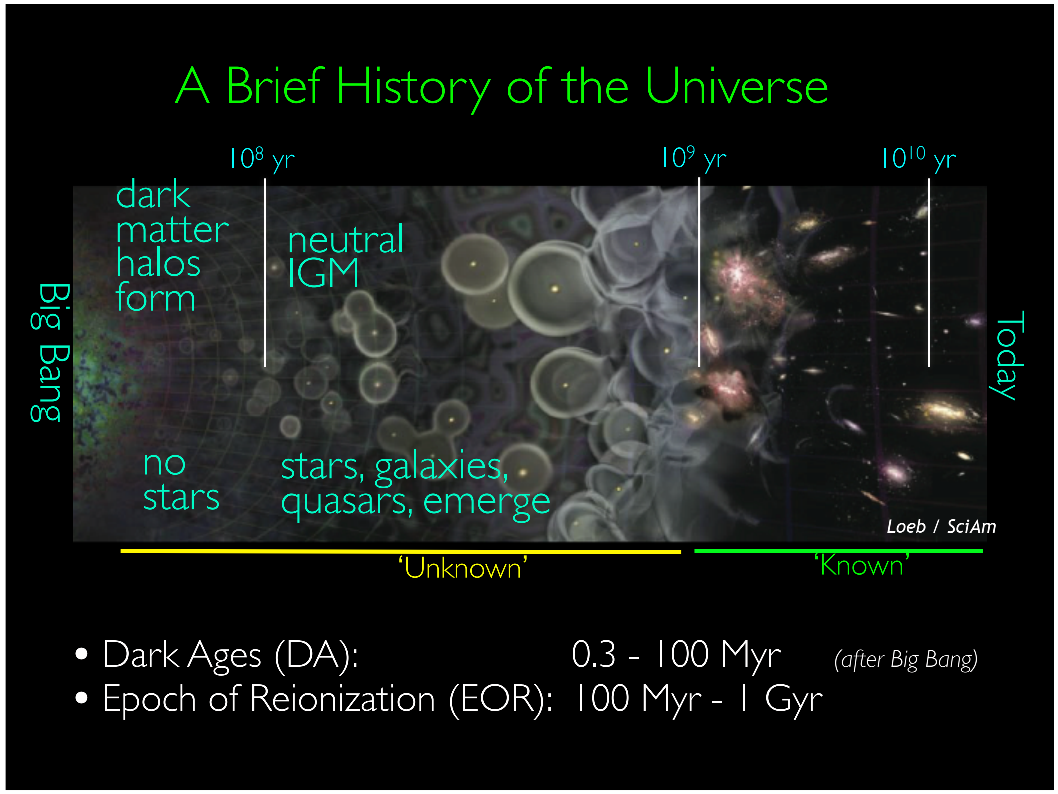
Detecting the Dark Ages With LEDA: An Update

LEDA
LARGE-APERTURE EXPERIMENT TO DETECT THE DARK AGES

Danny Price (et. al.), CfA
July 11, 2014
LWA User's Meeting, UNM

Good morning everyone
Introduce myself
Introduce project
Introduce collaborators



I'd like to start by cramming the entire 14 billion year history of the universe into a single one minute slide. (You may have heard some of this).

Short version:
Inflation - there's a hot dense elementary particle soup, and surprise! the universe is expanding.
Annihilation - matter & antimatter duke it out, leaving a matter dominated universe. Universe is 1s old.
Recombination - atoms form. Finally. They took their time. Universe is ~379000 years old.
Decoupling - Matter and photons decouple, cosmic background radiation released. We've spent a lot of time & money finding, measuring, and studying this, and have learnt a lot.
Dark ages - gravitational collapse forms structures (stars, galaxies, quasars).
Reionization - Radiated energy ionizes neutral hydrogen. Now up to 100 Myrs.

Then it gets boring. At least to cosmologists.

After an initial stage of inflation, the Universe remained extremely hot and consisted of 'quark soup' of elementary particles. As the Universe expanded and cooled, baryons (proton, neutron) and antibaryons (antiprotons and antineutrons) formed, which proceeded to annihilate, as did electron and positron pairs.

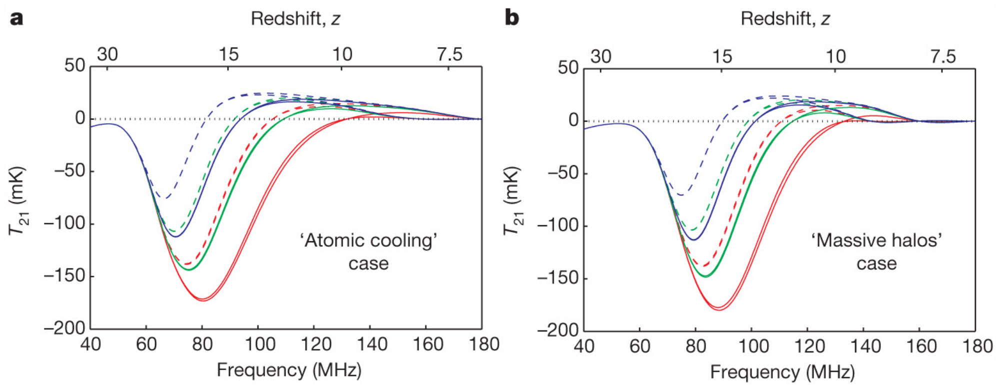
All antimatter was destroyed, leaving the matter dominated Universe that we see today. But, all of this happened within the first second of the Universe's life.

It was not until 379,000 years later that atoms could form en-masse. This is known as recombination, and this caused photons and matter decoupled. The photons from this decoupling epoch are the first source of radiation that we can probe and measure with telescopes. This signal is known as cosmic background radiation and we've spent a lot of money looking for it, finding it, and studying it, and have learnt a huge amount because of it.

Now, following from recombination is a period known as the Dark Ages. During this epoch, the structure of the Universe was forming through gravitational collapse, but stars had not yet reached the critical mass required for nuclear fusion to begin. One by one, the first stars of the Universe switched on, and the Dark Ages transitioned into the 'Epoch of Reionization'. This epoch saw the atoms formed in recombination split (ionized) back into their constituent protons and electrons via radiated energy from the first stars.

And after that, it gets boring. At least from the point of view of a cosmologist.

What are we looking for?



A. Fialkov et. al. (2014) doi:10.1038/nature12999

So what are we looking for? Well, theorists think we should be able to see a signature from the dark ages in the total power of the sky. That is, there should be a trough, of about 100 mK, in between 30 - 80 MHz. With radiometer, that is, an antenna with a spectrometer attached to it, we should be able to see the measured temperature change as a function of frequency.

The depth of the trough tells us about the physics at the early star forming stage in the universe.

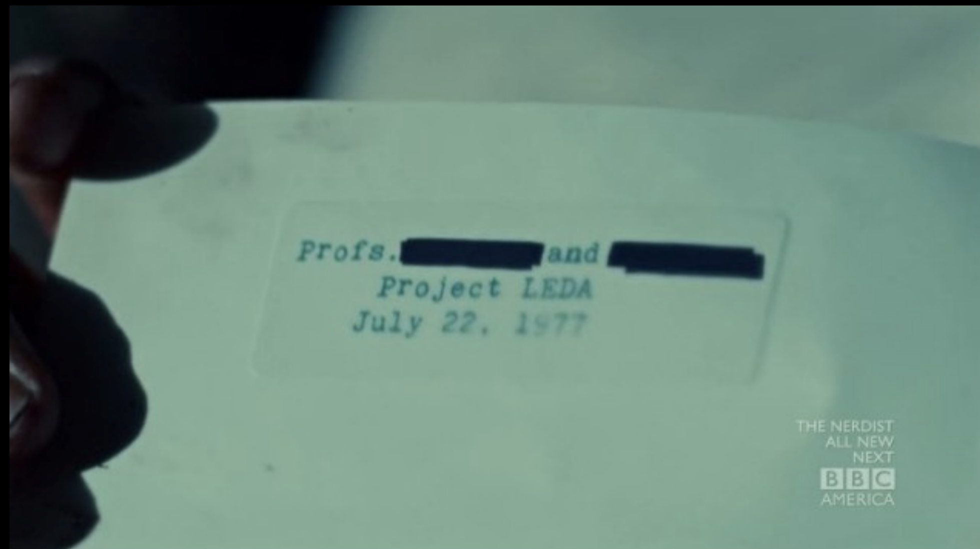
Why is this trough here? Well, it's due to a change in how efficiently neutral hydrogen 21cm line emission couples to Lyman-alpha radiation. This is called the Wouthuysen-Field effect. We can learn a lot about the early universe by finding and studying this.

OK: So all we need is a single antenna and a sensitive enough instrument to get to millikelvin. Let's go.

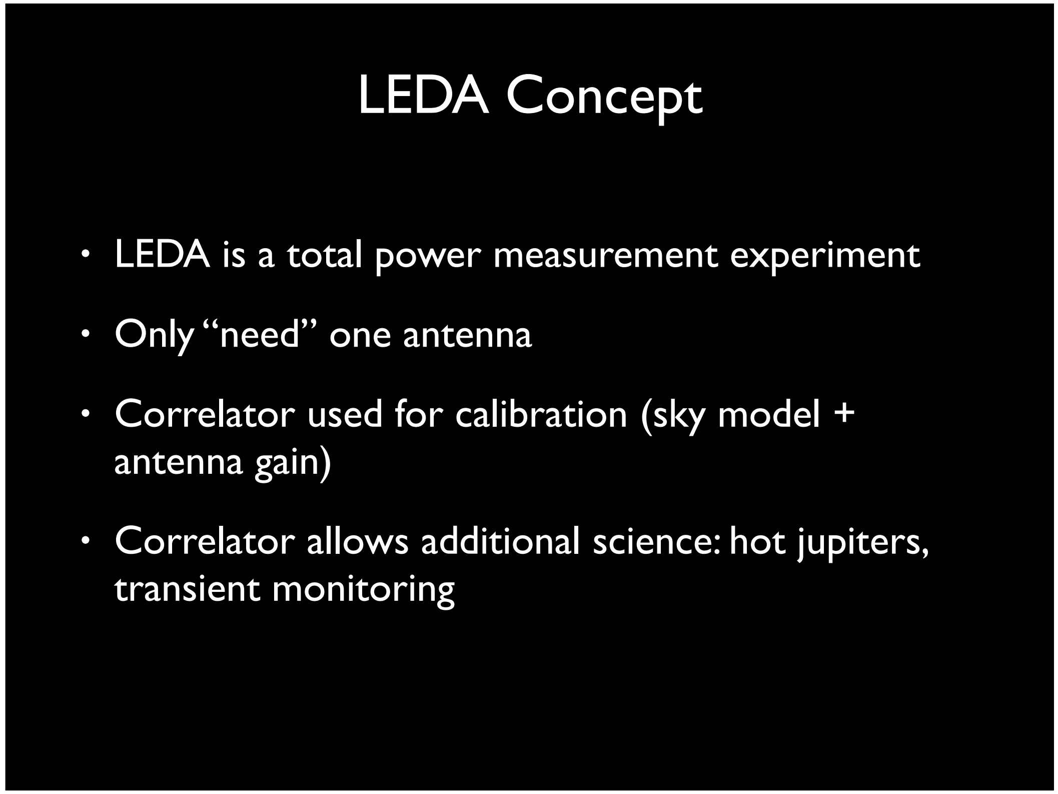
Wouthuysen-Field coupling is a mechanism that couples the excitation temperature, also called the spin temperature, of neutral hydrogen to Lyman-alpha radiation. At times when neutral hydrogen is in thermodynamic equilibrium with the photons in the cosmic microwave background (CMB), the neutral hydrogen and CMB are said to be "coupled", and the hydrogen line is not observable. It is only when the two temperatures differ, or decoupled, that the hydrogen line can be observed.

Wouthuysen-Field coupling is a mechanism that couples the spin temperature of neutral hydrogen to Lyman-alpha radiation, which decouples the neutral hydrogen from the CMB. The energy of the Lyman-alpha transition is 10.2 eV—this energy is approximately two million times greater than the hydrogen line, and is produced by astrophysical sources such as stars and quasars. Neutral hydrogen absorbs Lyman-alpha photons, and then re-emits Lyman-alpha photons, and may enter either of the two spin states. This process causes a redistribution of the electrons between the hyperfine states, decoupling the neutral hydrogen from the CMB photons.[2]

What is Project LEDA?



(this is from a tv show called orphan black, which is a scifi about clones).

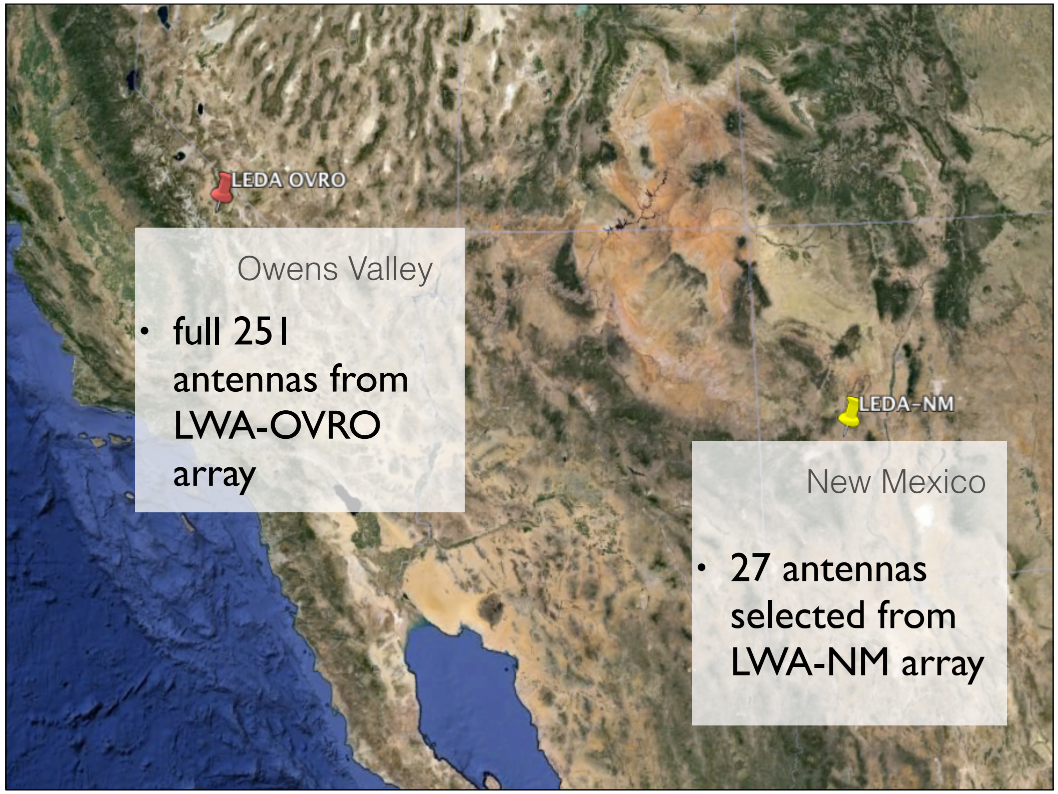


Right. We're looking for a small change in sky temperature. As such, LEDA is a total power measurement experiment. So we only "need" one antenna.

But there's a problem: calibration. We need to model the sky and antenna response as precisely as we can. So instead of using one antenna, we're actually using… 256. An instead of just computing the total power autocorrelation, we're going to compute the cross-correlations of 130,000 baselines.

That is significantly harder to build. But it can be done! And we don't have to start from scratch, we can piggy back of the Long Wavelength Array. And as an added bonus, there is some interesting science facilitated. We should be able to detect radio emission of hot-jupiter type Exoplanets (Gregg Hallinan is PI). Also, all-sky image based transient detection and monitoring.

In this talk, I'm going to focus on the first.


LEDA OVRO
Owens Valley
• full 251 antennas from LWA-OVRO array
LEDA-NM
New Mexico
• 27 antennas selected from LWA-NM array


LWA-OVRO


LWA-OVRO
image: Barsdell (2013)

OK, I know shipping containers are generally not very exciting, but I feel like this deserves some love. This is RF shielded, and has an extremely powerful airconditioning unit on it. Owens valley can get pretty hot.

LEDA - Outrigger antennas

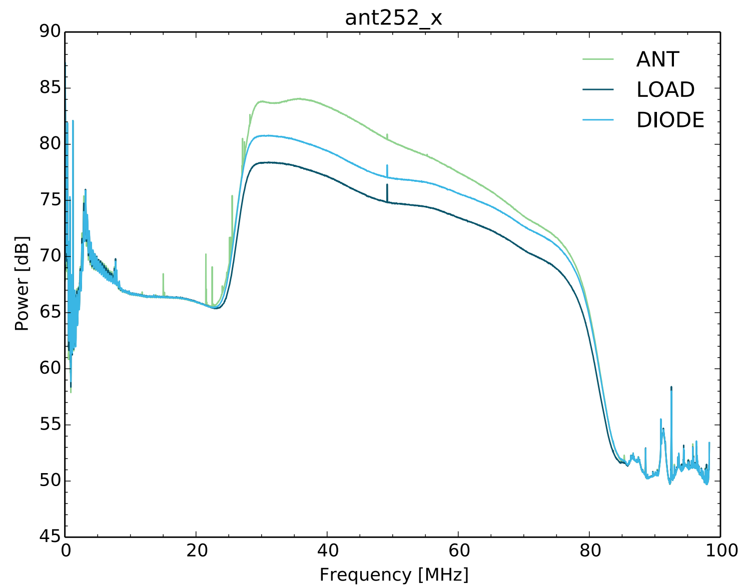
- Three-state frontend board (FEE) switches between antenna, load and noise diode + load
- Switching triggered by PPS, or can be controlled remotely

$$T_{ant} = T_{diode}\left(\frac{P_{ant} - P_{load}}{P_{diode} - P_{load}}\right) + T_{load}$$

$$\begin{aligned} P_{ant} &= G k_B \Delta\nu T_{ant} \\ P_{load} &= G k_B \Delta\nu T_{load} \\ P_{diode} &= G k_B \Delta\nu (T_{diode} + T_{load}) \end{aligned}$$

Ok. So that was the LWA analog components. For LEDA, we have a pretty tough calibration challenge. So we have modified the FEE to have three selectable states.

LEDA - Outrigger antennas



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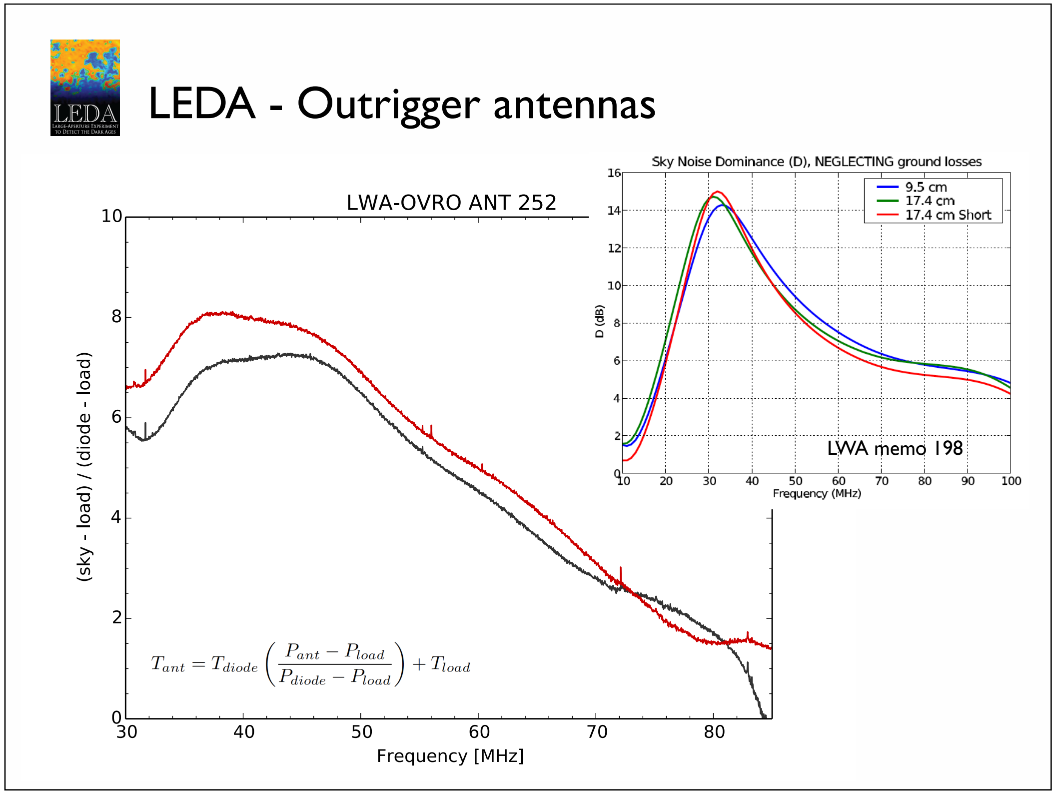

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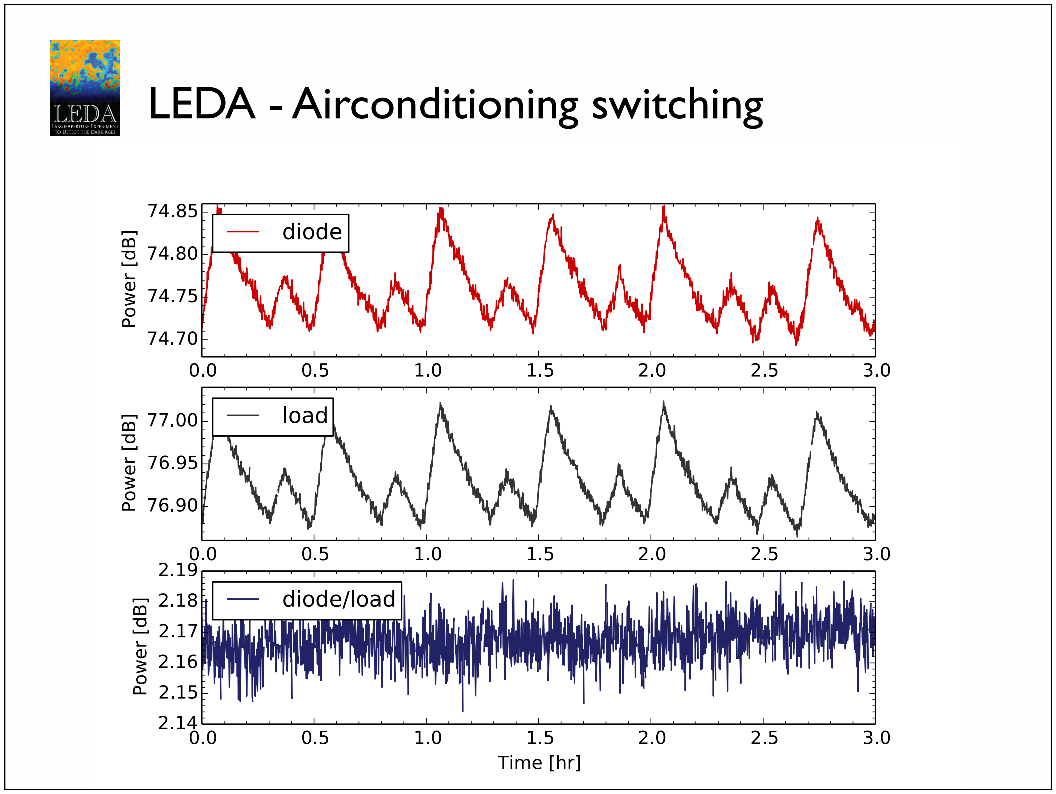

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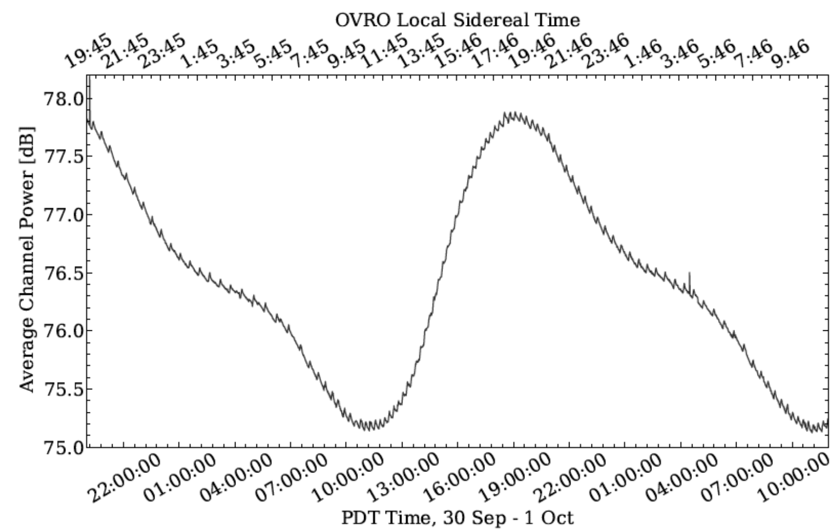
LEDA - Airconditioning switching



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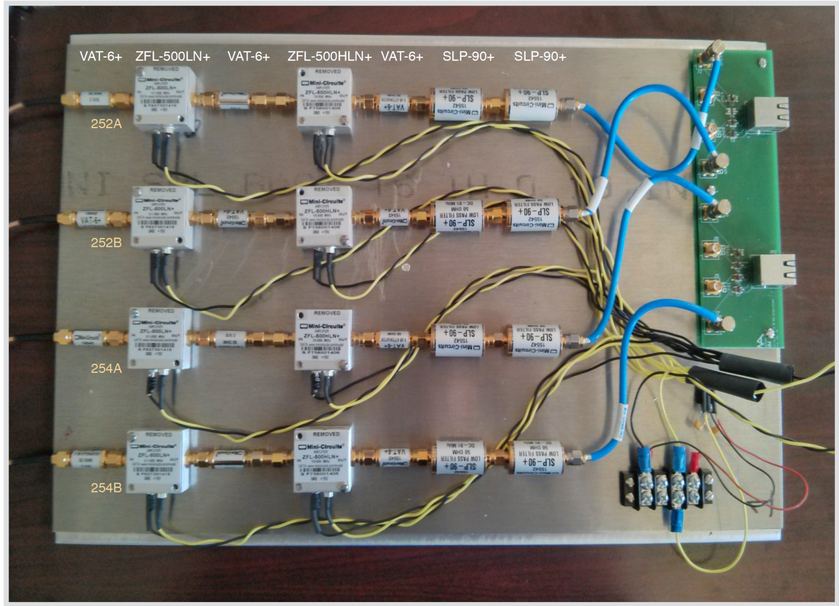
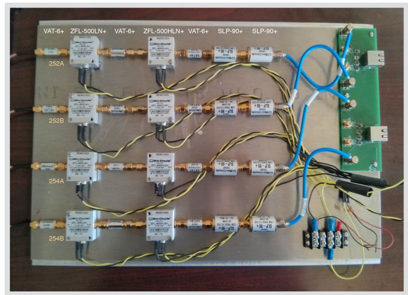
LEDA-CRX: Outrigger Analog System



Before I focus on the LEDA-specific instrumentation, but the LWA designed analog components deserve a bit more detail.

LEDA-CRX: Outrigger Analog System



- Discrete components for crosstalk performance
- FM notch filter at bulkhead
- 6dB attenuator @ input to amplifier for impedance match
- High IP3 second-stage amplifier
- Better for total power radiometry, but not reconfigurable

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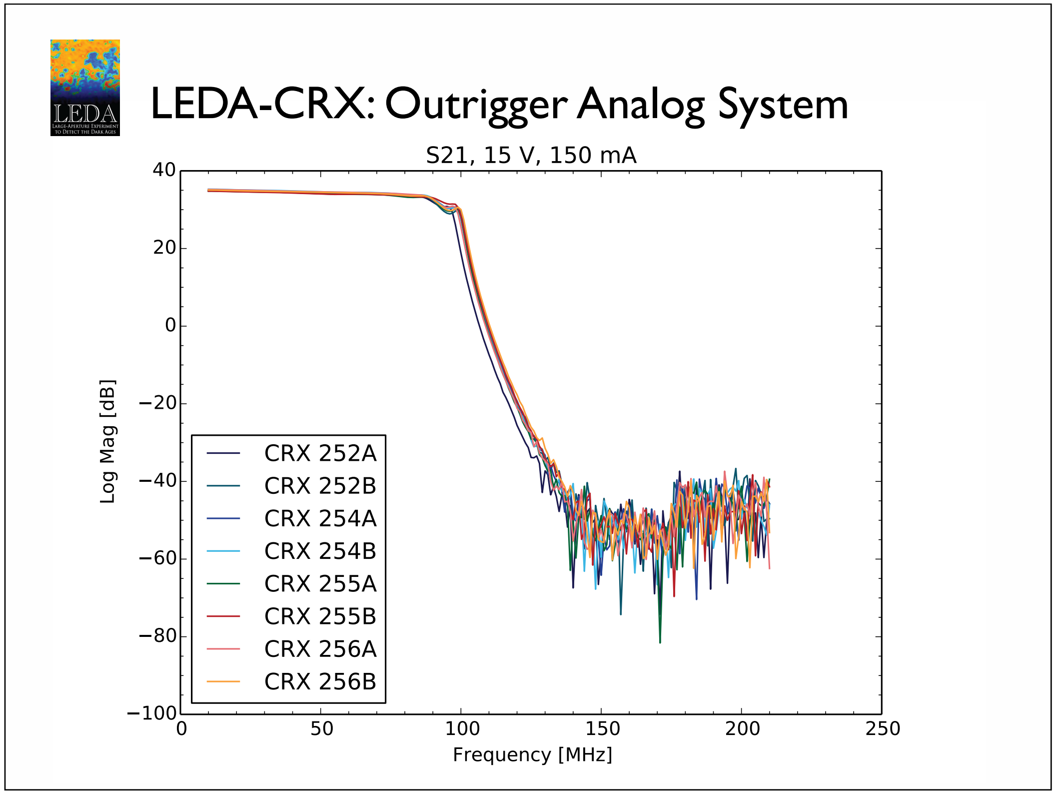

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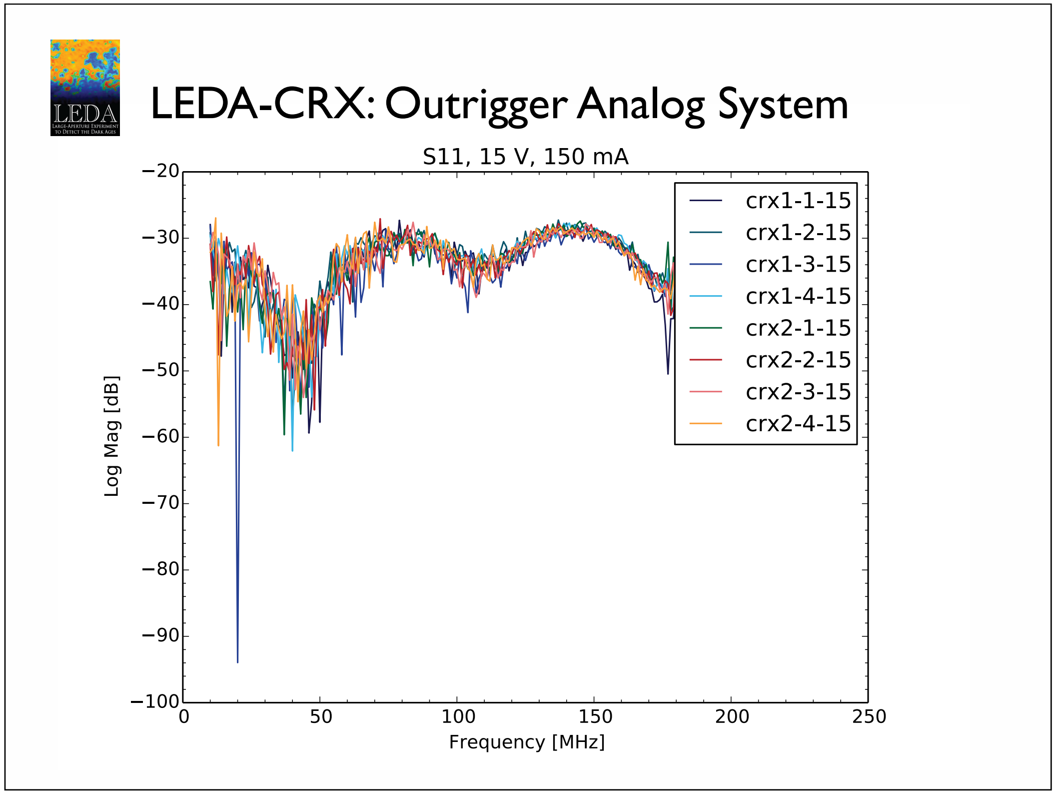

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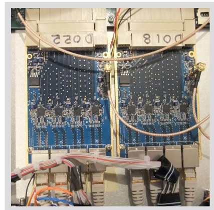
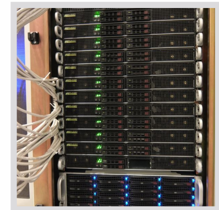
LEDA-OVRO - Digital Overview





ADC-16	F-	10/40 GbE	X-ENGINE
Signal digitization	CASPER ROACH2	Ethernet Switch	K20X GPU Servers

This brings us to to the digital realm. LEDA does not use the LWA DSP backend. Instead, we have implemented what we're calling a "hybrid correlator".

For those of you unfamiliar with the instrumentation side of radio astronomy, a correlator is a device that computes all the possible cross-correlations between antenna pairs. Each antenna pair tells us something about the sky brightness, depending on their separation. Large separations tell you about fine detail, and short baselines tell you about diffuse, large-scale detail. Auto-correlations, that is, an antenna cross correlated with itself, tells you about the total power, of the sky.

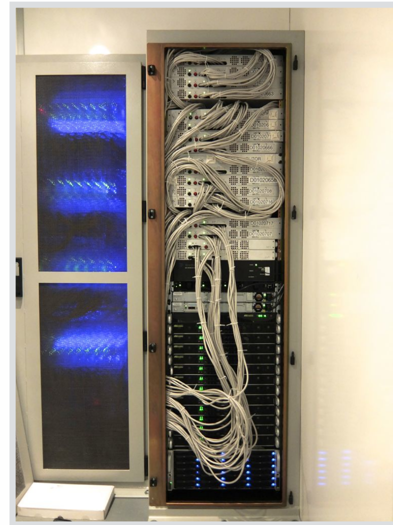
To get frequency information, we also need to do a Fourier transform.

In LEDA, we compute the F.T. on the F-engine, from each digitized time stream from every antenna. We then transport this to the X-engine, which computes the cross-correlation of each spectral channel. To do this requires what is essentially a matrix transpose, to group together like frequency channels, instead of like-antennas. We do this with an Ethernet switch.

It should be noted that we're not the only project doing this. A lot of new digital systems are designed this way, and you'll hear about some more coming up in this session.

LEDA-512 Correlator

- CASPER ADC + FPGA board
  - Dual 16-input 250 MS/s 8-bit ADCs
  - 32 F-engines per ROACH2
- Packetized architecture
  - uses Ethernet switch for corner-turn
- Capture to shared memory using PSRDADA
  - Each server captures 21.4 Gb/s



There are a couple of key components that allowed us to build the LEDA correlator rapidly. I should point out that a huge part of this was done by Jonathon Kocz, who will be giving a more scienc-y talk on Friday, and by Ben Barsdell & Mike Clarke, who are both amazing GPU programmers. I had the pleasure of walking in and helping to install a pre-designed system.

The first bit of rapid development is thanks to CASPER. There will be some CASPER talks later from Dan, John & Rurik. It meant that we didn't have to design a complex FPGA board, and we could use the CASPER toolflow.

The next key was using standard Ethernet for interconnect. No designing custom backplanes, just getting the cool kids at Mellanox to sell us a full-crossbar 40GbE switch.

Getting the data off the Ethernet card and into the GPUs is still a problem, but this has thankfully been solved by PSRDADA, which comes out of Swinburne.

Finally, 512 inputs = a lot of cross-correlations! GPUs are excellent at doing this sort of parallel task though, and xGPU is an open-source, very efficient GPU-based implementation.

So here we have it: everything in one place. And it all fits in one rack!
(256 × 257 ÷ 2) baselines × 4 pols × 57.6 MHz × 8 flops/cmac = 60.63 TFLOP/s

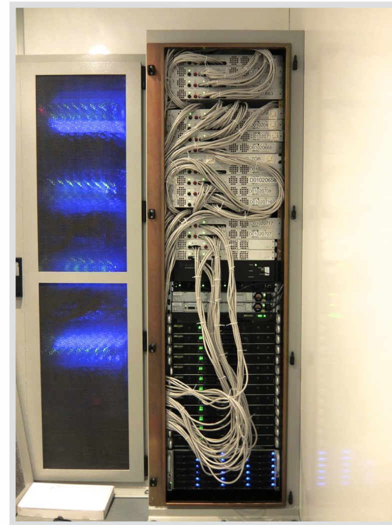
LEDA-512 Correlator

ACCELERATING RADIO ASTRONOMY CROSS-CORRELATION WITH GRAPHICS PROCESSING UNITS

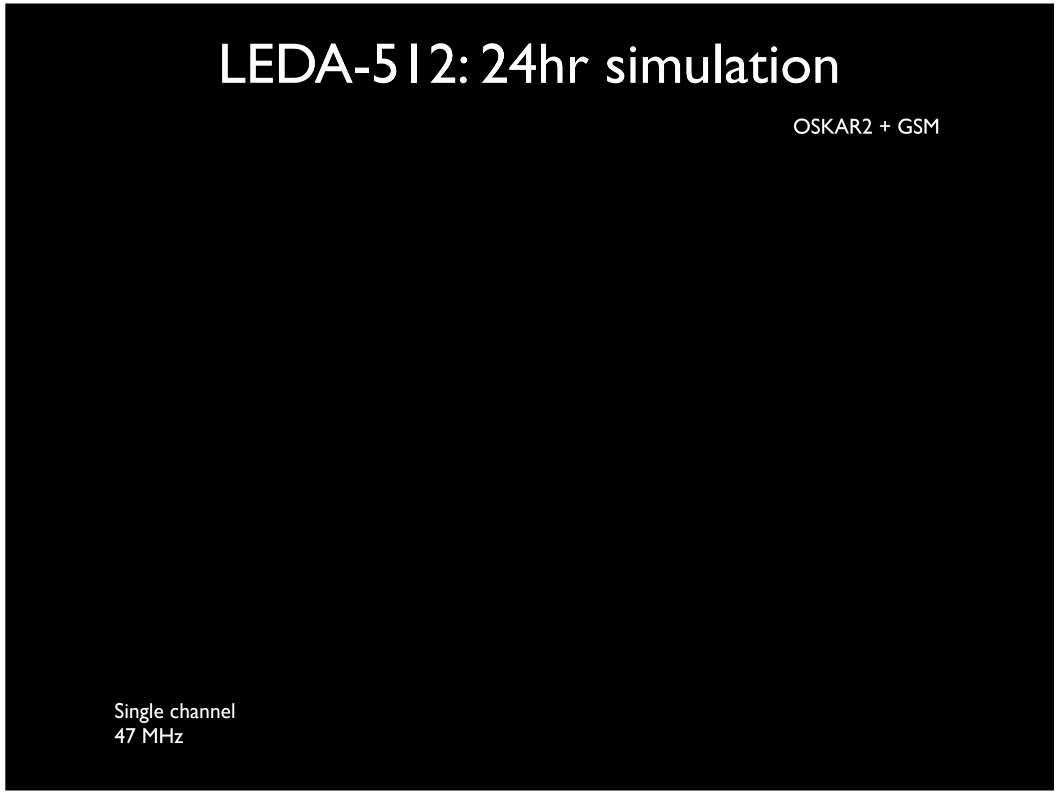
M. A. CLARK, P. C. LA PLANTE, L. J. GREENHILL
[arXiv:1107.4264 [astro-ph]]

A SCALABLE HYBRID FPGA/GPU FX CORRELATOR

J. KOCZ, L. J. GREENHILL, B. R. BARSDELL, G. BERNARDI, A. JAMESON, M. A. CLARK, J. CRAIG, D. PRICE, G. B. TAYLOR, F. SCHINZEL, D. WERTHIMER



MAKE THIS SLIDE BETTER — refs to articles

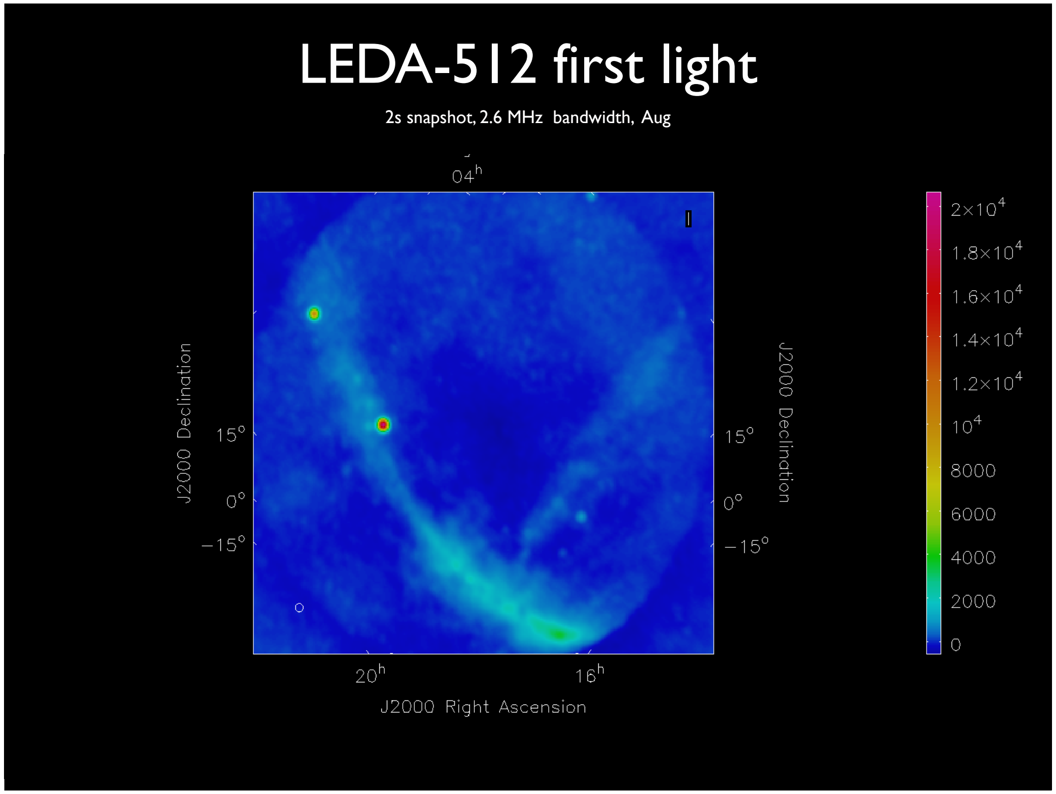


In Jonathon's science talk on Friday there will be more results. But to whet your whistle and to prove it works, here is our first light image for the 512 array.

This is a snapshot image of the entire sky, as seen with LEDA. This only 2s of data, and only 2.6 MHz of bandwidth. The centre frequency is 48 MHz. You can see the size of the primary beam down here, which sets our resolution.

Apparent in the map is Cas A, Cygnus A, Hercules A, and the galactic plane. The image was made in CASA, using only a point source model of Cygnus A to calibrate. So we can do better.

We will eventually use a GPU-based imaging pipeline called cuWARP to make these images in realtime, derive better antenna models, and provide constant calibration for the total power experiment. In addition, we'll be mining these for transient events.



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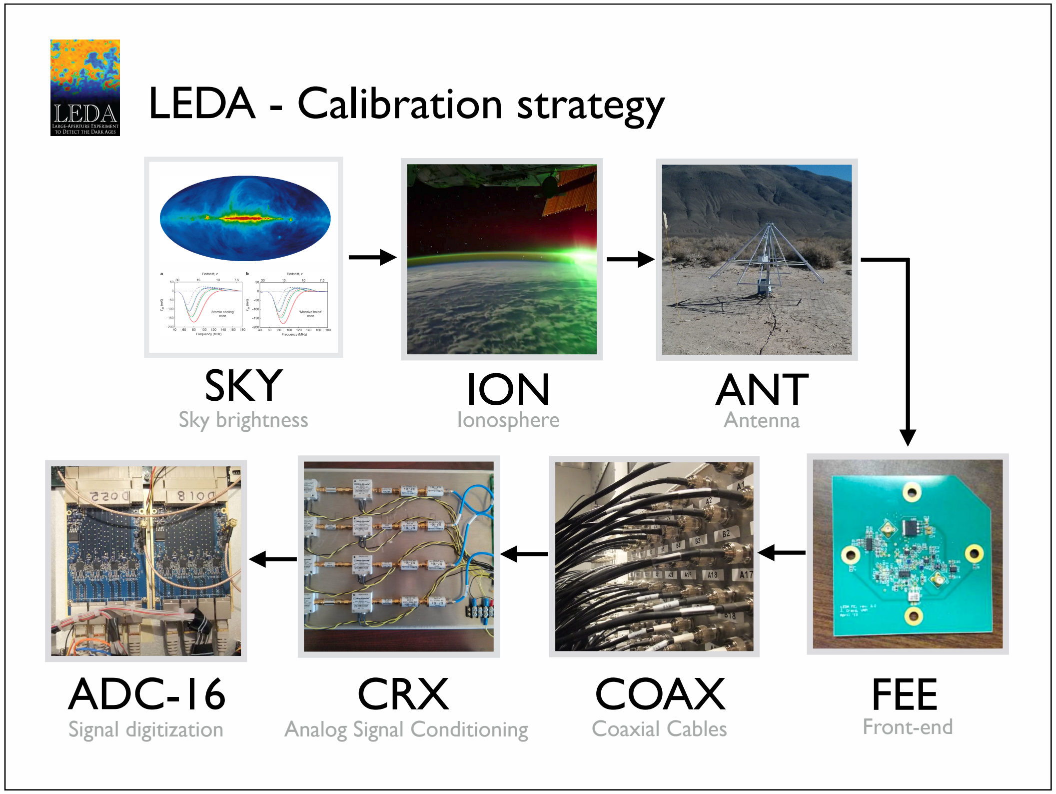
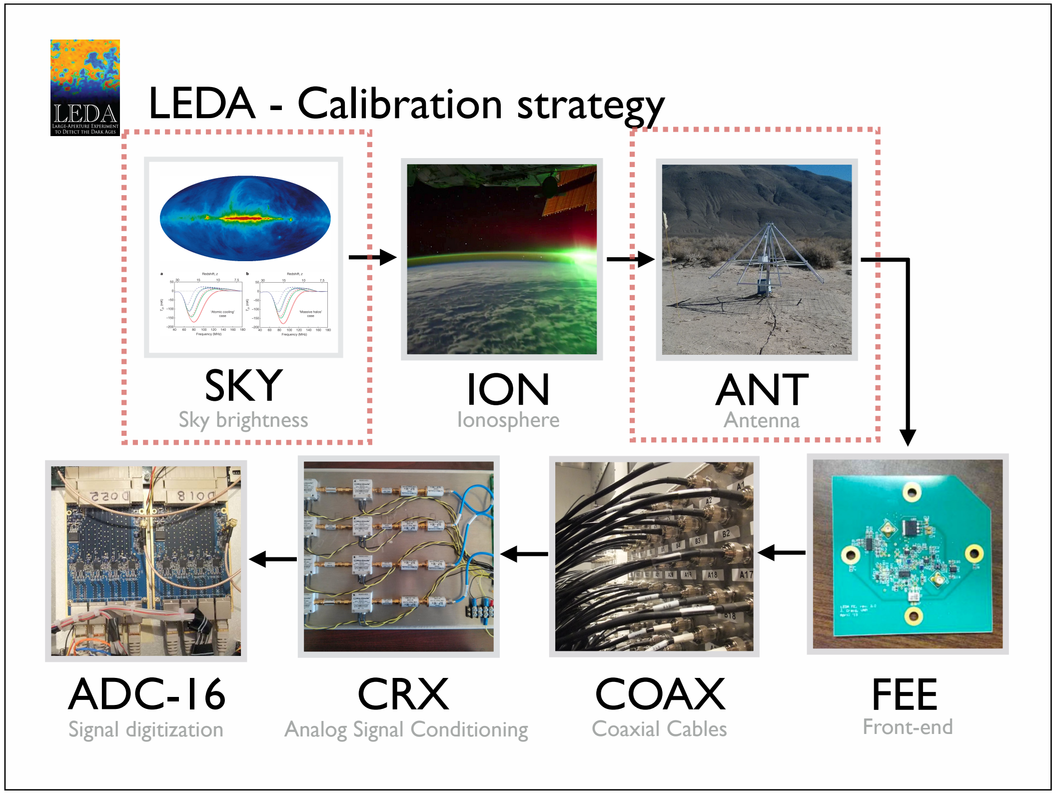
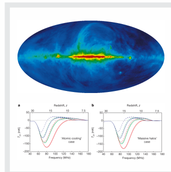


MAKE THIS SLIDE A LOT BETTER.

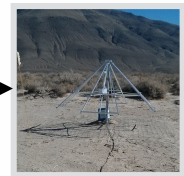


MAKE THIS SLIDE A LOT BETTER.

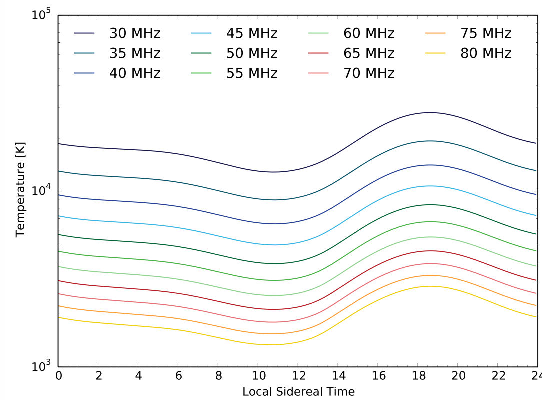
LEDA - Calibration strategy



SKY
Sky brightness



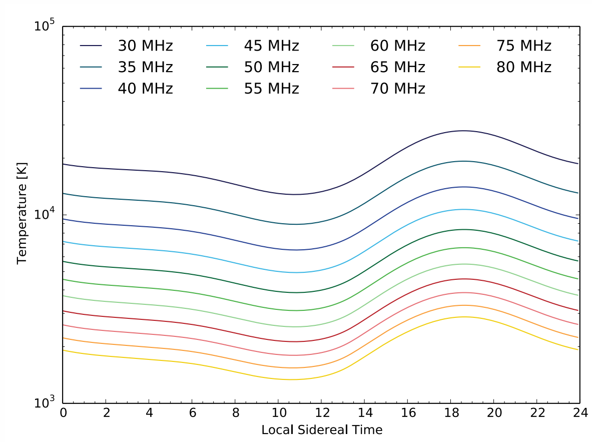
ANT
Antenna



$$T_{ant} = T_{diode}\left(\frac{P_{ant} - P_{load}}{P_{diode} - P_{load}}\right) + T_{load}$$

MAKE THIS SLIDE A LOT BETTER.

LEDA - Sky model + ant model



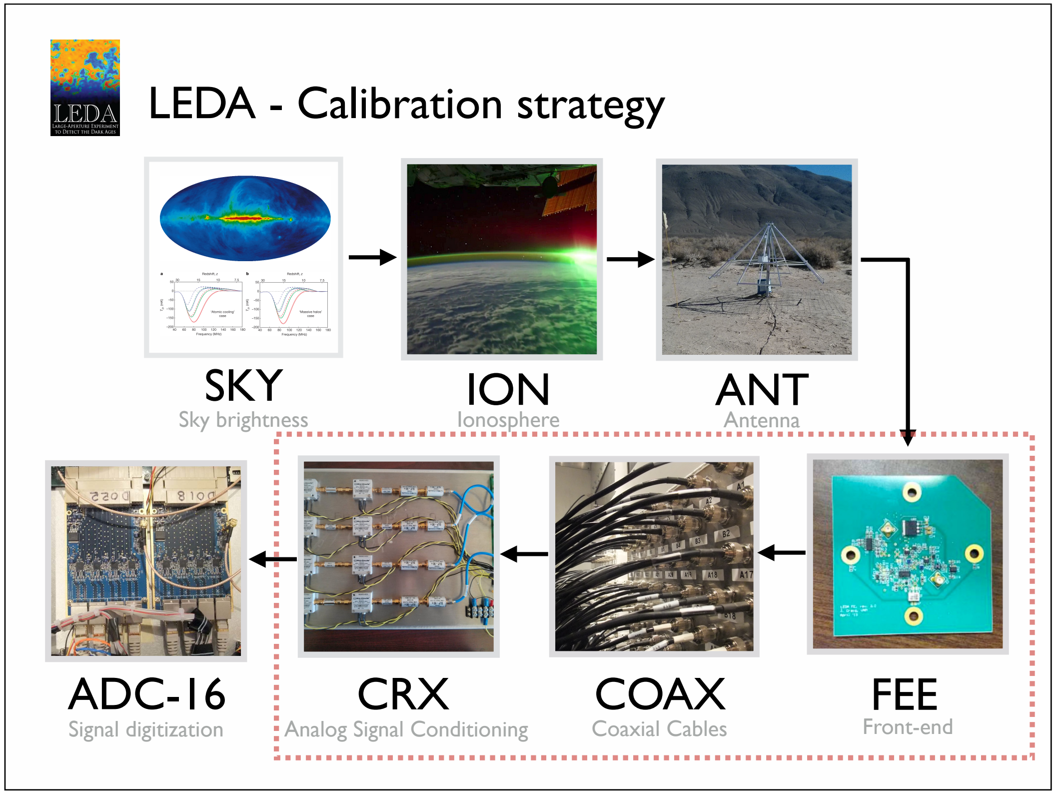
Initial:

- Global Sky Model (GSM): http://space.mit.edu/home/angelica/gsm/
- LWA Antenna Model (LSL): http://fornax.phys.unm.edu/lwa/

Long term:

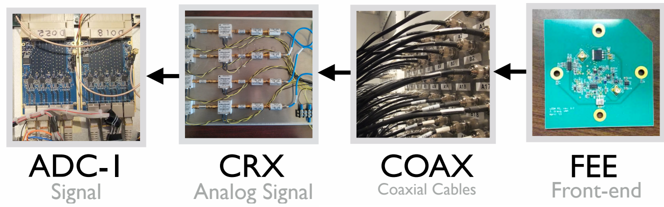
- Derive and update sky model, ionosphere model, and antenna model from correlator output.

Using LSL software library



MAKE THIS SLIDE A LOT BETTER.

LEDA - Calibration strategy



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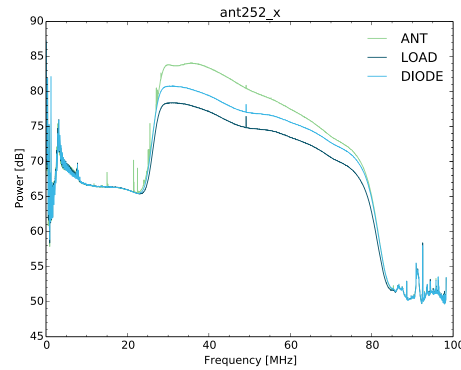

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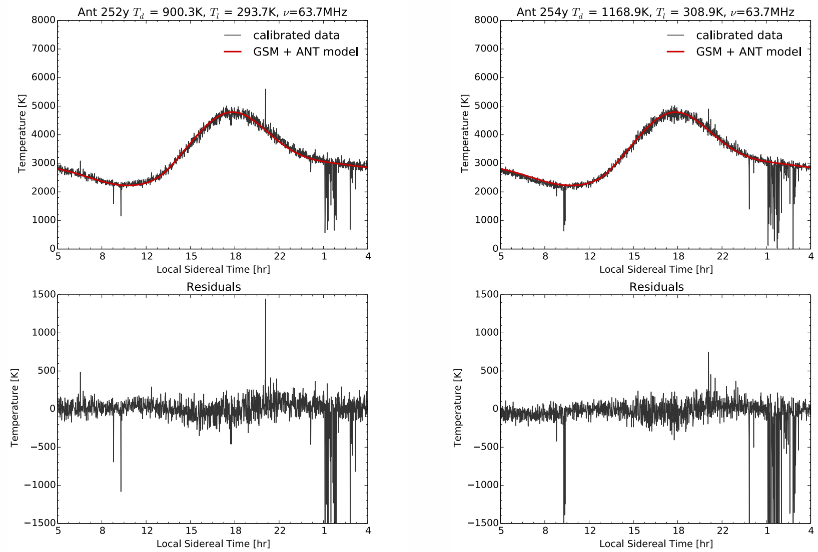
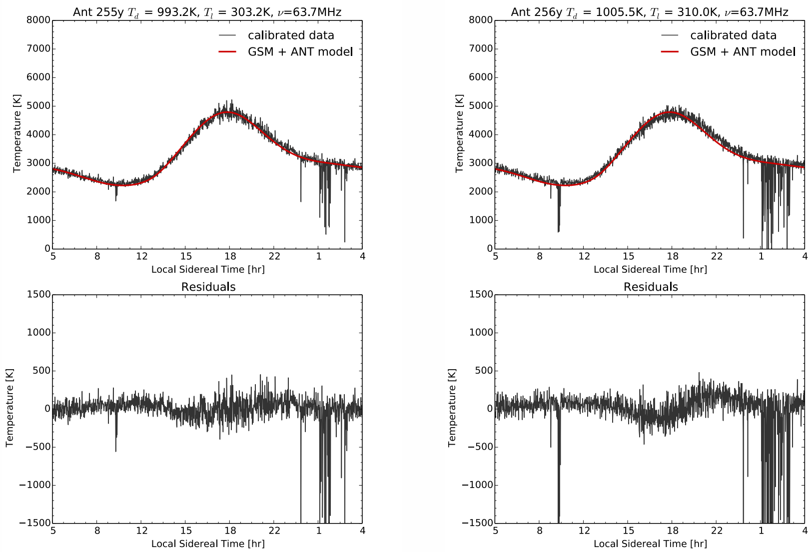
LEDA - Outrigger antennas



Calibrated only with static TA and static TD!

LEDA - Outrigger antennas



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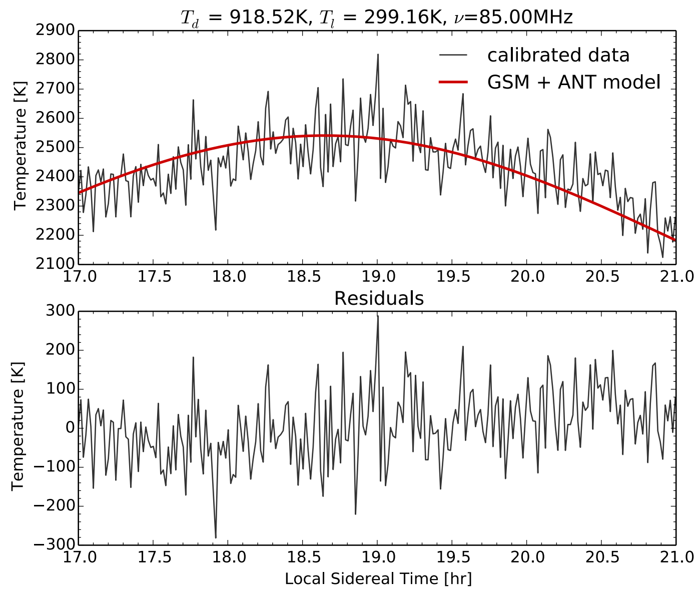

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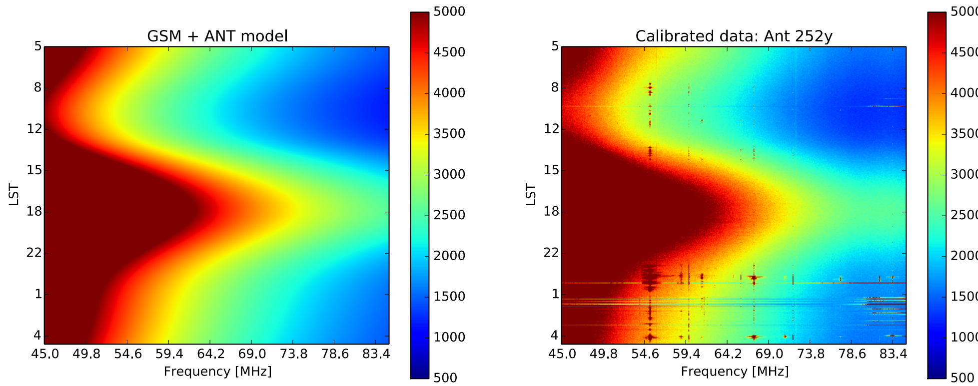

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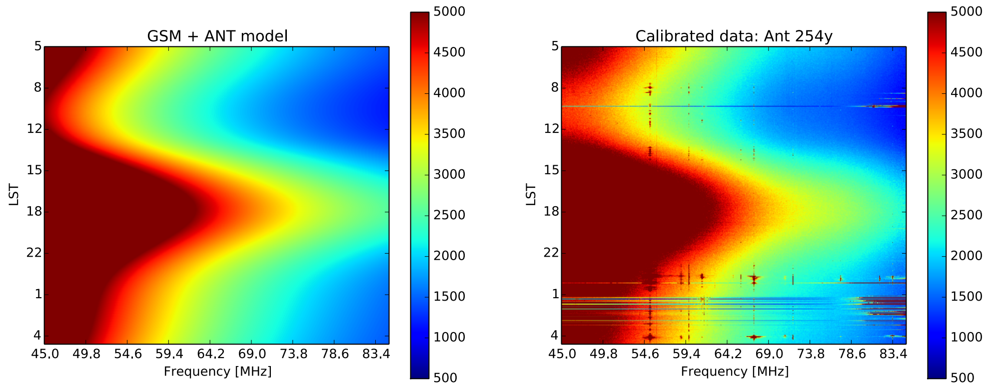
LEDA - Outrigger antennas



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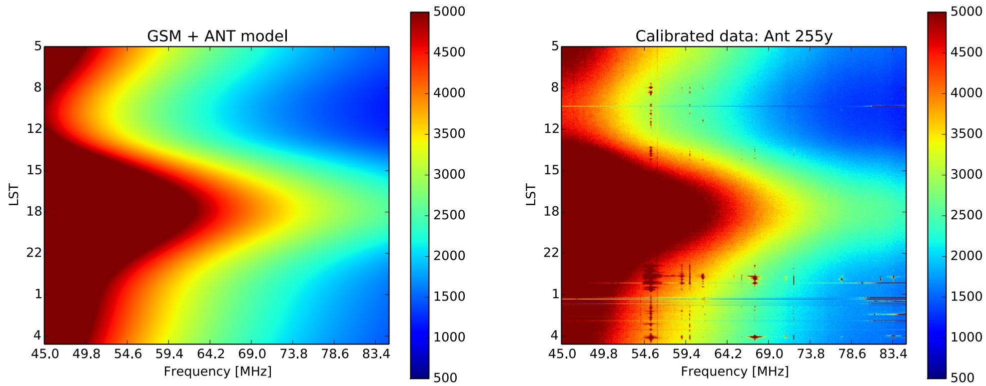

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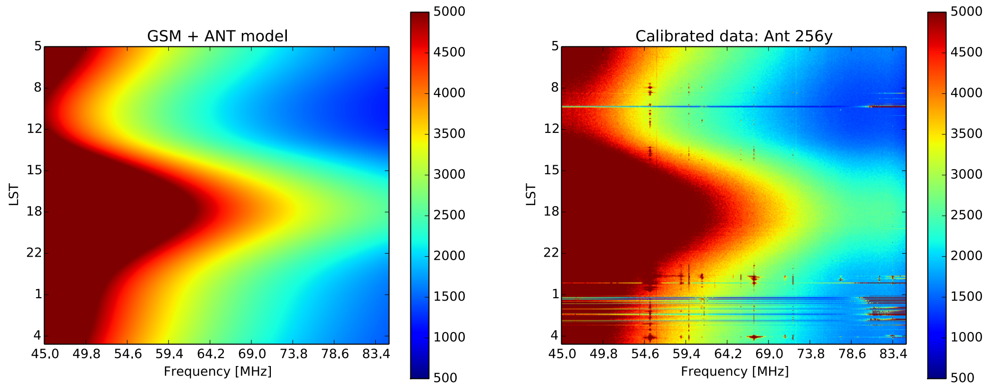

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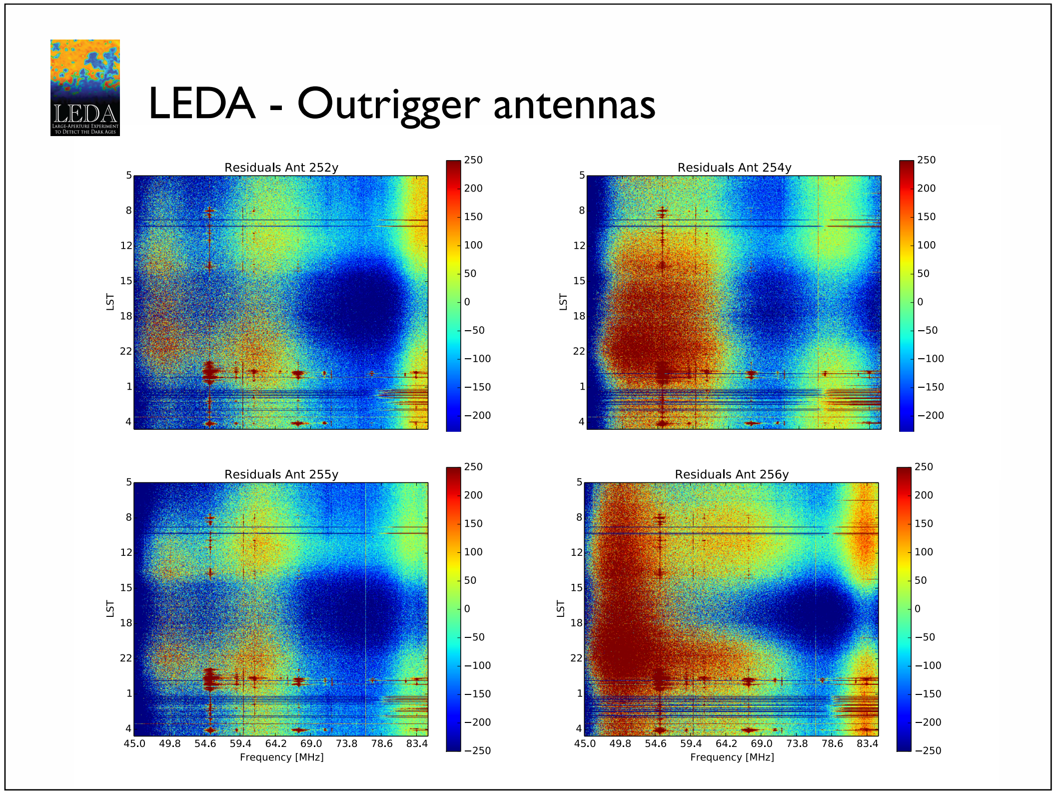

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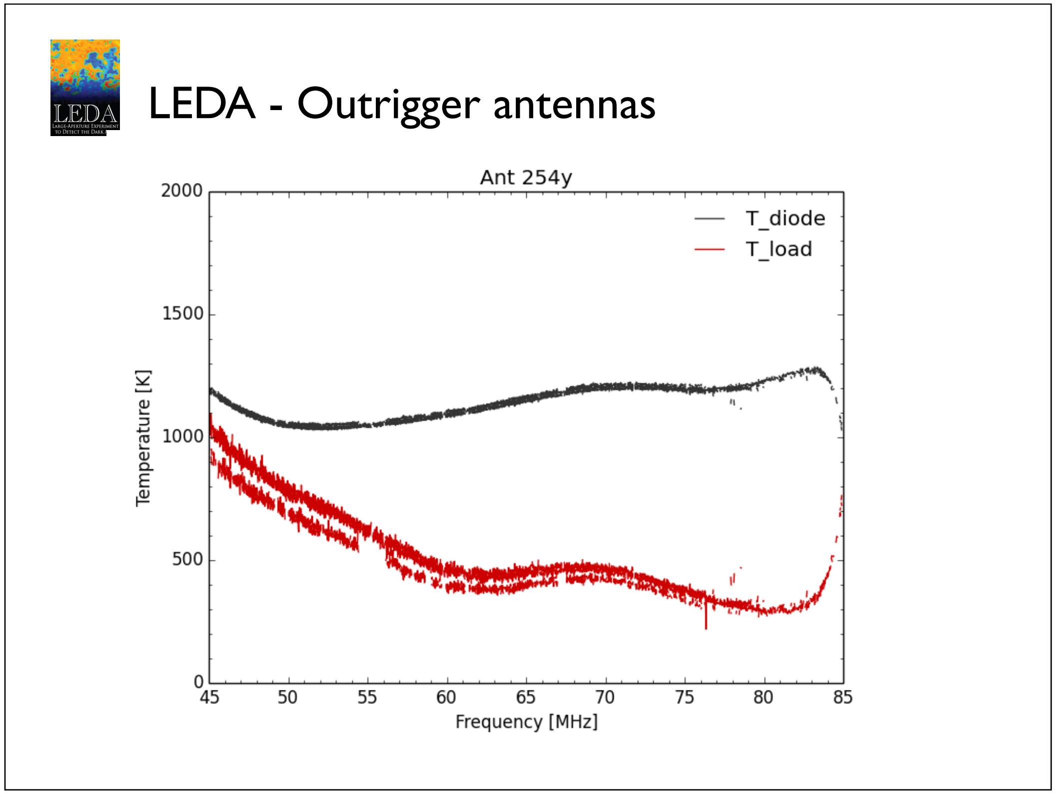

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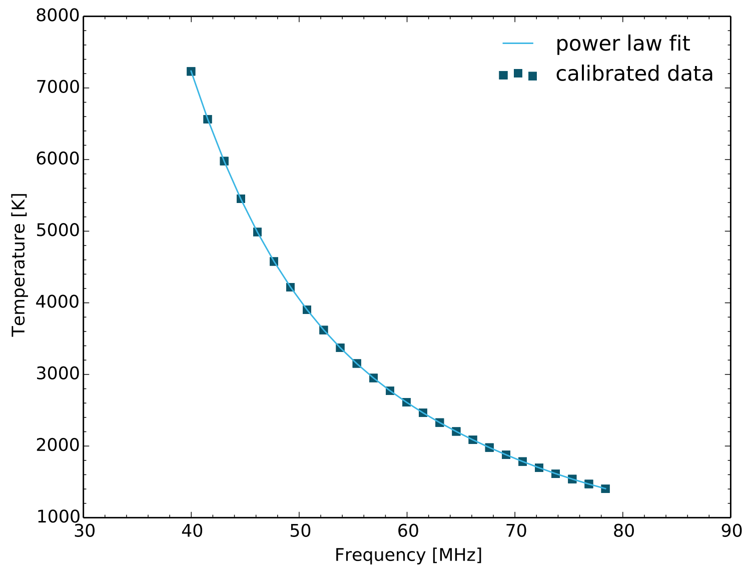
LEDA - Calibrated Spectrum



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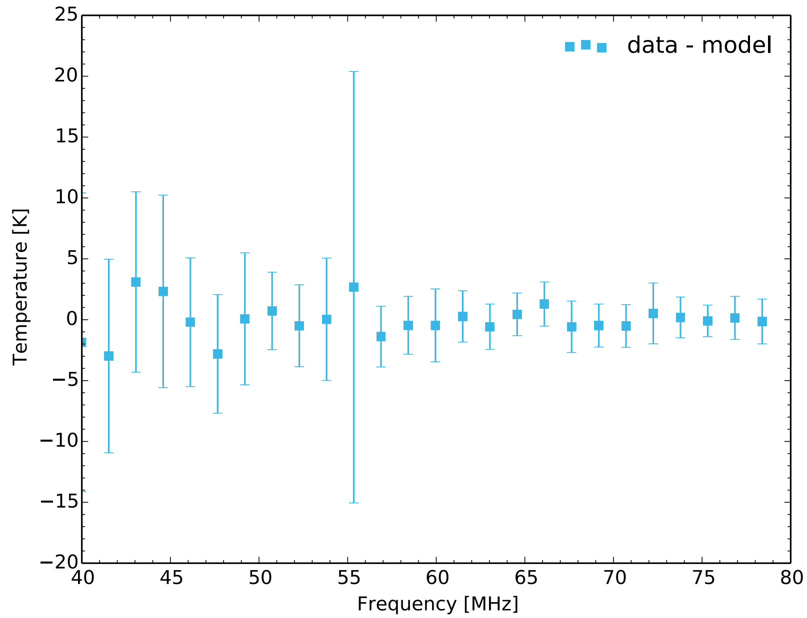
LEDA - Calibrated Residuals



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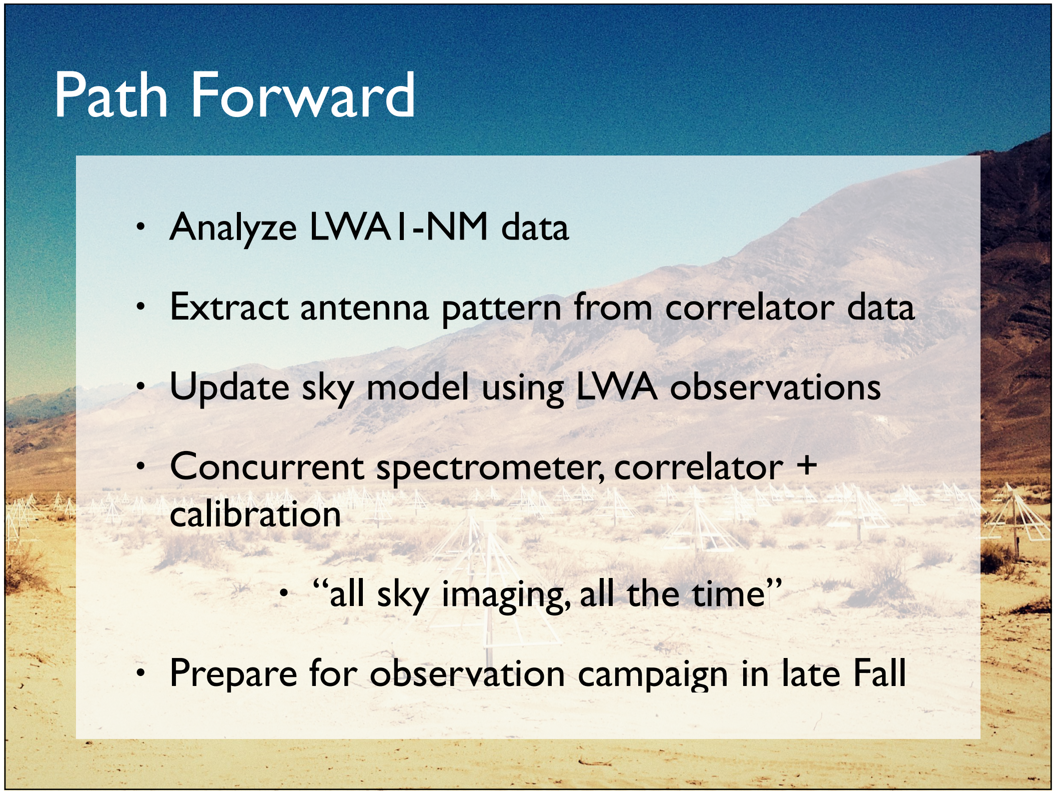


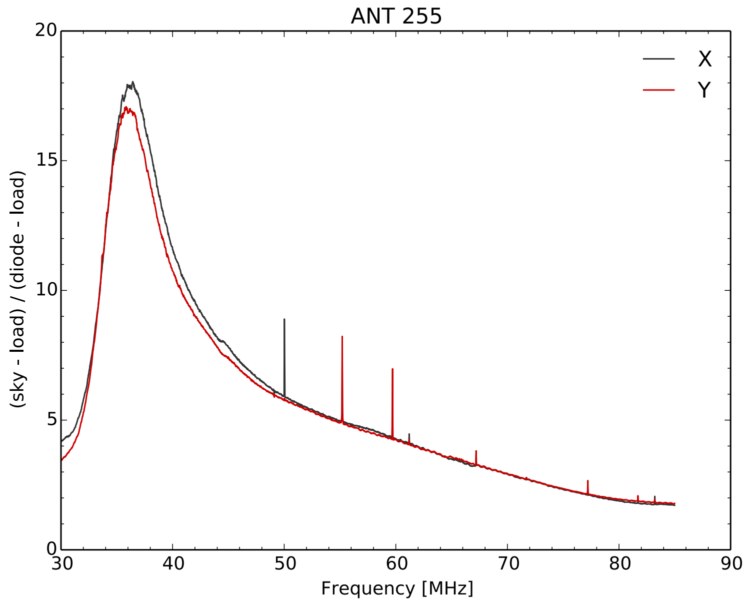
Finally, to recap: LEDA is a total power experiment that uses the LWA array. We have built new GPU-based correlators in New Mexico and Owens Valley, and have outrigger antennas with three-state switching for calibration. There is a science talk on Friday which will discuss our plans in more detail.

Thank you all for listening!

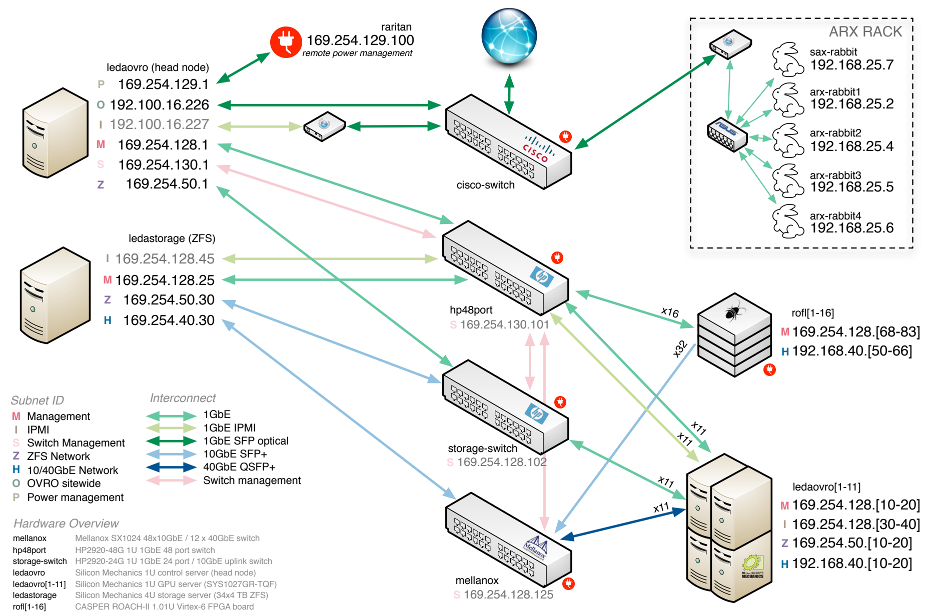
Finally, to recap: LEDA is a total power experiment that uses the LWA array. We have built new GPU-based correlators in New Mexico and Owens Valley, and have outrigger antennas with three-state switching for calibration. There is a science talk on Friday which will discuss our plans in more detail.

Thank you all for listening!

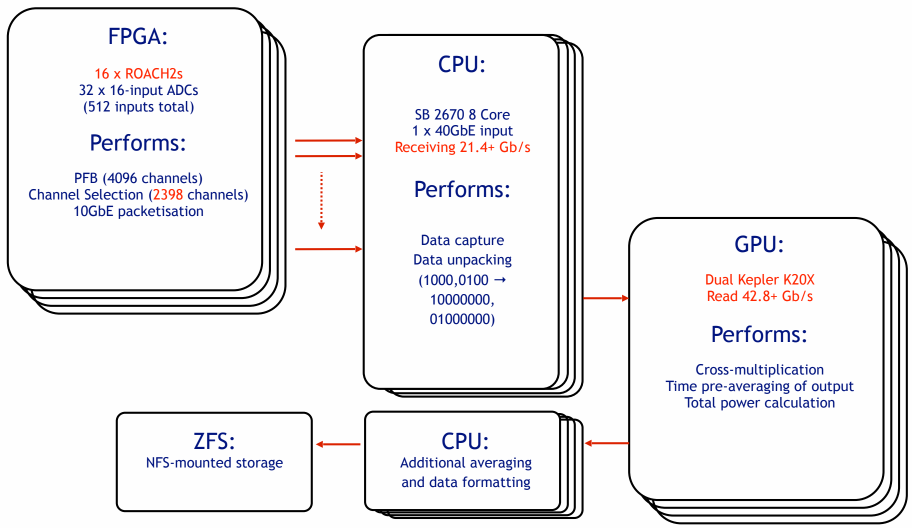
LWA1 - Switched Outrigger



LEDA-OVRO Networking Diagram



LEDA-512 Correlator



ROACH

FPGA:

2 x ROACH2
4 x 16-input ADCs
(64 inputs total)

Performs:

PFB (4096 channels)
Channel Selection (2398 channels)
10GbE packetisation

- Standard F-engine
- ADC Capture
- 4-tap PFB
- Equalization coefficients applied
- Output of PFB (18 + 18 bits) reduced to 4 + 4 bits.
- User selects 2398 channels blocks, to go to different 40GbE connections.

Channels packed in channels order, followed by antenna order

Switch

Mellanox SX1024:

48x SFP+

12x QSFP

- 32x ROACH2 SFP+
  - 7.36Gb/s
- 11x Server QSFP
  - 2x10.71Gb/s

•235.62 Gb/s input

•Flow control required

PSRDADA

Receiving:
- Create a series of data buffers
- Capture to RAM
- 21.4 Gb/s required

Achieved:
- Input capture up to 9.9Gb/s per 10GbE
- 30Gb/s+ using 40GbE (full pipeline).
- 40Gb/s (capture only).

CPU:

2 x 8 core
1 x 40GbE inputs
Receiving 21.42 Gb/s

Performs:

Data capture
Data unpacking
(1000,0100 → 10000000, 01000000)

CPU:

Additional averaging
Writes data to disk

Processing:
- Unpacker:
  - Calculation
  - Lookup table
- Write to different output buffer

Input from GPU, write to disk efficiently

http://psrdada.sourceforge.net

GPU X-Engine

Processing:

- Read in input through texture memory
- Perform correlation using memory tiling to gain maximum performance
- Results accumulate in registers before write
- Effective data reuse leading to high arithmetic intensity

Output to memory buffer.
[Integrated with PSRDADA]

GPU:

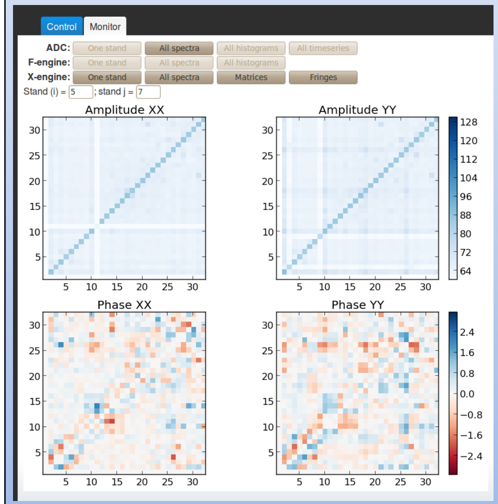
Dual Kepler K20X
Read 42.8+Gb/s

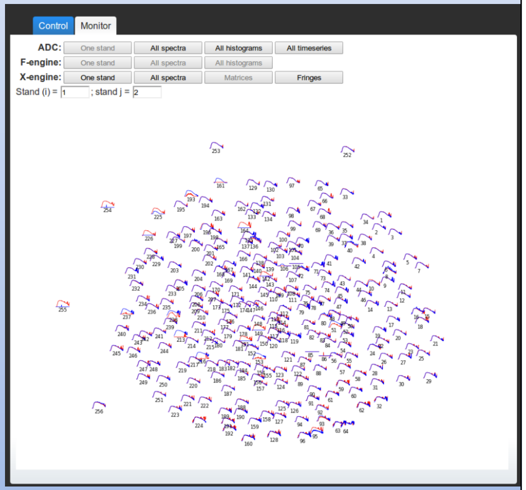
Performs:

Cross-multiplication
Time pre-averaging of output
Total Power Calculation

Clark, La Plante, Greenhill, JHPC
https://github.com/GPU-correlators/xGPU

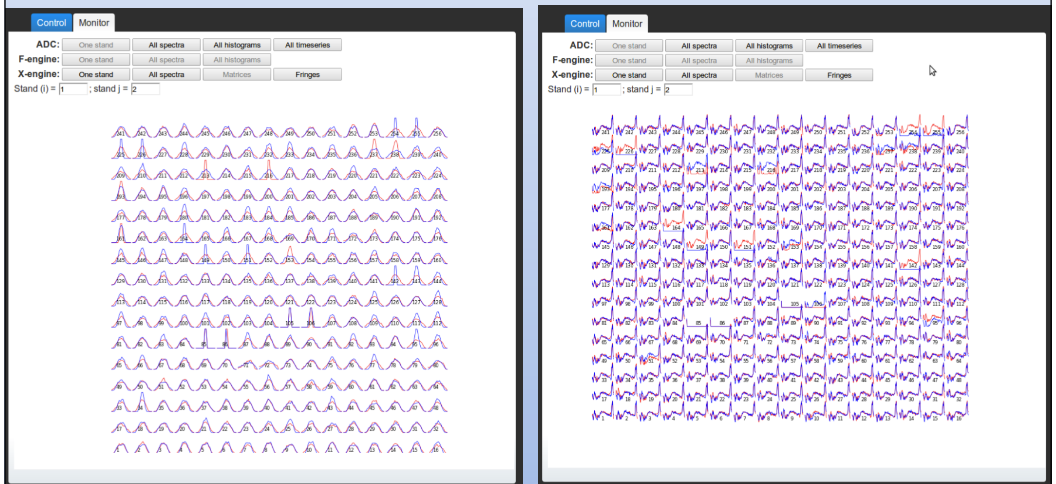
Control & Visualization





(Barsdell)

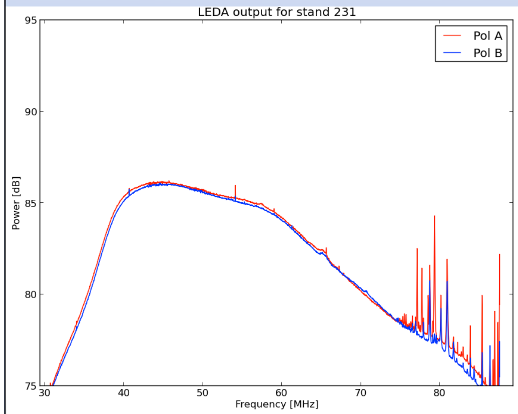
Control & Visualization

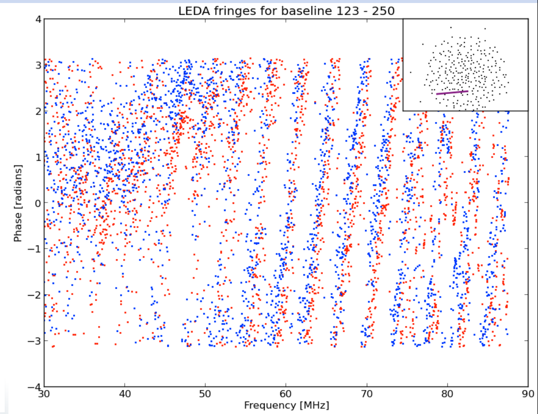


(Barsdell)

Can be operated by a mobile!

Control and Visualisation





(Barsdell)

While we have fringes. What I do have, is some realtime non-integrated plots.