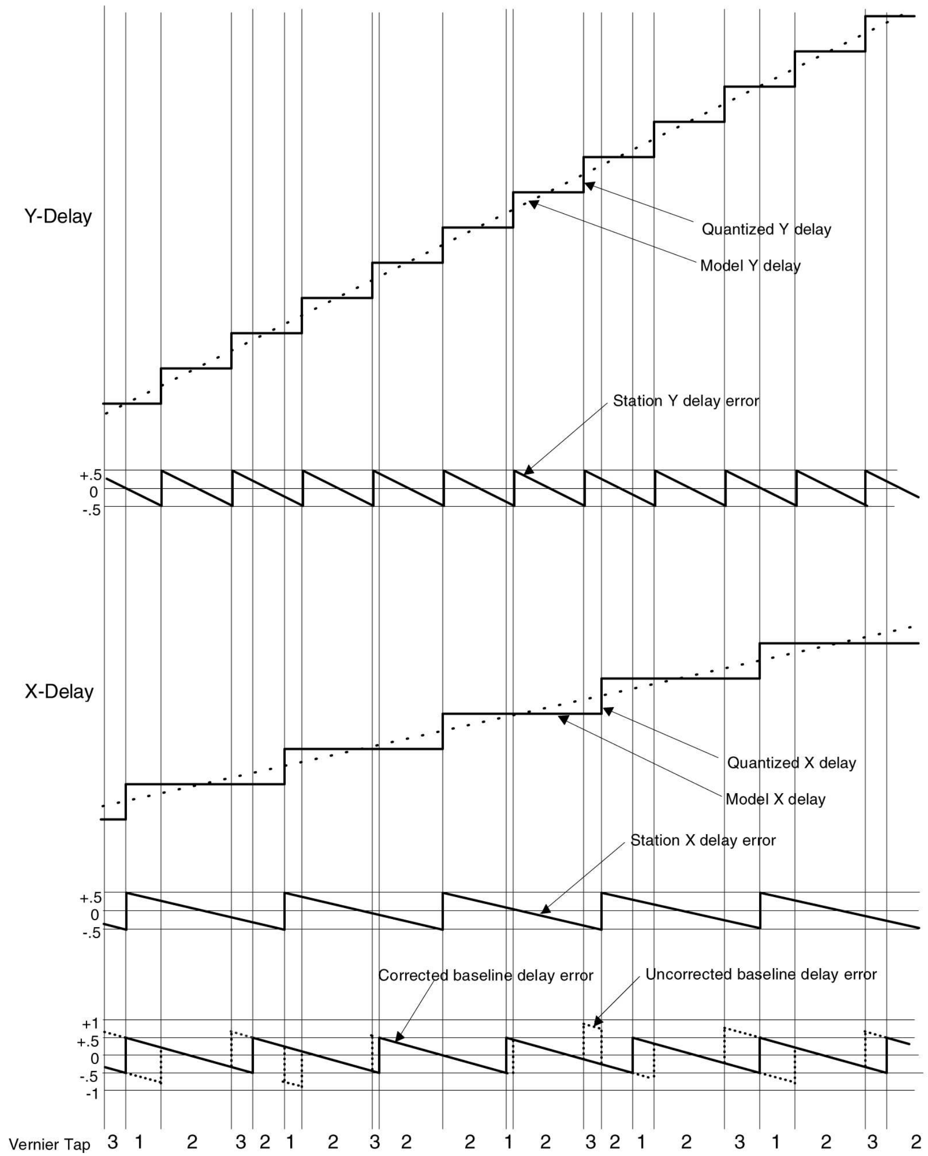
- Delay Control & Memory Modules
- Applies *a priori* model (polynomials) to data
  - Quintic over 2 min $\rightarrow$ quadratic over each correlator frame
- Creates correlator frames
  - Duration: $1/2 \rightarrow 1/64$ sec
  - Model parameters held constant over CF
  - CF headers added (delay/phase model, sideband, oversampling, etc.)
- State counts (sampler stats): distribution of H+, L+, L–, H– samples
- DMM byte slips
- 3 bit-streams to correlator: S, M, V

Station-based XF Correlator



- Same as baseline XF, **PLUS** the "Vernier" delay tap

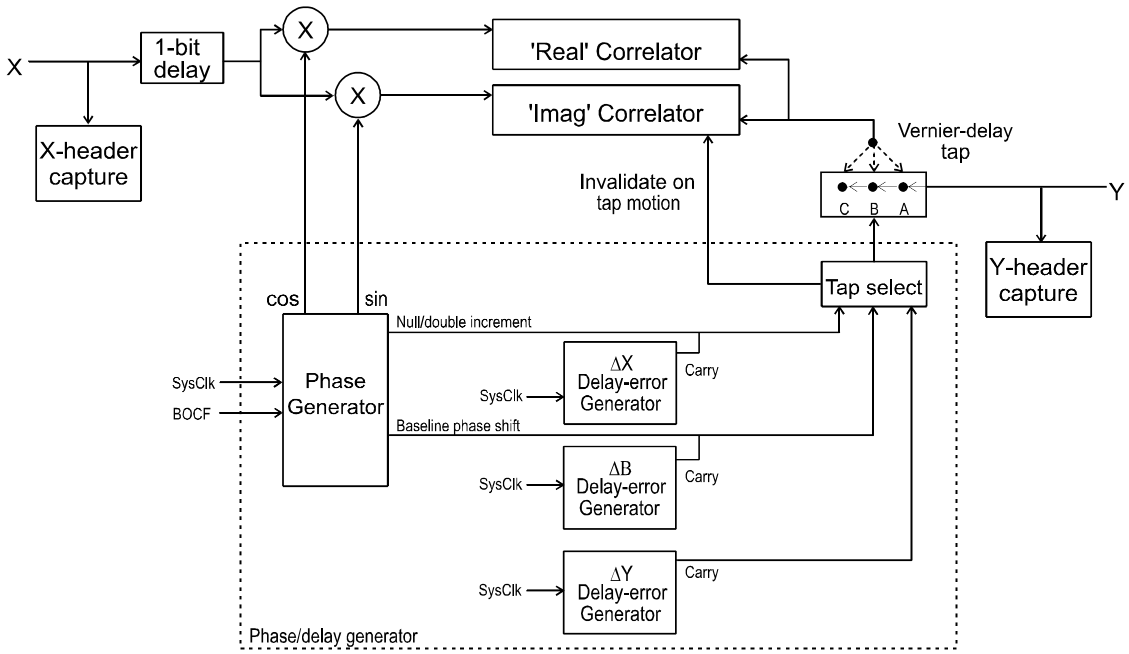
Station-based Delay Tracking



- $\exists$ periods of $|\delta\tau| > 0.5$ lag
  - Worse phase slopes accross band
- Vernier delay tap (± 1 lag) set to shift

  $|\delta\tau| > 0.5$ lag to $|\delta\tau| \leq 0.5$ lag

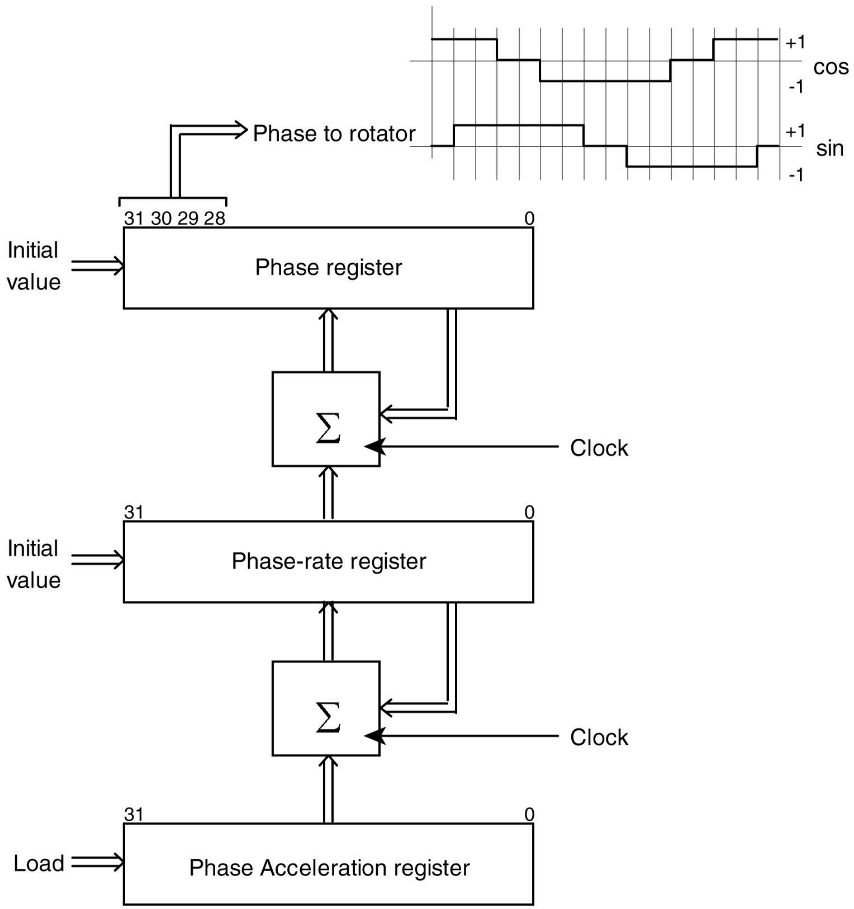
Vernier Delay Tap Rules



Condition	Actions on delay shift
$\dot{\tau}_x(t) > 0$	*On X delay-shift*: X Station Unit drops one sample; Shift upstream 1 tap position; Double-increment phase-generator
$\dot{\tau}_x(t) < 0$	*On X delay-shift*: X Station Unit duplicates one sample; Shift downstream 1 tap position; Null-increment phase-generator
$\dot{\tau}_y(t) > 0$	*On Y delay-shift*: Y Station Unit drops one sample; Shift downstream 1 tap position
$\dot{\tau}_y(t) < 0$	*On Y delay-shift*: Y Station Unit duplicates one sample; Shift upstream 1 tap position
$\dot{\tau}_b \equiv \dot{\tau}_y(t) - \dot{\tau}_x(t) > 0$	*On baseline delay-shift*: Shift upstream 1 tap position; Apply appropriate baseline phase shift
$\dot{\tau}_b(t) < 0$	*On baseline delay-shift*: Shift downstream 1 tap position; Apply appropriate baseline phase shift

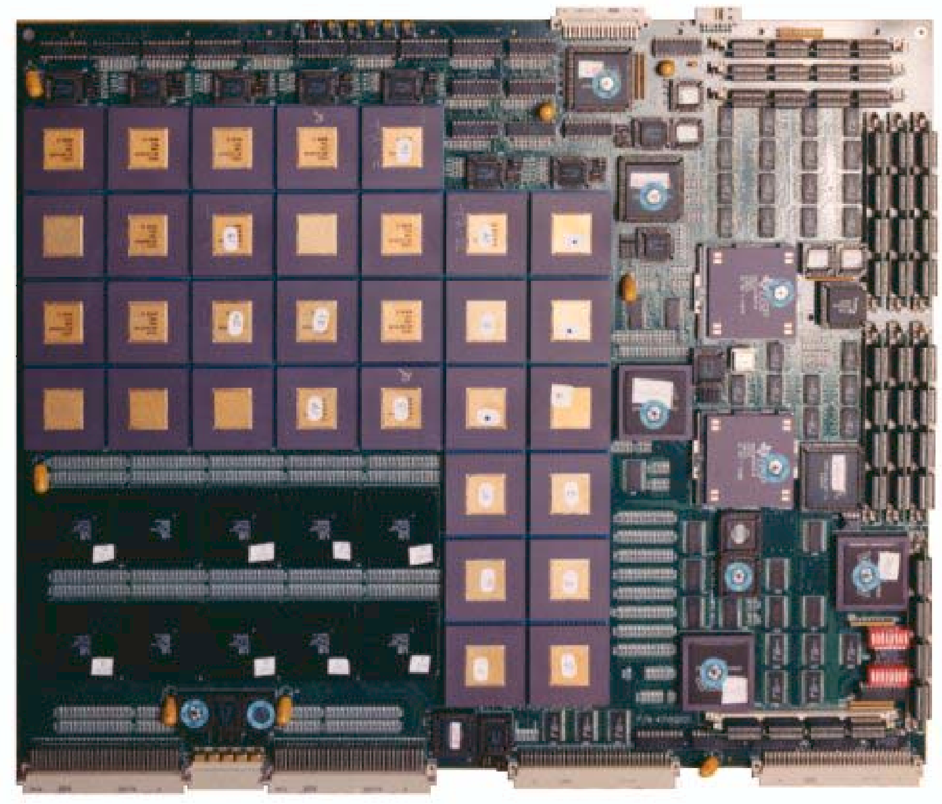
- Vernier tap actions completely determined by:
  - Signs of station/baseline model rates
  - Instances of station/baseline (integral-lag) model delay jumps

Why not fringe rotate both stations?



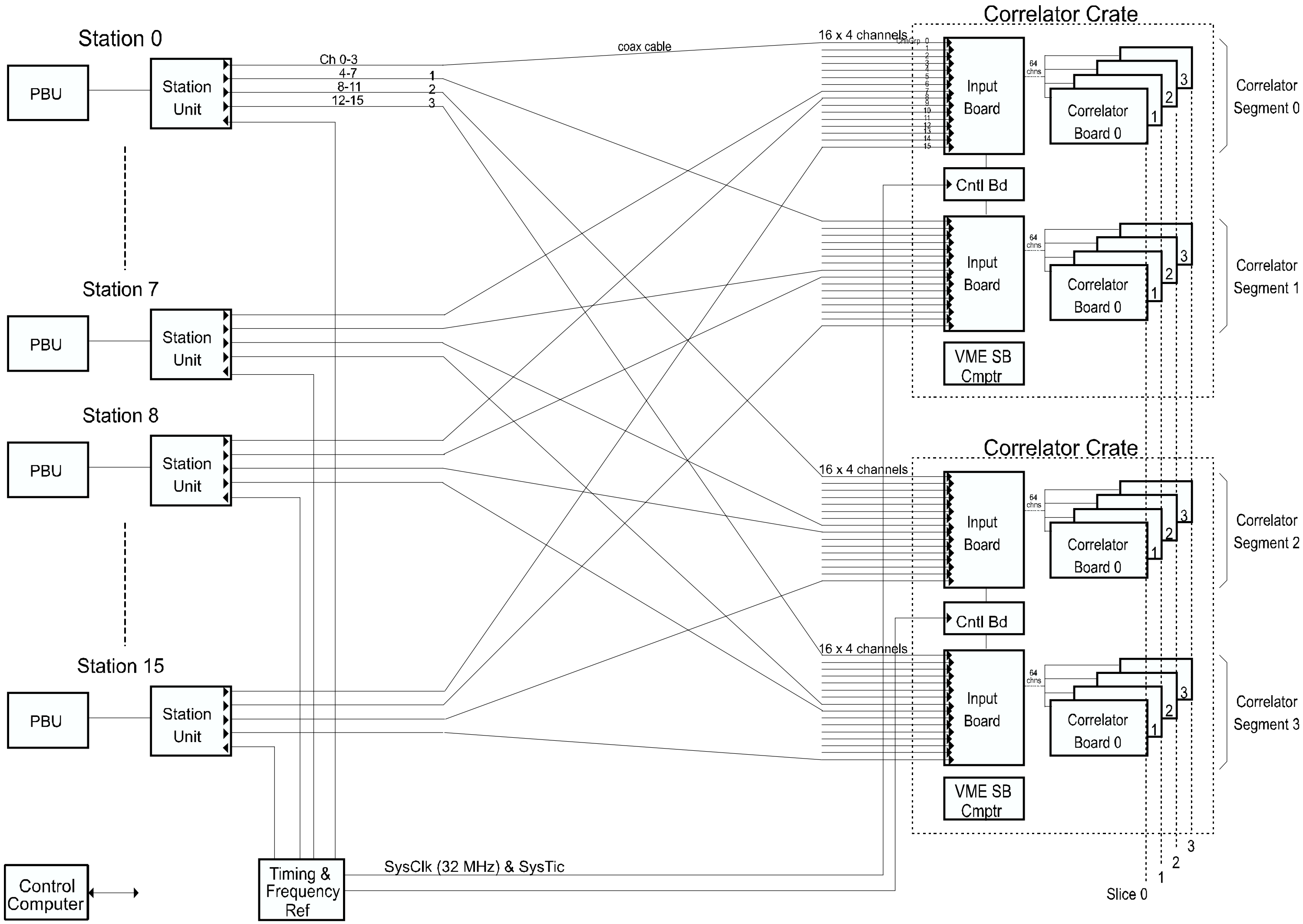
- 3-level sinusoids (+1, 0, –1)
  - doubled SNR loss
- Energy scattered into higher harmonics
- Fringe-rotating both stations would create two sets of spurious harmonics that correlate with each other
  - Delay-rate ~ 0 events
- Updating phase “integration”
  - Speed-up
  - Oversampling

Correlator Board



- Correlator has 32 boards; each board has 32 chips
  - each chip can handle 128 lags (in local validity)

Data Processor Connections



Flexible Correlator Configuration

$$N_{\rm sta}^2 \cdot N_{\rm sb} \cdot N_{\rm pol} \cdot N_{\rm frq} \leq 131072 \times \mathcal{Recirc} \times 2$$

$N_{\rm sta} = (4,\ 8,\ 12,\ 16)$; $N_{\rm pol} = (1,\ 2,\ 4)$; $N_{\rm sb} \cdot N_{{\rm pol}_\parallel} \leq 16$; $N_{{\rm frq}_{\rm max}} = 2048 \times 2$

Examples:				
	8 Sta	1 SB	1 Pol	2048 Frq
	16 Sta	1 SB	1 Pol	512 Frq
	16 Sta	8 SB	4 Pol	16 Frq

Maximal Spectral Resolution afforded ($N_{\rm frq} = 2048$):

$BW_{\rm SB}$ [MHz]	$\Delta\nu$ [Hz]	Velocity Resolutions for various lines [m/s] Δv_{1420}	Δv_{1665}	Δv_{6668}	Δv_{22235}
16	7813	1651	1408	351	105
2	977	206	176	44	13
0.5	244	52	44	11	3.3

The Future:

Recirculation: $\mathcal{R} \leq 16\,{\rm MHz} \,/\, BW_{\rm SB}$; $N_{{\rm frq}_{\rm max}}$ unaffected

Local $\longrightarrow$ Global Validity: $N_{{\rm frq}_{\rm max}}$ doubles if no data-replacement headers

Correlator Accumulation Rules

- Multiplication table for accumulation (24-bit registers) of correlation function:

			S	0	0	1	1	0	0	1	1
			M	1	0	0	1	1	0	0	1
			V	0	0	0	0	1	1	1	1
S	M	V									
0	1	0		0	3	0	0	0	0	0	0
0	0	0		3	3	3	3	3	3	3	3
1	1	0		0	3	0	0	0	0	0	0
1	0	0		0	3	0	0	0	0	0	0
0	1	1		0	3	0	0	6	4	2	0
0	0	1		0	3	0	0	4	3	3	2
1	0	1		0	3	0	0	2	3	3	4
1	1	1		0	3	0	0	0	2	4	6

- "3" added to all entries to stick with unsigned bytes (3 bits)
- Fringe-rotator 0 state (0,0,0): null product; increment counter
- Other Validity=0 states: null product; don't increment counter
- Complication: don't accumulate Low–Low (M=0) states
  - ⋆ Need to know the sampler stats for proper 2-bit van Vleck correction

Correlator Output Capacity

Raw output (local validity):

- lag-space correlation functions (32 kB/board) + headers (16 kB/board)
- Full-correlator $t_{\mathrm{int}_{\mathrm{min}}} = 1/4$ sec

  Max. operational output rate = 6 MB/s

Approximate FITS file growth rate:

$$\frac{1.75\,\kappa\,f}{t_{\mathrm{int}}}\ \text{GB per hour of observation}$$

$\kappa \sim$ 1–1.7 (fudge-factor for "efficiency" of MS,FITS storage)

f = fraction of correlator used

$\Longrightarrow$ Record for a single observation: 268.2 GB $\Longleftarrow$

experiment: 674.9 GB $\Longleftarrow$

The Future:

Full-correlator $t_{\mathrm{int}_{\mathrm{min}}} \rightarrow 1/64$ s

Global validity ($\rightarrow$ 64 kB/board of correlation functions)

$\succ$ Maximum output rate $\rightarrow$ 160 MB/s

Some Resources

- Correlators
  - Whitney, 2000, *How do VLBI Correlators Work?*, IVS General Meeting 2000
  - Whitney+, 2004, *Mk4 Correlator Architecture & Algorithms*, Rad.Sci., **39(1)**, RS1007
  - Whitney, 2005, *Track Data Formats, etc.*, (`www.haystack.mit.edu`; Mark4 memo 230)
  - Schilizzi+, 2001, *The EVN Mark IV VLBI Data Processor*, Exper.Astron., **12**, 49
  - JIVE web page: correlator status sheet, FoV guide
- Model Issues
  - IERS: (`www.iers.org`) Conventions, Technical Notes (esp. TN32)
  - Sovers, Fanselow, & Jacobs, 1998, Rev.Mod.Phys., **70**, 1393
  - Seidelmann & Fukushima, 1992, A&A, **265**, 833 (exposition of the various time scales)
  - Explanatory Supplement to the Astronomical Almanac 1992
  - IAU Division I commissions & working groups (`www.iau.org`)