LWA1 Technical Status

Steve Ellingson
Virginia Tech

LWA1 Users Meeting – July 26, 2012

Virginia Tech Observatory Staff

Steve Ellingson
– VT URO Principal Investigator,
  Obs. Assoc. Dir. / Tech. Dir.
– Monitoring & Control System
– Commissioning
– Transients

Chris Wolfe
– Ph.D. student, Computer Engineering
– Data Recorders
– High Performance Computing

Hank Tillman
– Ph.D. student, Electrical Engineering

(New Student)
– Ph.D. student, Electrical Engineering
– EM, Beamforming

Helping Out:
Cameron Patterson (Faculty, CpE)
John Simonetti (Faculty, Physics)

Alumni
– Qian Liu (Ph.D. 2012)
– Mahmud Harun (Ph.D. 2012)
– Kyehun Lee (Ph.D. 2009)
– Wyatt Taylor (M.S. 2006)

Outline of this Talk

Instrument overview & user-relevant specifications

Beamforming ("DRX" mode)
– Calibration (= figuring out how to point beams)
– Commissioning observations demonstrating performance
– Current Issues & Limitations

LWA1 Features & Capabilities
– What's still not available
– What's in Development

URO Technology Development Plan (TDP)

Backup Slides

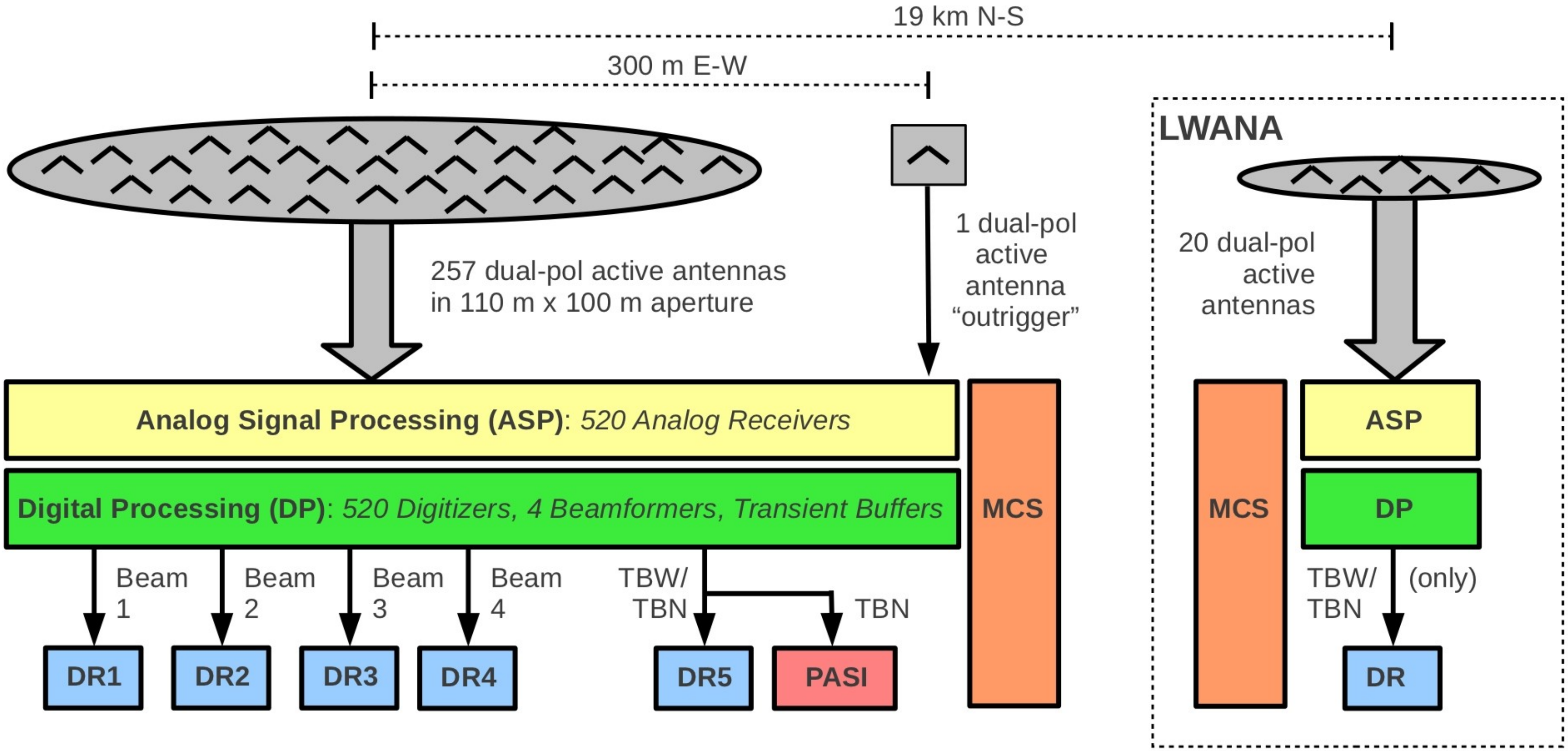
LWA1

10-88 MHz usable, Galactic noise-dominated (>4:1) 24-87 MHz
4 independent beams x 2 pol. x 2 tunings each ~16 MHz bandwidth

Beam SEFD ~[6,30] kJy for $Z=[0^\circ,65^\circ]$,
- **Also depends on sidereal time, (RA,Dec) of pointing, frequency**
- **~ 8 Jy (5σ) for 1 s, 16 MHz, Zenith**

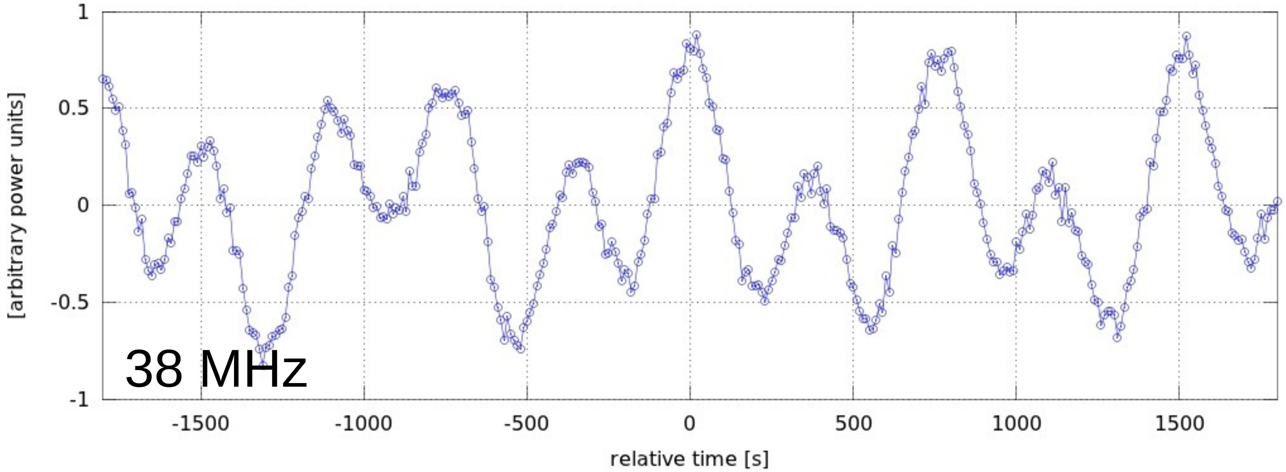
Main lobe FWHM < $(4.3^\circ)((74\ \mathrm{Mhz})/\nu)^{1.5}$ for $Z<45^\circ$
Sidelobe levels are high; ~ 10 dB at maxima without much rolloff

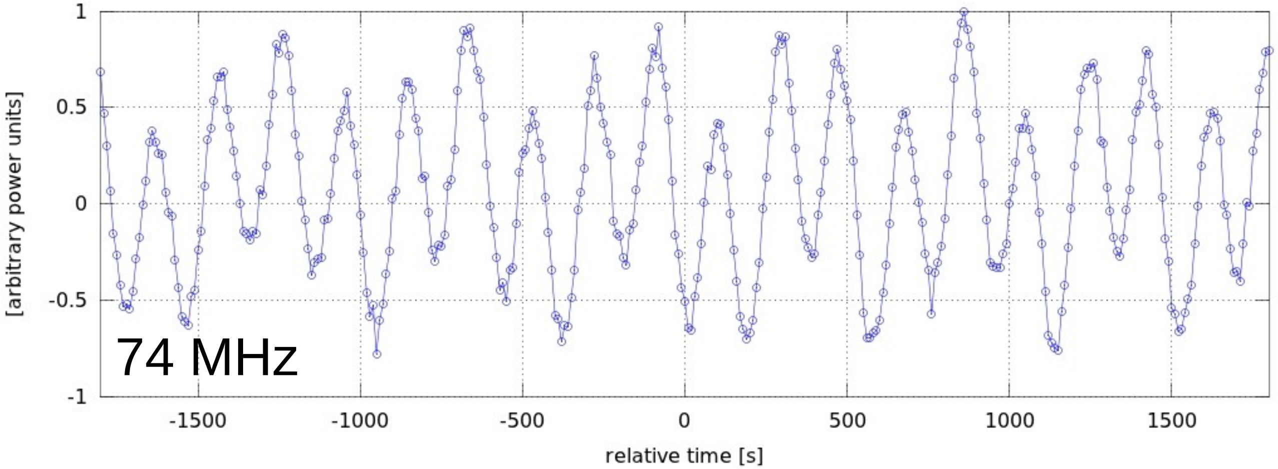
LW1 Observatory Architecture

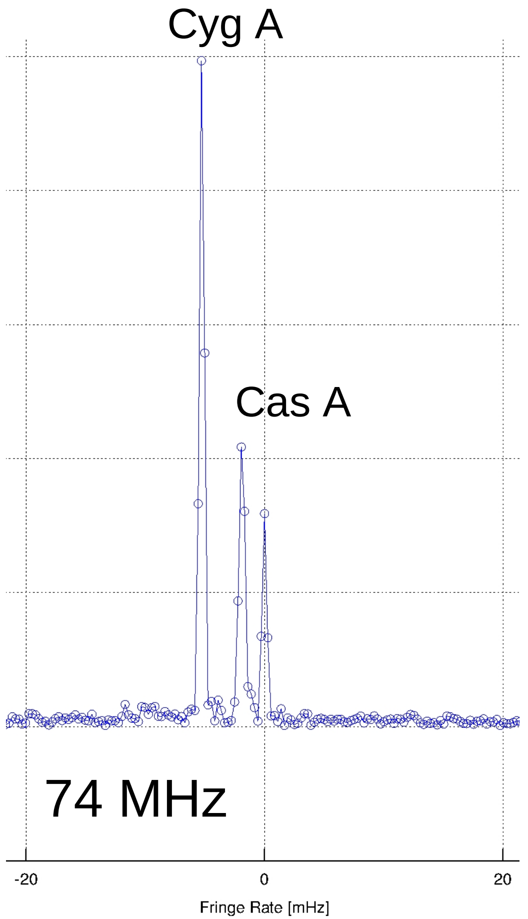


DRs on beams (DRX) record *voltage* or *spectra* (32 ch now, increasing soon)
“TBN” mode provides all dipoles, continuously (~70 kHz BW)
“TBW” mode provides all dipoles in 61 ms bursts (~70 MHz BW)
Outrigger provides baselines ~[10,88]λ at [10,88] MHz

Array Cal: Use of Outrigger + TBN to Extract "Embedded" Dipole Response







Fringe Rate Spectrum

Fringes: Stand 248 * Outrigger (389 m E-W baseline)
~70 kHz bandwidth
10 s integrations with ~0.01% time domain blanking

LWA Memo 184, 186

<u>TBN</u> Calibration Strategy

Select a source which is:

- **Strong (e.g., Cas A, Cyg A, Tau A, 3C123)**
- **Produces a high fringe rate (to distinguish from background)**
- **Produces a fringe rate which is distinct from other strong sources**

Cross-correlate every dipole with the outrigger for

– at least 1 fringe rotation period (preferably many)

– but not more ~3 h (so dipole pattern response is approx. constant)

Fringe rate filtering is useful to further suppress background and other strong sources

The resulting visibility is essentially the response to the selected source

System response <u>other than dipole</u> is independent of direction, so:

Extrapolate to other directions using a parametric model of "standalone" dipole pattern fit to the above result (LWA Memo 178)

This approach captures the effect of mutual coupling in the measured direction, but neglects it in the extrapolation to other directions

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LWA Memo 184, 186

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DRX Beam Calibration Strategy

DRX beamforming is by "simple" delay-and-sum:

– Beamformer equalizes the sum of the *known* geometrical delays + the *estimated* instrumental delays

– So, need the instrumental delays, which we assume to be dominated by the cables

Repeat TBN calibration over a range of frequencies

– Requires exact same observation each time, so takes days

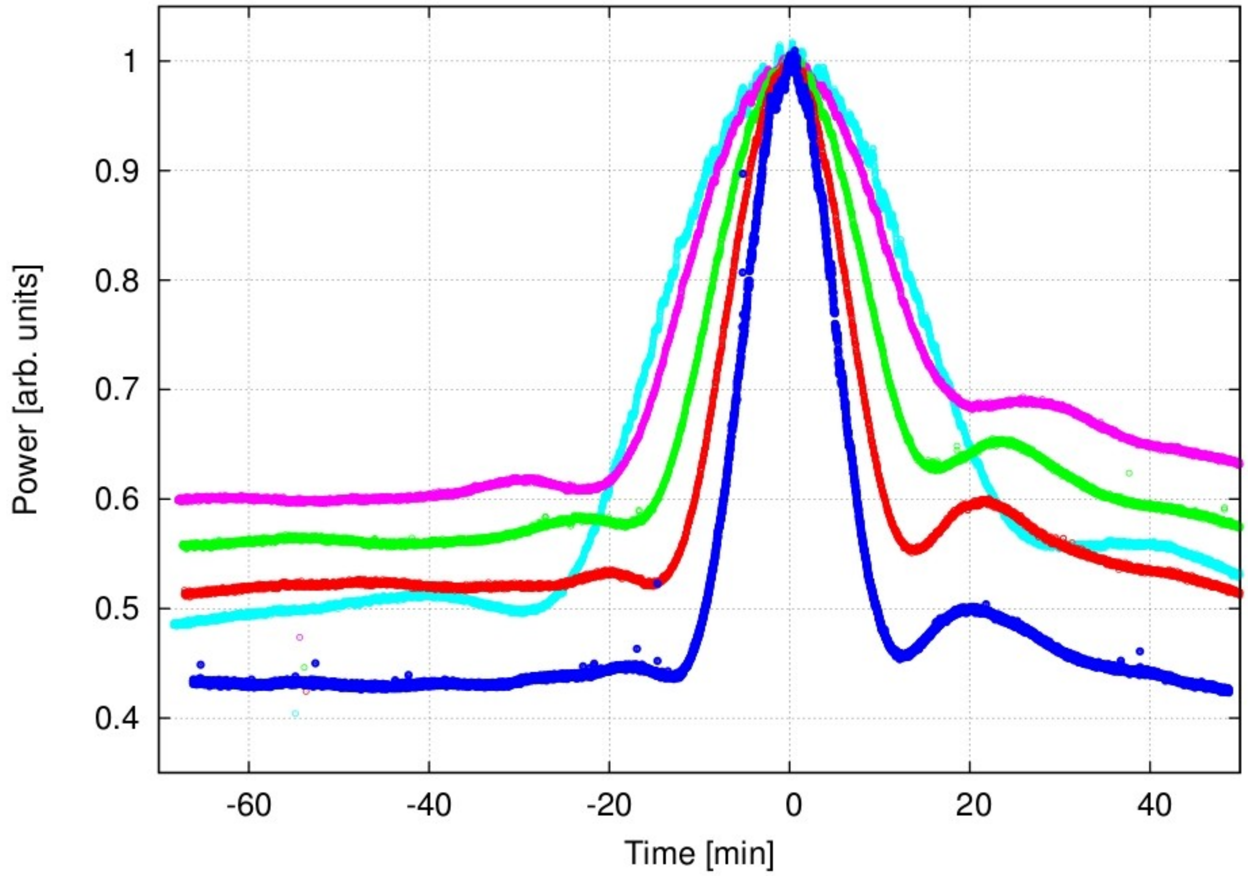
Collect these into a dataset of phase as a function of frequency

Fit cable response (parameterized in terms of length) to above data

– Yields estimate of instrumental delay for each dipole-path

– Neglects antenna dispersion – effect seems to be small(?)

DRX Beamforming Demo (>30 MHz)



LWA Memo 186

Fig. 9. Simultaneous drift scans of Cyg A at 85.00, 74.03, 62.90, 52.00, and 37.90 MHz. Scans can be identified by peak width, which increases with decreasing frequency. All scans are normalized to a common maximum. Bandwidth: 211 kHz, Integration time: 786 ms, Single (N-S) polarization, no RFI mitigation.

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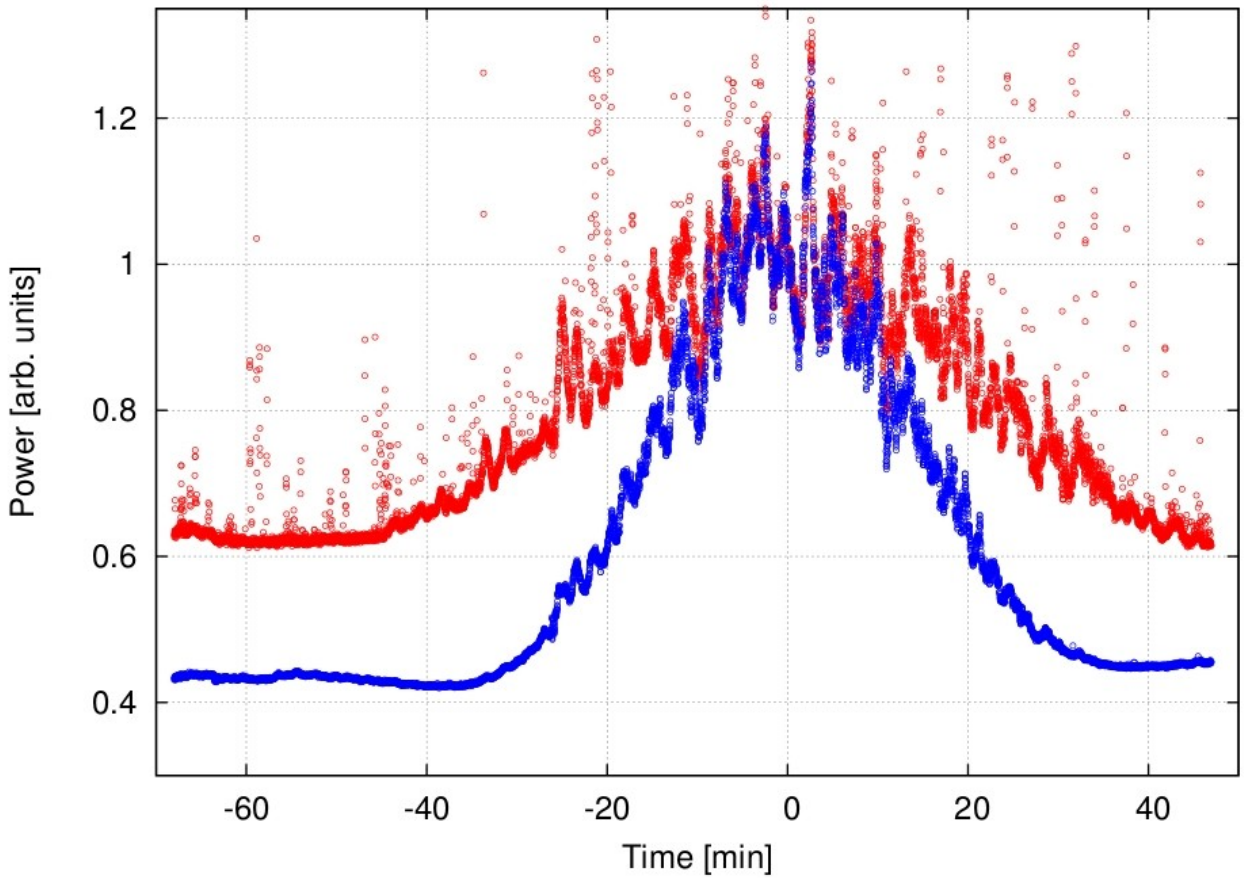
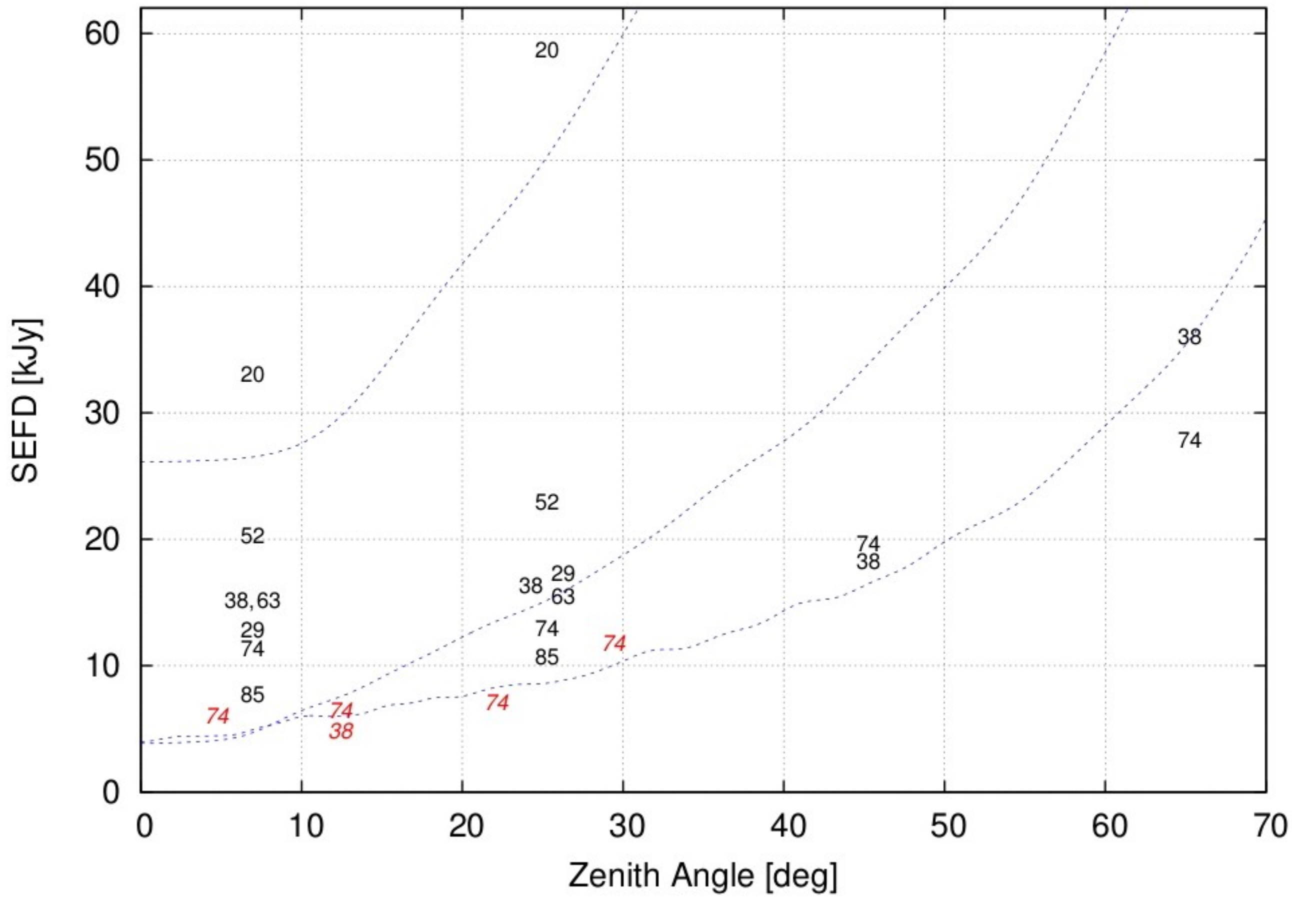
DRX Beamforming Demo (<30 MHz)



LWA Memo 186

Fig. 10. Simultaneous drift scans of Cyg A at 28.80 and 20.50 MHz. Scan magnitudes are normalized. Bandwidth: 211 kHz, Integration time: 786 ms, Single (N-S) polarization, no RFI mitigation.

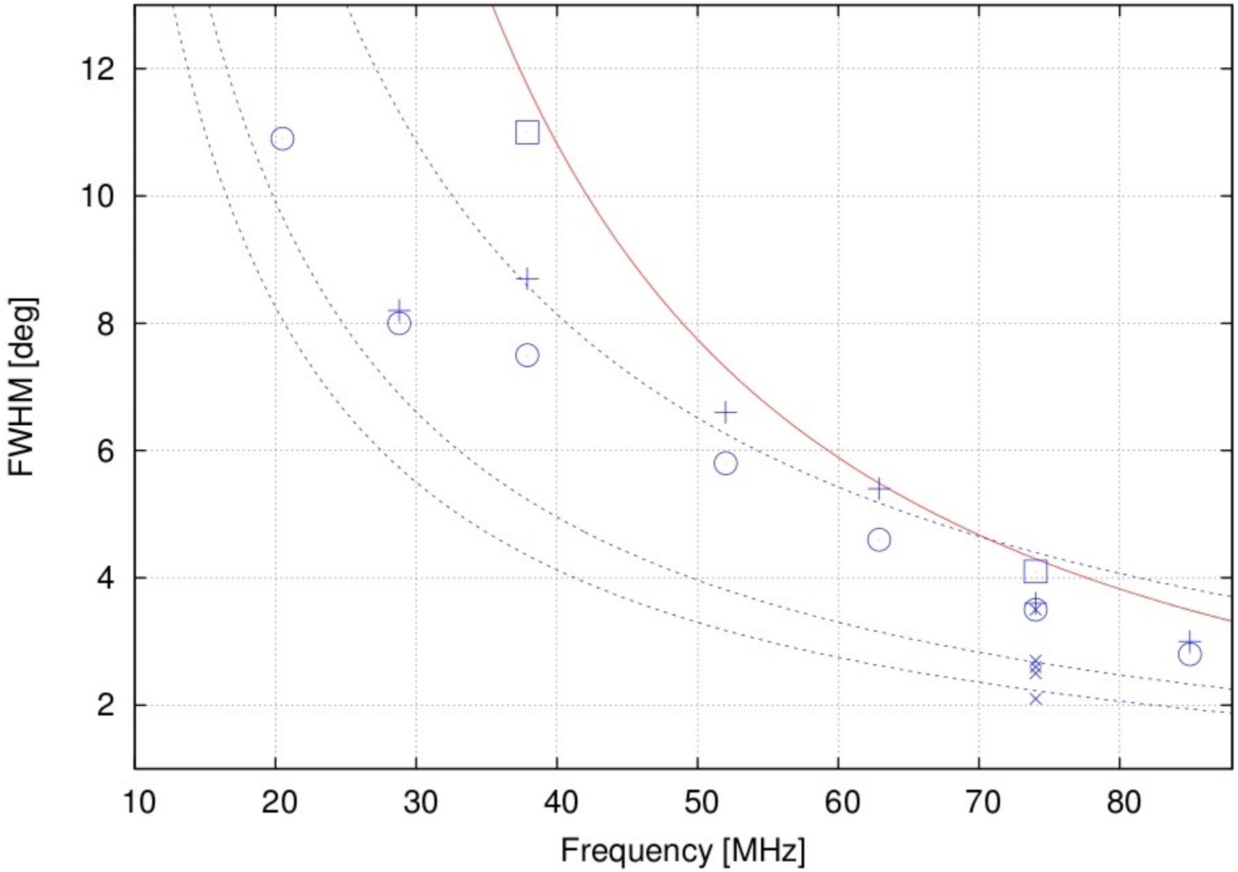
DRX Beam Sensitivity Estimates



LWA Memo 186

Fig. 11. Sensitivity (SEFD) vs. Z obtained from drift scans. The numbers used as data markers indicate the frequency rounded to the nearest MHz. Markers in red italic font represent transit drift scans of the sources 3C123 ($Z = 4.4°$), Tau A ($12.1°$), Vir A ($21.8°$), and 3C348 ($29.1°$); all others are Cyg A. The curves are predictions from Fig. 8 of [9] for (bottom to top) 74, 38, and 20 MHz. The use of both polarizations is assumed.

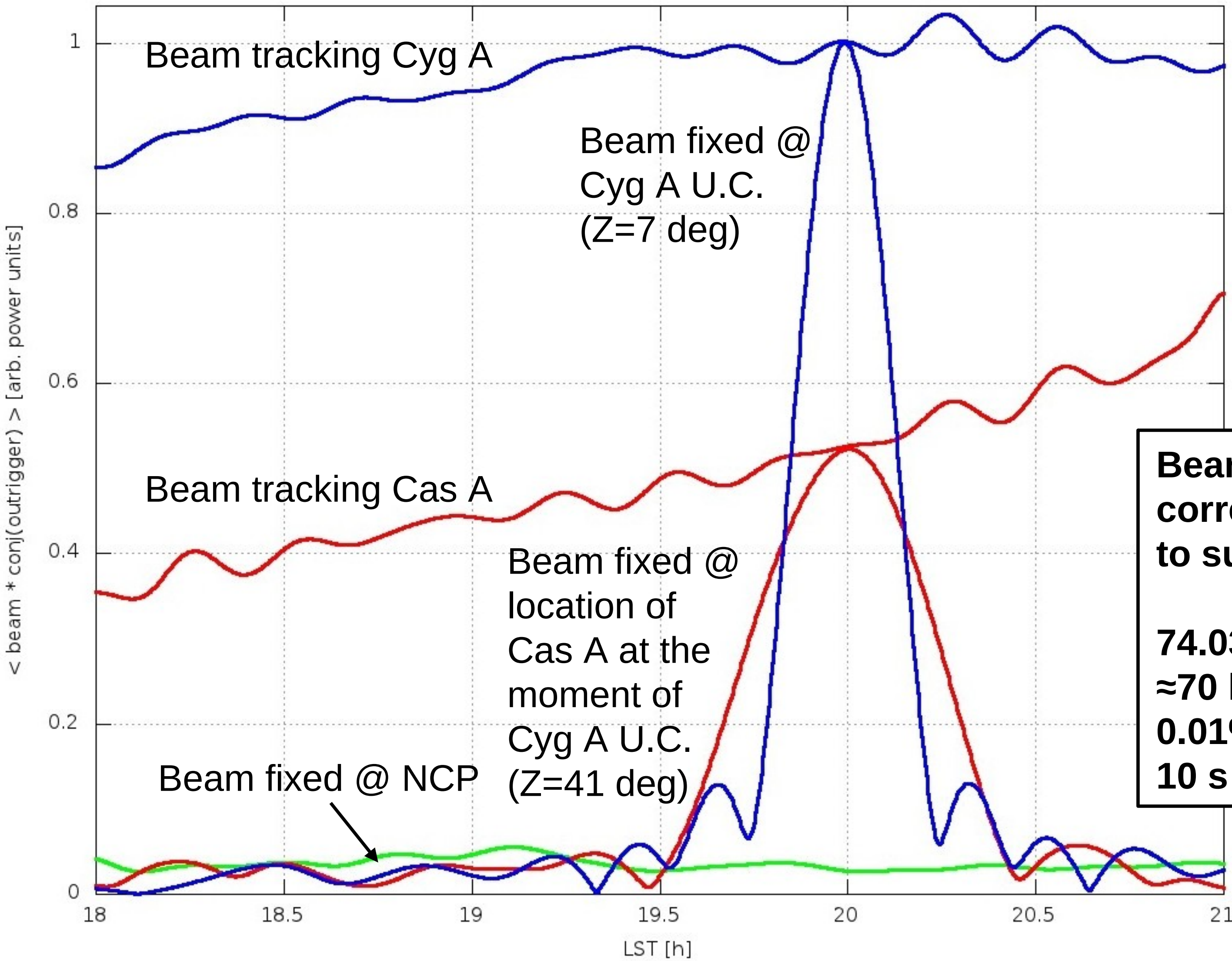
DRX Beamwidth Estimates



LWA Memo 186

Fig. 12. Beamwidth (FWHM) vs. frequency obtained from drift scans. Markers indicate Z: "○", 6.7°; "+", 25°; square, 45°; all using Cyg A. "×" are 74.03 MHz results using transit drift scans from the same additional sources identified in the caption of Figure 11, all at 74.03 MHz. The solid lines, from bottom to top, are: the FWHM model evaluated at 6.7°, 25°, and 45°; and (red/solid) the upper bound described in the text.

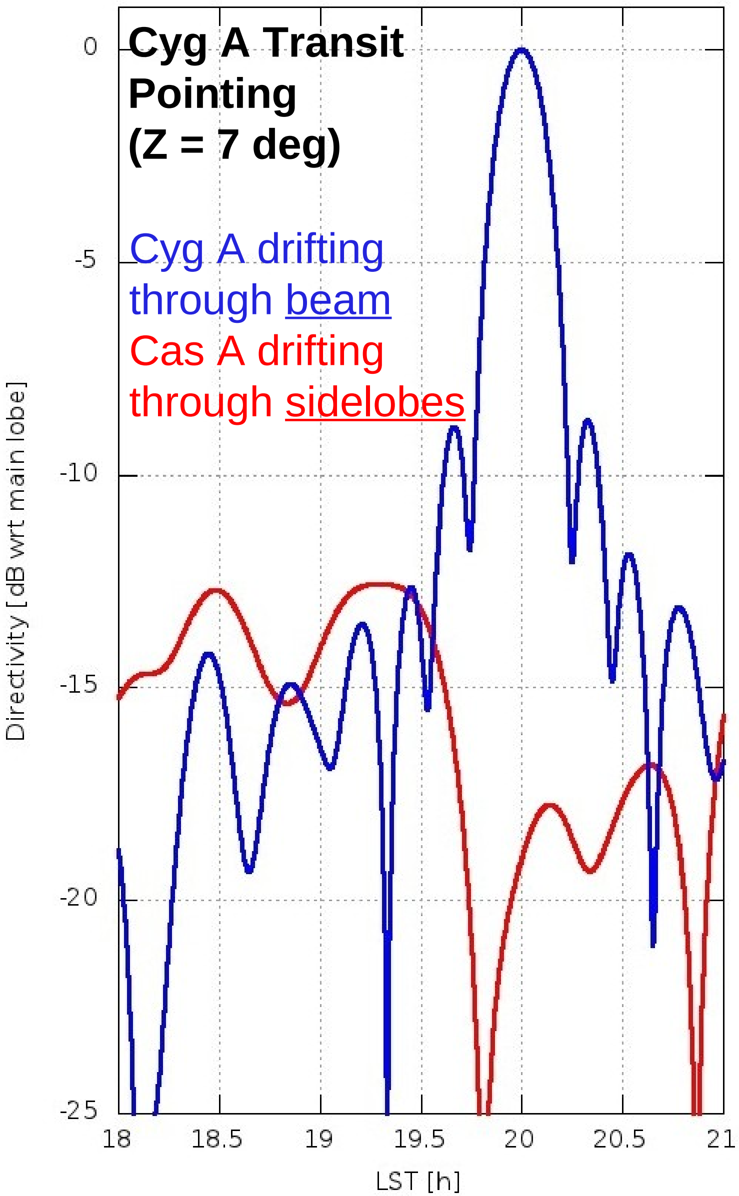
Beam Pointing & Tracking (Using TBN)

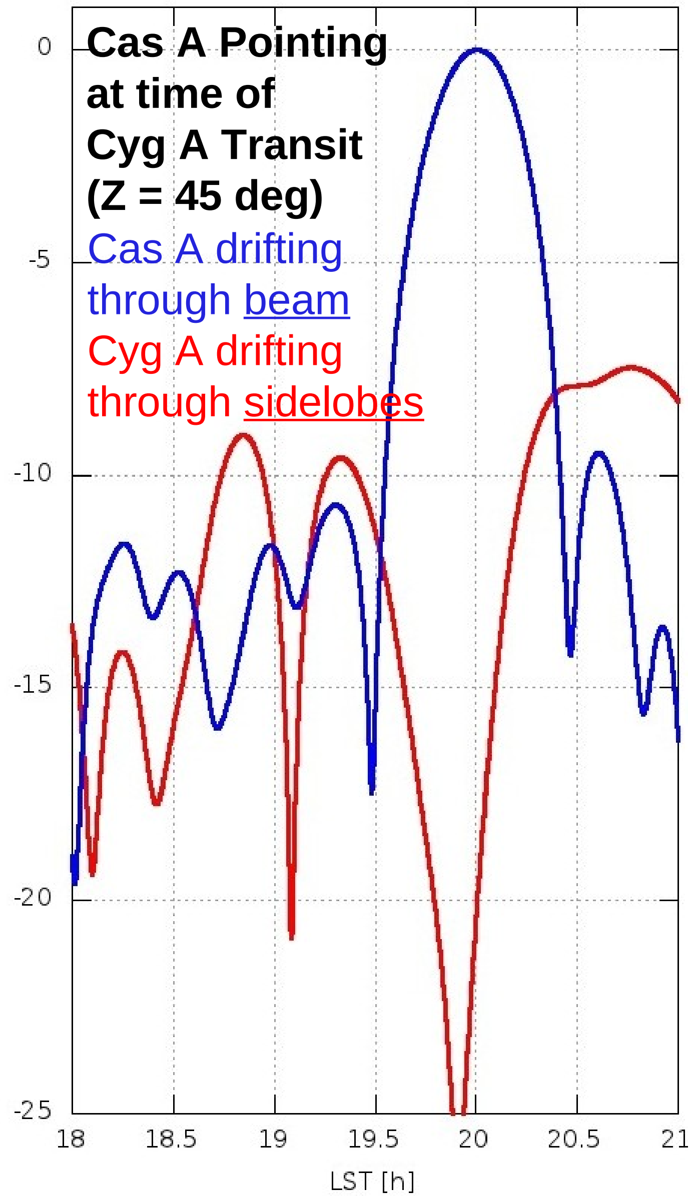


Beam output cross-correlated with outrigger to suppress confusion

74.03 MHz center
≈70 kHz bandwidth
0.01% time blanking
10 s integrations

Sidelobe Characterization (Using TBN)





74 MHz

Beam Pointing Error

Makes zenith appear to be shifted northward by roughly 1 deg, and makes a given RA appear to transit about 430 seconds later expected (increasing with decreasing frequency).

Reason for this error remains a mystery

Apparent and similar in both DRX and TBN, but still not clear if the error is exactly the same for both

"Discovered" in March 2012
Characterized (approximately) in April 2012
Manual correction (SDF editing) since mid-April 2012

It is likely that for any DRX data taken at frequencies above ~38 MHz before SDF editing began, the source effectively outside the beam

Automatic (MCS-internal) correction being commissioned now

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Other Things to Know About Beamforming

Sky noise correlation is strong and currently ignored

- **SEFD improvement of ~50% possible when taken into account**
- **To be addressed as part of URO Tech. Dev. Plan**

Unequal cable gains are currently ignored

- **SEFD improvement of 10%-20% possible**
- **Should be added to LWA1 Tech To Do List**

Unequal cable dispersion (due to unequal lengths) is currently ignored

- **Penalty is only ~2% in SEFD; not worth effort to address**
- **But – keep in mind if your science might be sensitive to this!**

Unequal antenna dispersion (due to coupling) is currently ignored

- **Effect not currently known.**
- **Keep this in mind if your science might be sensitive to this**

LWA Memos 166, 187

Other "Issues"

"Shimmering"

RFI – esp. power lines

Beam <u>tracking</u> degrades TBN

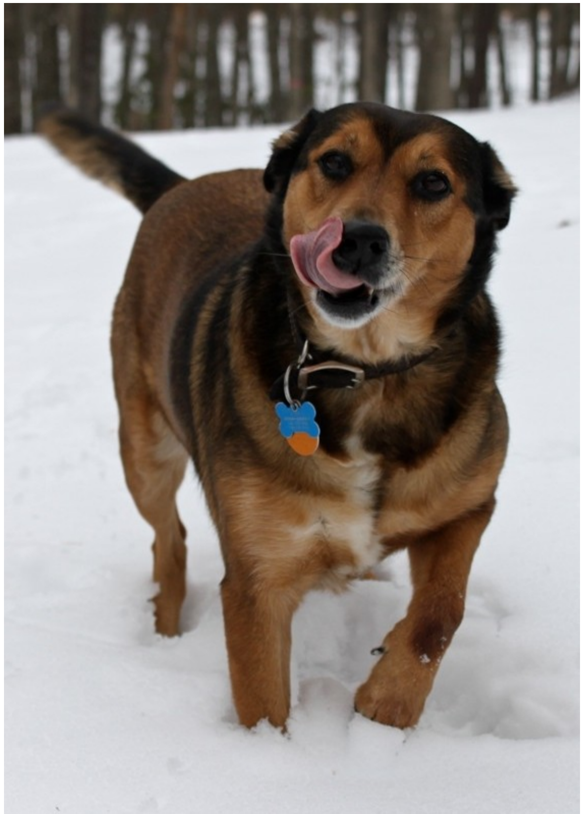
Timetag offsets and glitching
– Associated with center frequency changes
– Does not affect data, but makes checking data integrity difficult

Jupiter and solar tracking modes are not currently implemented
– Specify as RA/Dec-tracking instead

"STEPPED" mode not yet implemented; Work-arounds available

http://lwa1.org/tech/limitations-problems
LWA1 Tech To Do List (updated weekly, ask a staff member)

New Capabilities Coming



DR Spectrometer Upgrades
- Software-only increase in #channels from 32 to between 256—2048
- Full Stokes processing
- Cross-correlation

LEDA Outriggers
- Increases # outrigger stands from 1 to 5
- Absolute power (Dicke switching) calibration

Data Analysis Software
- LSL (Python)
  - Available now, continuously improving (See talk by Jayce Dowell)
- Loa (C)
  - Lightweight, memory-savvy, single-executable software for DRX
  - Intended for quick-look and HPC cluster computing applications

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Loa

From Wikipedia, the free encyclopedia

The **Loa** (also *Lwa* or *L'wha*) are the spirits of Haitian Vodou. They are also referred to as Mystères and the Invisibles

Raw DRX output file from DR

foo.job (human-readable text file)

Loa

(42KB executable)

```
$ ./loa foo.job
```

***Run-time* memory recon & allocation**

File I/O minimized,
No intermediate files
(unless you want them!)

Frame metadata (What the heck is this file?)
Frame-to-frame metadata checking
Sample statistics

Input sample flagging/blanking
Time-frequency flagging/blanking

Time/Frequency-domain calibration
Polarization combining

Time-series analysis
Integrated spectra
Spectrogramming

Incoherent Dedispersion
Folding
Pulse-matched filtering & detection

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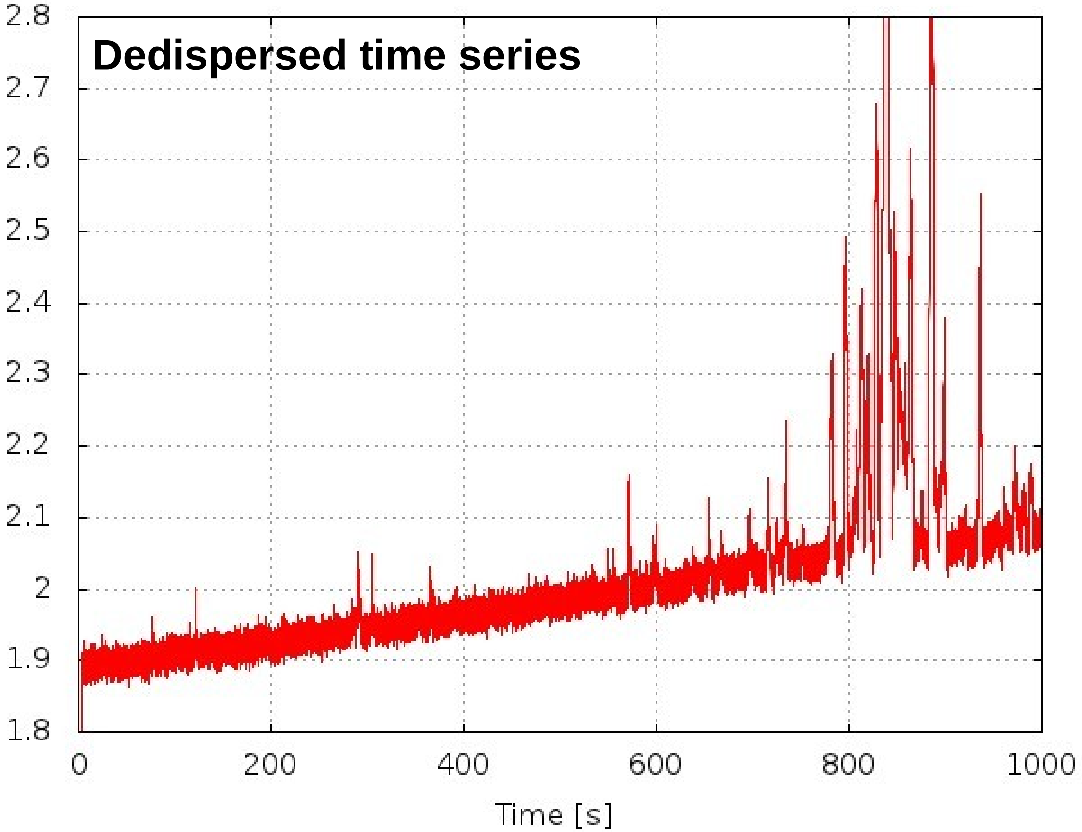
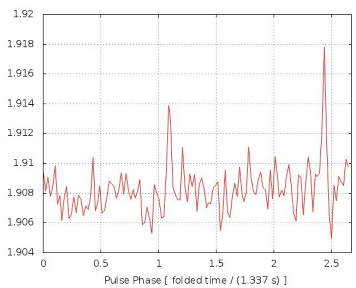
LOA Demo

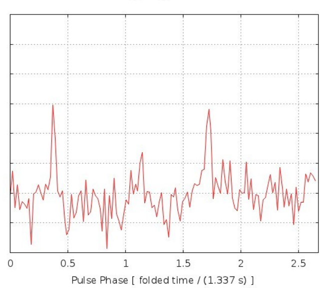
055841_002593525
PSR B1919+21
(Pointing Error in Effect)
37.9 MHz x 2 MSPS
No RFI mitigation



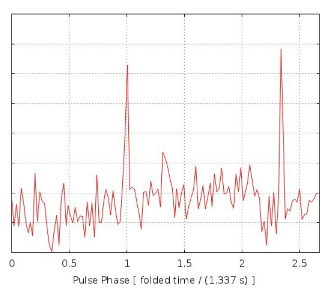
Pulse profiles



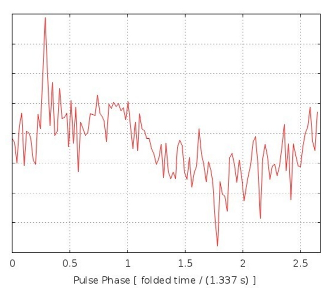
0-200 s



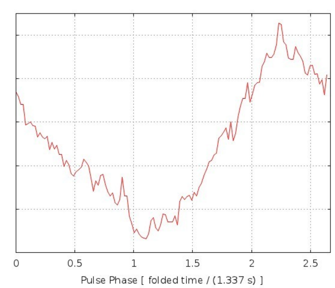
200-400 s



400-600 s



600-800 s



800-1000 s

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URO Tech. Dev. Program (TDP)

1. Electromagnetic Characterization (models & measurements)
    - Beam shape
    - Sidelobes
    - Polarization (Using PSR B1929+10, Jupiter)
    - Embedded patterns

    NEC4 (moment method) model available (LWA Memo 166)

2. Enhanced Beamforming
    - Increasing sensitivity ("Optimum SNR" beamforming)
    - Precision control of beam pattern

3. Enhanced RFI Mitigation

4. Dynamic & autonomous scheduling
    - External Triggers (e.g., GCN)
    - Internal Triggers (e.g., PASI)

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URO TDP (cont'd)

5. On-the-fly Data Processing & Reduction

- Continue to add real-time processing capabilities to the DR
- Planning to add FPGA board to PC to further improve capabilities
  - Already demonstrated "null-processing" path
- Applications:
  - Spectrometer: Beyond 1024 channels
  - On-the-fly RFI characterization & "data gating" (record when conditions are good, don't when conditions are bad)
  - On-the-fly RFI mitigation

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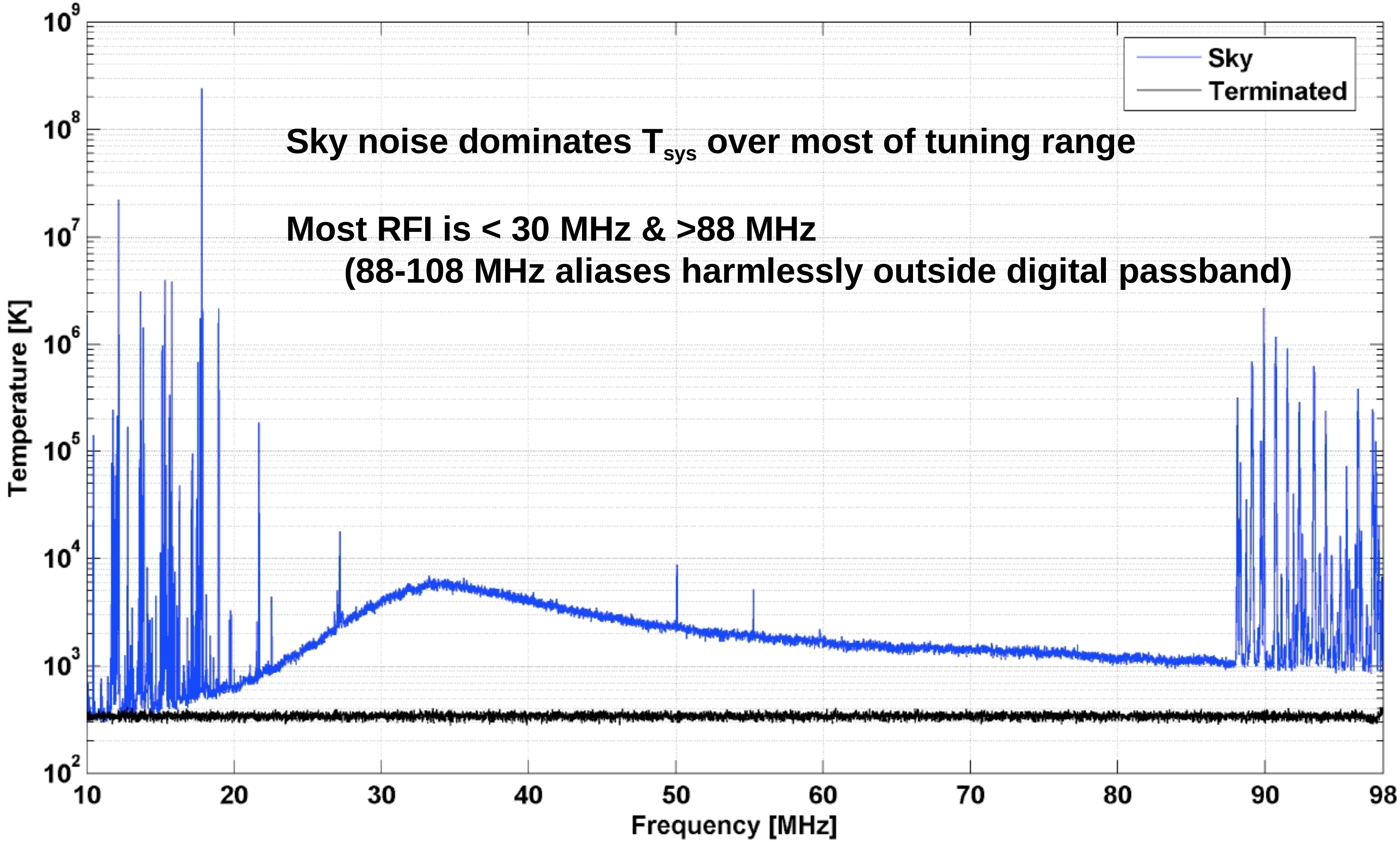
Questions?

Backup Slides

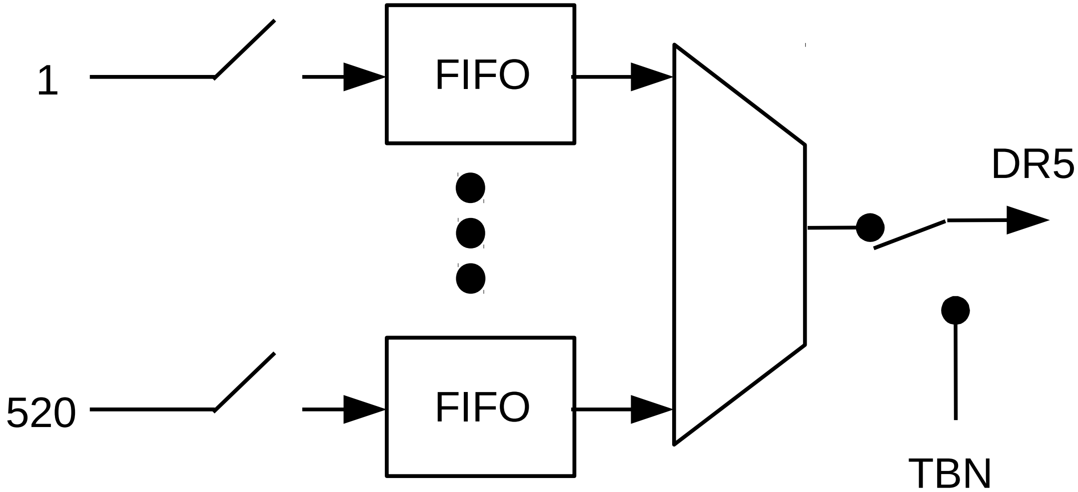
Active Dipole Output Spectrum



Antenna through digitizer (12 bits @ 196 MSPS)
10 s integration, early afternoon local time
6 kHz spectral resolution

TBW ("Transient Buffer Wideband")

196 MSPS
x 12 bits
from A/Ds



Per Trigger:
12,000,000 12-bit samples (61.2 ms) → Δν ~16 Hz
OR
36,000,000 4-bit samples (183.7 ms) → Δν ~ 5 Hz

~60 s between triggers (~0.1% duty cycle)

Engineering Uses
Diagnostics/Status
Station Level Cal
Panoramic RFI assessment
Impulsive RFI assessment
Directional RFI localization

Science Uses
Long duration "total power" transients
Solar } *
Riometry

* Could also be done with beams, but doing it with TBW frees up beams for other uses.

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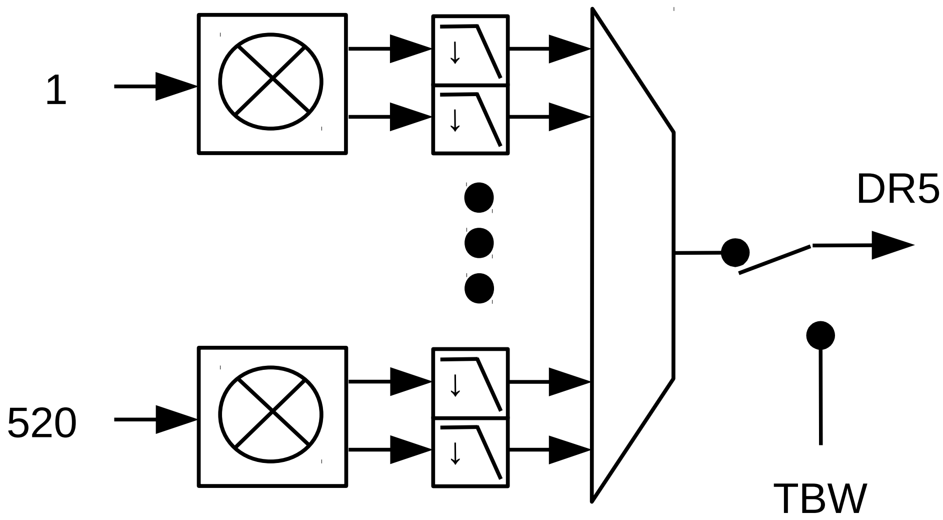
TBN ("Transient Buffer Narrowband")



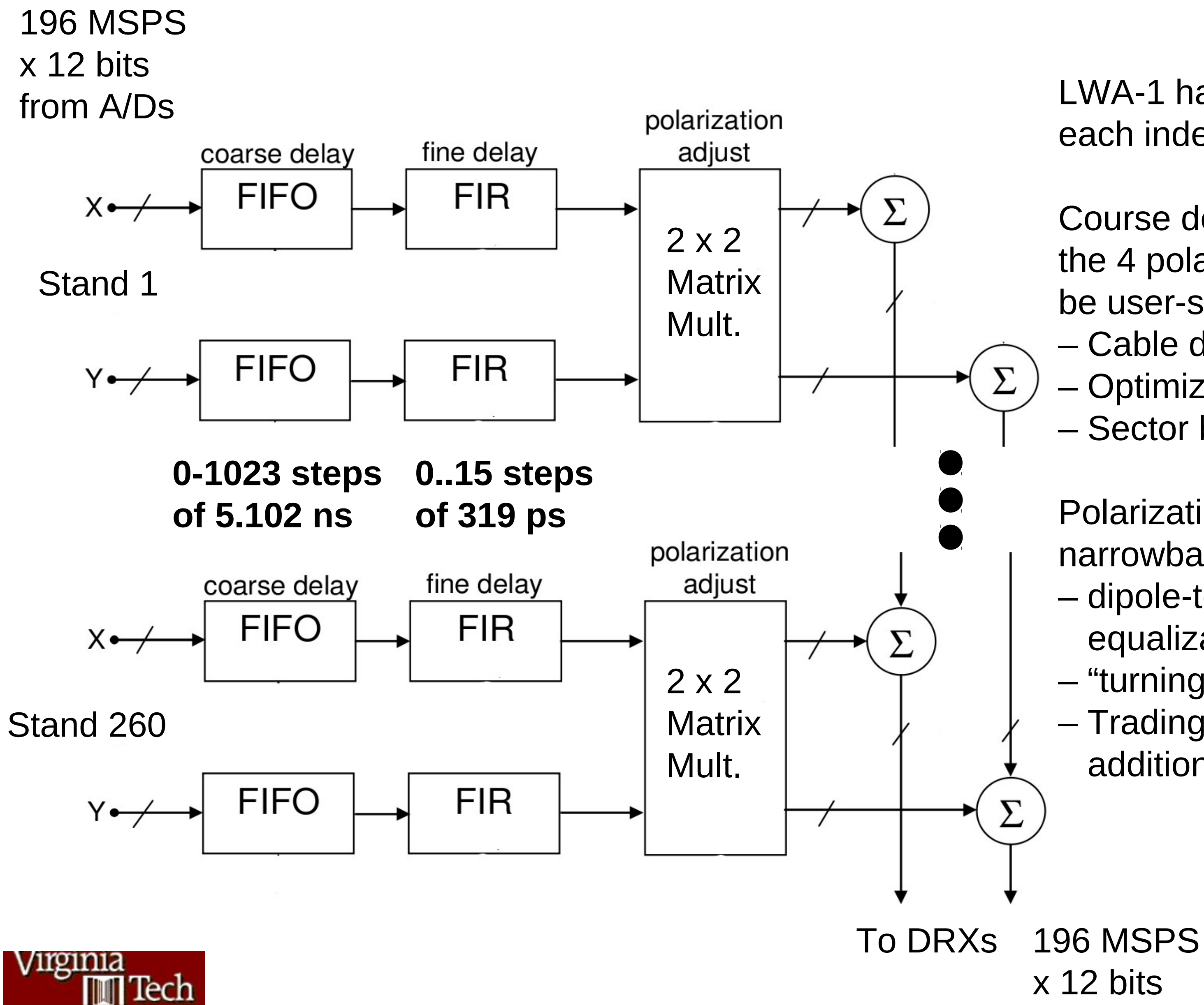
Engineering Uses
Station-Level Cal
Narrowband RFI assessment
High-sensitivity RFI assessment
Directional RFI Localization

Science Uses
All-sky transient search (PASI)
Radio recombination lines, maybe
(Post-observation customization of beam shape, Positioning of RFI-suppressing nulls, etc.)

Can run continuously (100% duty cycle)
Center frequency selectable in 10-88 MHz
Rate selectable 1 - 100 kSPS (3-dB bandwidth ~ 2/3 rate)
Output samples are 8-bit I + 8-bit Q

This mode sets the data recorder throughput requirement (~113 MB/s for all stands @ max BW)
Can do this up to ~30 hours without gaps; ~60 hours without physical intervention
(assuming 15TB DRSUs)

Beamformer

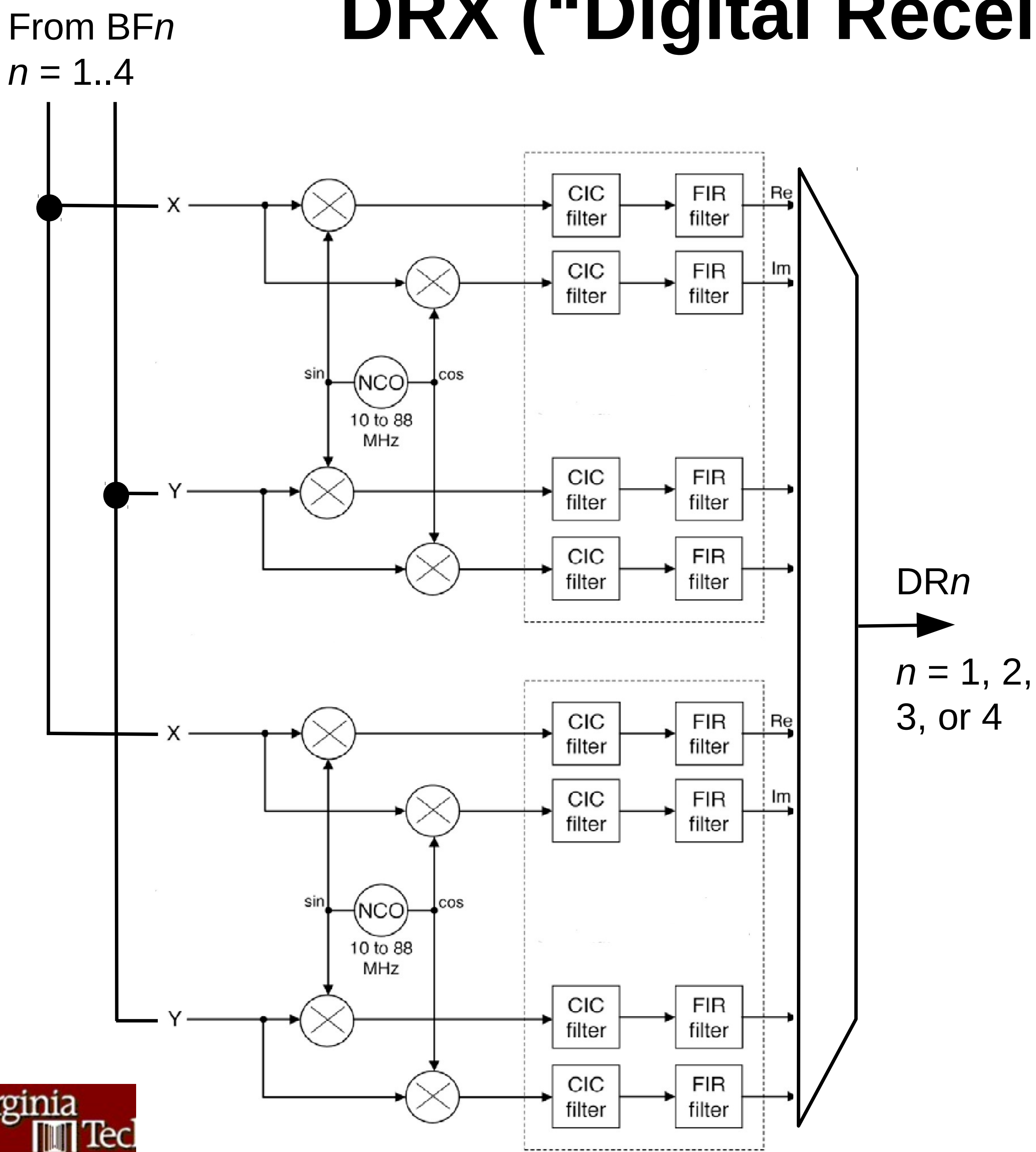


LWA-1 has 4 of these, each independently-pointable

Course delay, fine delay, and the 4 polarization coeffs can be user-specified if desired
- Cable dedispersion
- Optimized beamforming
- Sector beams, nulls

Polarization adjustment is narrowband. Other uses:
- dipole-to-dipole gain equalization
- "turning off" dipoles
- Trading polarizations for additional beams

DRX ("Digital Receiver")



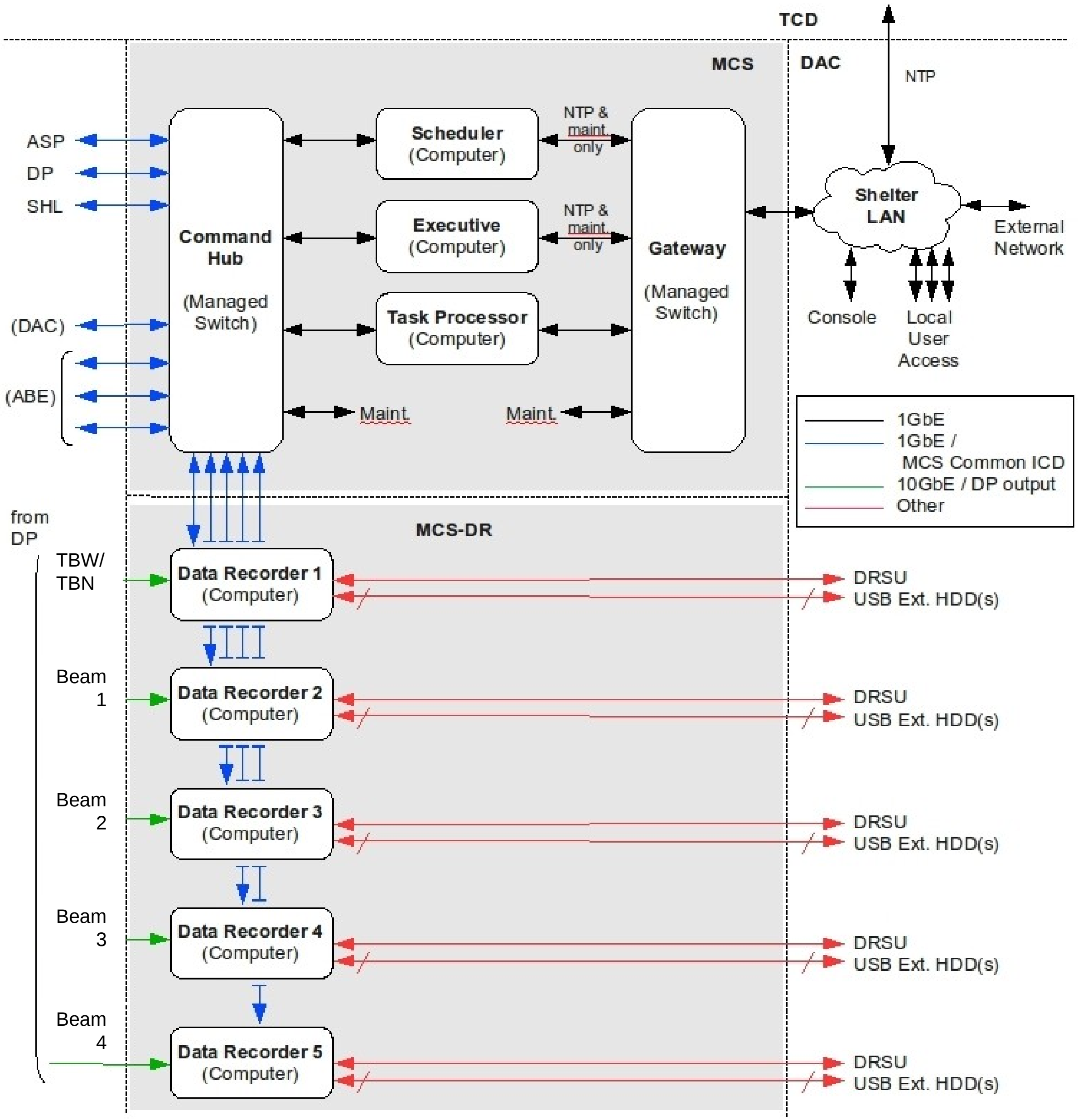
Each beam gets two "tunings" (10-88 MHz)

Output samples are I4+Q4

250 kSPS -- 19.6 MSPS;
(Exact ratio of bandwidth to sample rate not yet known; probably between 2/3 and 7/8)

NO FFT!

MCS & Data Recorder Architecture



- **MCS has 3 parts:**
  - **“Scheduler”**
  - **“Executive”**
  - **“Task Processor”**
- **5 MCS-DRs**
  - **One per beam**
  - **One for TBW/TBN**
  - **Record to DRSUs (5/10/15TB vers.)**
  - **2 DRSU per DR**
- **Data Exits:**
  - **DRSU**
  - **Ext USB HDD**
  - **Internet (slow)**

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LWA-1 Observing Terminology

- ***Mode***: A thing you can do with a DP output (i.e., one of the 4 beams, or TBW/TBN)
  - TRK_RADEC: Beam tracks specified RA / DEC
  - TRK_SOL: Beam follows Sun
  - TRK_JOV: Beam follows Jupiter
  - STEPPED: Beam repointed/retuned in discrete steps according according to user-provided table
  - TBW or TBW

- ***Observation***: Continuous use of one of the 5 DP outputs with no change in *mode* or station configuration

- ***Session***: A contiguous set of *observations* using the same DP output
  - You might call this an "observing run" – the *observations* include things like multiple sources, off-source calibration observations, etc.

- ***Project***: A set of *sessions*, not necessarily contiguous & not necessarily using the same DP output
  - Purely an administrative distinction; used to associate sessions with PIs and proposals

Details: MCS0030

Session Definition File (SDF) – TBW

- Mininum info required to define observation
- In-file comments
- Req'd by MCS for scheduling and to organize metadata

MPM = milliseconds past midnight (UTC)

```
PI_ID            1
PI_NAME          Ellingson, Steven

PROJECT_ID       TPSS0003
PROJECT_TITLE    Project Title
PROJECT_REMPI    Project REMPI
PROJECT_REMPO    Project REMPO

SESSION_ID       1
SESSION_TITLE    tp_session_sch SDF test #3
SESSION_REMPI    Test SDF consisting of 2 TBW observations
SESSION_REMPO    Session REMPO

OBS_ID           1
OBS_TITLE        Observation 1 Title
OBS_TARGET       Observation 1 Target
OBS_REMPI        Observation 1 REMPI
OBS_REMPO        Observation 1 REMPO
OBS_START_MJD    55616
OBS_START_MPM    0
OBS_START        UTC 2011 Feb 24 00:00:00.000
OBS_MODE         TBW

OBS_ID           2
OBS_TITLE        Observation 2 Title
OBS_START_MJD    55616
OBS_START_MPM    70000
OBS_START        UTC 2011 Feb 24 00:01:10.000
OBS_MODE         TBW
```

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Session Definition File (SDF) – TBN

- Mininum info required to define observation
- In-file comments

```
PI_ID           1
PI_NAME         Ellingson, Steven

PROJECT_ID      TPSS0002
PROJECT_TITLE   Project Title
PROJECT_REMPI   Project REMPI
PROJECT_REMPO   Project REMPO

SESSION_ID      1
SESSION_TITLE   tp_session_sch SDF test #2
SESSION_REMPI   Test SDF consisting of 2 short TBN observations
SESSION_REMPO   Session REMPO

OBS_ID          1
OBS_TITLE       Observation 1 Title
OBS_TARGET      Observation 1 Target
OBS_REMPI       Observation 1 REMPI
OBS_REMPO       Observation 1 REMPO
OBS_START_MJD   55616
OBS_START_MPM   0
OBS_START       UTC 2011 Feb 24 00:00:00.000
OBS_DUR         10000
OBS_DUR+        00:00:10.000
OBS_MODE        TBN
OBS_FREQ1       438261968
OBS_FREQ1+      19.999999955 MHz
OBS_BW          7
OBS_BW+         100 kSPS
```

duration [ms] → OBS_DUR

Center freq encoded as this x (196 MHz) / 2^{32} [Hz] → OBS_FREQ1

Sample rate (thus, bandwidth) → OBS_BW

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Session Definition File (SDF) – TRK_RADEC

- Mininum info required to define observation
- In-file comments

RA [h]

DEC [deg]

Beam Type (only SIMPLE is implemented currently)

```
⋮
OBS_ID           1
OBS_TITLE        Observation 1 Title
OBS_TARGET       Observation 1 Target
OBS_REMPI        Observation 1 REMPI
OBS_REMPO        Observation 1 REMPO
OBS_START_MJD    55616
OBS_START_MPM    0
OBS_START        UTC 2011 Feb 24 00:00:00.000
OBS_DUR          10000
OBS_DUR+         00:00:10.000
OBS_MODE         TRK_RADEC
OBS_RA           5.6
OBS_DEC          +22.0
OBS_B            SIMPLE
OBS_FREQ1        438261968
OBS_FREQ1+       19.999999955 MHz
OBS_FREQ2        1928352663
OBS_FREQ2+       87.999999977 MHz
OBS_BW           7
OBS_BW+          19.6 MSPS (but not exactly su
```

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Other Things Users Should Know

- **TBW and TBN data are not "calibrated"**
  - **Corrections for antenna gain, cable delay & loss, ARX & DP responses, etc. must be applied post-observation. (This is done on-the-fly for beamforming modes)**
  - **The necessary information is available via SSMIF, SDM, and observation metadata**
- **<u>No</u> modes are currently calibrated to remove chromatic dispersion**
  - **Antenna responses & cable lengths are unequal; so not safe to assume this can be perfectly corrected after beamforming**
- **Antennas closest to shelter and perimeter fence may have distorted patterns (M.141, M.129)**
- **Polarization calibration has not received any attention. Recommend saving raw linear polarizations. Here, many challenges lie ahead (M.140)**
- **Night is much better than day for RFI**

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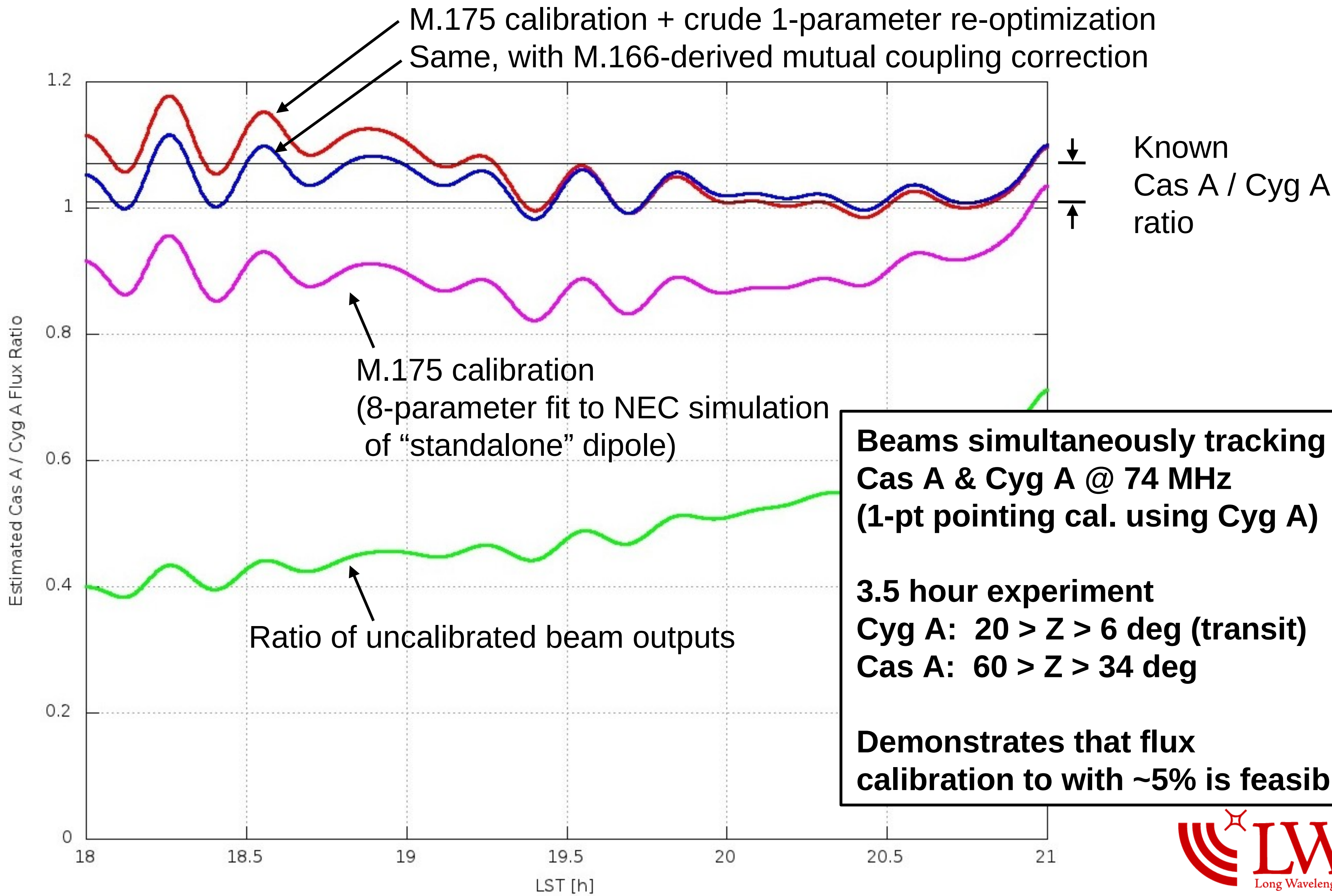
Beam Flux Calibratibility

(Cas A – Cyg A Flux Ratio)



Beams simultaneously tracking Cas A & Cyg A @ 74 MHz (1-pt pointing cal. using Cyg A)

3.5 hour experiment
Cyg A: 20 > Z > 6 deg (transit)
Cas A: 60 > Z > 34 deg

Demonstrates that flux calibration to with ~5% is feasible

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