Figure 1: ATA 42 antenna array at Hat Creek

**********ADAPTIVE REAL TIME IMAGING FOR RADIO ASTRONOMY*********

Melvyn Wright, ICCS workshop, Berkeley, Jan 2011

Acknowledgements: Colleagues, staff and students: Allen Telescope Array, CARMA Telescope, PAPER Telescope, CASPER collaboration.

Dedicated to the Don Backer, my colleague and friend who died last year.

MOTIVATION

- Astronomers primarily interested in astronomy.
  - Data reduction preoccupies radio astronomy specialists.
  - Telescopes should be easily used by non specialists.
- Old paradigm: custom DSP + off-line calibration & imaging.
  - Mismatch between on-line and off-line processing bandwidths
  - Off-line can handle only a few percent of data rates from DSP.
  - Data processing problems for large-N arrays.

- PROBLEMS

- Data reduction bottleneck. Large time before analysis.
- User expertise with aperture synthesis data.
- RFI, bad data, flagging & editing.
- Background & confusing source subtraction.
- High data rate and Power management.
- Lost science opportunities without real time feedback.

SOLUTIONS

- Heterogeneous DSP: FPGA, GPU & clusters for flexible programming.
- Image large FOV with high frequency and time resolution.
- Simultaneously image: science targets, calibrators & confusing sources.
- Variable sources and RFI handled in real time.
- Real time feedback into imaging and deconvolution.

SCIENCE REQUIREMENTS

- Simultaneous images of multiple regions.
- Image fidelity $\sim 10^4$
- Bandwidth $\sim$ 4 - 40 GHz .
- Spectral channels per band $\sim 10^5$.
- Sample and integration interval $\sim$ 1 ms - 10s.
- Image size $\sim 10^6$ pixels.

DATA PROCESSING MODEL

- Calibration and editing in close to real time using a sky model.
- Calibration parameters fed back into imagers and beam formers.
- Subtract sky model from uv data before imaging.
- Observations update and improve the a-priori model.
- Sky model is final calibrated image when observations are complete.

- High dynamic range need to subtract strong sources from the data.
- Antenna station beam pattern is time variable.
- Deconvolving large FOV is very expensive off-line
- Sky model used to calibrate uv data & subtract confusing sources.

SYSTEM DESIGN FEATURES

- Multiple delay & phase centers for targets over a wide FOV.
- High performance DSP handle high data rates in parallel.
- RFI mitigation with high time and frequency resolution.
- Calibration and feedback into beam formers in real time.
- Image & deconvolve in close to real time.

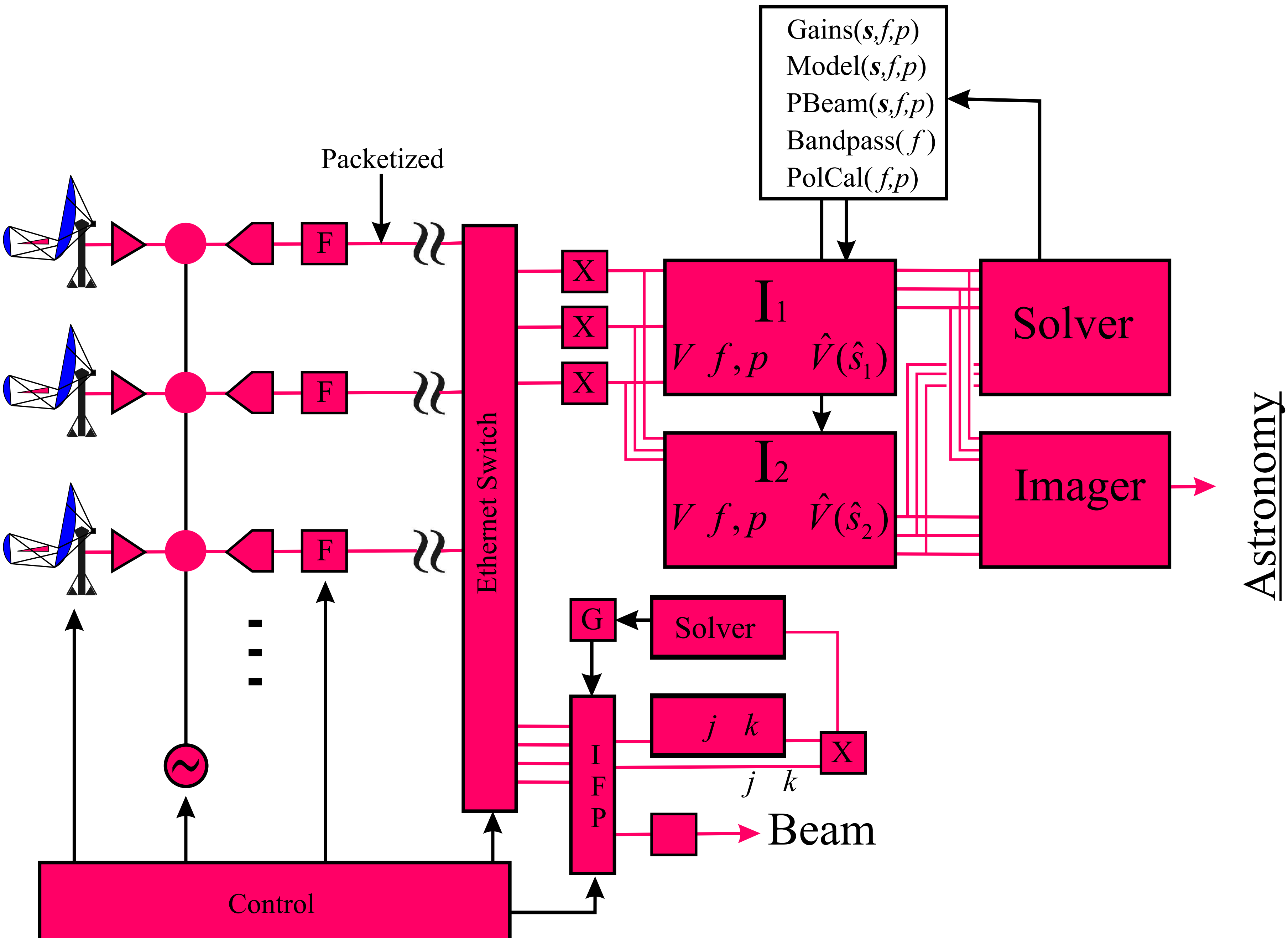


Figure 2: Data flow from telescopes to images.

- Hierarchical beam formation & correlators image large FOV.
- Phased array beams can be formed anywhere in the sky.
- Correlators image multiple regions in a large FOV.
- Beam formers channel collecting area into expensive back ends.
- Correlator and Beam formers are shared DSP resources.

- COTS rather than custom backplanes for large N_{ant}.
- Packets can be routed to multiple asynchronous DSP engines.
- Include metadata needed to calibrate & image multiple regions.
- Flexible routing to beam formers & correlators.
- DSP can be upgraded & reprogrammed with minimum interruption.

——————- EXAMPLES ——————-

- ATA: 4 32 ant x 4 pol x 100 MHz 1000 channel correlators (FPGA)
- ATA: 3 42 ant x 2 pol x 100 MHz beam formers (CASPER FPGA)
- VLBI: 8 ant x 1 pol x 1 GHz beam former (CASPER FPGA)
- PAPER: 32 ant x 4 pol x 100 MHz correlator (CASPER FPGA)
- CARMA: 23 ant x 1 pol x 4 GHz correlator (custom FPGA)
- ALMA: 50 ant x 4 pols x 8 GHz correlator (custom ASIC)

- Input bandwidth $N_{ant} \times B \times N_{pol}$.
  - digitize & packetize using COTS hardware and protocols.
- Data bandwidth $N_{ant} \times 2B \times N_{pol} \times N_{bits}$,

  $4\ 10^{12}(N_{ant}/1000)(B/GHz)(N_{pol}/2)$ bytes/s

using 8-bit digitization.

- Spectral resolution, RFI rejection, multifrequency synthesis.
- Science & RFI require large N_{chan} — favors FX architecture.
  - polyphase filter isolates frequency channels. e.g. RFI.
- Data bandwidth $N_{ant} \times 2B/N_{chan} \times N_{chan} \times N_{pol} \times N_{bits}$.
  - reduce bit width after RFI rejection
- Parallel processing reduces data rate by N_{chan}

- Cross correlation of the sampled wavefront between pairs of antennas.

- Data bandwidth from correlator for full FOV:

$$N_{ant}(N_{ant}+1)/2 \times N_{pol} \times N_{chan} \times N_{bits} \times 2\ sdot \times D_{max}/\lambda$$

$$\sim 10^8 (N_{ant}/1000)^2 (N_{pol}/4)(D_{max}/km)(\lambda/cm)^{-1} \text{ bytes/s}$$

using 2×16 bits per complex channel.

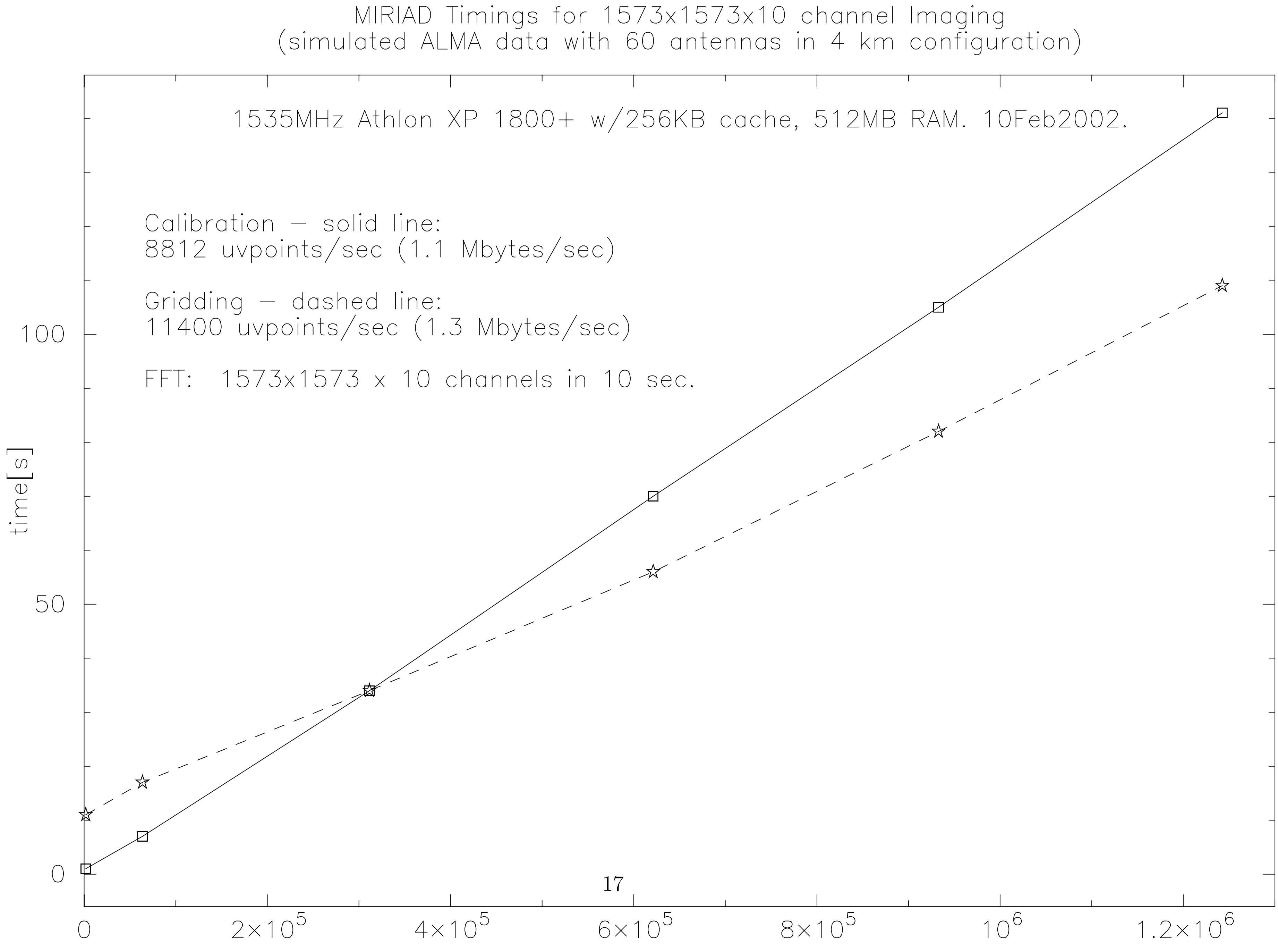
INTEGRATE AT MULTIPLE PHASE CENTERS

- Average to reduce data rate and FOV at each phase center.
- Data bandwidth for antenna primary beam is:

$$N_{ant}(N_{ant}-1)/2 \times N_{pol} \times N_{chan} \times N_{bits} \times 2\ sdot \times D_{max}/D_{ant}$$

$$\sim 10^5 (N_{ant}/1000)^2 (N_{pol}/4)(D_{max}/km)(D_{ant}/12m)^{-1} \text{ bytes/s.}$$

using 2×16 bits per complex channel.

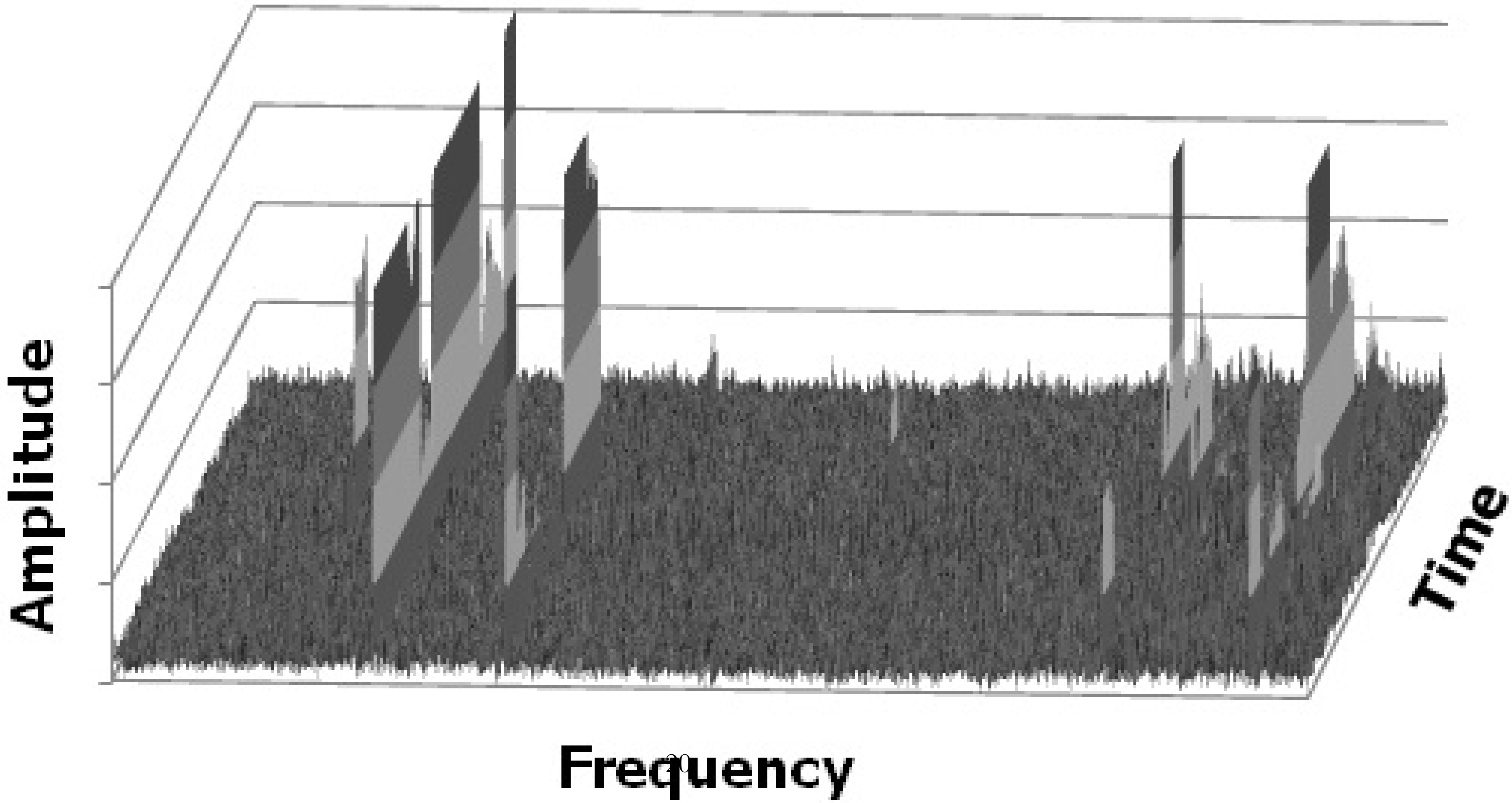


MIRIAD Timings for 1573x1573x10 channel Imaging
(simulated ALMA data with 60 antennas in 4 km configuration)
1535MHz Athlon XP 1800+ w/256KB cache, 512MB RAM. 10Feb2002.
Calibration – solid line:
8812 uvpoints/sec (1.1 Mbytes/sec)
Gridding – dashed line:
11400 uvpoints/sec (1.3 Mbytes/sec)
FFT: 1573x1573 x 10 channels in 10 sec.
time[s]
0
50
100
0
2×10^5
4×10^5
6×10^5
8×10^5
10^6
1.2×10^6

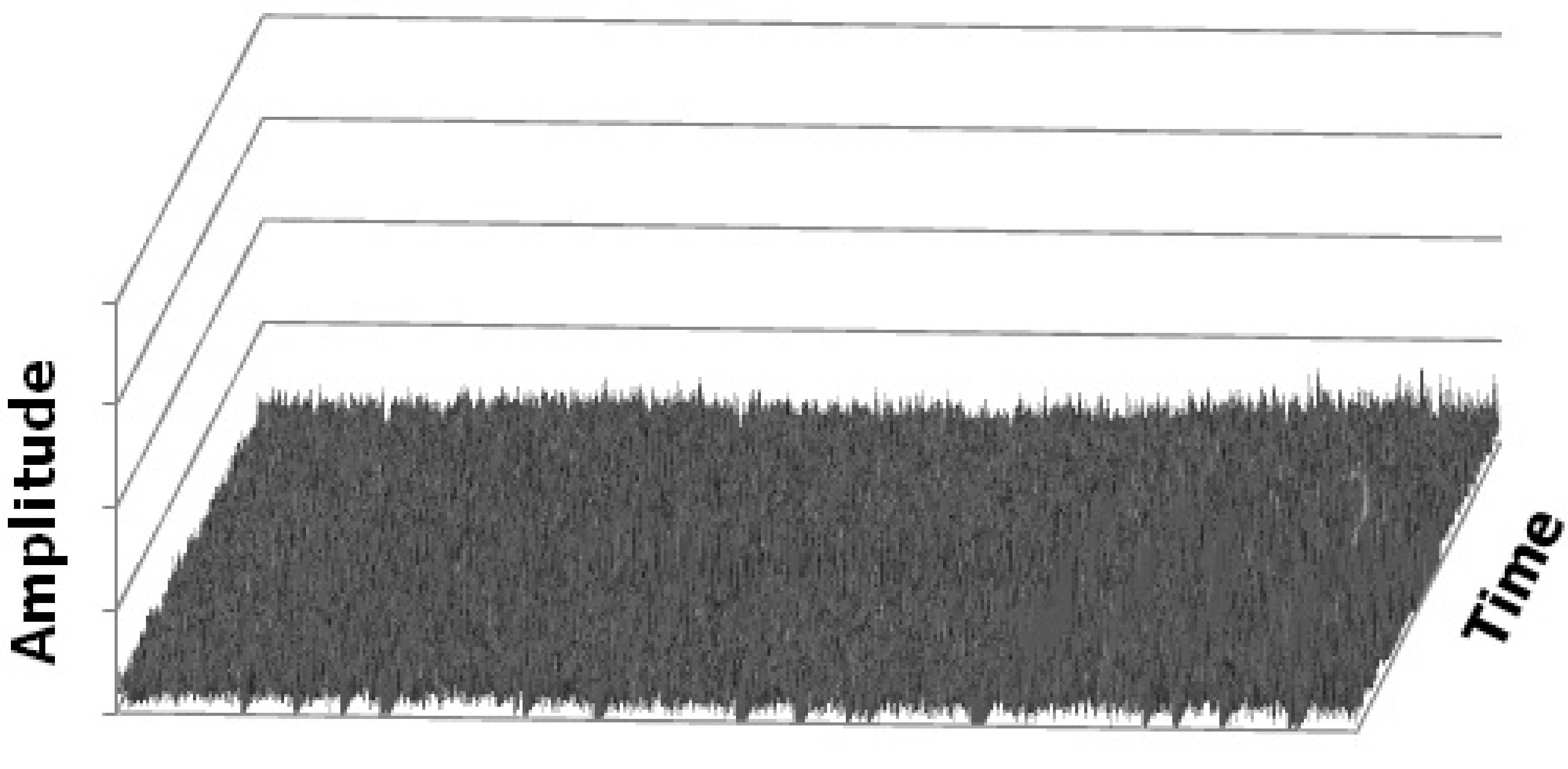
- Station Beam, Gain, Bandpass, & Polarization.
  - primary beam is complex product of station voltage patterns.
  - time variable PB, pointing & atmospheric fluctuations.
- Non isoplanicity – calibrate the data for each phase center.
- Image science targets, calibrators, & confusing sources.
  - identify confusing sources from a-priori images.

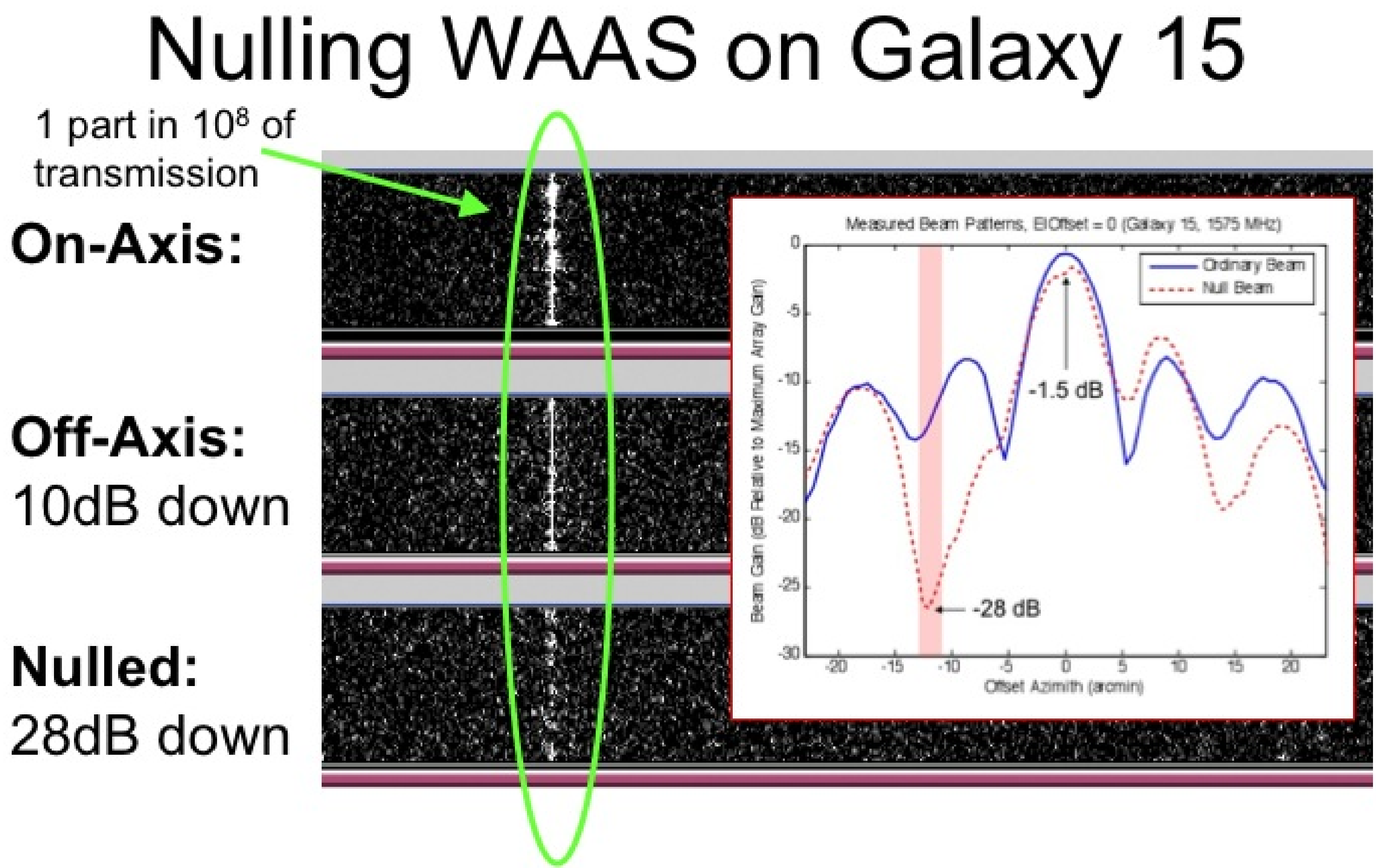
- Subtract RFI before averaging in time and frequency.
  - Gaussian filtering: MAD, Spectral Kurtosis
- Characterize RFI as a function of time, frequency and polarization.
  - SNR improved by pointing some antennas at RFI sources.
  - may need fast sampled uv data (e.g. satellites)
- Null formation by controlling station beam.

Pre-flagged Data



Post-flagged Data





Nulling WAAS on Galaxy 15
1 part in 10^8 of transmission
On-Axis:
Off-Axis:
10dB down
Nulled:
28dB down
Measured Beam Patterns, ElOffset = 0 (Galaxy 15, 1575 MHz)
Ordinary Beam
Null Beam
-1.5 dB
-28 dB
Beam Gain (dB Relative to Maximum Array Gain)
Offset Azimith (arcmin)

- Image parallel uv data streams with a-priori model subtracted.
  - difference images update the model & improve calibration.
- Deconvolve by subtracting model & sidelobes of confusing sources.
  - stop when model image is consistent with uv data streams.
- Transient source are inconsistent with the model. Save this uv data.
  - make and keep χ^2 image to identify transient & RFI sources.

- Imaging is a dynamic process.
  - look at convergence of sky model and χ^2 image.
- Phase centers can be moved for science goals, or better calibration.
  - new sources are discovered in the imaging process.
  - isoplanatic patches may vary during observations
  - calibration across the FoV.

- High bandwidth archive is an integral part of real-time system.
  - save uv data streams with metadata.
  - uv data can be replayed though imaging system.
- Better sky model used to improve calibration.
- Save transient source data for further analysis.

- CONCLUSION

- Delayed calibration & analysis limit the science which can be done.
- Real Time Imaging reduces burden of data reduction on users.
  - expertise which many users do not have.
- Bandwidth Management at every stage of data processing.
- Make best use of both telescope and human resources.