Overview of Digital Signal Processing for Imaging and Spectroscopy

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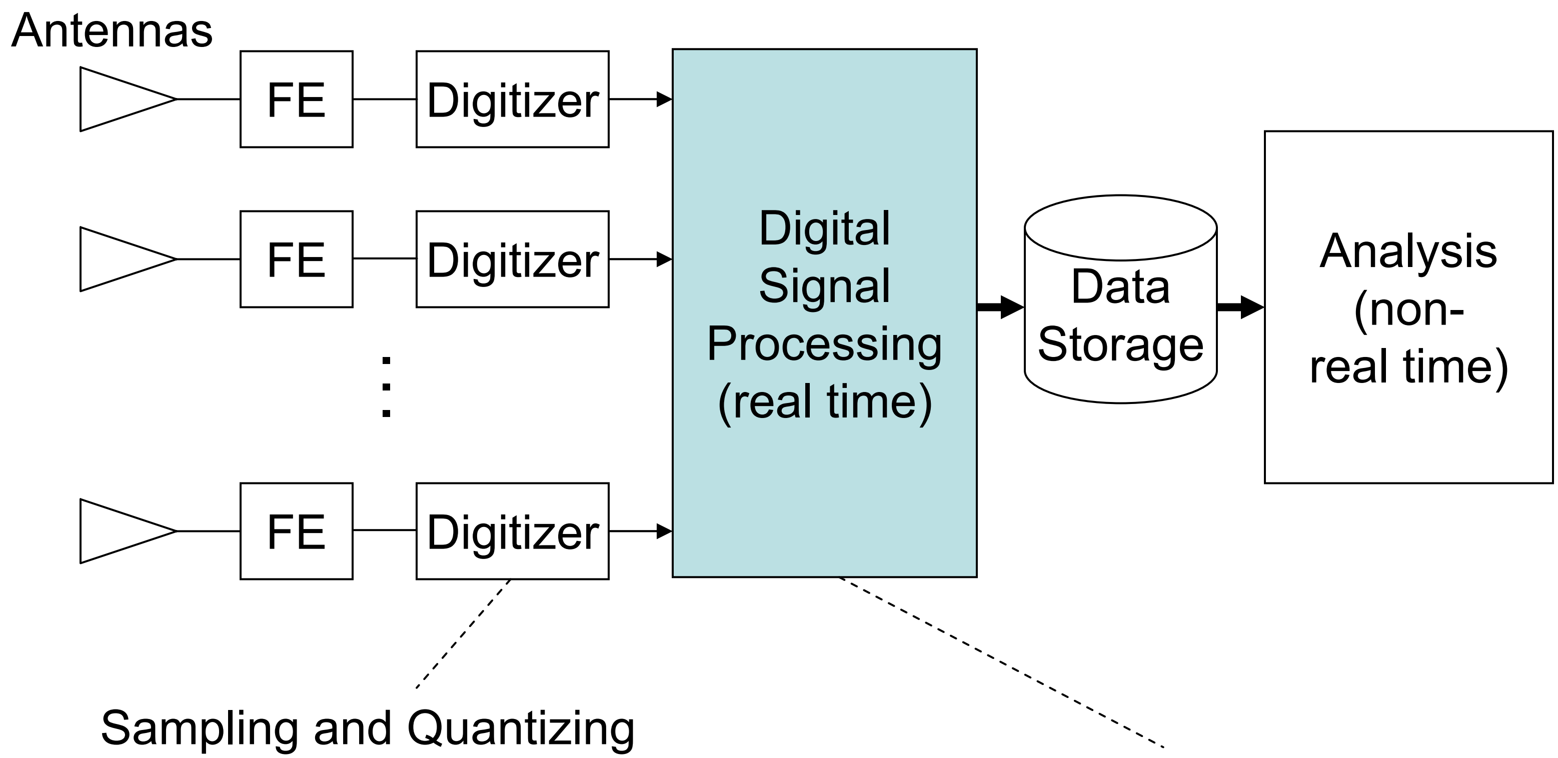
Basics



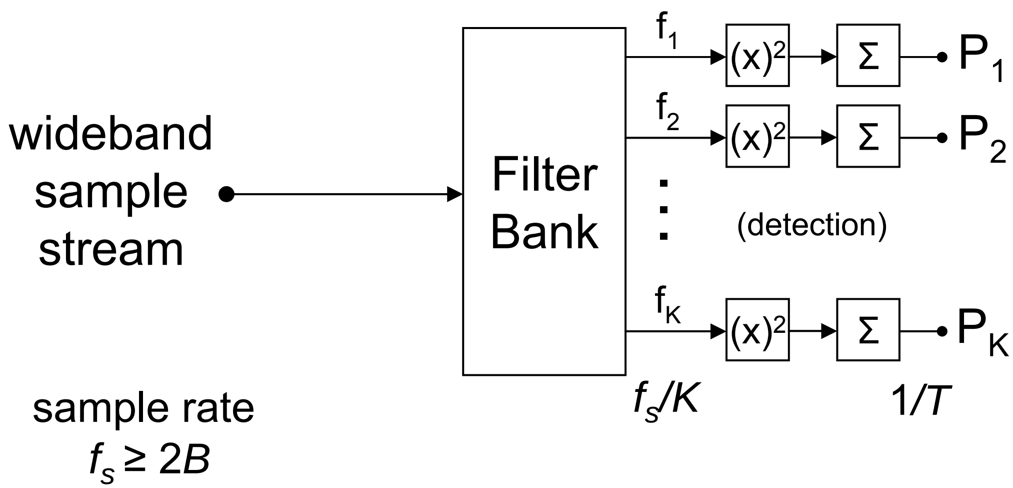
Sampling and Quantizing
- coarse quantization
- speed >> input bandwidth

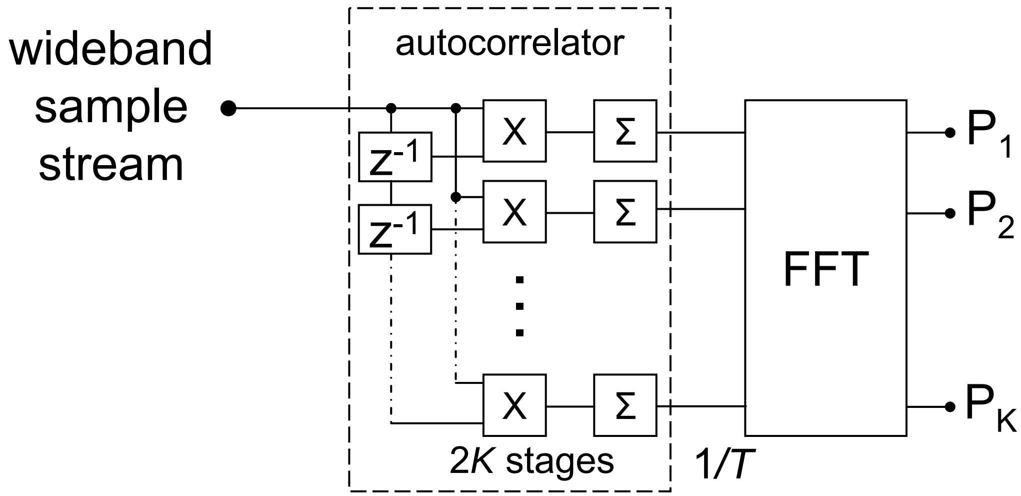
Includes detection
and integration

Types of Digital Processor used in Astronomy

- *Spectrometer*
  - one per antenna or pixel
- *Beam former* type 1: each antenna views sky
  - single beam from all antennas: light bucket
  - multiple beams [LOFAR, LWA, ATA]
- *Beam former* type 2: each antenna samples focal plane of a large aperture
  - beamformer synthesizes an efficient feed for the larger optics
  - can synthesize many feeds simultaneously, tiling the focal plane
  - no constraints on beam spacing
- Beam former output is sample stream; still needs detector.
- *Fourier synthesis* (cross-correlation) [VLA, ALMA]
  - each antenna views sky
  - signals cross-correlated among antennas, yielding FT of spatial brightness distribution

Spectrometers





Beam Formers: Type 1

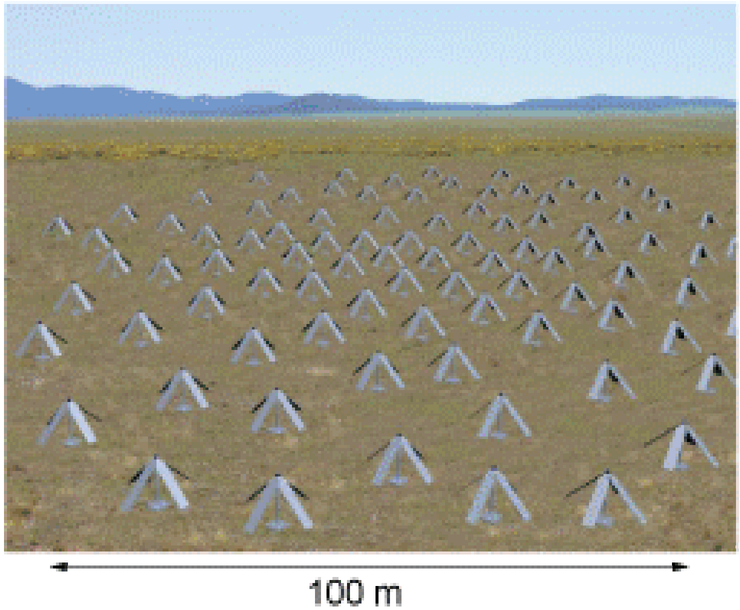
Allen Telescope Array (when complete):

351 paraboloids, 6.1m diameter

0.5-11 GHz

16 dual-polarization beams

~100 MHz bandwidth



Long Wavelength Array

Each station:

256 dual polarization dipoles

10-88 MHz

~4 beams, 8 MHz bandwidth

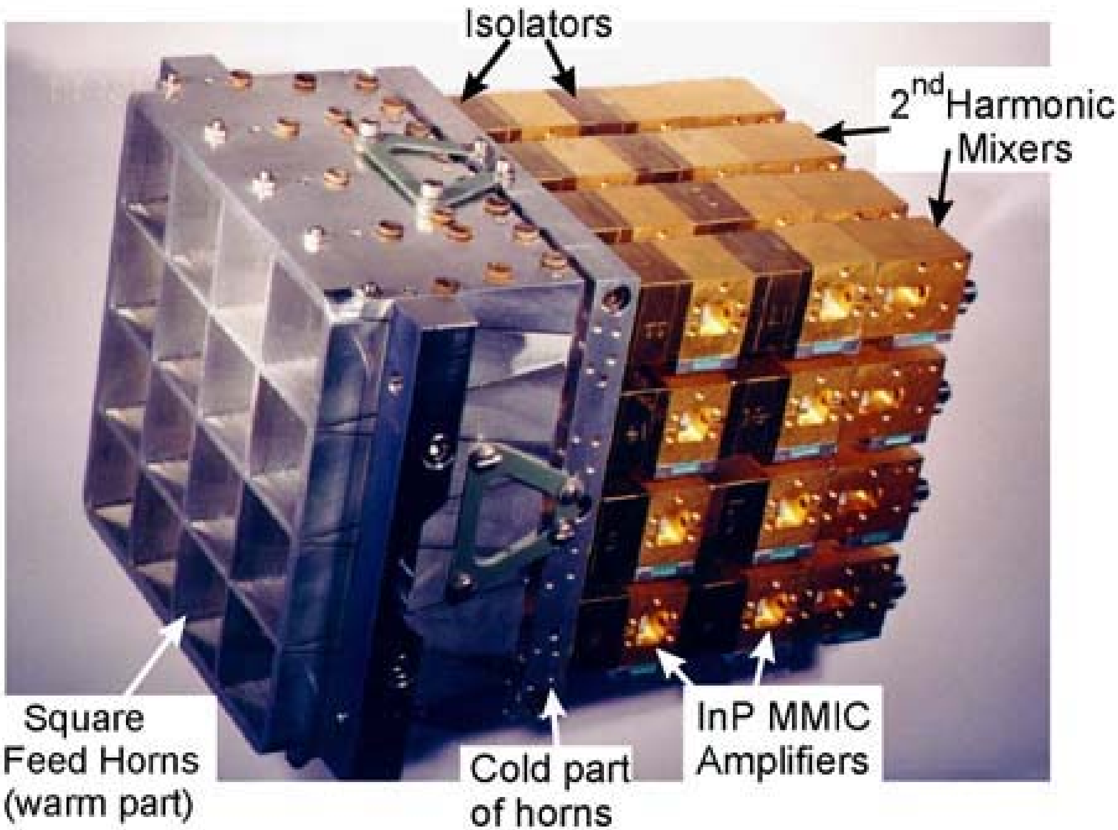
Phased Array Feeds (PAF) – Beam Formers Type 2

Checkerboard Array: Printed patches on PCB form 4x5 array in each linear polarization. Developed at CSIRO, Australia, as a precursor to a ~100 element dual-polarization array for use in the focal plane of a large reflector for SKA. Beamformers will synthesize ~30 feed antennas from the ~100 elements.

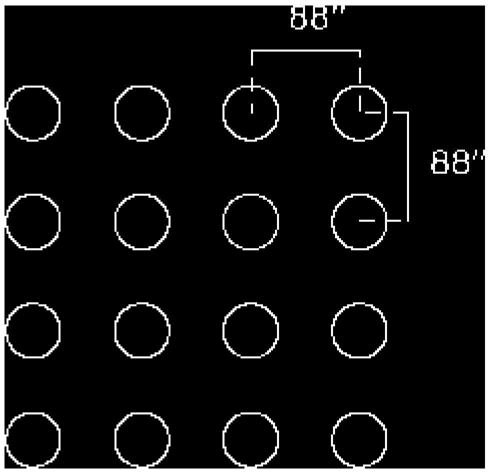
From: Hay, S.G.; O'Sullivan, J.D.; Kot, J.S.; Granet, C.; Grancea, A.; Forsyth, A.R.; Hayman, D.H., "Focal Plane Array Development for ASKAP (Australian SKA Pathfinder)" EuCAP 2007: The Second European Conference on Antennas and Propagation,11-16 Nov. 2007.

Focal Plane Array (FPA) of Independent Feeds

SEQUOIA array at FCRAO



Beam pattern on sky



Fourier Synthesis Telescopes

Image courtesy of NRAO/AUI

VLA:

27 paraboloids, 25m diameter

75 MHz – 43 GHz

200 MHz (becoming 8 GHz) bandwidth

Full cross-correlation imaging

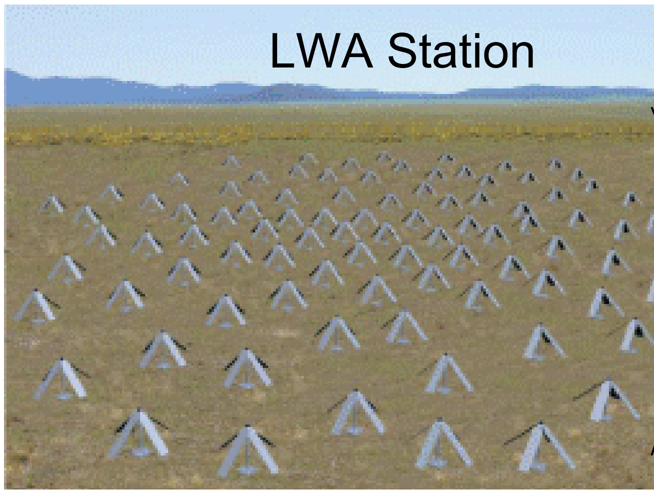
ATA (when complete):

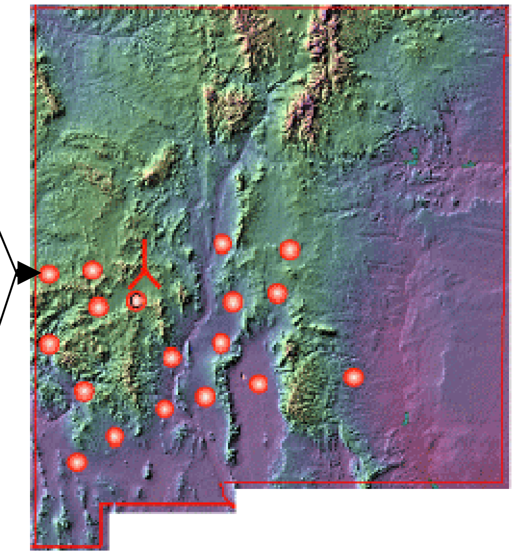
351 paraboloids, 6.1m diameter

0.5 – 11 GHz

Full cross correlation imaging

Combining Beamforming and Fourier Synthesis





Type 1 BFs

LWA (when complete):

17 stations in southern New Mexico.

Central correlator for Fourier synthesis.

Type 2 BFs (PAFs)

SKA (one of several concepts):

2000 paraboloids, 15m diameter,

Each with 30-beam PAF.

Central correlator for Fourier synthesis.

Scaling Rules

- Processing and power consumption
  - proportional to input bandwidth for all configurations
  - relatively easy to calculate
    - spectrometers:

      $c_1\, B\, N\, (a + \log K)$ filter bank, where *a* is a small integer (~5 to 10)

      $c_2\, B\, N\, K$ autocorrelator
    - beam formers

      $c_3\, B\, N\, M$
    - cross-correlators

      $c_1\, B\, N\, (a + \log K) + c_4\, B\, N^2$ + interconnections
- Total cost
  - much harder to calculate
  - NRE vs. construction
  - large systems can be dominated by *interconnections* and packaging rather than *processing*
    - architectures which minimize interconnections are valuable

Scaling Rules, Continued

- Relative sizes

	B, MHz	*N*	*M*	*K*	"Size"
Spectrometer	1000	1	n/a	1000	1
Spectrometer array	1000	32	n/a	1000	32
Beamformer	1000	100	32	n/a	3200
Beamformer+spectrometers	1000	100	32	1000	3232
Fourier synthesis array	1000	100	n/a	1000	10000
ALMA	16000	64	n/a	1024	65536
SKA (100x30 bf/antenna)	1000	2000	30	1024	1.3e8

Notes:

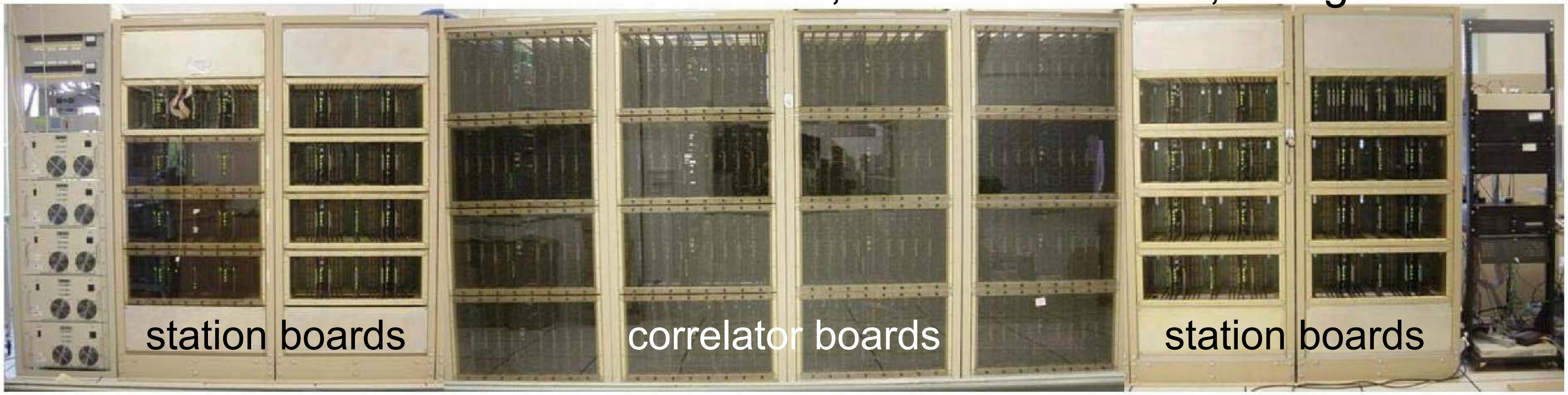
- These calculations unrealistically treat all coefficients c_i as equal, so results are approximate.
- *B* is total bandwidth per antenna element, so for dual-polarization receivers each channel has bandwidth *B*/2.

Examples of Current Digital Backends

Supercam Spectrometer Array: 64 spectrometers, 250 MHz each, single 3U x 19 in chassis.

From: C. Walker, at *Spectroscopy with CCAT* workshop, May 2008.

1/4 of ALMA Correlator: 64 antennas, 4 GHz bandwidth, 8 large racks



From: R. Escoffier *et al.*, "The ALMA Correlator." North American Radio Science (URSI) meeting, Ottawa, 2007.

Implementation Choices

- Chip level
  - Full custom ASIC (transistor level)
  - Semi custom ASIC (standard cells, gate arrays)
  - Internally programmable logic (FPGA)
  - General purpose processors, externally programmable (software)
- Above list is in order of increasing
  - Size, mass, and power consumption (for same functionality)
  - Numbers of available designers
- All *large* radio astronomy correlators built to date have used ASICs
  - "Large" refers to how it was regarded when built
  - Old: VLA (circa 1974). 100 MHz clock, separate multiplier and accumulator ASICs
  - New: ALMA (circa 2002). 4096 lags/chip, 3 bit quantization, 125 MHz clock (XF).
- For space applications, NRE for ASIC may be affordable even if few chips are needed.