# Allen Telescope Array

Not F***ing Around

# Colby Gutierrez-Kraybill

Joined UC Berkeley Radio Astronomy Lab as a staff software engineer and systems analyst in June 2001 and worked for the RAL until 2011, and then SRI International on the ATA until 2012.

Started undergraduate astrophysics studies in 1989, left before completion and worked at SGI and various startups before joining UC Berkeley.

Returned to undergraduate studies in 2012 at University of New Mexico, Albuquerque.

Joined MIT Media Lab staff as “Complex Web” Systems Admin for LLK/NeCSys, primarily focused on https://scratch.mit.edu

Will complete dual Computer Science and Mathematics undergraduate degrees end of this year …
Profit!

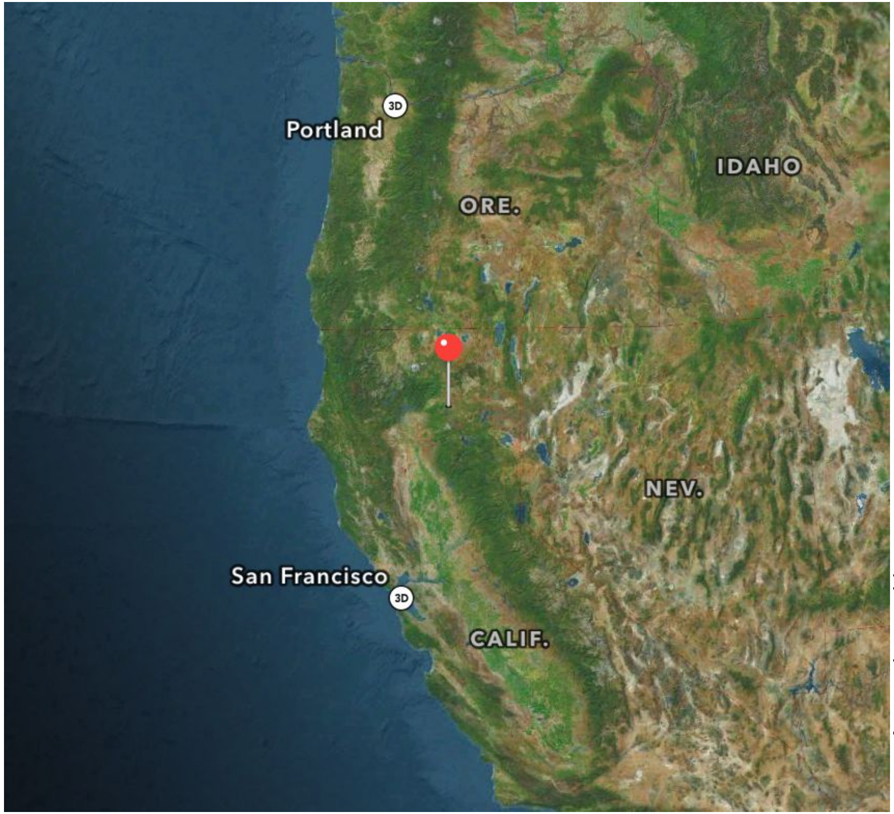
# Hat Creek Radio Observatory

Founded in 1958 by the Radio Astronomy Lab an Organized Research Unit of the UC Berkeley Astronomy Department

1958-1970 33-Foot and 85-Foot dishes first constructed and operated, many other antennas and amplifier designs.

1968 - Welch and Townes find ammonia in Sag B2 and soon after water and hydrogen cyanide

1970-1990 - first mm-wave interferometer constructed




Apple maps, May 2016

# BIMA

Berkeley-Illinois-Maryland-Assoc MM-Wave Array

Operated from 1992-2004

9 antennas, 6m diameter

~72GHz - 115GHz, ~3-mm

~275GHz - 350GHz, ~1-mm

Receivers cooled to 2-3K

Moved to Owens Valley in 2004

*Gutierrez-Kraybill, June 2004*

# ATA Stats

42 Antennas

6m diameter

1-15GHz operating range

4 bands, 100MHz wide each

Dual polarization

FOV ~2.45 degrees diameter at 1.420 GHz, ~1 degree diameter at 5GHz

Total collecting area: 1227$m^2$, 736$m^2$ eff

Can track LEOs through zenith

1000 meters elevation

*SETI Inst, 2008*

# Antenna Design

Offset Gregorian

6.1 x 7.0 meter primary, 1/40th RMS of target wavelength. Hydroformed!

2.4 meter secondary

Construction cost is ~$95,000 without receivers and electronics. With receivers and electronics, ~$250,000 (adj 2016)

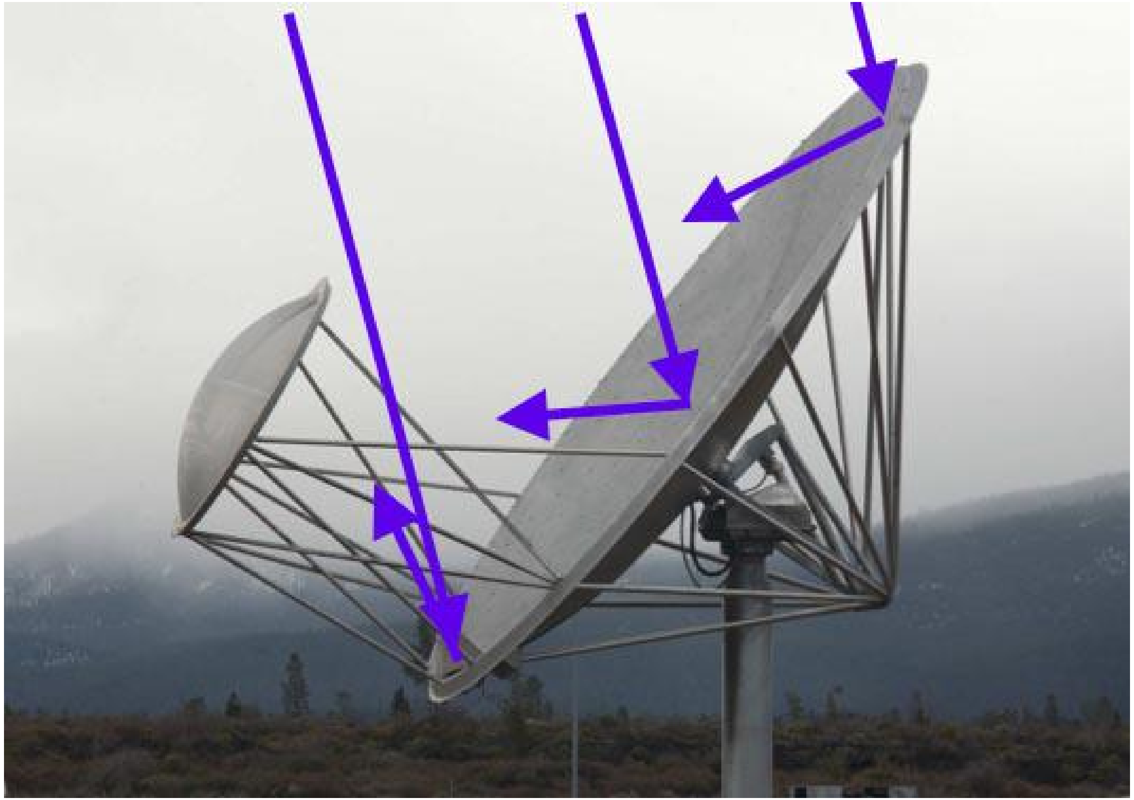
VLA Antenna: ~$8.12 mil (adj 2016)

ALMA Antenna: ~$14.70 mil (adj 2016)

*Gutierrez-Kraybill, June 2005*

# Antenna Design

Signal path



*Gutierrez-Kraybill, June 2005*

# Antenna Design

Focal point

Alt-Az tracking vs Equatorial

Pointing accuracy of ~30arc sec rms design

In practice, ~1-5arc sec tracking

*Gutierrez-Kraybill, June 2005*

# Antenna Design

Sand blasted surface to avoid blinding flying aircraft and local micro and mega-fauna.

42 Antennas installed by 2007 with receivers.

*Gutierrez-Kraybill, June 2006*

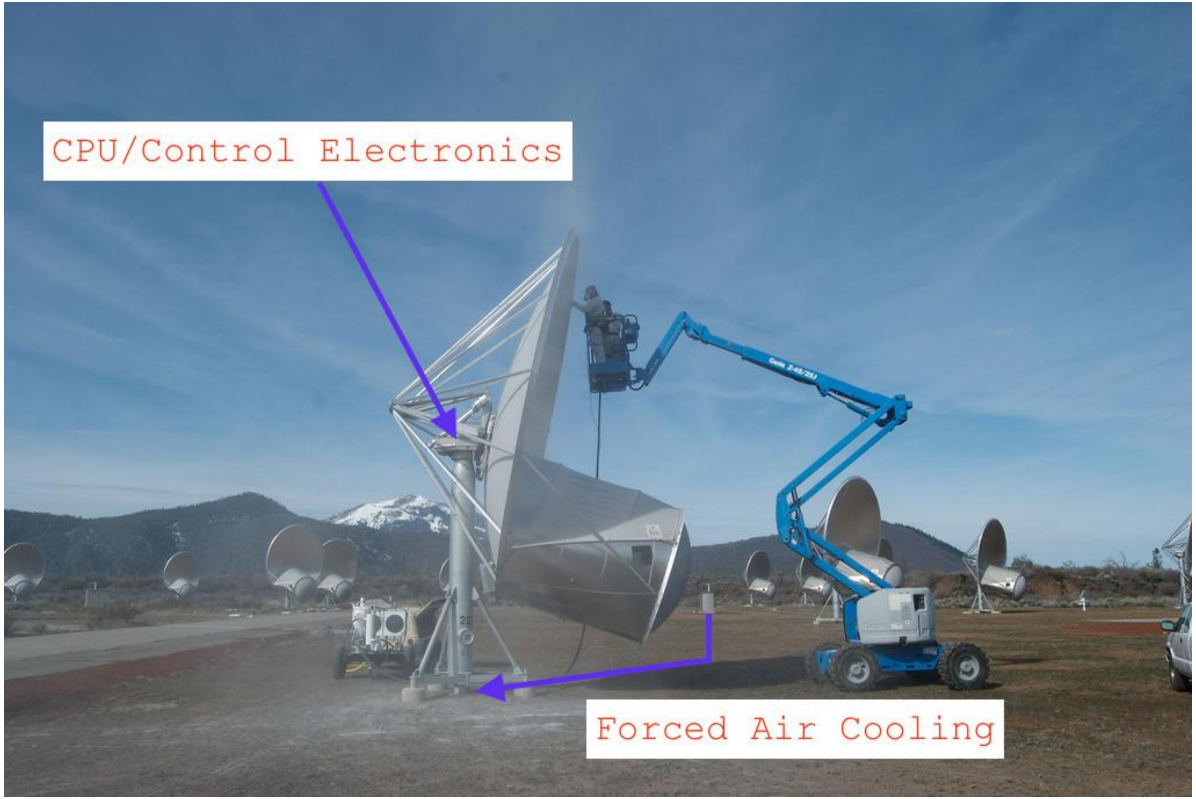
# Antenna Design

The control electronics are cooled via air that is forced into bottom of the primary support from underground ducts and fed by outlying support sheds.

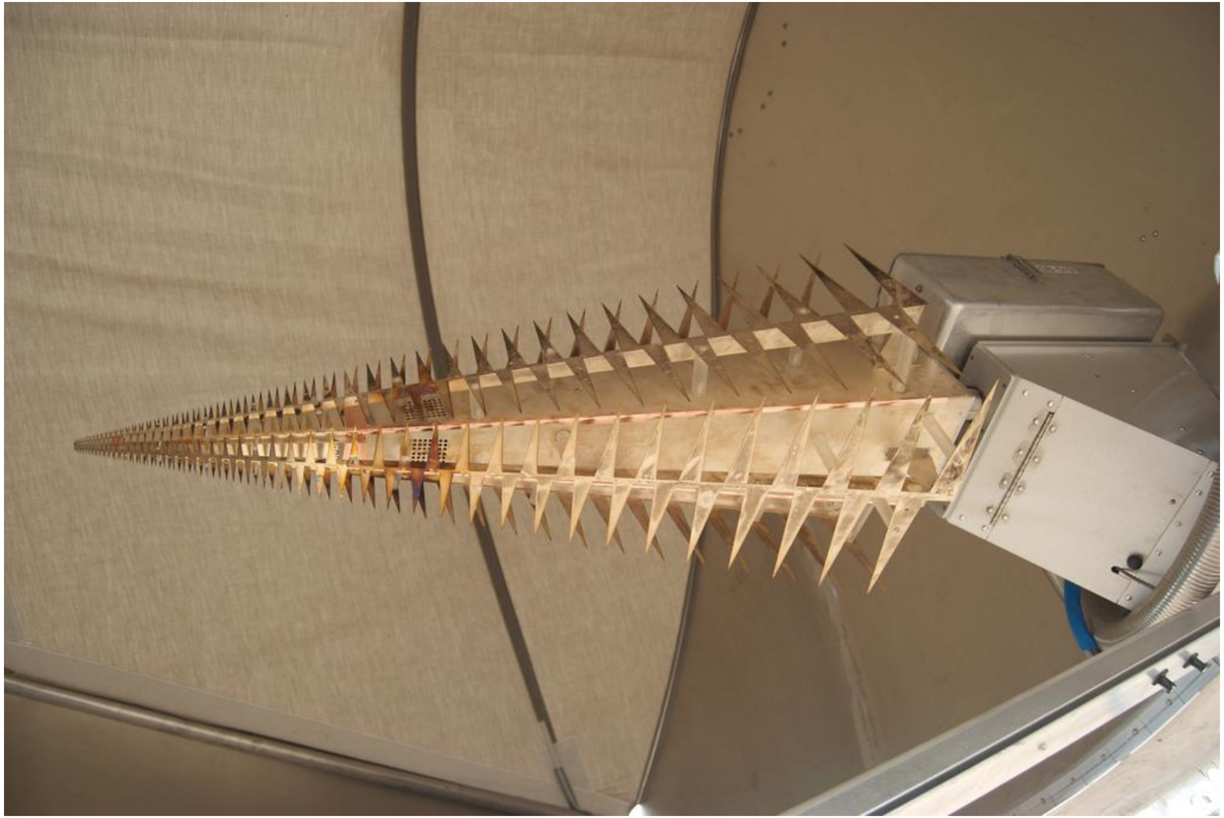
An small form factor computer is in a small and weather proof compartment on the back of the primary dish.

These computers are 1GHz Geode NX, 512MB RAM, 1GB flash

Running Java 6 JVM and control software on a custom build openSUSE. Hybrid servo loop with Kalman trajectories.




*Gutierrez-Kraybill, June 2006*

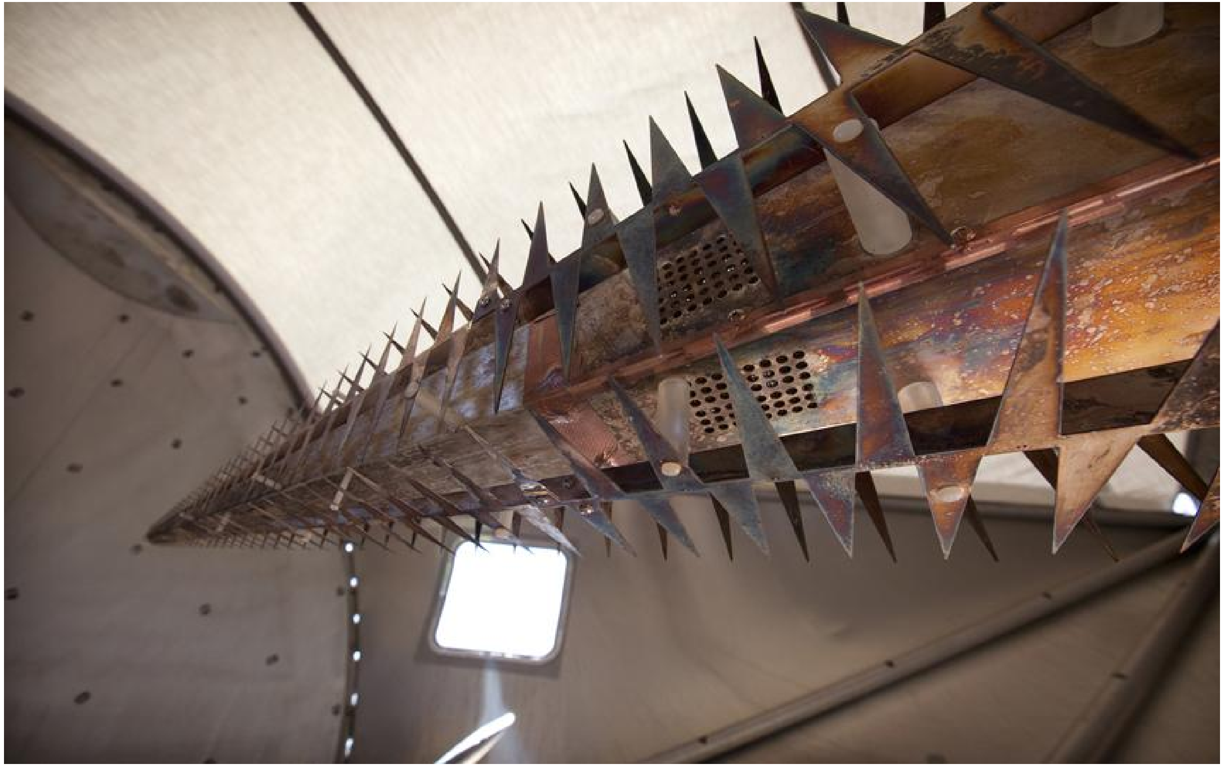

Gutierrez-Kraybill, Oct 2007

# Feed Design

Original receiver is a Log Periodic design

~500MHz - ~11GHz

Multi-stage amplifiers with attenuators designed to allow for strong signal decimation from satellites/solar



*Charles Lindsey, June 2009*

# Feed Design

Receiver is a Log Periodic design

Tip of receiver has a small circuit board that inputs signals into the inner module, which is a vacuum dewar, with the primary amplifier cooled to ~77K

Designed to hold vacuum and cooling for a decade. In practice, ~2-3 years so far.

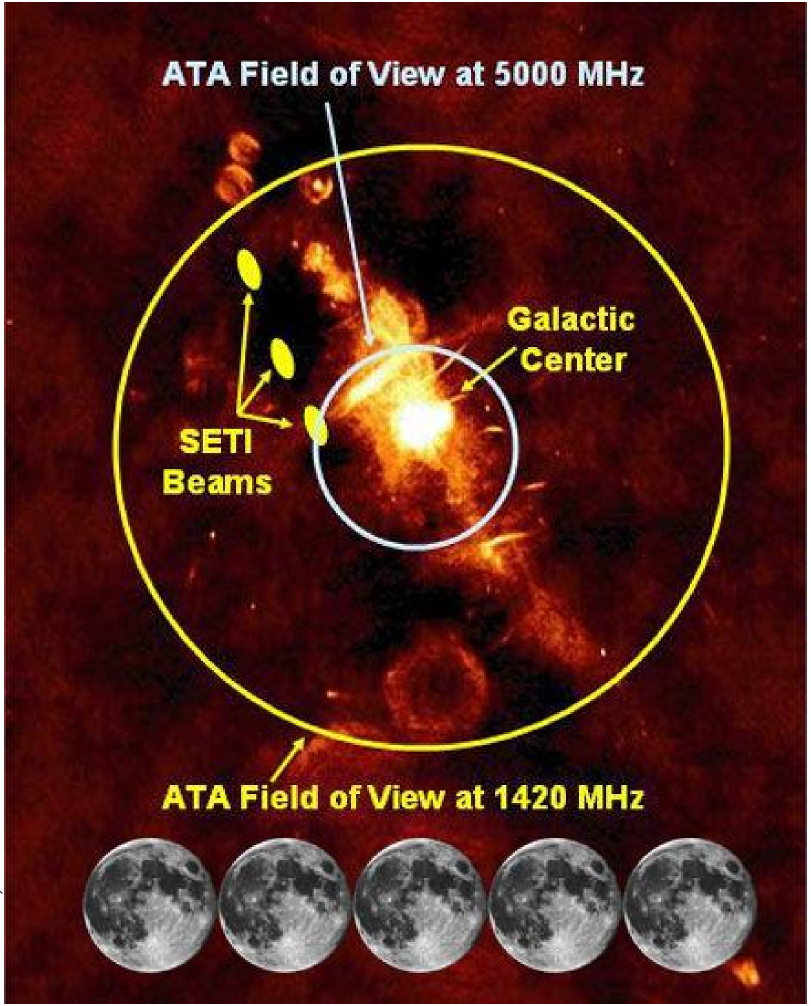
*NRAO, 2013*

# Feed Design

A single feed for 0.5-11GHz unheard of before.

Prevailing designs required multiple feed horns and receivers to cover different octaves

VLA example




D. Deboer, 2003

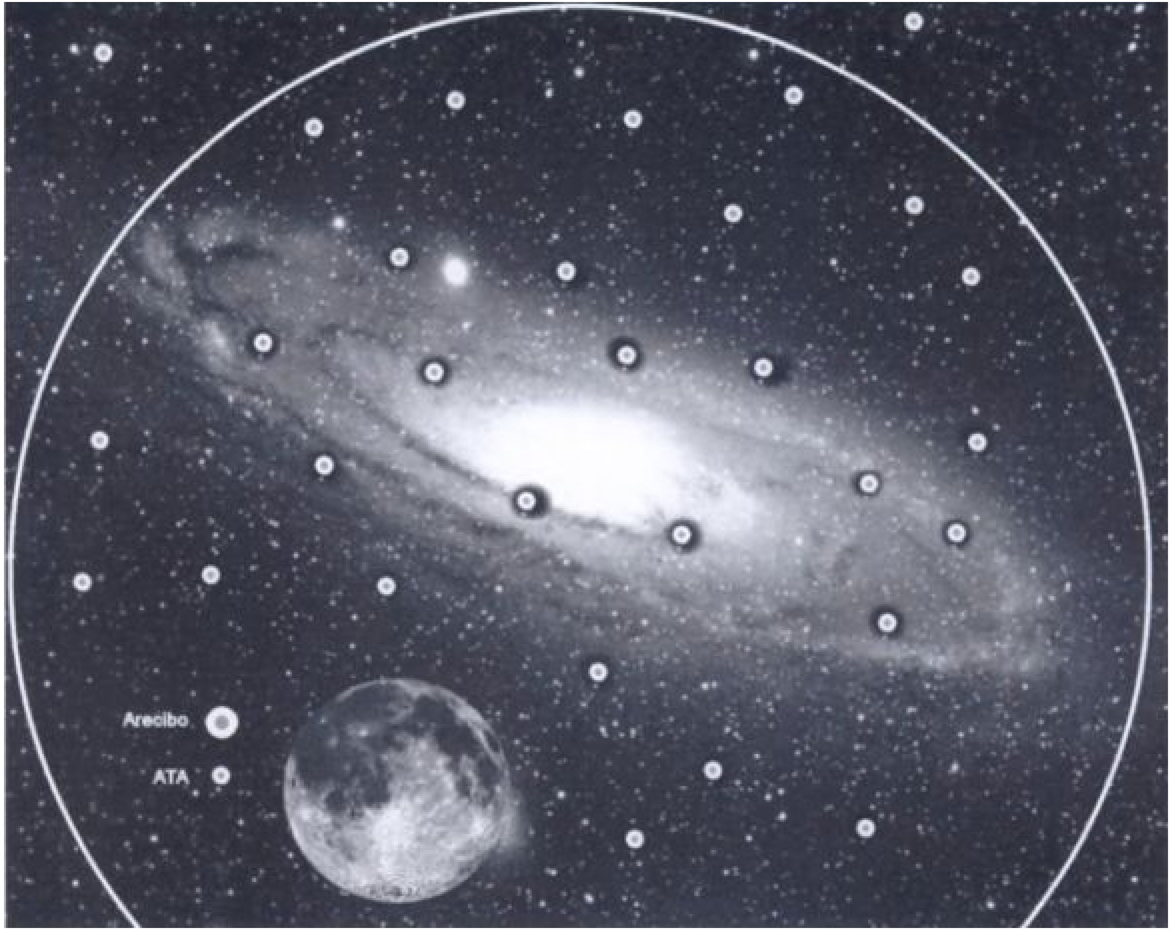
# View of the Sky - ATA

$$FOV \approx \frac{\lambda}{D}$$

1420MHz - Hydrogen line at 21cm

Moon is ~0.5 degrees across

ATA can form individual beams for SETI work



*D. Deboer, June 2003*

# View of the Sky

ATA compared to the Arecibo dish

Large circle is overall FOV at 1420MHz

Individual dots are beam former sizes for SETI work.

(not our galaxy)

D. Deboer, June 2003

# Planned Layout

Intended to be comprised of 350 antennas with a maximum baseline length of 2km

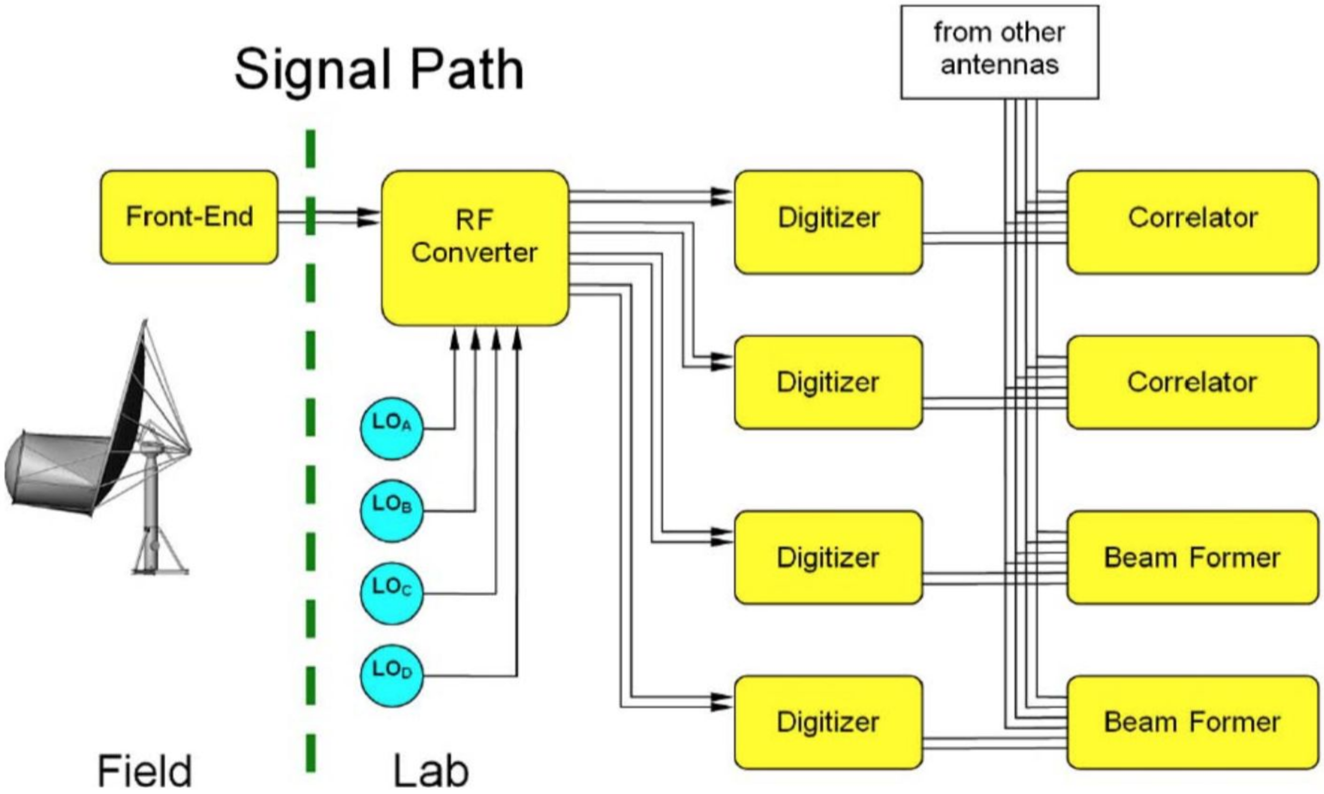
If built out, designed to detect an Arecibo sized radar (1MW) from 1,000 light years away.

*Apple Maps, May 2016*

# Actual Layout

42 Antennas operating

Limited by collecting area and 4 channel bandwidth sampling sizes of 100MHz across, dual polarization.



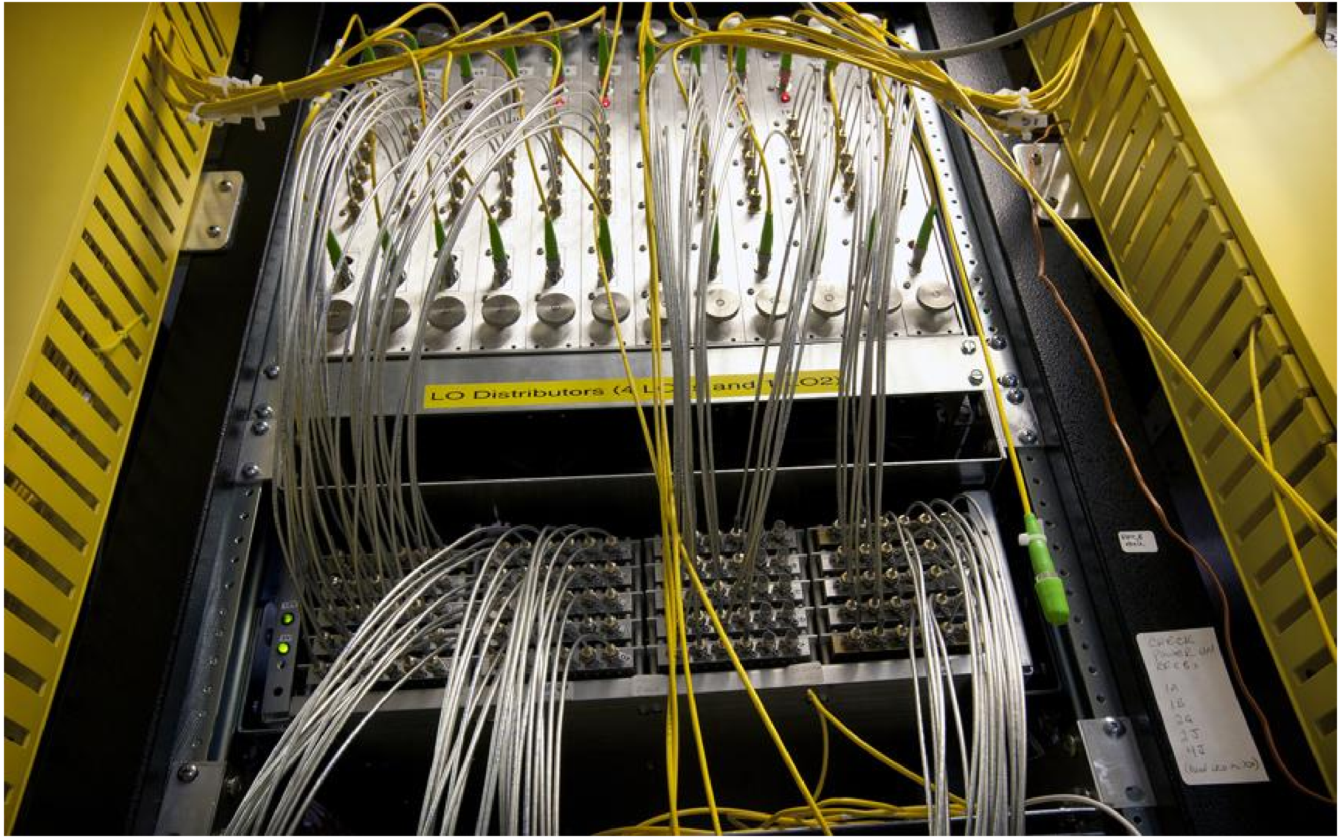

Entire feed signal is put onto analog optical fiber into control building.

Local Oscillators A,B,C,D provide for 4 window bands.

Digitized in control building.

Can be distributed to many processors for beam forming, imaging or other experiments

*Welch, Et al, IEEE 2009*



*Gutierrez-Kraybill, Oct 2007*

# Optical to coax

Single-mode fiber

Selection of 100MHz bands across the 1-11GHz into coax cabling


*Gutierrez-Kraybill, Oct 2007*

# Digitizers

Boards on the bottom digitize signals from the antennas and send this data over 10Gbps links to other backend systems for further processing. Including an FX correlator, beamformers and a direct to disk beowulf processing cluster.

$$f(t) \star g(t) = \int \hat{f}(\omega)\hat{g}(\omega)e^{i\omega t}d\omega$$

$$f(t) \star f(t-\tau) = \frac{1}{2\pi}\int |f|^2 e^{i\omega(t-\tau)}d\omega$$

$$\mathcal{C}_{ij}(v) = \mathcal{F}(f_i \star f_j)$$

$$\mathcal{C}_{ij}(v) = \mathcal{F}(f_i) \cdot \mathcal{F}(f_j)$$

# Radio Imaging

With radio interferometers, imaging is done via taking individual samplings of the interference patterns between pairings of antenna signals. These can be projected onto the *uv*-plane or frequency/fourier space.

Starting with the correlation theorem, it can be shown that one can determine the power of a signal for different delays of time shifting between individual signals.

*Arron Parsons*

$$f(t) \star g(t) = \int \hat{f}(\omega)\hat{g}(\omega)e^{i\omega t}d\omega$$

$$f(t) \star f(t-\tau) = \frac{1}{2\pi}\int |f|^2 e^{i\omega(t-\tau)}d\omega$$

$$\mathcal{C}_{ij}(v) = \mathcal{F}(f_i \star f_j)$$

$$\mathcal{C}_{ij}(v) = \mathcal{F}(f_i) \cdot \mathcal{F}(f_j)$$

*Arron Parsons*

# Radio Imaging

The last equation is used with FX correlation, or, by taking the fourier transform of the signal (F) and then cross-multiplying (X), with one signal from each pairing of antennas (or each polarization) being conjugated.

One of the benefits of imaging this way is that the functions to analyze these signals will reduce noise in the correlated signals by $t^{-1/2}$ as the signal is integrated up. Therefore, signals that are nearby the array are uncorrelated given their time-lags differ from the expected lag from the sky.

$$XF \approx N^2$$

$$FX \approx \frac{N(N+1)}{2}$$

$$\text{Still! } O(N^2)$$

# Radio Imaging

Radio astronomers tend to want a frequency domain result, which lead to the development of XF correlators. This works okay for small numbers of antennas, but the number of transforms required is on the order of $N^2$. And at each cross-product all frequency data must be available.

In the FX architecture, the frequency work is done upfront, and the cross-product need only be against the frequency per pairing, very parallelizable. Still a lot of data and operations.

# Radio Imaging

$$ops_{total} \approx 2B(Nlog_2(F)(10ops) + \frac{N(N+1)}{2}(4)(8ops))$$

$$N = 42 \text{ Antennas}$$
$$B = 100,000,000\text{Hz} \quad F = 1024 \text{ Channels}$$
$$\approx 6.6192 \text{ Top/s}$$

$$N = 350 \text{ Antennas}$$
$$B = 500,000,000\text{Hz} \quad F = 2048 \text{ Channels}$$
$$\approx 2.008 \text{ Peta-op/s}$$

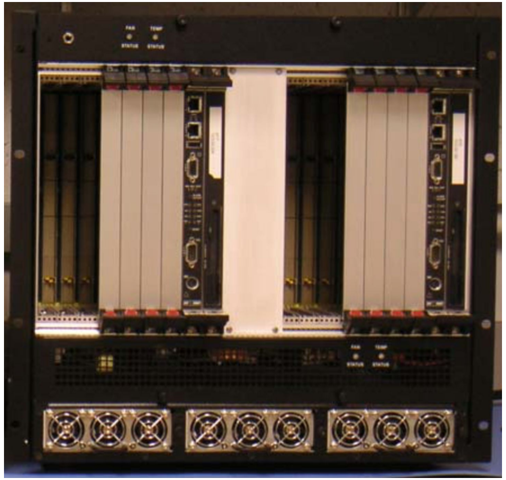
For the ATA FX correlator with 42 antennas (x2 counting dual polarizations), the number of operations per second can be estimated in the following way.

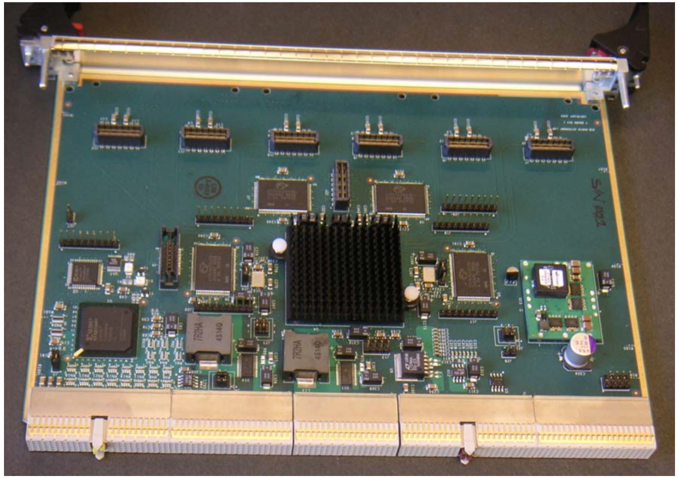
Today one GTX 1080, ~9 Tflops single-precision, PCIe 3.0 x16 ~15GBytes/s data flow.

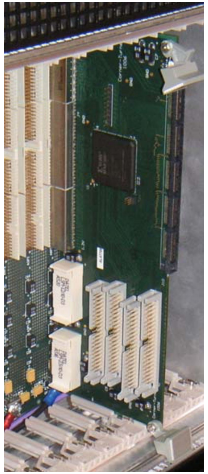
Data input:
~20 GBytes/s for 42 antennas,
~220 GBytes/s for 350 antennas

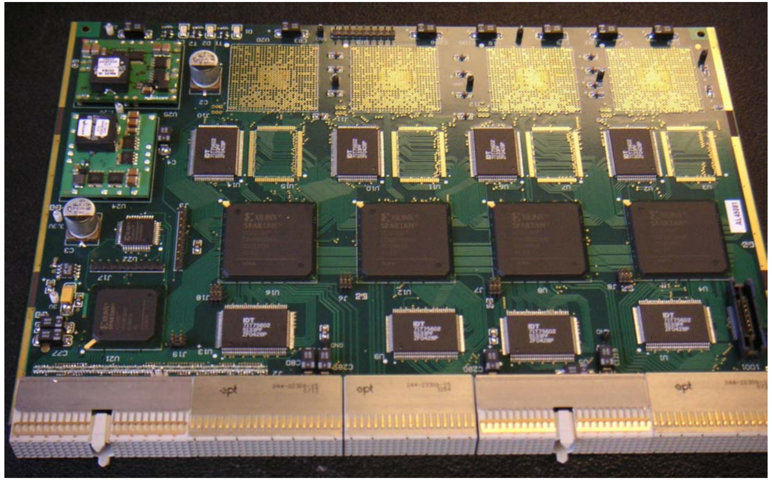
Data output is

ATA-42 depending on integration times: ~350KBps, ~30GB/day.
ATA-350: ~23MBps, ~2TB/day







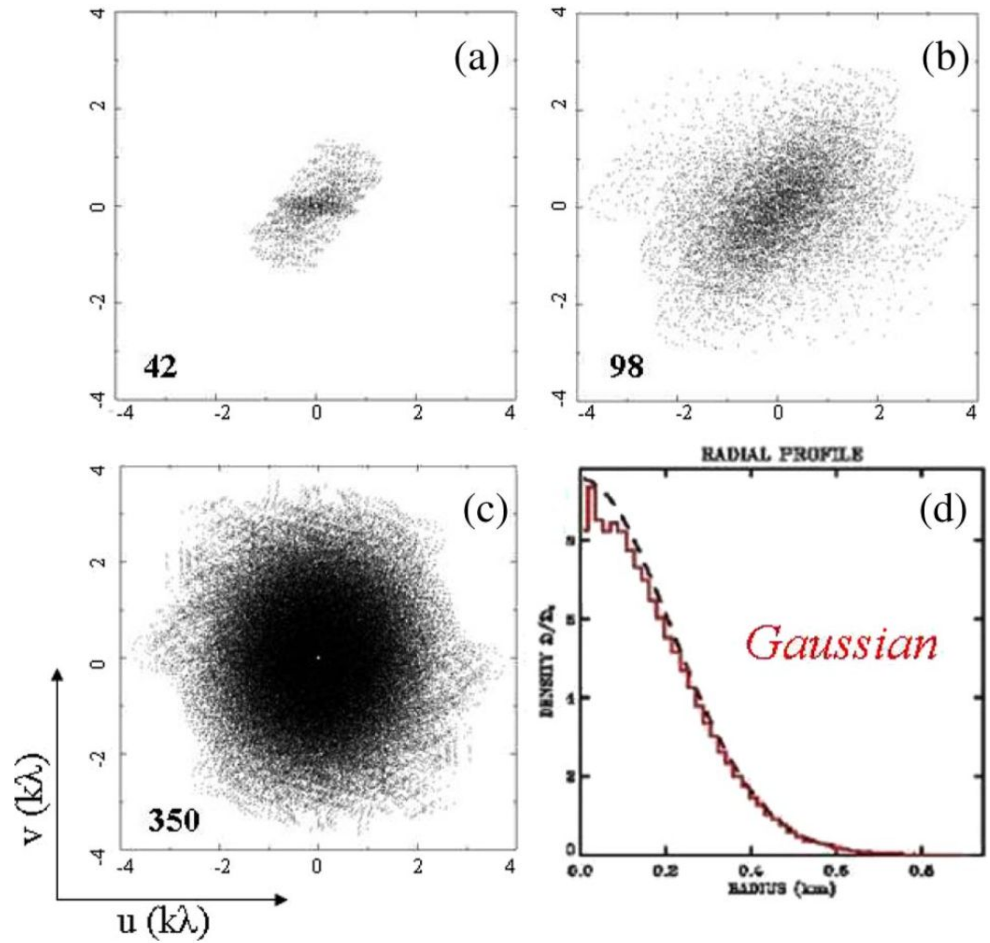


# Radio Imaging

ATA-42 FX correlator utilized compactPCI crates, computers and custom designed boards with Xilinx FPGAs for the F part and X parts, as well as a specialized “corner-turner” that reordered signals in an innovative way.

For those so inclined: XC2VP50-6FF1152C and Spartan III 5000 series Xilinx Chips.

90nm, 5mil gates, run at 100MHz, donated




# Radio Imaging

Back to the *uv*-plane and sampling

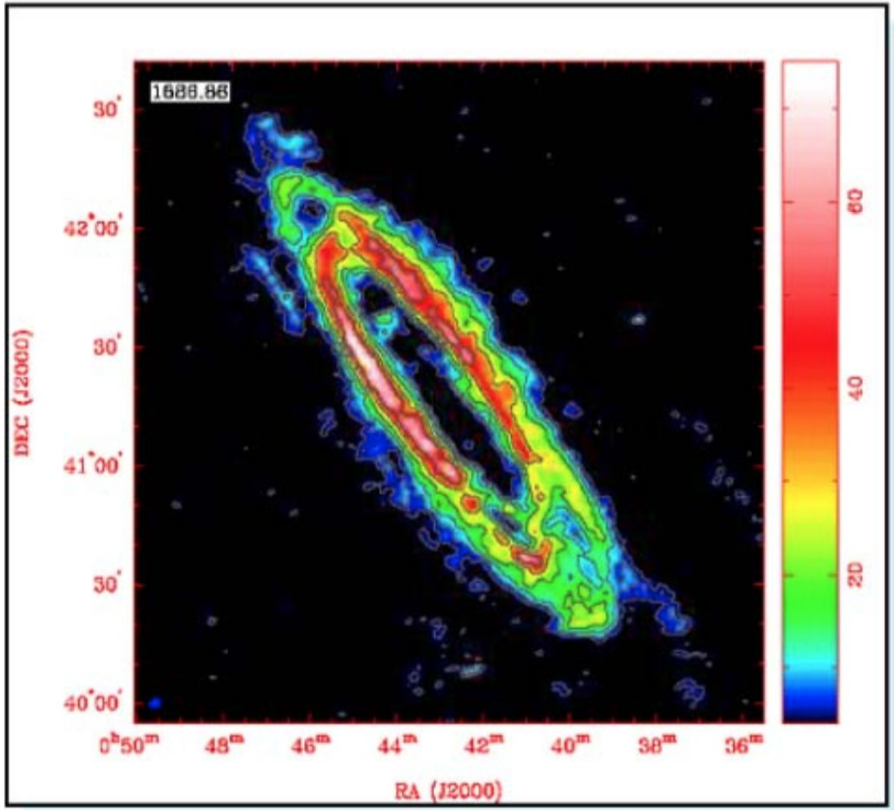
In figure (a), 42 antennas, when paired create these samplings of the *uv*-plane, (b) 98, and (c) 350.

Figure (d) shows the distribution of baseline lengths for pairings of antennas.

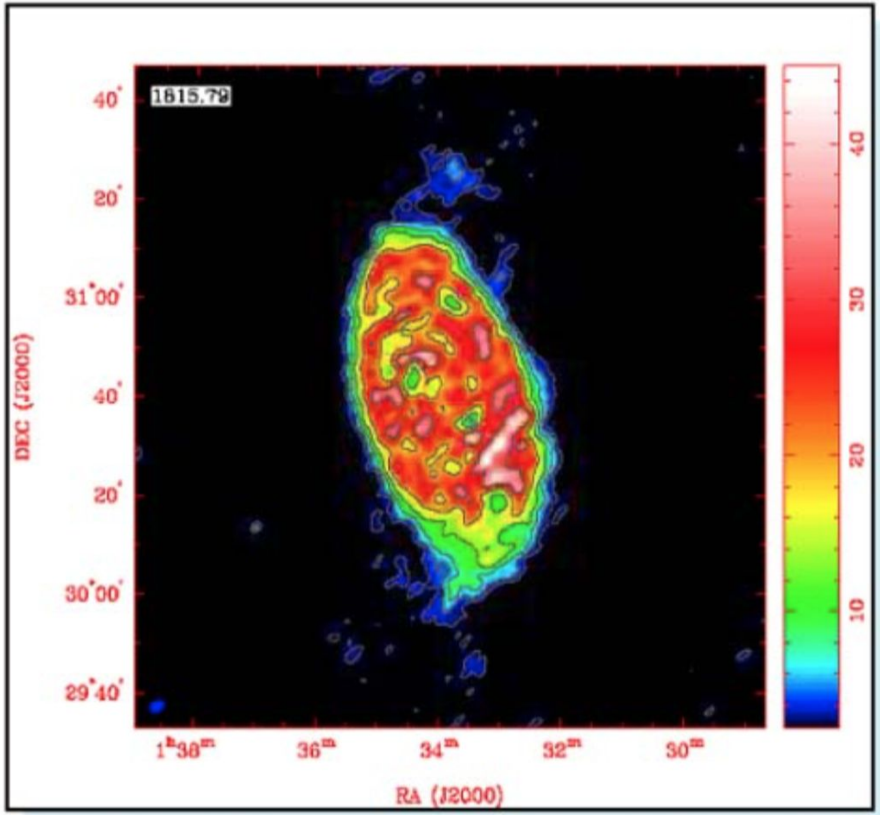
To fill out samplings of the *uv*-plane requires more dwell time for the 42 antennas, while the 350 antennas would make imaging nearly instantaneous.

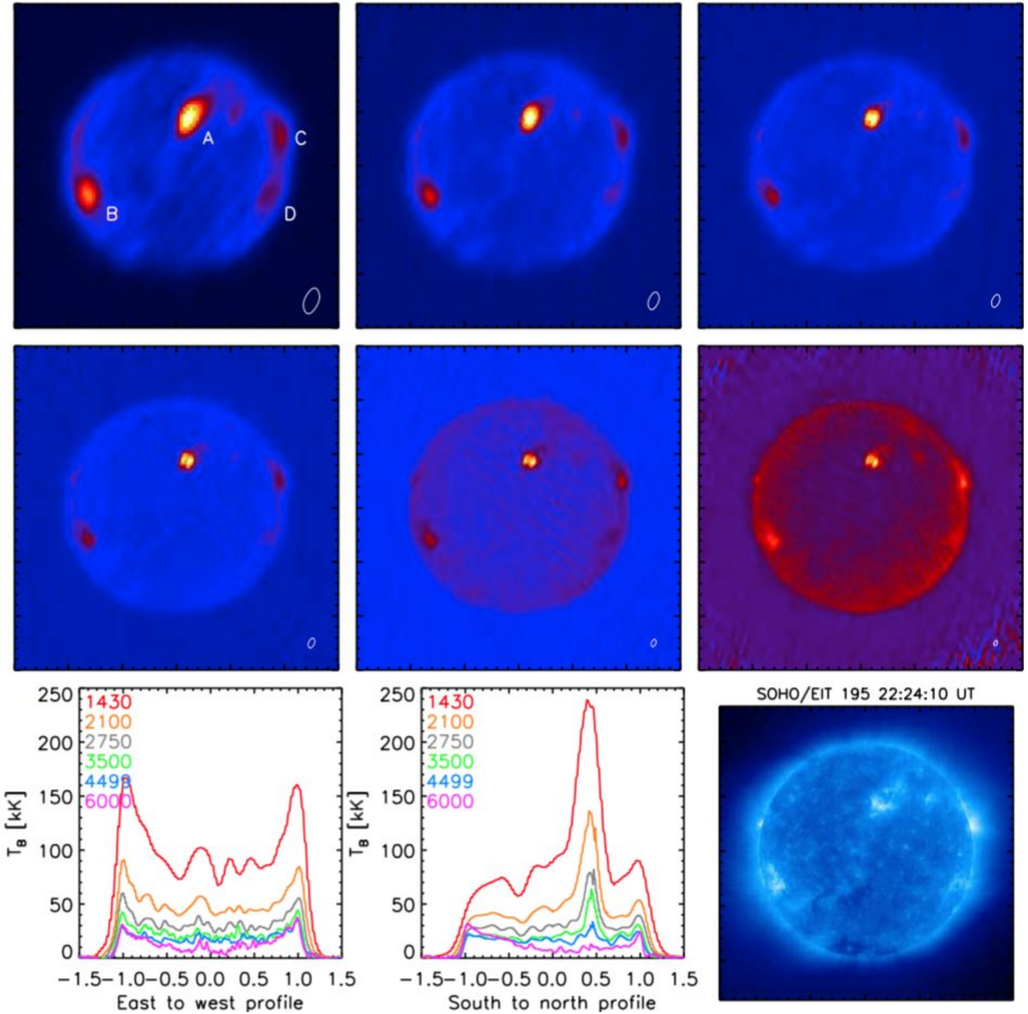
# Radio Imaging

M31




M33






# Radio Imaging

Can observe the sun safely!

ATA-42 observation of the Sun in 2010. Starting at upper left, maps of the sun at 1430, 2100, 2750, 3500, 4500, and 6000 MHz. SOHO/EIT EUV image at lower right.

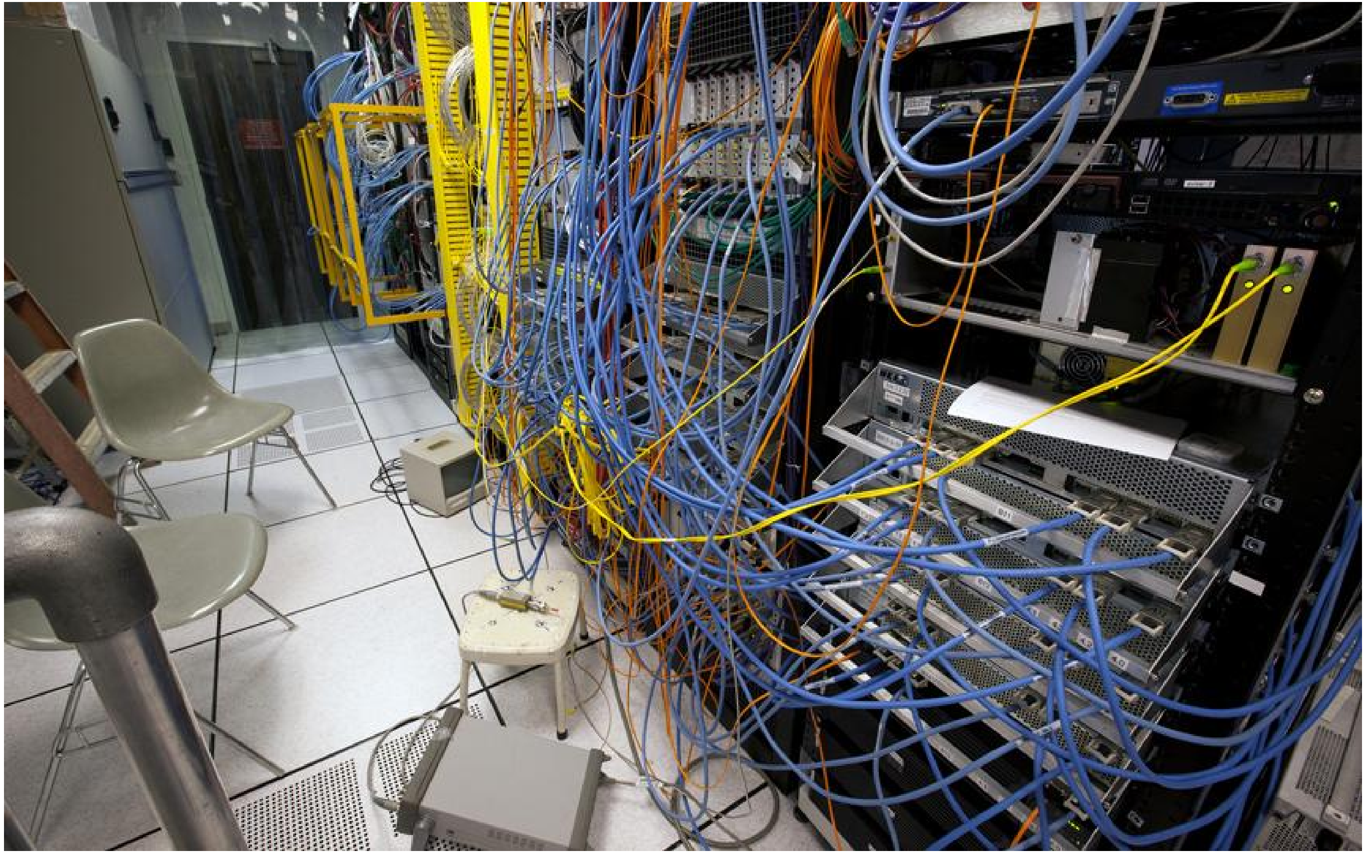
# Radio Imaging Software Stack

The correlators are configured and read out by a ruby and rails application.

The data is sent over UDP to individual ports on an archiving computer (one port per channel). These are read by a Java application that is integrated into a controlling network that is itself controlled via JRuby scripts.

The underlying systems run openSUSE Linux.

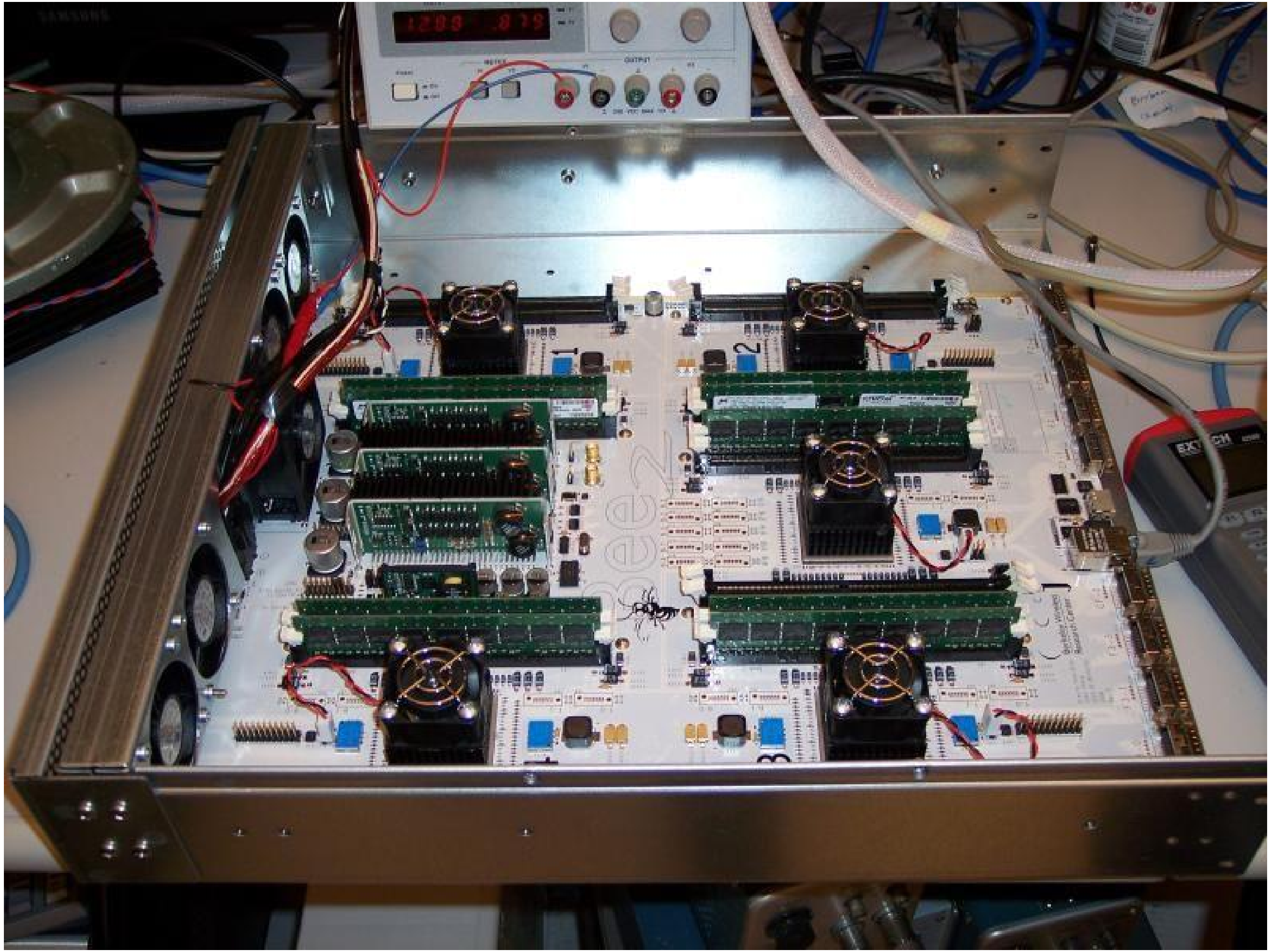
# Beamformers



*Gutierrez-Kraybill, Oct 2007*

The metal cases on the right and center are the BEE2 - Berkeley Emulation Engines.

These boards are used for beamforming and each blue cable is a 10Gbps link. There are links on both the front and back of the BEE2 boards.


Berkeley Wireless Research Center

# Beamformers

3 independent beamformers, each using 5 BEE2 boards.

Each BEE2 board is a 28-layer board with 4 processing FPGAs, and 1 control FPGA. Each processing FPGA has separate data paths to the other processing FPGAs with 5 10Gbps links.

The processing FPGAs then have another 4 10Gbps data paths on the edge of the board.

These are Vertex II Pros

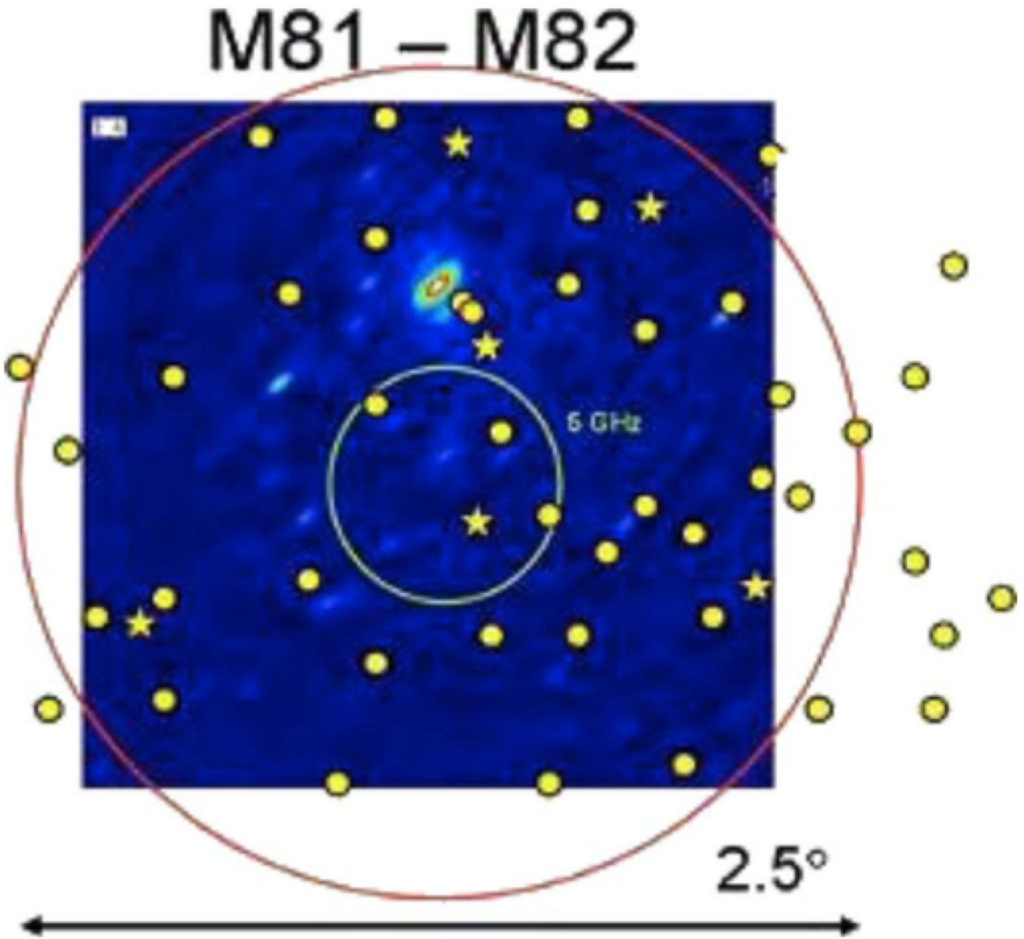
# Beam forming Software Stack and Outputs

The beamformers are configured by a rails application.

The data is also sent over UDP directly from the FPGAs to individual ports into a packet switched system that mirrors data on multiple low-latency 10Gbps ports and received by custom written catching software in C++ on openSUSE linux. Allows simultaneous distribution to multiple backends, SETI, Beowulf cluster, …

Fujitsu XG2000 at the time was only switch out of 6 types tested that did not drop packets at full 10Gbps rates on all ports simultaneously (~2007).


XG2000



*Welch, et al, 2009*

# SETI

At a high-level, beamforming allows the instrument to focus on small, individual areas of whatever is in the current field of view on the sky.

At any point of the sky, SETI can currently use 2 beams to study individual stars, while the third beam is used for RFI mitigation techniques.

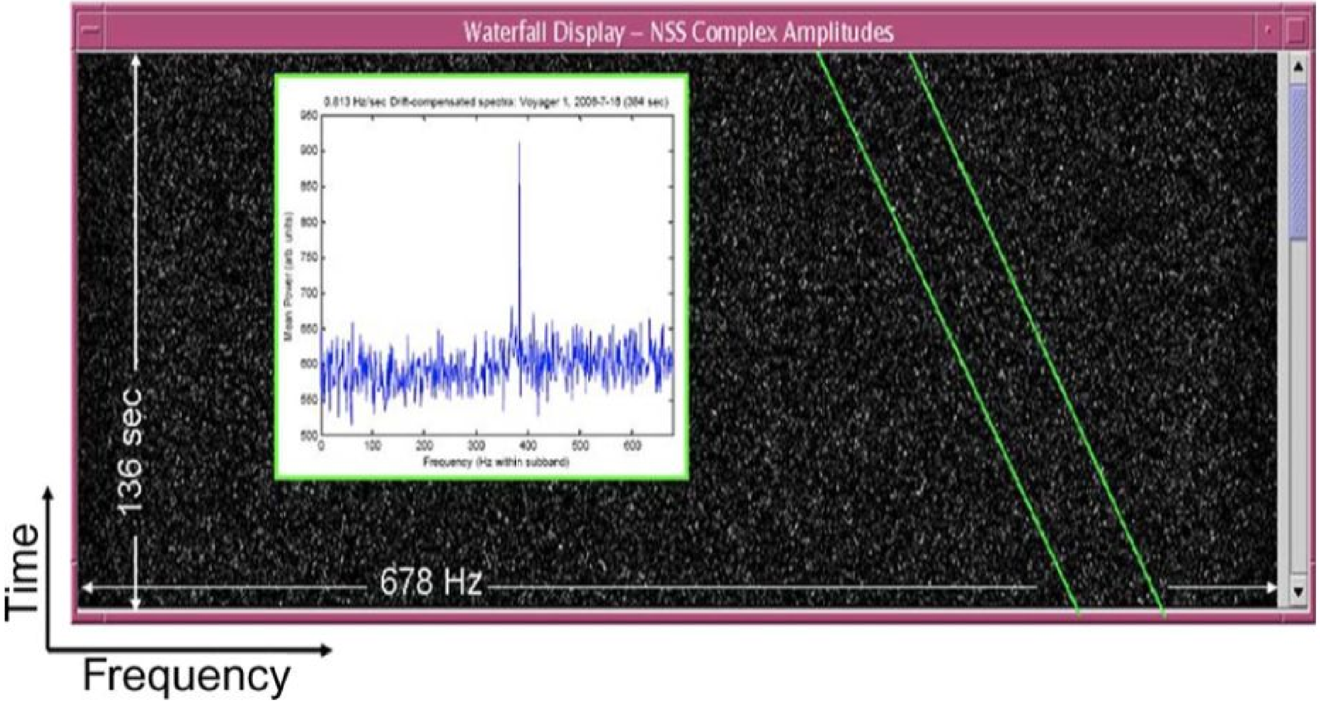
The output of the beamformers supply 2x10Gbps links, while SETI's SonATA system picks out very narrow bands to study out of the supplied 100MHz

# SETI

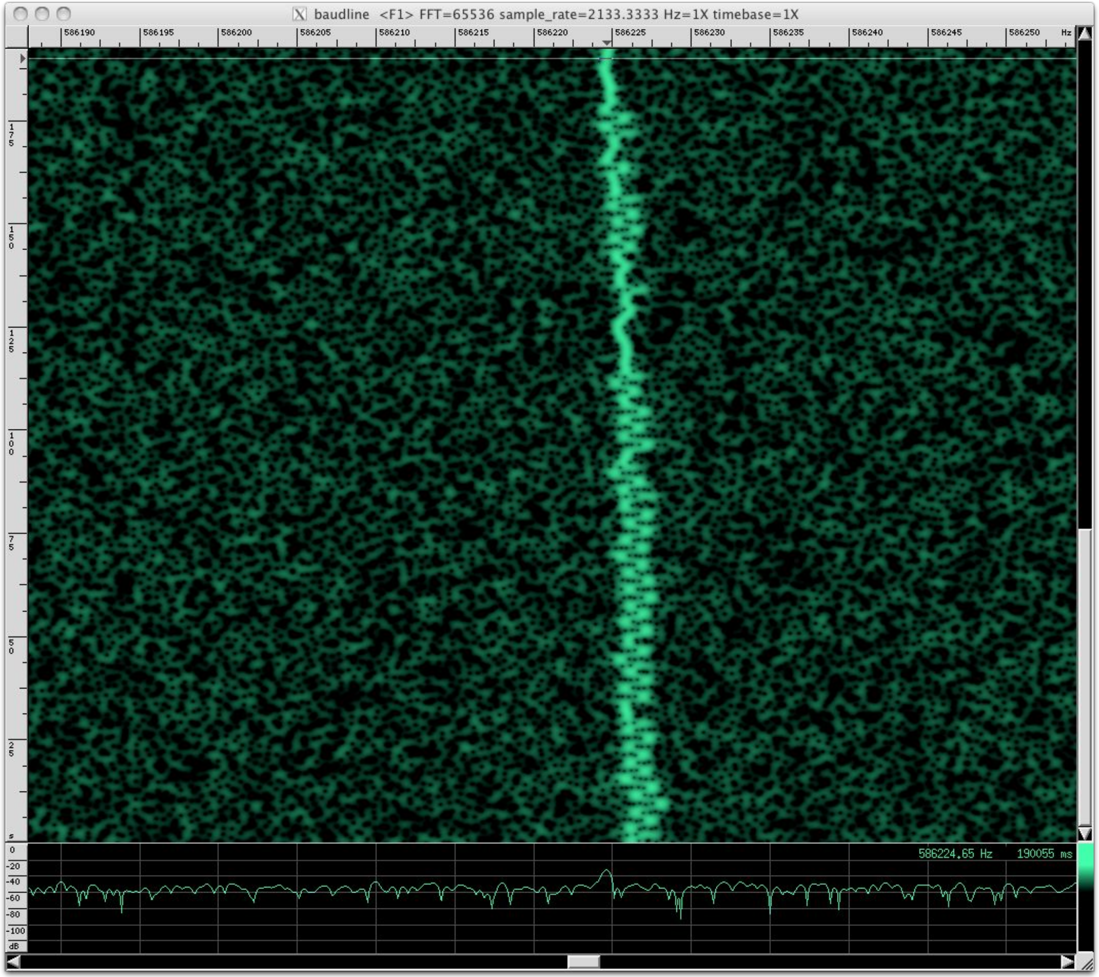
The SETI detection system provides a visualizer that displays waterfall plots of narrow bands, with 1Hz resolution.

These data sets are used actively with the SETI Quest project.

http://setiquest.org




*SETI Institute*




http://baudline.blogspot.com

# SETI

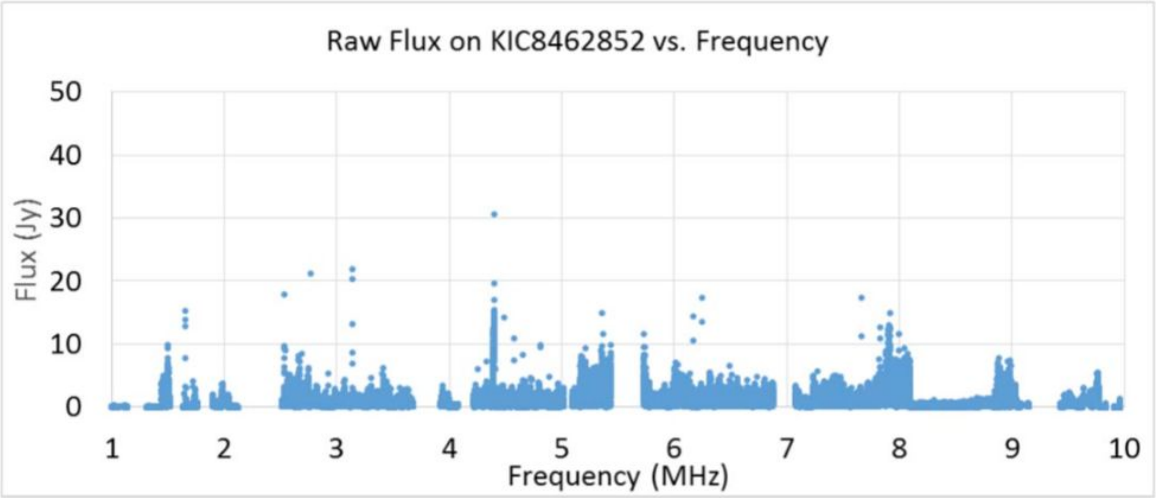
Picks up thousands of signals daily. Most are local noise (Earth). Hierarchy of detection algorithms decimate these and there is a growing collection of unexplained and *unrepeated* detections.

Many individuals devoting time to analyzing signal captures.

# SETI

We can *barely* look. Variable space is large: if a transmitter is broadcasting straight at the Earth or merely passing by on a regular basis due to rotation and orbits of both the remote transmitter and our local receiver, GHz worth of possible frequencies and the number of directions to look.

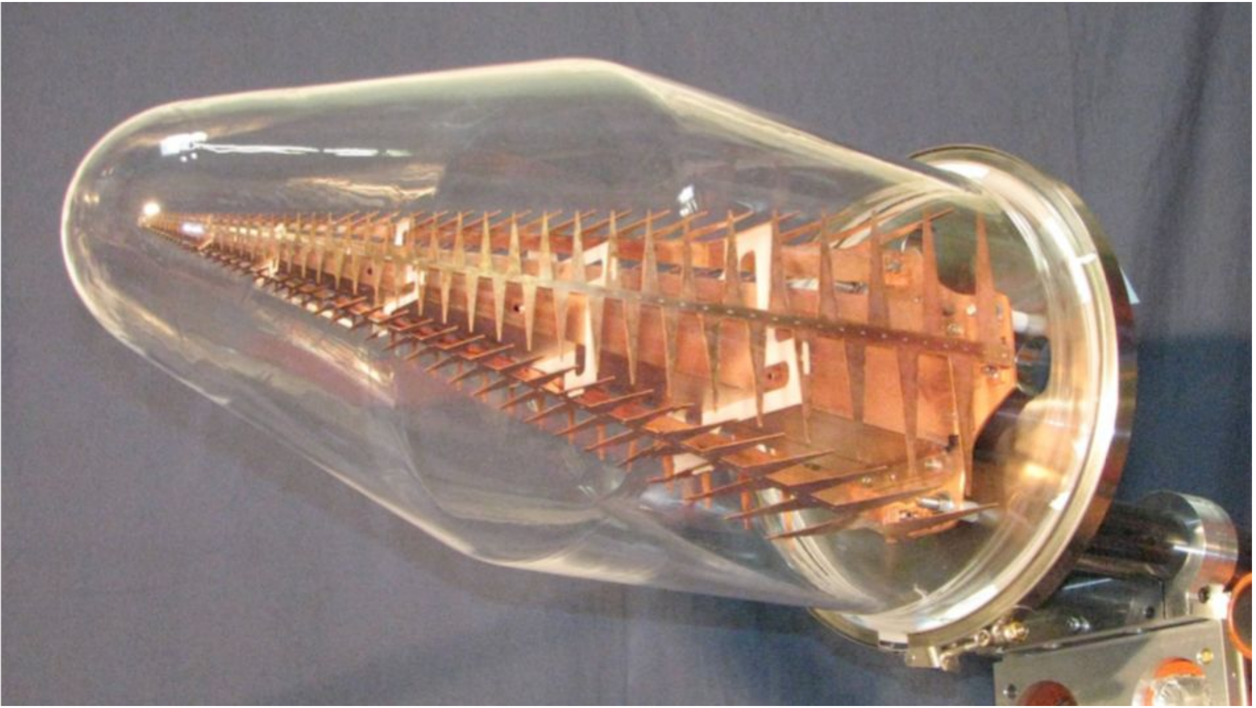
KIC 8462852, the “potential megastructure” star, ATA-42 could only rule out that a radar was not pointed at us with 1,000 times the energy that can be produced by our own Arecibo pointed at it.
~$10^{13}$ W EIRP vs $10^{16}$W EIRP




*Harp et al, http://arxiv.org/pdf/1511.01606v3.pdf*

# ATA Influence

Square Kilometer Array antenna design



# New Developments

Receiver design has moved forward with SRI International and UC Berkeley.

By removing the trailing part of antenna, 500MHz of response was removed while adding a short section to the front added another several GHz.

The addition of a dewar to cool the entire antenna assembly gives the system noise temperatures that are similar to current VLA new receivers, $T_{sys}$ ~ 22K vs $T_{sys}$ ~ 65K

Now operates over the entire spectrum of 1GHz-15GHz

# New Developments

Now with the capability of sensing up to 15GHz, efficient bi-static radar operations are easier.

By pointing a dish at a strong source in geo-stationary orbit, and the remaining array at the horizon, can do 3D-tomography of the entire sky in that direction passively.

ATA-42 can detect objects the size of a basketball in LEO.

ATA-350 could detect objects the size of a golfball.