any questions?

Mapping Speed

- How long would GBT take to map half of sky to 200 μJy RMS, with T_{sys}=25K, 400 MHz of bandwidth at 600 MHz?
  - Beam size ~1.22λ/D, 50cm wavelength, ~20' beam.
  - need 1.5e5 beams. $t_{obs}=(T/dt)^2/B$, dt=400μK, t=10s/beam, 1.5e6 s total~20 days.
- CHIME sensitivity after one day? Similar gain, 50K Tsys, 90 degree by 1 degree strip. 4 minutes to cross strip. dT=50/sqrt(240*400e6)=160 μK, or 80 μJy. Equivalent to ~100 days of GBT(!).

Will This be Our Noise?

- Maybe. If we're lucky. But probably not…
- 1/f noise always exists in amplifiers.
- If integrate longer than 1/f knee, noise gets *worse* with longer integrations.
- 1/f modulates T_{sys}, so often dominates after ~ms timescales.
- Usual solution - switched receiver. Use two feedhorns going into one amplifier, switch back & forth between them. Can also switch against loads.
- How does this affect our noise?

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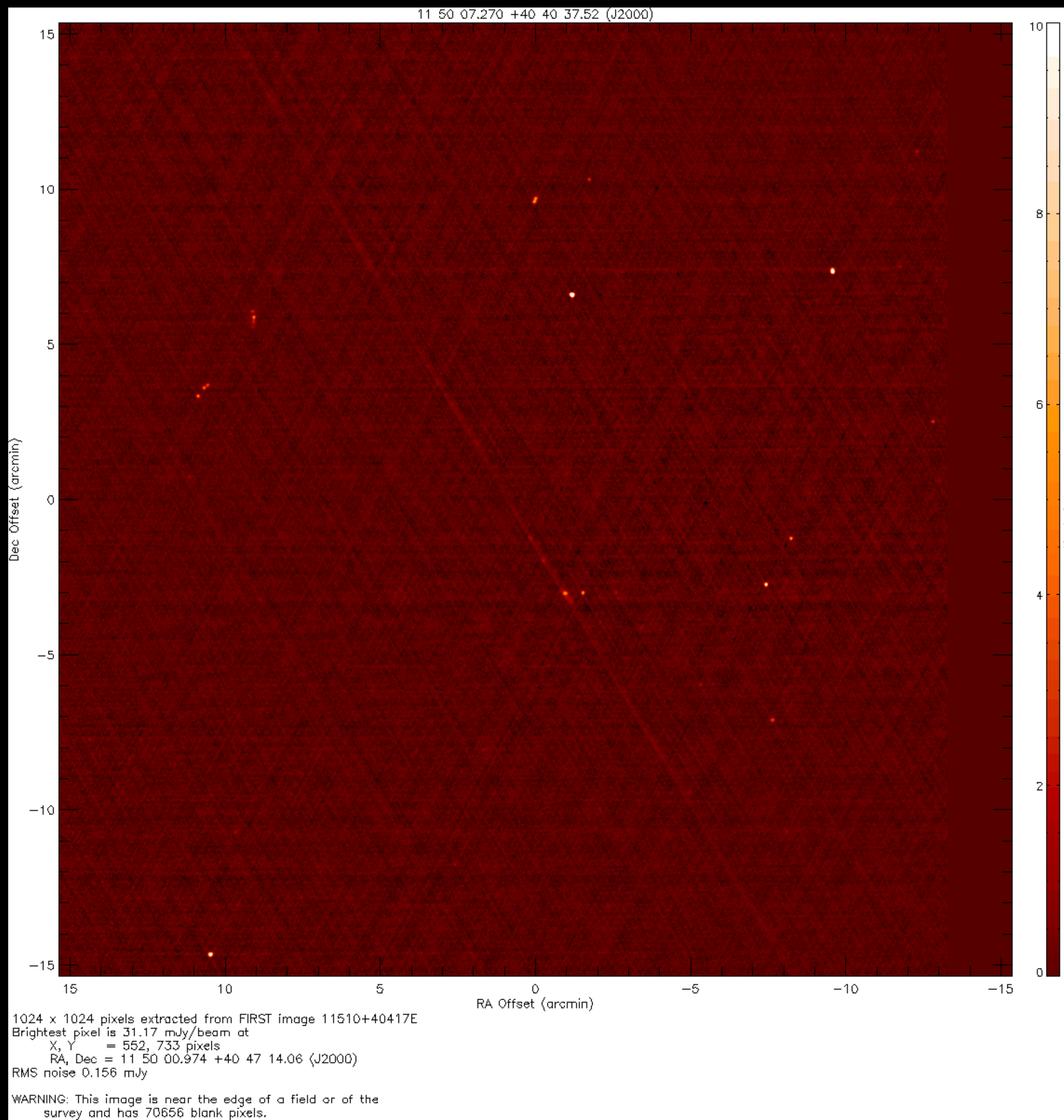
  - spend half time on-source, half time off-source. Then difference the two. Half as much time double the variance, subtracting two same-variance #'s doubles again, so σ goes up by 2, t_{obs} goes up by 4.

Random Square Degree from FIRST



Lots of Sources

- Our telescope will read out true sky convolved with telescope beam.
- If I point at source, but second source falls in beam, I will measure combined flux.
- Alternatively, convolve map of sky with telescope beam, what is median scatter?
- Unwanted sources contaminate signal, called *confusion noise*. Does not integrate down with time.
- How does importance of confusion noise scale with time?
- How does confusion noise scale with resolution?

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- Unwanted sources contaminate signal, called *confusion noise*. Does not integrate down with time.
- How does importance of confusion noise scale with time?
  - gets worse, since SNR on faint sources goes up.
- How does confusion noise scale with resolution?
  - gets better, since odds of second source in-beam go down.

Quick GBT Confusion Limit

- FIRST survey has ~100 sources/square degree to 1 mJy
- What is GBT beam size at 1.4 GHz? $1.22\lambda/d \sim 10'$
- How many sources per beam? $100*(10/60)^2=2\text{-}3$
- What is confusion limit? ~sqrt(2-3)*(>1 mJy) ~few mJy
- How long does it take to get there? 3 mJy=6 mK, BW=400, Tsys=25, $dT/T=1/\mathrm{sqrt}(Bt)$ so $t=(T/dT)^2/B=(25/0.006)^2/400e6=0.04$s.
- Say looking for 10 km/s spectral line - BW=1.4e9*(v/c)~50 kHz. $t=(T/dT)^2/50e3=6$ min.

Receivers

- Radio waves come into detector.
- Something needs to measure them - usually an ADC (analog to digital converter)
- ADCs are noisy, and we may have signal loss en route through cables.
- So, usually amplify signal as soon as it comes in.
- Amplifiers usually quoted in logarithmic dB, 10 dB a factor of 10 in power. (sometimes electric field, so be careful)
- If I have 20K coming into 20 dB amplifier, how much comes out?
    - 20dB=$10^{(20/10)}$=100x increase, so at 2000K.

Receiver Noise

- If I add 10K noise before amplifier, what is my new power? If I add 10K after amplifier, what is new power?
- 3000K, 2010K respectively.
- If I had 1K signal, what is my output signal level?
- 100K, 100K.
- SNR? 100/3000 vs. 100/2010. Adding noise after amplification didn't make much difference, but before makes huge difference.
- So, huge emphasis on noise of first amplifier in a system, and in reducing noise upstream of that. Downstream matters much less.

Quantum Limit

- Heisenberg uncertainty principle says $\delta x \delta p > \hbar/2$
- But also, $\delta E \delta t > \hbar/2$ - if I take a measurement over a short time, energy uncertainty grows (thankfully, since this is why structure exists in the universe).
- If I coherently amplify a wave (i.e. keep phase the same), time uncertainty should be less than a radian, or $1/2\pi\nu$.
- Means $\delta E = k\delta T > h\nu/2$, or $\delta T > h\nu/2k$. This is quantum limit.
- 30 GHz, limit is ~1K. Good amplifiers get within factor of few. Other noise wins at low frequency, but amplifier often sets noise at high frequency.
- Why do bolometers not suffer from this?

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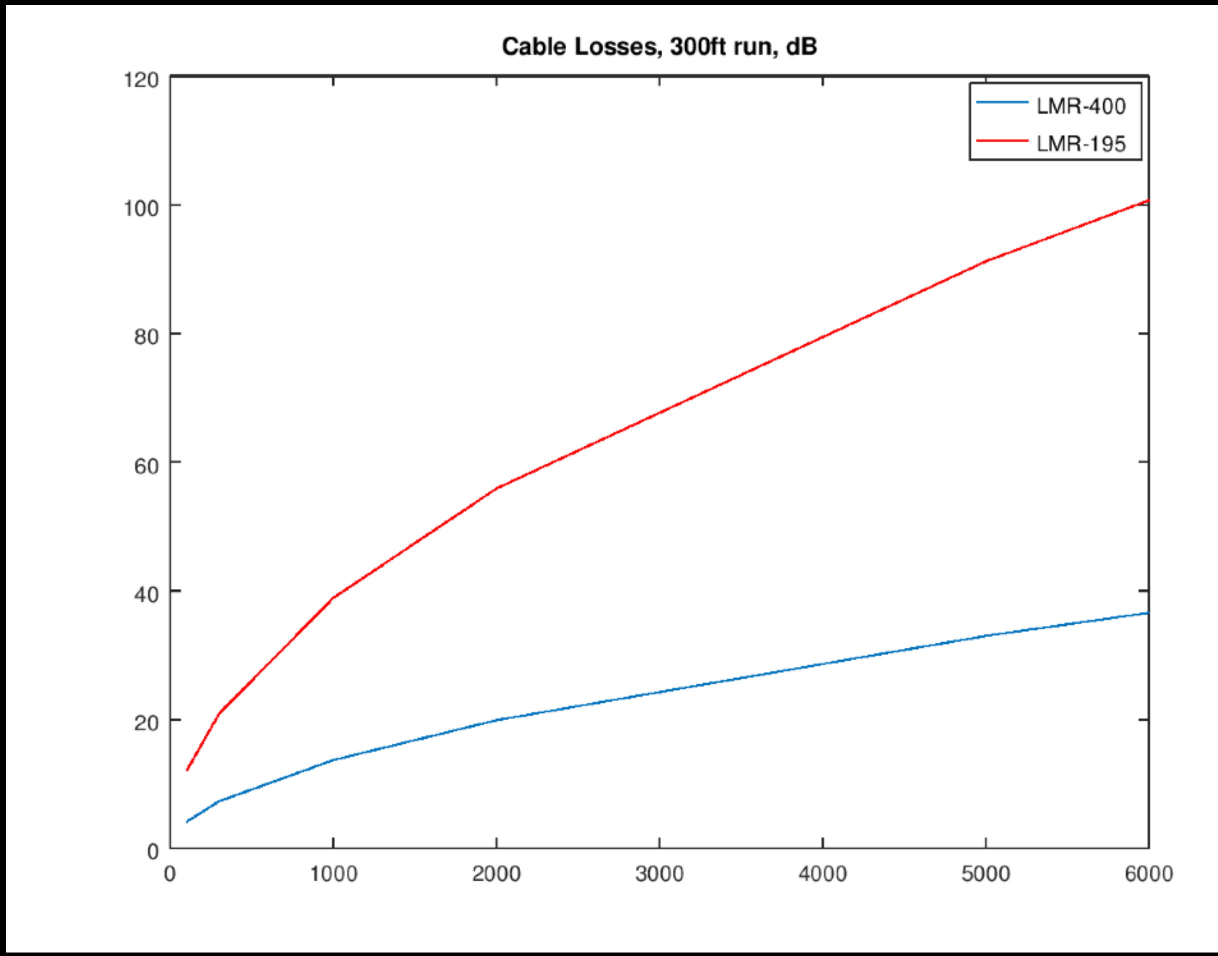
- 30 GHz, limit is ~1K. Good amplifiers get within factor of few. Other noise wins at low frequency, but amplifier often sets noise at high frequency.
- Why do bolometer not suffer from this?
    - Not trying to amplify phase, so arrival time uncertainty can be much larger.

Mixing

- We'd like to be able to observe at any frequency.
- ADCs will only work at some frequency. Usually (but not always) lower than frequencies we care about.
- Sending high frequencies along cables is also challenging. Cable loss grows quickly with frequency.
- Getting signal down from GBT at 5 GHz could lose 999,999,999 out of every billion photons(!)

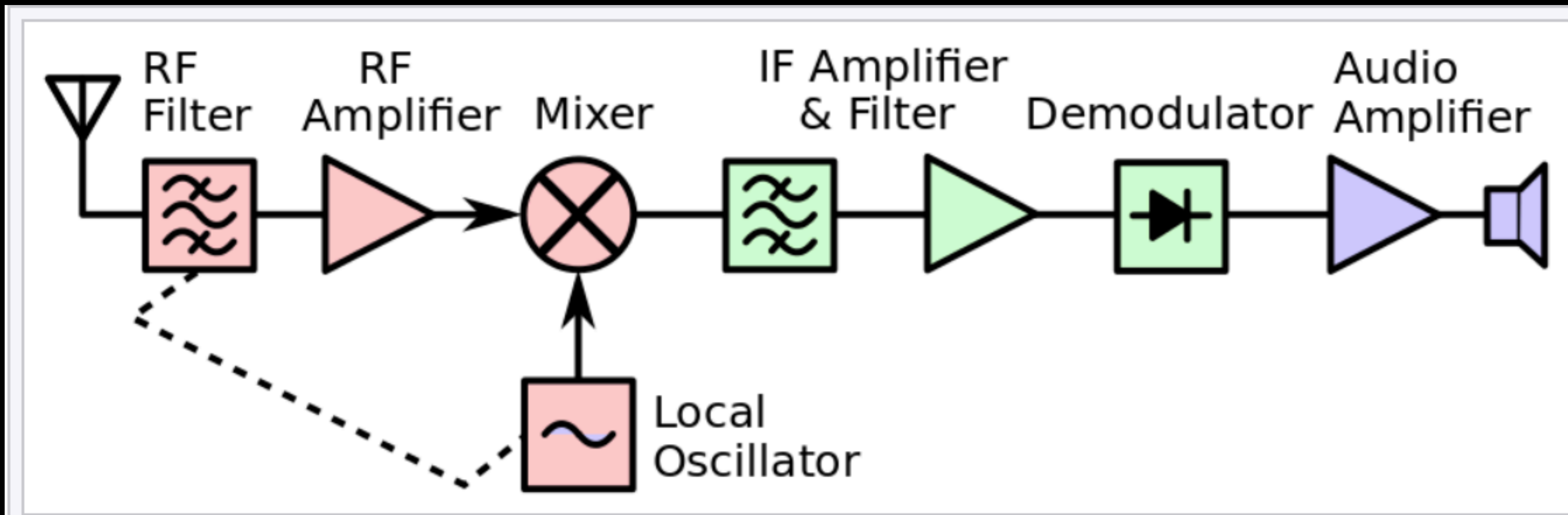


Cable losses from handy-dandy Times Microwave online calculator

Mixing V2

- Can we do something about this?
- Yes! If I have a nonlinear component, and put in two signals V_1,V_2, output will be $c_1(V_1+V_2)+c_2(V_1+V_2)^2+\ldots$
- Second term gets a V_1V_2 component. What does this look like if V_1 and V_2 are sine waves closely spaced in frequency?
- $V1=a\sin(2\pi v_1 t)$, $V2=b\sin(2\pi v_2 t)$. Angle summation formulas give $\sin(2\pi(v_1-v_2)t)$ $+\sin(2\pi(v_1+v_2)t)$
- We can filter out the v_1+v_2 term with analog device, leaving v_1-v_2. We have shifted the signal to lower frequency.
- Process is called heterodyning (developed by Canadian Reginald Fessenden), and nonlinear device is called a mixer.
- Good mixers only put out one frequency combination, but others can put out various combinations of v_1,v_2, called intermodulation products. These are bad.
- NB - both v+dv and v-dv will generally get mixed in - these are the *sidebands*. Can make mixers that separate them out, can filter one out beforehand, or can just eat them.

Super Heterodyne Receiver



- Signal comes in. Gets amplified/filtered (often amplified before the filter. Why? half dB loss typical, equals 30K if warm)
- Separate signal from local oscillator gets piped into mixer, to shift to lower intermediate frequency (IF).
- IF much easier to move around. Usually goes into another thing that does the detecting, often gets mixed again.

CHIME

- Instead, we could sample directly if ADC fast enough.
- CHIME works 400-800 MHz. Normally need to run at 1600 Msamp/sec (why? Nyquist…)
- BUT - if we analog filter everything outside of band, then we could run at 800 Msamp/s. We would alias low-frequency power, but that is gone.
- This is called working in the second Nyquist zone.
- Other low-frequency telescopes (e.g. PAPER, HERA) directly sample electric field w/out any tricks at all.

Interferometry

- Resolution from single dishes not great. But we can do better!

- If I have two telescopes separated by distance d, observing source at angle θ at wavelength λ, what is phase difference in arriving electric field?

- Source in far field (probably) so path length is $d\sin(\theta)$. Phase difference is $2\pi d/\lambda \sin(\theta)$.

- If I measure electric fields and multiply together $\langle E_1 E^*_2 \rangle$, I will get $E_0^2 \exp(2\pi i d/\lambda \sin(\theta))$

- Call d/λ b, the dish separation in wavelengths, and assume small angles on the sky, and $I=E_0^2$. Then we get $I \exp(2\pi i b\theta)$

Signal over Sky

- If I have many sources, I have to integrate over the (2D) sky brightness. Gives: $\langle E_1 E_2^* \rangle = \int I(\theta) \exp(2\pi i \mathbf{b} \cdot \theta) d^2\theta$
- Have you seen this before?
- Yes! This is just one component of the FT of the sky, measured at wavevector *b*.
- This time-average is the fundamental output of a radio array, called a *visibility*.
- Resolution set by *baseline length*, not by dish size.

Interferometer

- An array of radio telescopes working together is called an interferometer. Every pair of antennas (called a *baseline*) gets multiplied together in the *correlator*, producing a visibility.

- Vector separation labelled by (u,v(,w)) where u is EW, v is NS (and w is vertical separation, generally much less important).

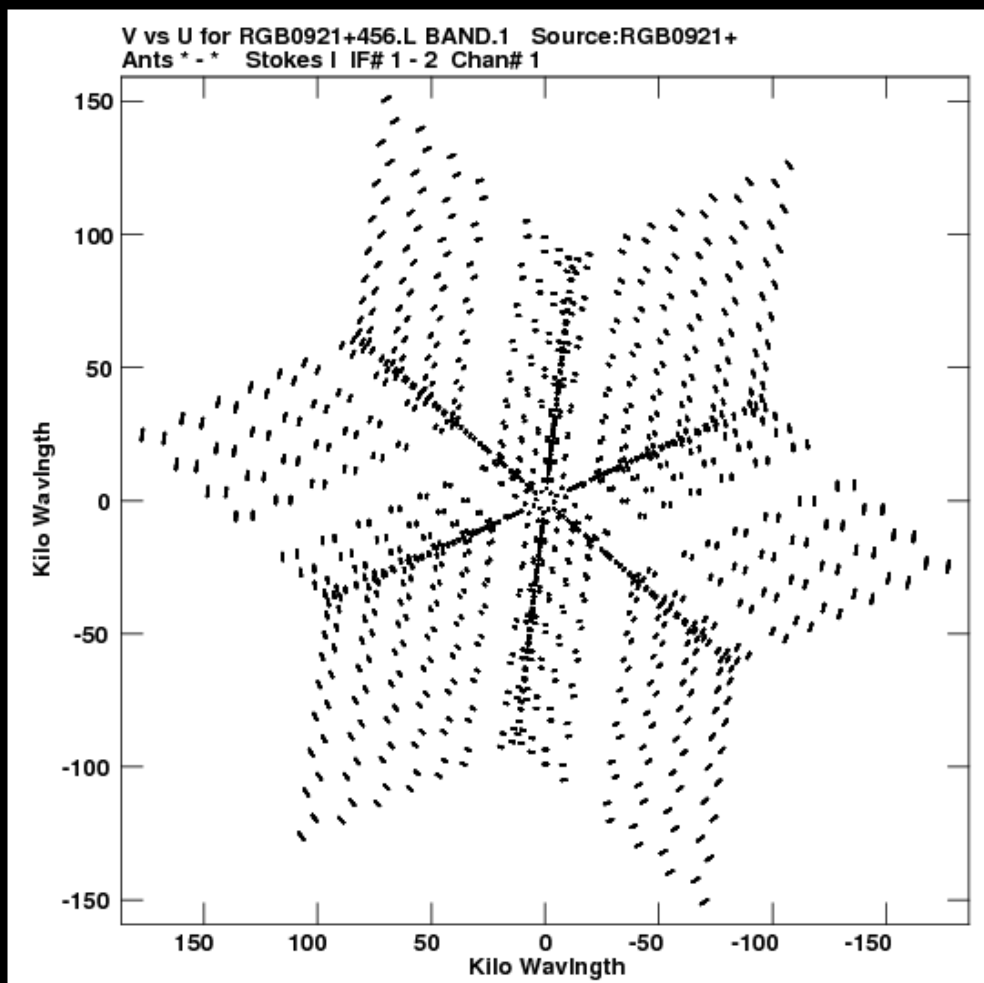
- UV coverage is sampling of points in UV plane - denser sampling means better understanding of sky.

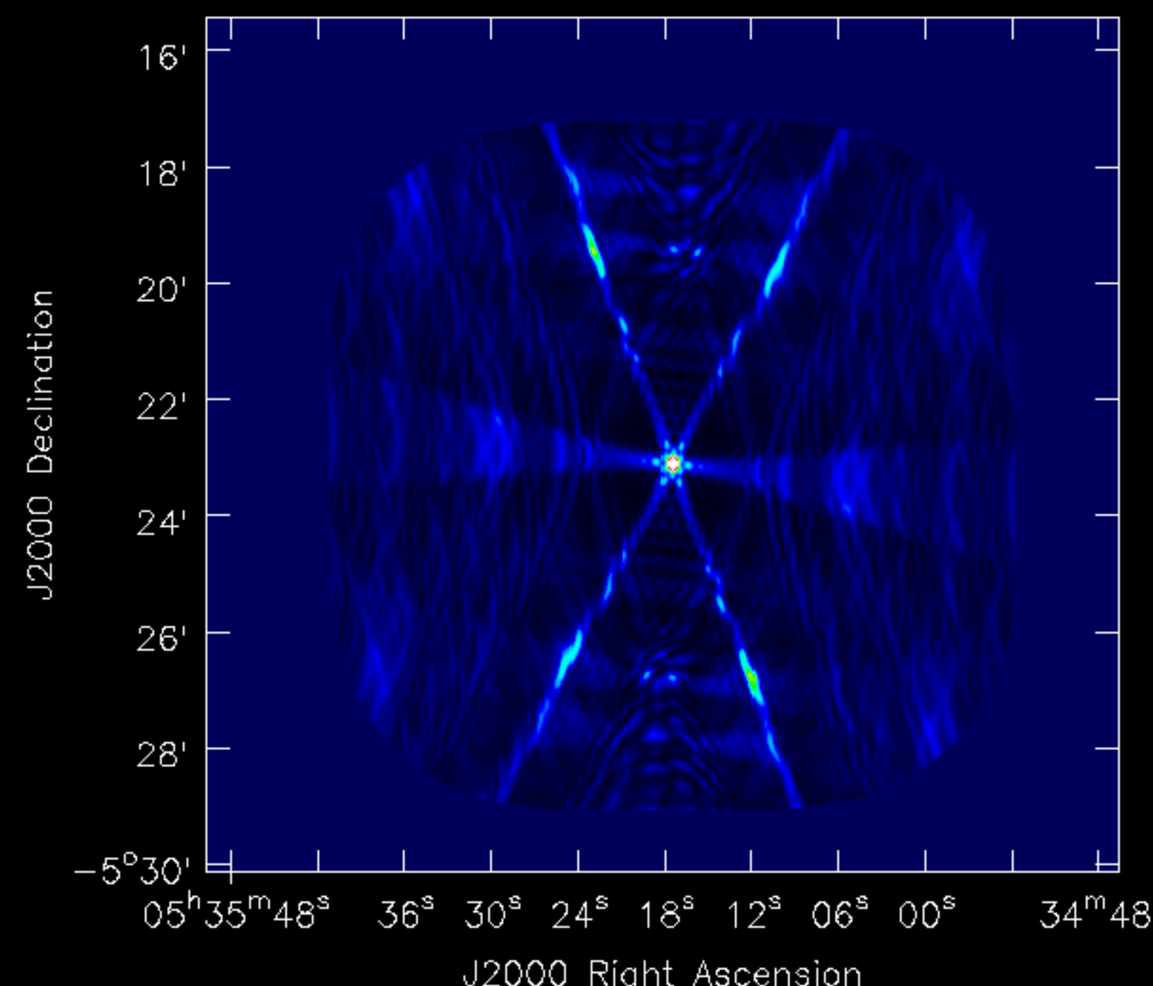
- Telescope PSF given by FT of UV coverage - which may not surprise you given FT optics result from Monday. Every antenna acts as a radiator.

How many operations to correlate?

- Correlation used to be done by analog circuits. Almost uniformly no longer the case.
- VLA - 27 dual pol receivers, 8 GHz bandwidth (total - they split up). 54 inputs, npair=54*55/2~1500 * 8e9*8 ops/complex multiply+add = 100 TFlops.
- CHIME - 1024 dual pol, 400 MHz - 6.7 PFlops. Lots of crunching needed for large arrays.

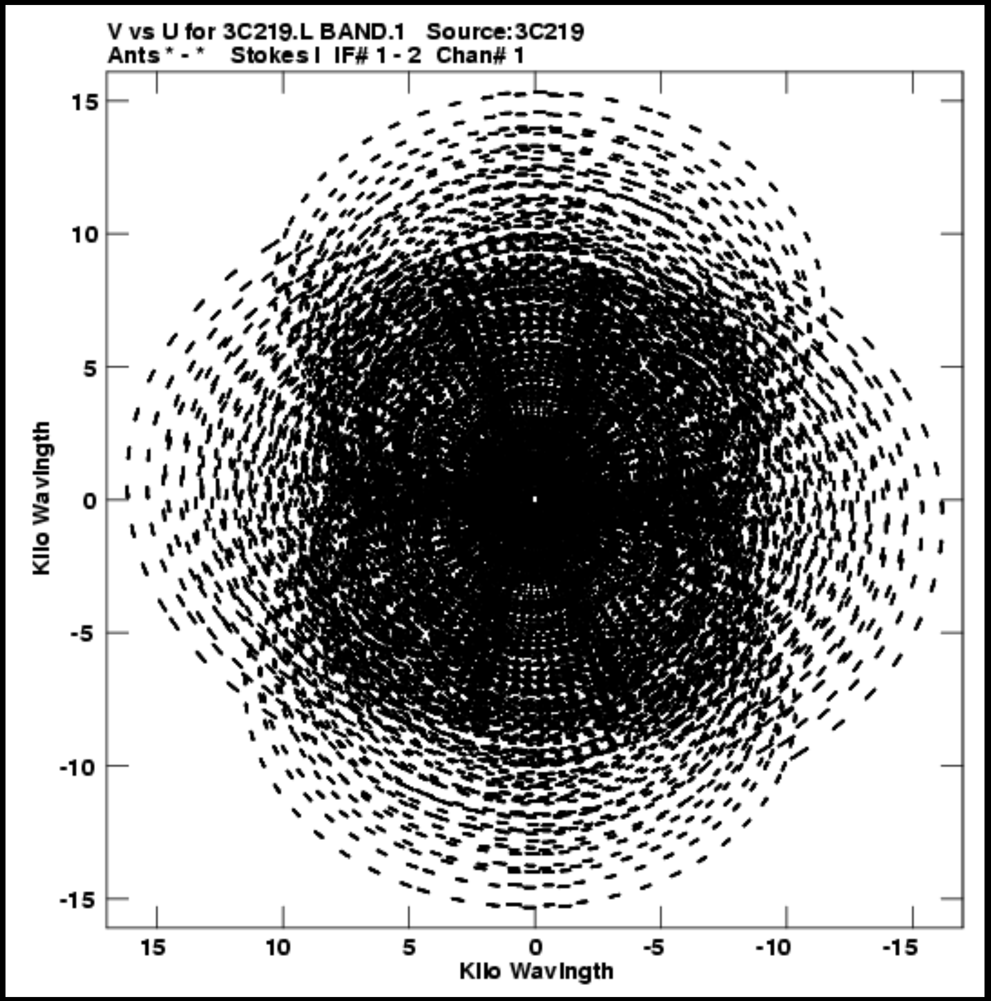
VLA UV Coverage





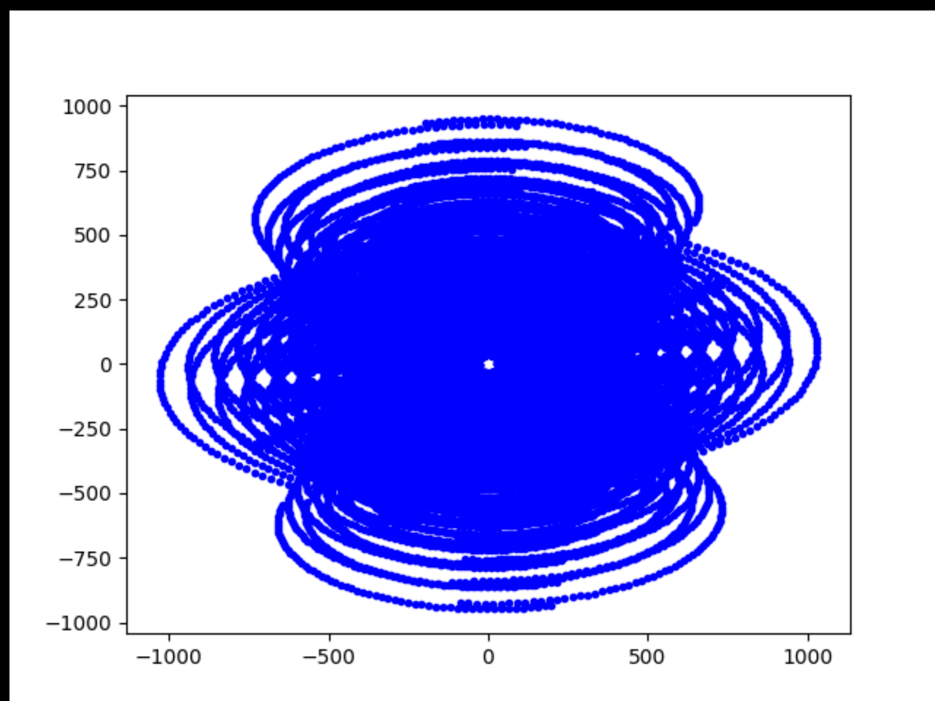
Left: Instantaneous UV coverage from VLA
Right:

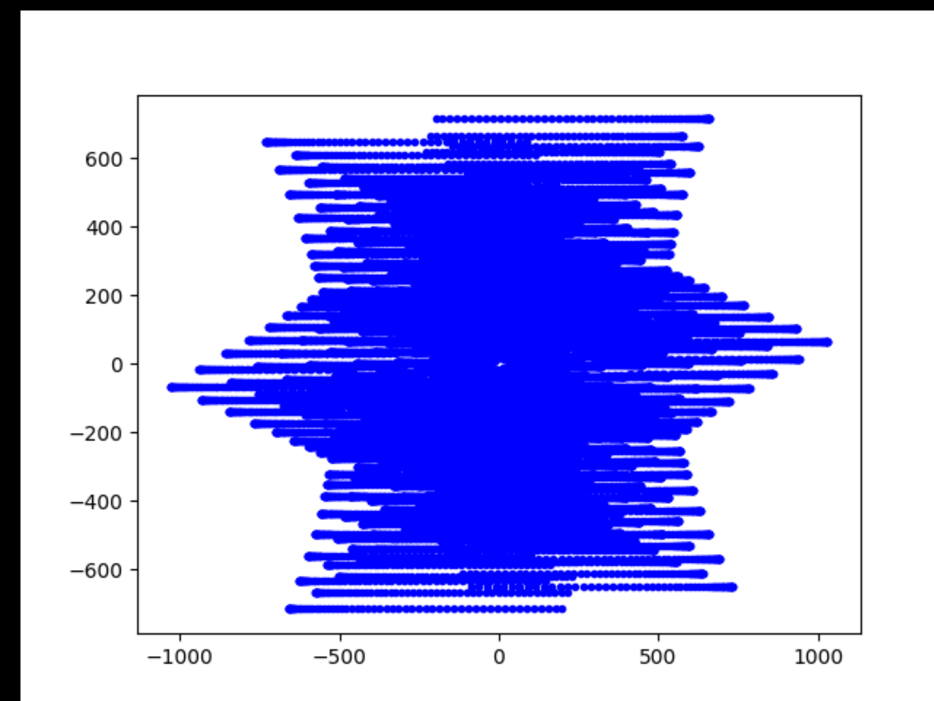
Rotation

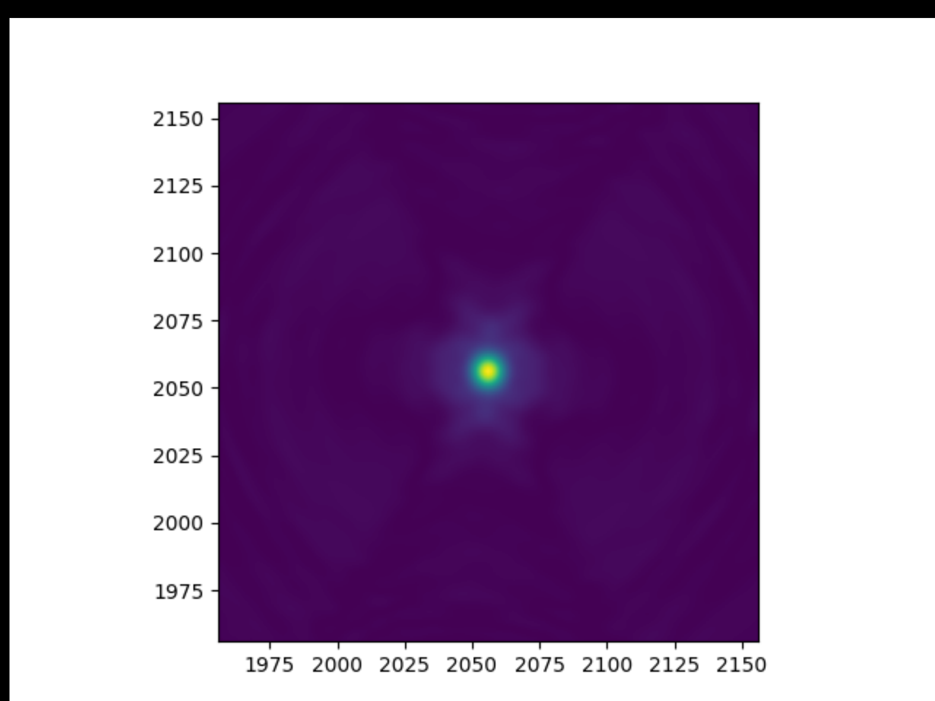


- We want as much UV coverage as possible, right?
- Instantaneous snapshots usually not great.
- However, we are on a rotating platform. Wait long enough, and baseline moves relative to source.
- UV coordinate set by baseline separation perpendicular to field center. Fills things out enormously.
- Multiple channels also samples UV plane radially.

UV, Beam after 8 hours
dec=30 (left), and equator (right)







Primary Beam

- Dishes have a response on the sky, usually limits field of view
- In interferometer, each dish sees primary *beam times* sky, so visibility is $\int A(\theta)I(\theta)\exp(2\pi i u\cdot\theta)d^2\theta$ where A is the primary beam (in power)
- In UV space, we measure not the sky transform, but the sky transform convolved with the primary beam transform. PB sets UV-space resolution
- PB is electric field response squared, so in UV space, that's electric field response convolved with itself. But, electric field response is just aperture illumination, so PB transform is just dish+feed autocorrelation with itself in wavelengths.

Imaging

- If we build telescopes, we usually want to take pictures of things…
- If I measure FT of sky, I can just IFT to get map, right?
- Well… There are usually gaps in UV coverage. If baselines sampled more densely than dish diameter, this might work.
- Not possible for high-resolution. To make a map of sky, we must fill in UV plane with some guess.
- Unobserved parts of UV could be anything! The art of imaging is sensibly filling in those unobserved areas.
- Remember - we understand very well how to predict data/measure χ^2 given a map of the sky. It's only inverse problem that is ill define.

CLEAN

- One standard way to do this is CLEAN. Pretend the sky is full of point sources.
- Make a dirty map - direct FT of visibilities. Requires putting visibilities on a grid - how fine does that grid need to be?
- Look for brightest peak (or peaks).
- Subtract from data. Repeat.
- Experience has shown that subtracting fraction of peak brightness works better in practice - say 30-50% of peak.
- When should we stop?

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- Make a dirty map - direct FT of visibilities. Requires putting visibilities on a grid - how fine does that grid need to be?
  - UV resolution set by dish diameter in wavelengths. Need to have grid be significantly finer than that.
- Look for brightest peak (or peaks).
- Subtract from data. Repeat.
- Experience has shown that subtracting fraction of peak brightness works better in practice - say 30-50% of peak.
- When should we stop?
  - We know what noise in dirty map should be - weight is just sum of visibility weights, so stop when noise is (roughly) equal to that.

CLEAN CTD.

- Process of cleaning gives us a list of source fluxes/positions, plus dirty map that may be noise.
- Usual reported thing is to put sources into map, convolve with Gaussian with same size as main dirty beam, add in noise map.
- Significant freedom available in how we weight data. Often density in UV space higher at short baselines.
- Least-squares (“natural”) weighting may not give “best” images since weight across UV plane uneven.
- For pretty pictures, you may want to use “uniform” weight, where each *area* of UV plane gets same weight.

Bayesian

- General imaging problem is usually under constrained. We have to "make up" data to make an image.

- Amongst all the possible maps that agree with the data, *you* need to decide which one you think makes sense.

- Which brings us to the Reverend Bayes. P(a|b)P(b)=P(b|a)P(a). P(m|d)=P(d|m)P(m)/P(d) for data d and map m.

- Drop P(d) because we already have the data. P(d|m) is straightforward to calculate. Effectively, mapping problem is deciding on P(m)

- There are many ways to do this - multiscale clean where you fit Gaussians instead of sources, maximum entropy… Do think about what you're looking at as it will guide choice of imaging.