Beamforming and Null Formation*

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September 16, 2010

ATA/SETI/RAL DSP Meeting

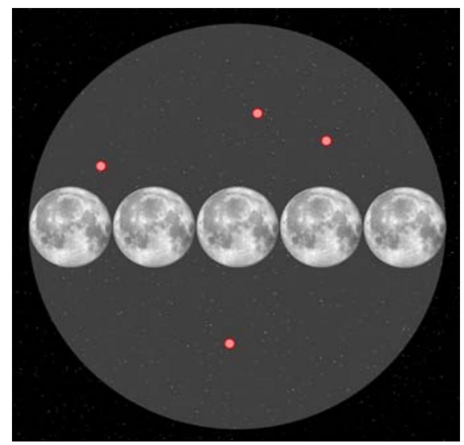
*A thorough treatment of the subject and all related areas in 10 minutes or less

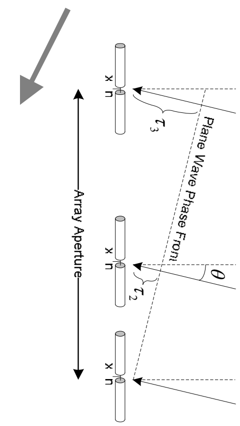
Talk Outline

- Introduction
- Designing Beamformers
- Mitigating Interferers
- What the ATA has Done
- Conclusion and Directions

Multiple Beam-Forming Greatly Expands the Power of the Radio Telescope!

Signals from wide FOV antennas

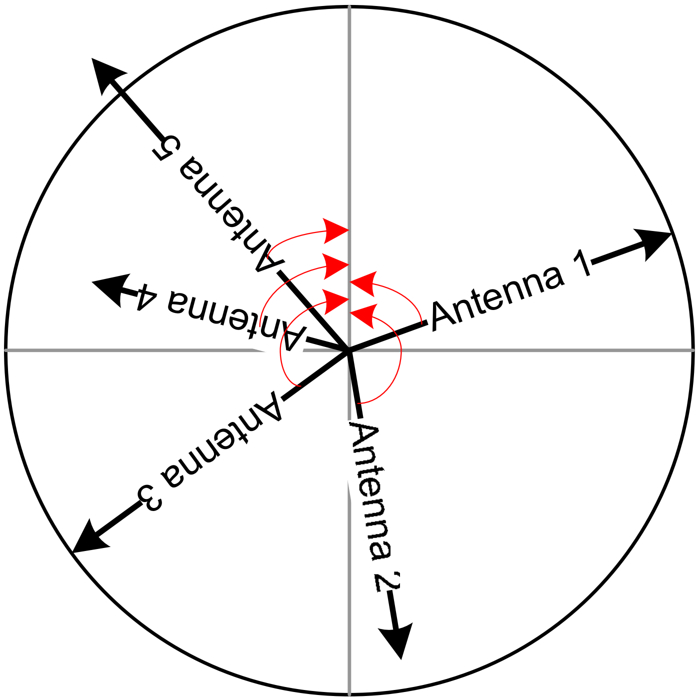




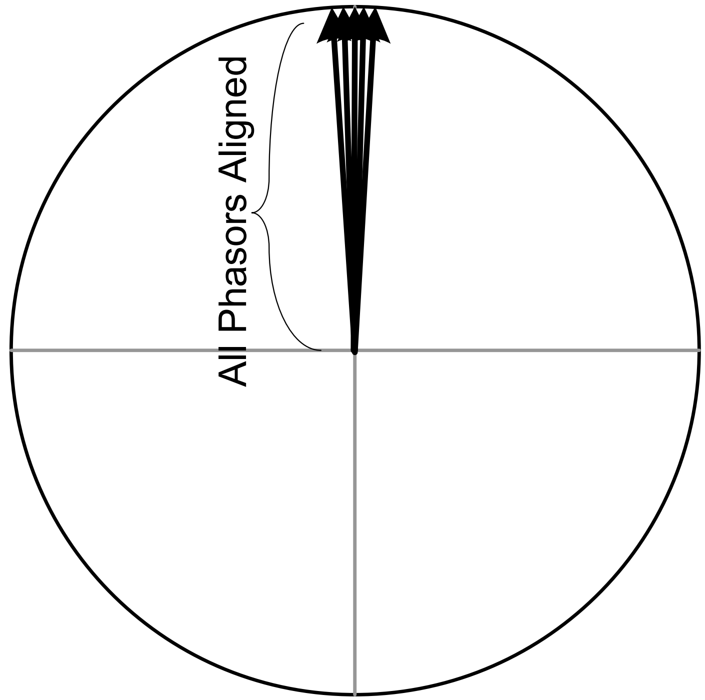
Flexible phased array beams

ALLEN TELESCOPE ARRAY

Beamforming is Simple



Antenna Phasors on Unit Circle
Vectors Must Be Processed

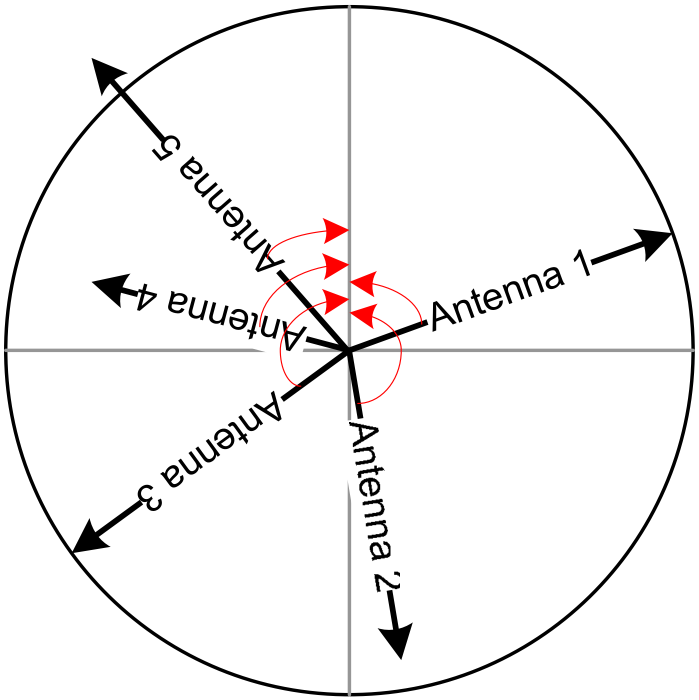


Antenna Phasors on Unit Circle
Beam Response is Sum

Geometric corrections are easy, but instrumental corrections must be found (and they change…)

Allen Telescope Array

(It's Calibration that's Hard)



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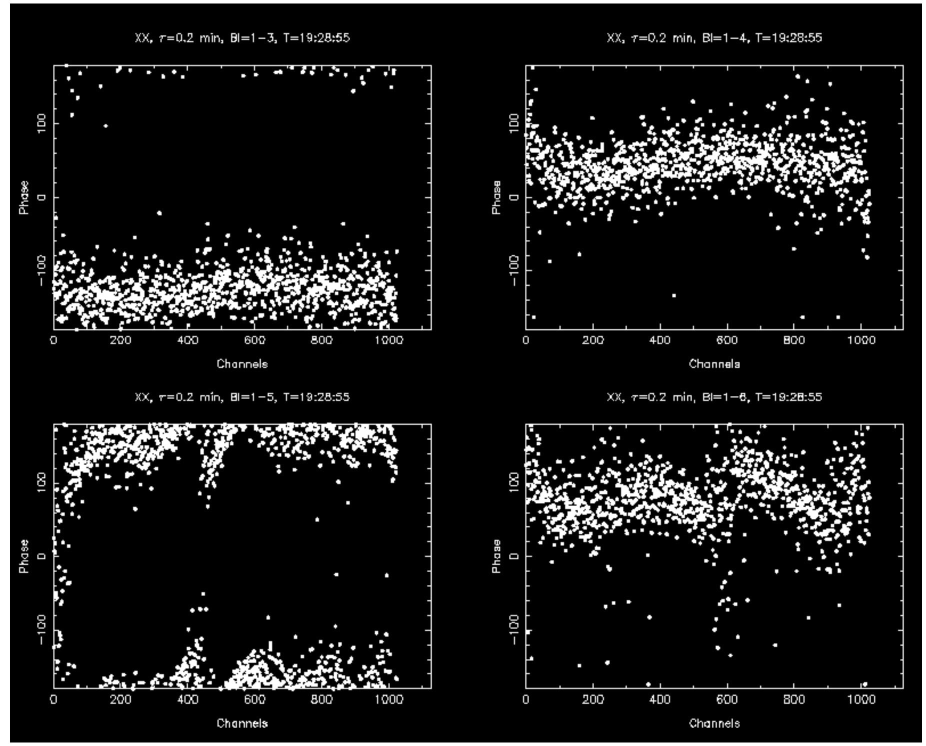
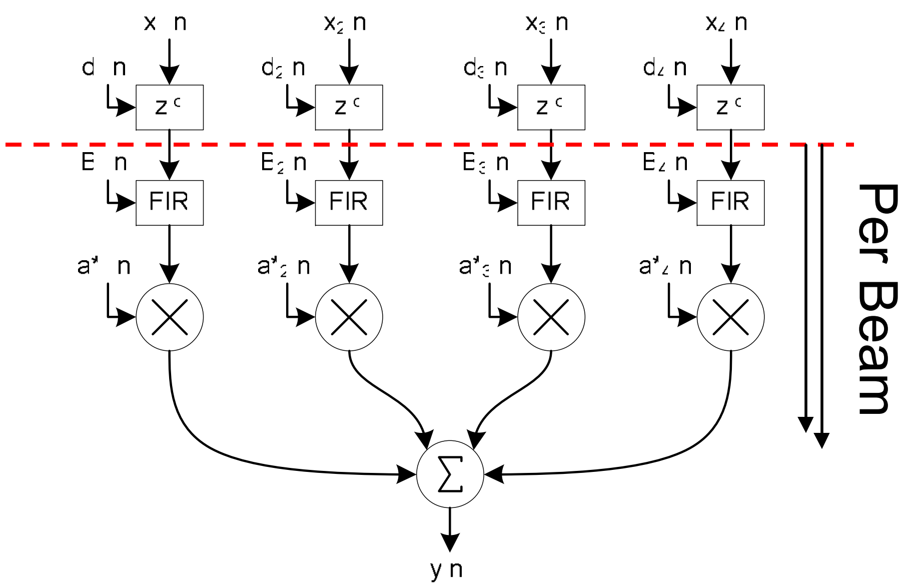
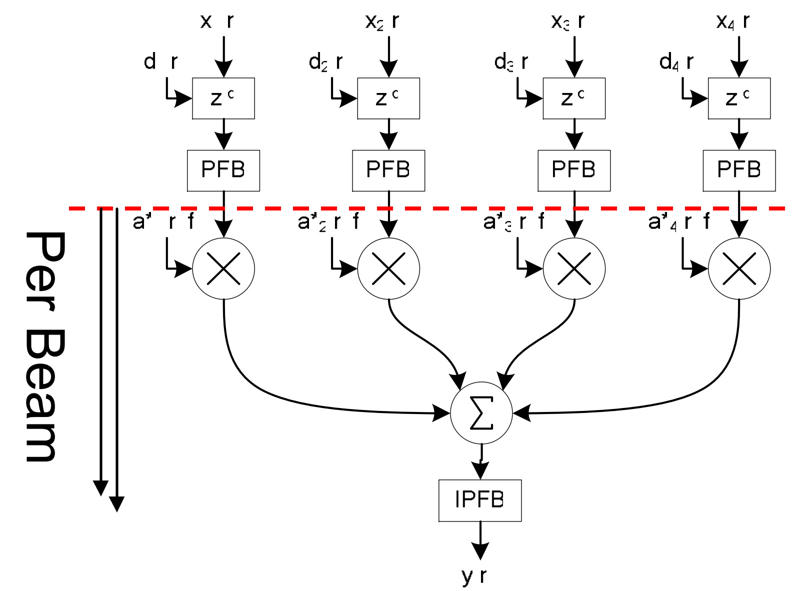


The best way to calibrate is with a correlator – but that takes expensive space in the FPGA

TDBF vs. FDBF

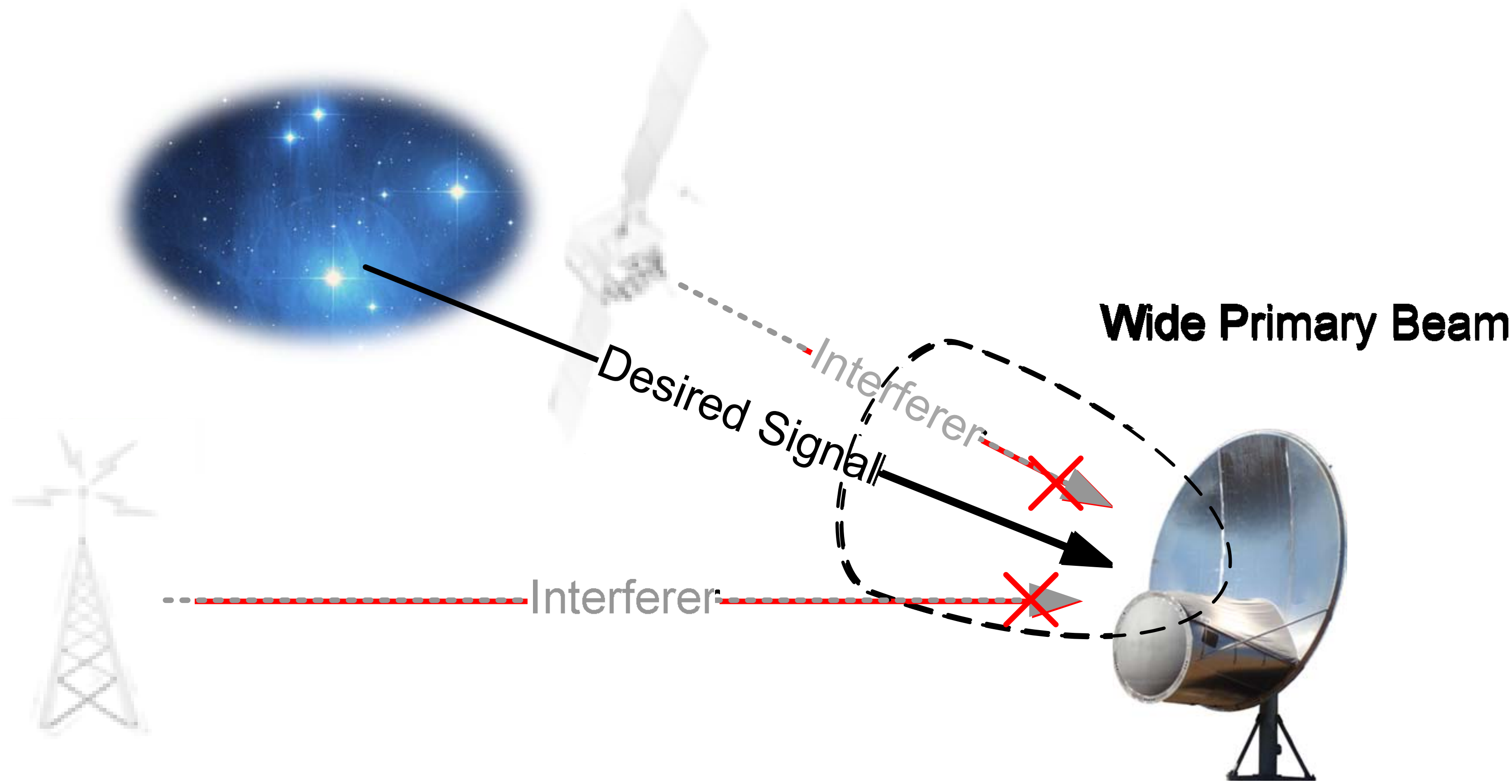




- Time Domain
  - High FIR cost per beam to minimize modulation errors
  - CFIR required for bandpass, non-conjugate symmetric ops
  - Also Requires FFTs, but smaller than FDBF
  - Cheaper for few beams
- Frequency Domain
  - Low Per-Beam Cost (one multiply/LUT*)
  - FFT/PFB for each antenna must be long (free if part of a correlator)
  - IFFT required for output beam
  - Cheaper for many beams

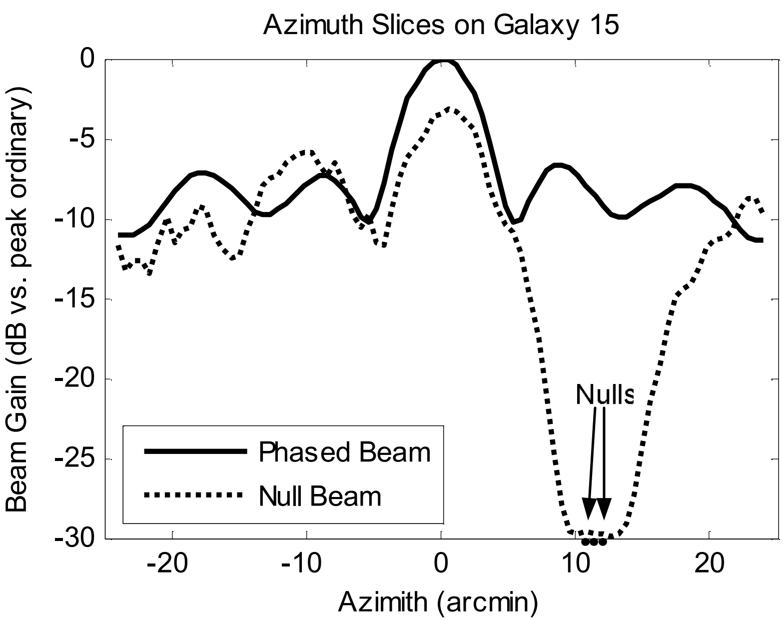
* Cost of LUT memory oughtn't be neglected

A Perfect World



ALLEN TELESCOPE ARRAY

Interference Nulling



- Mitigating interference while retaining the ability to observe (vs. Blanking)
- Modify steering function to reduce synthetic beam response in vector of the interferer
- Many methods of varying complexity, performance
- **Time-varying solutions influence depth of LUT in BF design**

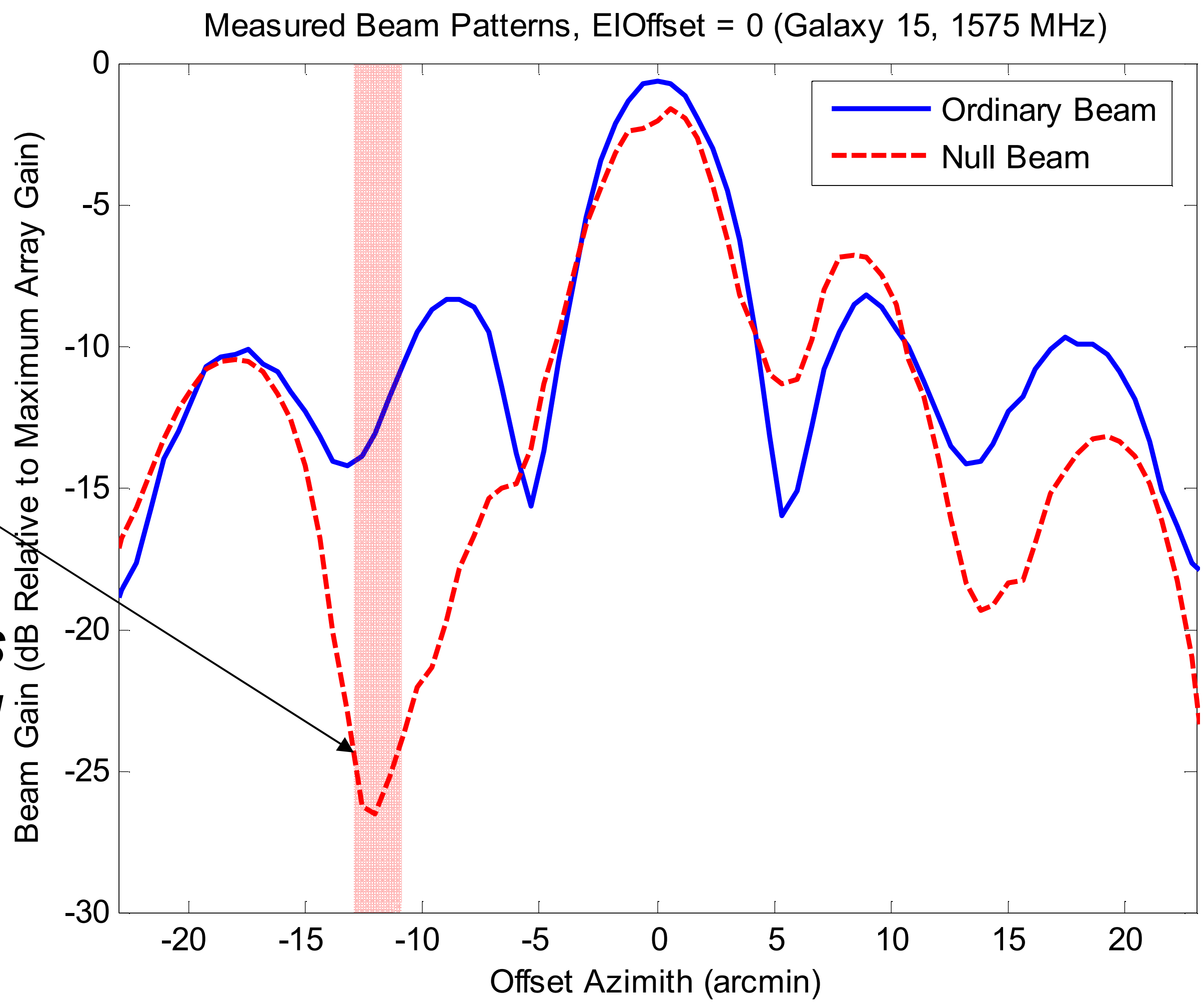
Types of Mitigation/Nulling

- Projection Nulls
  - Matrix operation on steering vector
  - Deep, narrow null
  - One DOF per null
  - Good for known interferers, orthogonal beamsets
- Optimization Pattern
  - Iterative/Evolutionary
  - Processing-intensive and no guarantee of unique solution
  - Good for wide shallow suppression, fewer DOFs
- Adaptive/ Correlation Nulls
  - Correlate on interferer to determine steering direction
  - Feed-back steering vector in real-time to projection null
- Wiener Filtering
  - Estimation and subtraction of a sampled interferer
  - Requires a reference antenna or beam
  - 30 dB on GPS/Glonass (Bower, *ATA Memo 31*)
  - Experimented with on XM

Projection Null

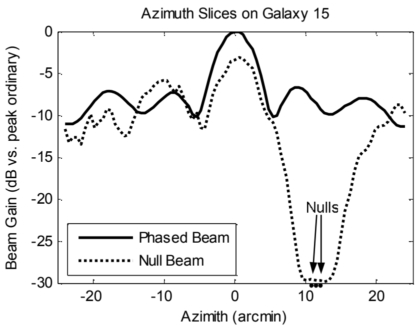
Projection Nulls from 11.4' – 12.6'

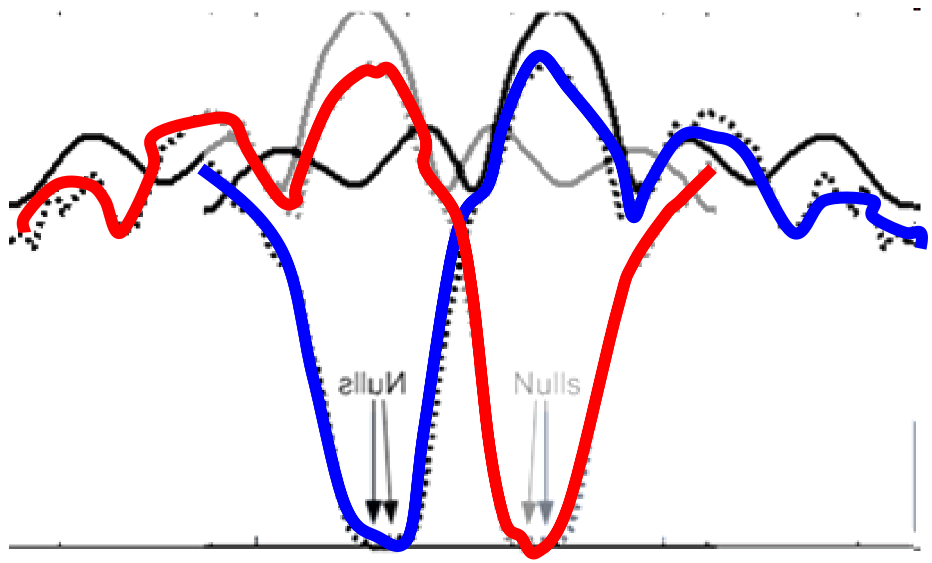
Null-out interferers or form orthogonal beam-set



ALLEN TELESCOPE ARRAY

Orthogonal Beam Sets

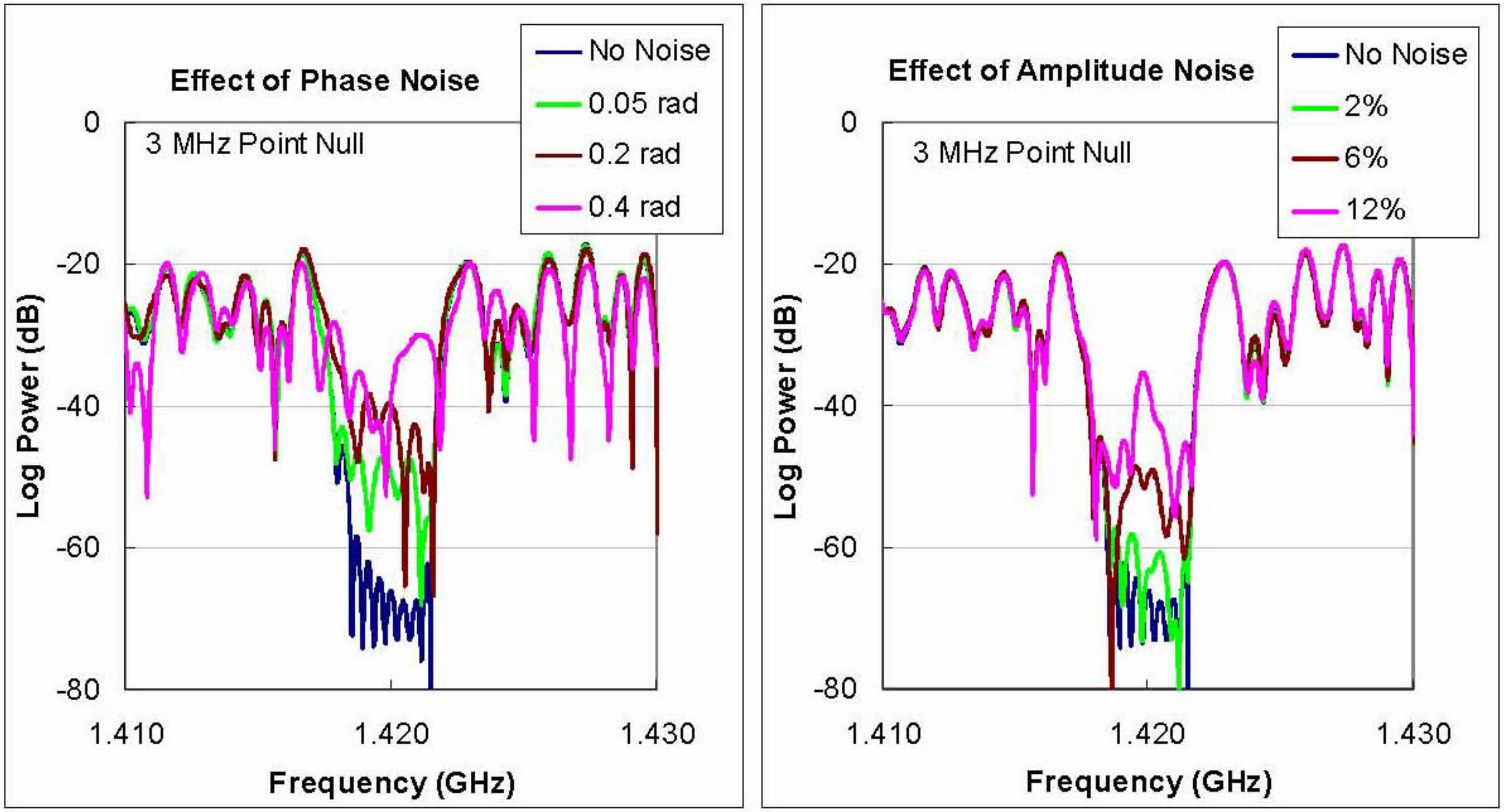




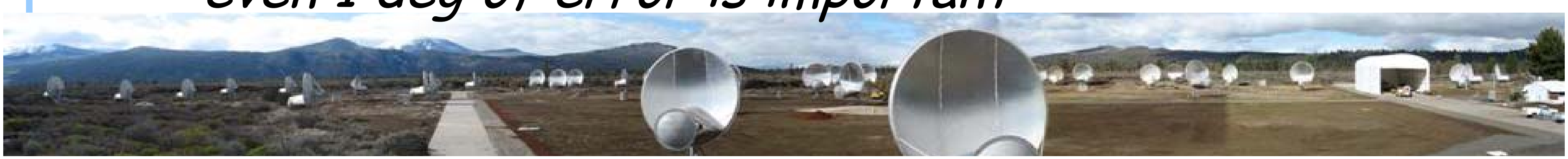
- Used in multibeam surveys (SETI)
- Each beam has nulls in the direction of every other beam
- Creates convenient set of continuous off-points

Importance of Accuracy

(Harp, ATA Memo 51)

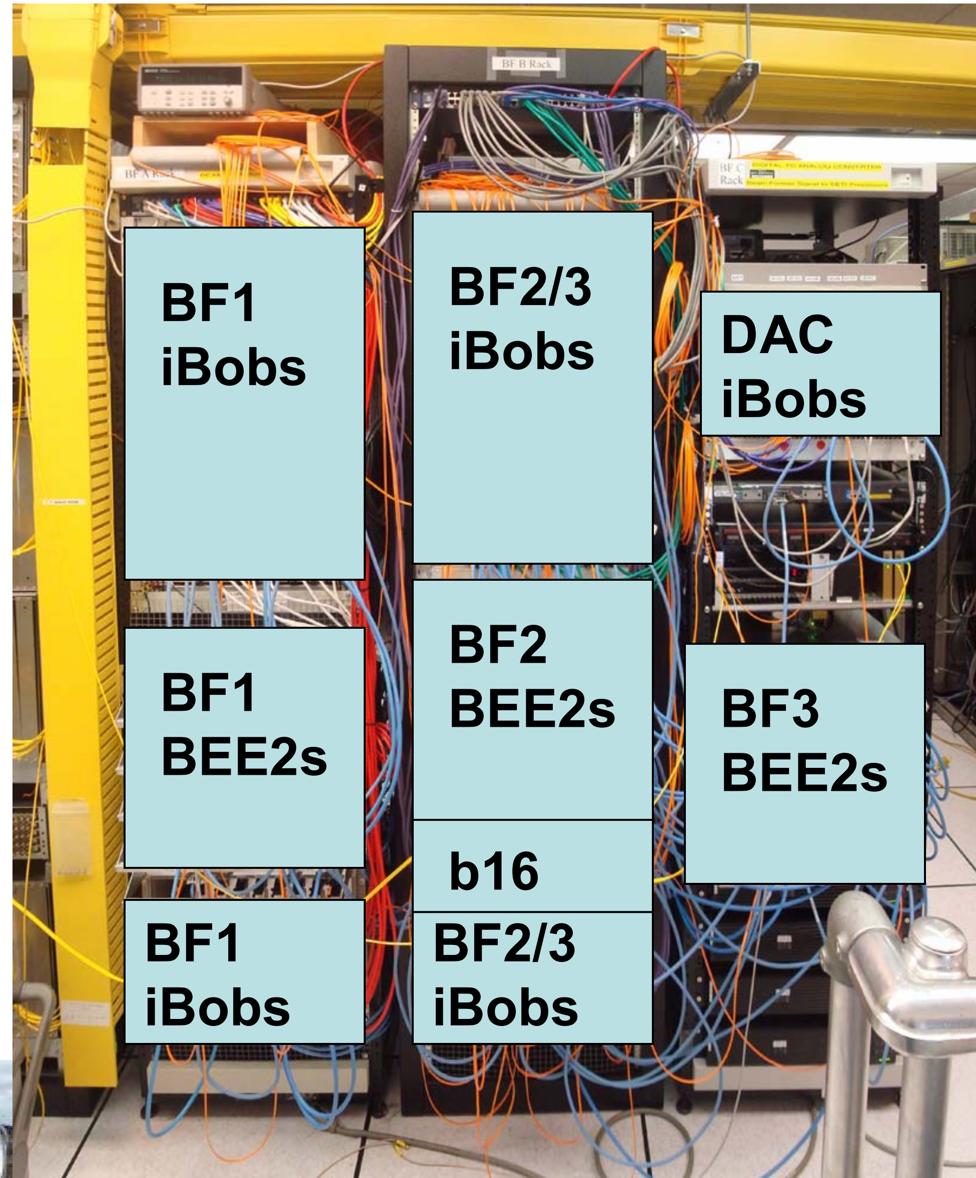


Accuracy is calibration as well as instrumental
– even 1 deg of error is important

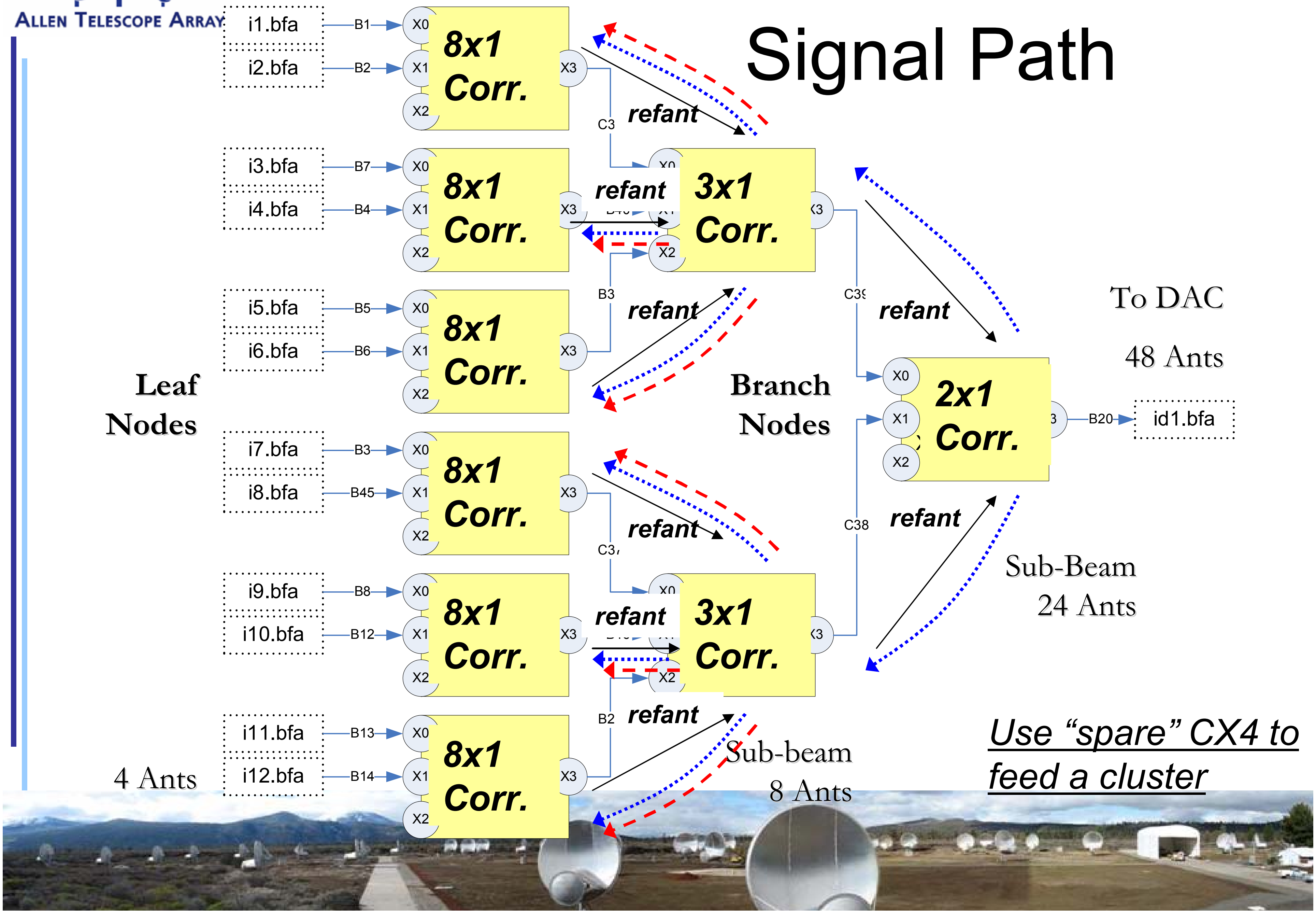


ATA: Time Domain Beamformer

- 3x Beamformers: Dual-pol, Two IFs
  - 84 Antpols
  - 104 MHz
- Some Users
  - Prelude / SonATA
  - setiQuest
  - BAPP/ GPU Pulsar
  - JPL-PRSR
  - MLM
  - REU Masers
  - LCROSS
  - Lunar X-Prize (Planned)
- Reconfigurable Hardware
  - 16x BEE2s, 54 iBobs
  - 45-node Foxtrot
  - CoBI?

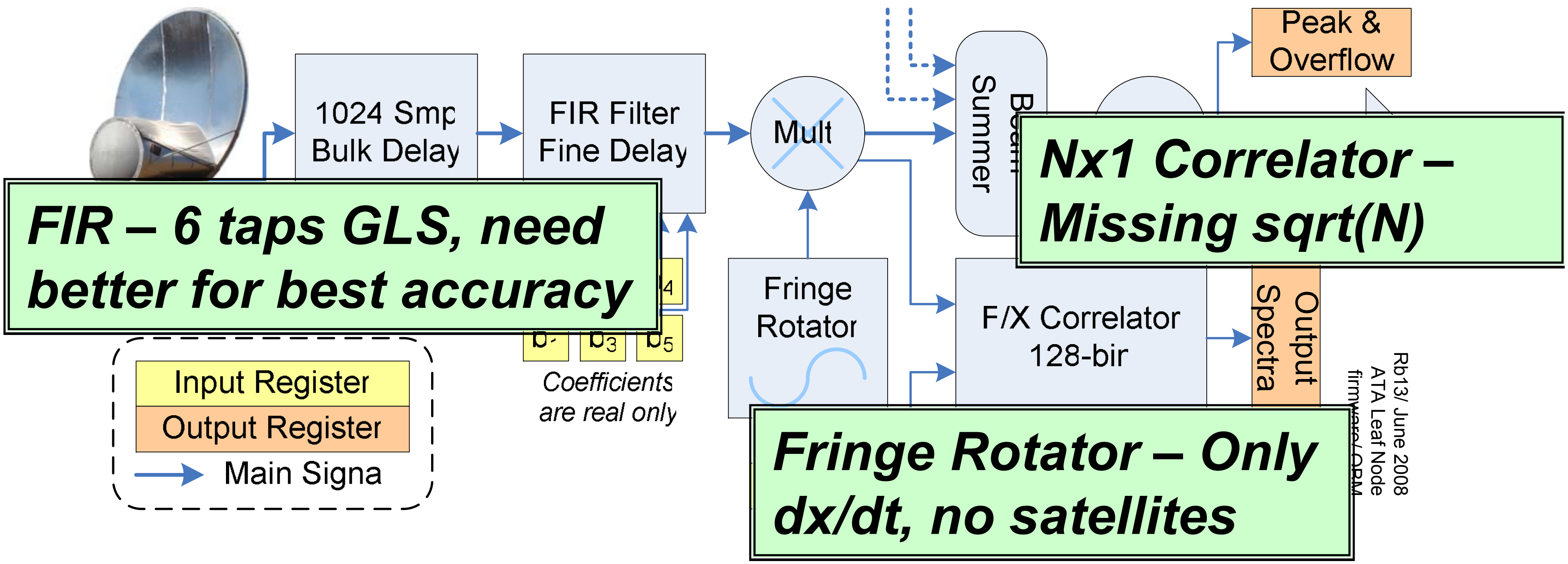


Signal Path



Use "spare" CX4 to feed a cluster

Signal Path & Lessons Learned

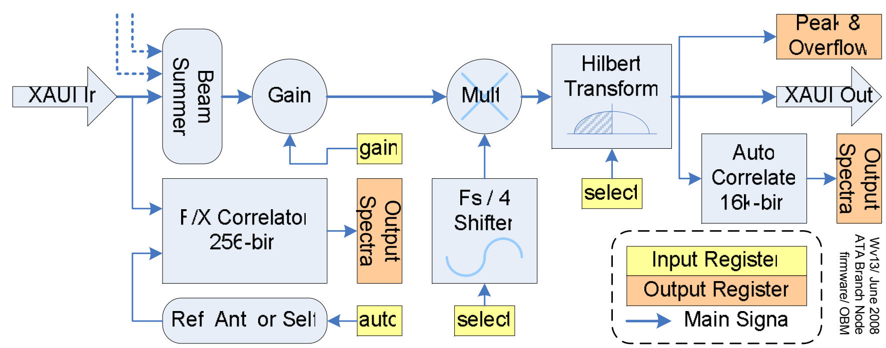


FIR – 6 taps GLS, need better for best accuracy

Nx1 Correlator – Missing sqrt(N)

Fringe Rotator – Only dx/dt, no satellites

- Bulk Delay: 1024-sample buffer memory
- Fine Delay: 6-tap Real FIR Filter (12-bit coefficients)
- Fringe Rotator: Programmable phase angle and rate



The Future: Moore's Law Helps

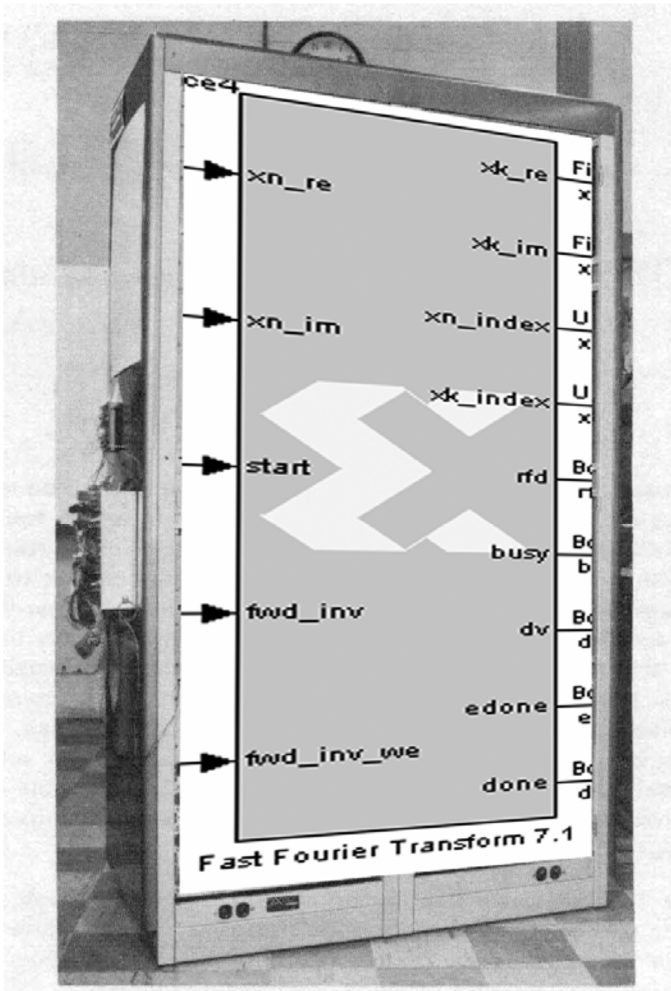


Fig. 5. Pipeline processor machine.

- Dropping in a FFT (1970)
  - 512 Channels x 4 streams
  - 19 KHz (a few Mbps)
- Today, slightly easier
  - Xilinx or CASPER blocks
  - Beamformer 128 channel, 8 stream complex, 104 MHz in a little less space
- Hardware is still improving: ROACH
  - Smaller, less power, more gates, faster clock than the BEE2
  - Less I/O, though – could this be a problem? Depends on architecture
- Designers are still improving:
  - Learn to use hardware efficiently
  - Re-learn old tricks, develop new ones

Karto: It's Still Faster than Awk!

Conclusions

- Time vs. Frequency Domain depends on
  - Number of beams
  - Availability of free F-transform
  - Relative cost of LUT versus Multiplies
- Take pains to avoid instrumental errors
  - 1 deg (arc) on 300m is ±9 turns in 1 GHz BW (3 deg per ch in 1024ch)
  - Few deg, few % errors can wreck nulls (Harp, *ATA Memo 51*)
  - Errors on 1%-5% level can be “devastating” (Wright, *SKA Memo 103*)
- Time-varying terms require LUT or Taylor expansion
  - E.g., Fringe rate might require three derivative terms for some types of sourcee
- Need more work to bring real-time adaptive nulls into the instrument
  - Real-time feed back from correlator
- *Foxtrot: Software Beamforming/Correlating at the ATA (?)*

Done!