any questions?

Observing Proposal

- Typical observing proposals: 4 page limit (sometimes less), including figures.
- First part - science case. Why do you want to observe something? What are you going to learn?
- Second part - technical justification. What instruments/camera are you going to use? What sky are you going to point at? How much time do you need to get to your science goals?

Time Allocation Committee

- Proposals go to a committee of general astronomers.
- One person assigned to be primary - they lead the discussion. One person assigned to be secondary - they need to summarize TAC review.
- TAC discusses proposals, then everyone grades each proposal.
- Your proposals will be read by non-experts - make sure they can understand!
- Need to read all proposals, primary and secondary need to read especially closely.

Schedule

- Think about your projects. Pick a subject by next week?
- We can spend first week of December reading proposals, have TAC meeting 10/12 Dec.?
- Given focus on analysis, will weight technical justification more - make sure you understand how noise translates to your science goal, and how much you need.
- Talk to me if you have questions.

Radiometer Equation

- We'll start on radio astronomy.
- Sensitivity works different than higher wavelengths, so let's work that out.
- If we have *n* photons/s arriving, what is uncertainty on *n*?
- total photons is nt, so uncertainty might be $\sqrt{(nt)}$, and fractional error is total/uncertainty - $1/\sqrt{(nt)}$. Brighter source=better fractional error.
- This is often true. but not always! Why?

Radiometer ctd.

- What happens when photons overlap? I can't "count" them anymore. End up in classical wave limit.

- If I have signal up to frequency ν, then electric field can't change any faster than $1/\nu$. Rather than waiting for new photon, I get new signal measurement every $1/\nu$ seconds.

- I can multiply by sine wave at freq. ν_0. That just shifts everything, so I now have signals between ν_0 and $\nu_0+\nu$. Usually $\nu_0 >> \nu$, so I'll have a fast sinewave modulated by slowly varying amplitude.

- The range of frequencies we observe is called the *bandwidth* B.

Radiometer Concluded

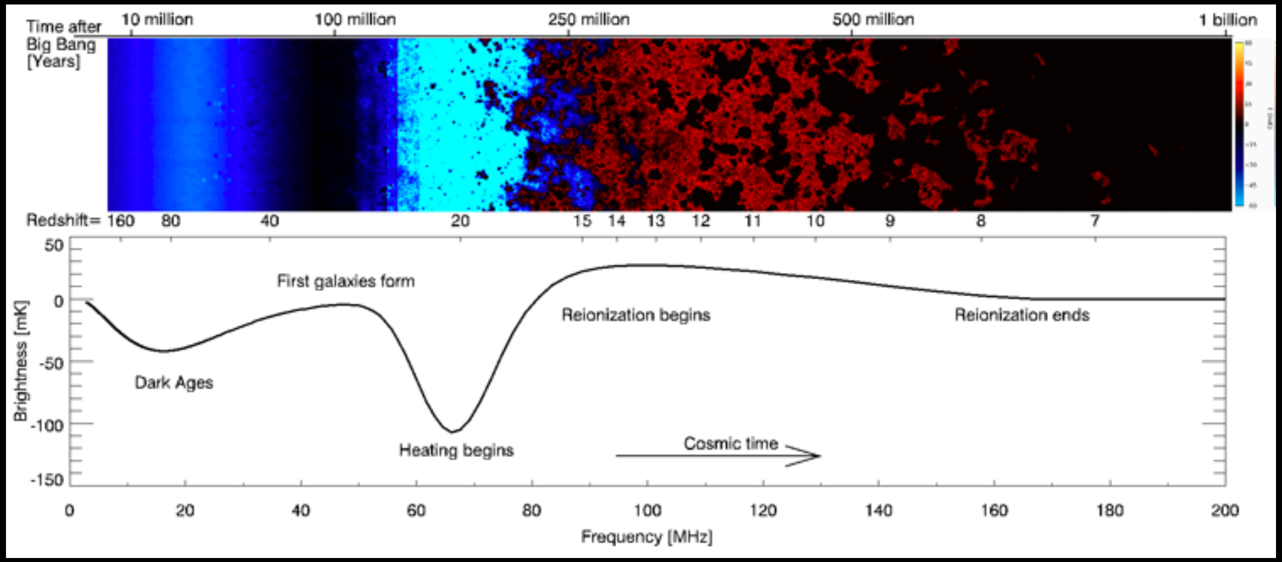
- If it takes 1/B seconds to get new measurement, then I have total of t/(1/B)=Bt independent measurements.

- Uncertainty in power dP is P/sqrt(measurements) = $P/\sqrt{(Bt)}$. or, $dP/P=1/\sqrt{(Bt)}$.

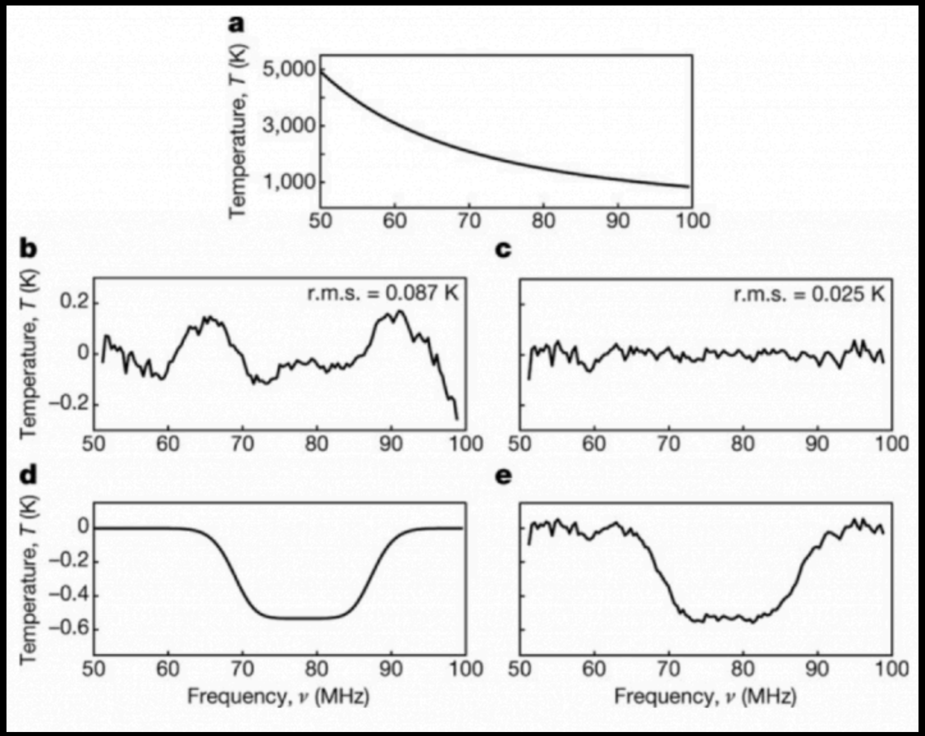
- At low frequencies (where “low” means Rayleigh-Jeans), P~T, so $dT/T=1/\sqrt{(Bt)}$.   Key - brighter source does *not* have lower fractional noise.

- All power going into detector needs to be counted. Usually noise from detector/telescope dominates, and we call this system temperature T_{sys}. In that world, $dT=T_{sys}/\sqrt{(Bt)}$.

Radiometer Example



- Take EDGES example. At low frequencies (~100 MHz), sky noise dominates. Milky Way ~1500K.



- Say we observe with 1 MHz channels, what is uncertainty after 24 hours?

- B=1e6, t=86400, T=1500. ~1500/√(1e6*1e5) ~ 1500/3e5 =5 mK.

- Top:theory. Bottom: data. Differences >>5 mK. Unclear if EDGES correct, but it's not sensitivity.

Radio Astronomy

- Unlike (ground-based) optical, radio telescopes are usually diffraction-limited
- What's the shape of ideal dish?
- Distance from infinity, bouncing off dish, to point should be constant across dish.
- Gives a parabola.

What does the beam look like?

- phase delay across disk leads to imperfect summing of phases
- Integrating the phase gradient across an aperture gives summed electric field
- This is just the Fourier transform of the aperture(!)
- Electric field intensity is then just |FT(aperture)|
- And power is intensity squared.
- Circular aperture works out to be $I_0(2J_1(x)/x)^2$ where $x=ka\sin(\theta)$, $k=2\pi/\lambda$, a= dish radius.

Huygens Principle

- Every point on a wavefront is a source. So, can work out based on emission from wavefront.
- Every receiver is also a transmitter if you run backwards in time.
- We can also work out the far-field beam by adding phases across a circular aperture equivalent to field coming out of dish.
- Again gives FT^2 of aperture at constant phase (true if in focus).

Near/Far Field

- How far does a source need to be to be in focus?
- Put a source at finite distance, focus drops off when phase difference across dish is comparable to wavelength.
- At height x, distance to edge is $\mathrm{sqrt}(x^2+(d/2)^2)$. Difference is $\mathrm{sqrt}(x^2+(d/2)^2)-x \sim\lambda$.
- For dishes, $x>>d$, so expand to $x(1+d^2/4x^2)-x\sim d^2/4x=\lambda$
- Solve for x: $x=d^2/4\lambda$. Sources much further than this will be in focus. (NB - usual expression puts 4 in numerator, $4d^2/\lambda$)
- Sources closer will be out-of-focus.

Perytons/Beam Mapping

- If you want to map your beam, best to put source in far field (although near field mapping can be done with care)
- If you see a source out-of-focus, it's in the near-field.
- Example - perytons, which came from Parkes microwave oven. Mimicked FRBs, but were out-of-focus

Fresnel/Frauenhofer

- Rayleigh-Sommerfeld Integral: $E(z)=\int A(r)\exp(2\pi i \mathcal{r}/\lambda)/|\mathcal{r}|d^2r$ where r is position in aperture plane, $A(r)$ is aperture illumination, z is vector from aperture plane reference (i.e. $r=0$) to observer, and $\mathcal{r} = z - r$.

- Frauenhofer: treat $\mathcal{r}$ in denominator constant, exponential expanded to first order.

- Fresnel: treat $\mathcal{r}$ in denominator constant, exponential expanded to second order.

- Near (reactive/non-radiative) field: a mess!

- Designing antennas/feeds is a black art. Lots of fancy software packages; often only loosely agree with each other and reality.

XKCD - What if?

FIRE FROM MOONLIGHT

Can you use a magnifying glass and moonlight to light a fire?

—ROGIER SPOOR

At first, this sounds like a pretty easy question.

A magnifying glass concentrates light on a small spot. As many mischevious kids can tell you, a magnifying glass as small as a square inch in size can collect enough light to start a fire. A little **Googling** will tell you that the Sun is 400,000 times brighter than the Moon, so all we need is a 400,000-square-inch magnifying glass. Right?

How Much Power Comes In?

- If I make dish larger, beam gets smaller. Total power goes like surface brightness * collecting area * beam solid angle.
- Collecting area * beam area is constant, so power coming into antenna from uniform temperature independent of size, effective area $\sim\lambda^2/4\pi$.
- RJ power is $2kT\nu^2/c^2$ ergs per area per steradian per Hz per second.
- Multiply by antenna effective area ($\sim d^2$) and solid angle ($\sim(\lambda/d)^2$) to get $\sim 2kT$ erg/s/Hz.

Antenna Gain

- Power coming in from a small source is flux*effective collecting area. What temperature change needed to make that flux change?

- $FA_{eff}=2kT$, $T/F \sim A_{eff}/2k$.

- This is called the telescope gain - it tells us the change in temperature at focus given by a source of fixed flux.

- Note that this is independent of frequency! As long as A_{eff} is constant (and Rayleigh-Jeans holds).

Gain in K/Jy

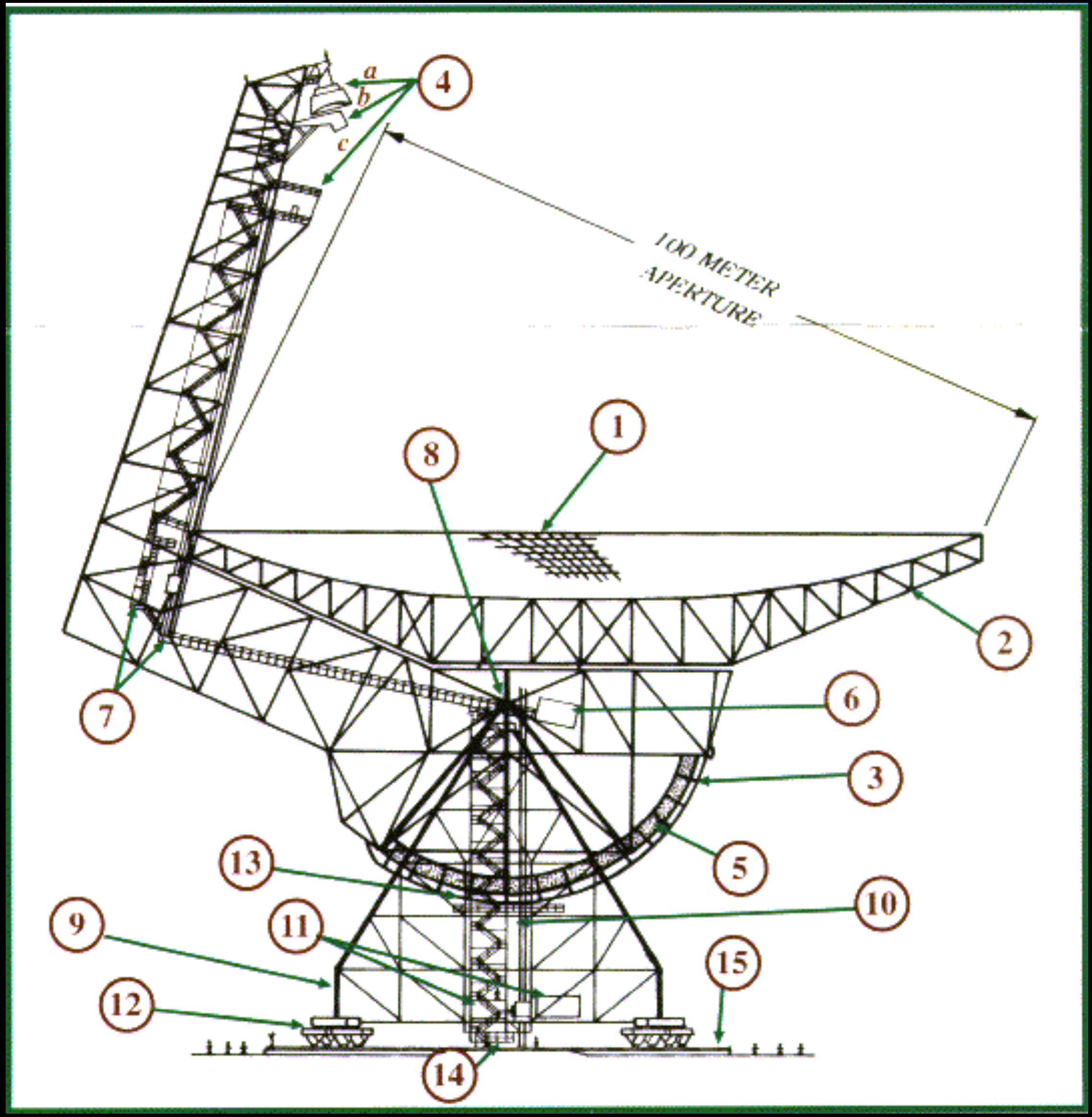
- Usual flux unit is a Jansky, equivalent to 10^{-23} erg/cm^2/s/hz = 10^{-26} W/m^2/s/hz.
- Example: GBT has 100m diameter, 70% aperture efficiency at low frequencies.
- $0.7*\pi(5000)^2/2k=2e23$ K (for 1 erg/s/hz source) = 2 K/Jy.
- If I have 1 GHz of bandwidth on GBT, with Tsys=20K, what is error in Jy after 1 minute?

Gain in K/Jy

- Usual flux unit is a Jansky, equivalent to 10^{-23} erg/cm^2/s/hz = 10^{-26} W/m^2/s/hz.
- Example: GBT has 100m diameter, 70% aperture efficiency at low frequencies.
- $0.7*\pi(5000)^2/2k$=2e23 K (for 1 erg/s/hz source) = 2 K/Jy.
- If I have 1 GHz of bandwidth on GBT, with Tsys=20K, what is error in Jy after 1 minute?
    - dT=20K/sqrt(Bt)=20k/sqrt(1e9*60)=8e-5. Gain is 2K/Jy, so equivalent to 4e-5 Jy = 40 µJy. 2 pols would get sqrt(2) more

GBT Optical Design/A_{eff}

- In practice, usually have a secondary mirror that routs signals into feeds.
- Feeds have beam patterns too.
- Picture feed as transmitter. Edges of primary won't (in general) be as brightly illuminated as center.
- A_{eff}=Area times average illumination relative to peak.
- Hard to get A_{eff} >70% of area, often lower.



Feed Beams

- We can try to tune the beam of the feed.
- We will want to match this to the telescope we use, especially the focal ratio.
- If the feed beam is small, most of the dish isn't used, this is called *underillumination*.
- If the feed beam is very large, most of it misses the dish.
- If you are designing a telescope, think *very* carefully about this. Rays that end up on ground see 300K and can increase T_{sys} a lot. This is called ground spill.
- You can reduce ground spill at the price of underillumination. One of the main tradeoffs in building telescopes.

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(!).

Receivers

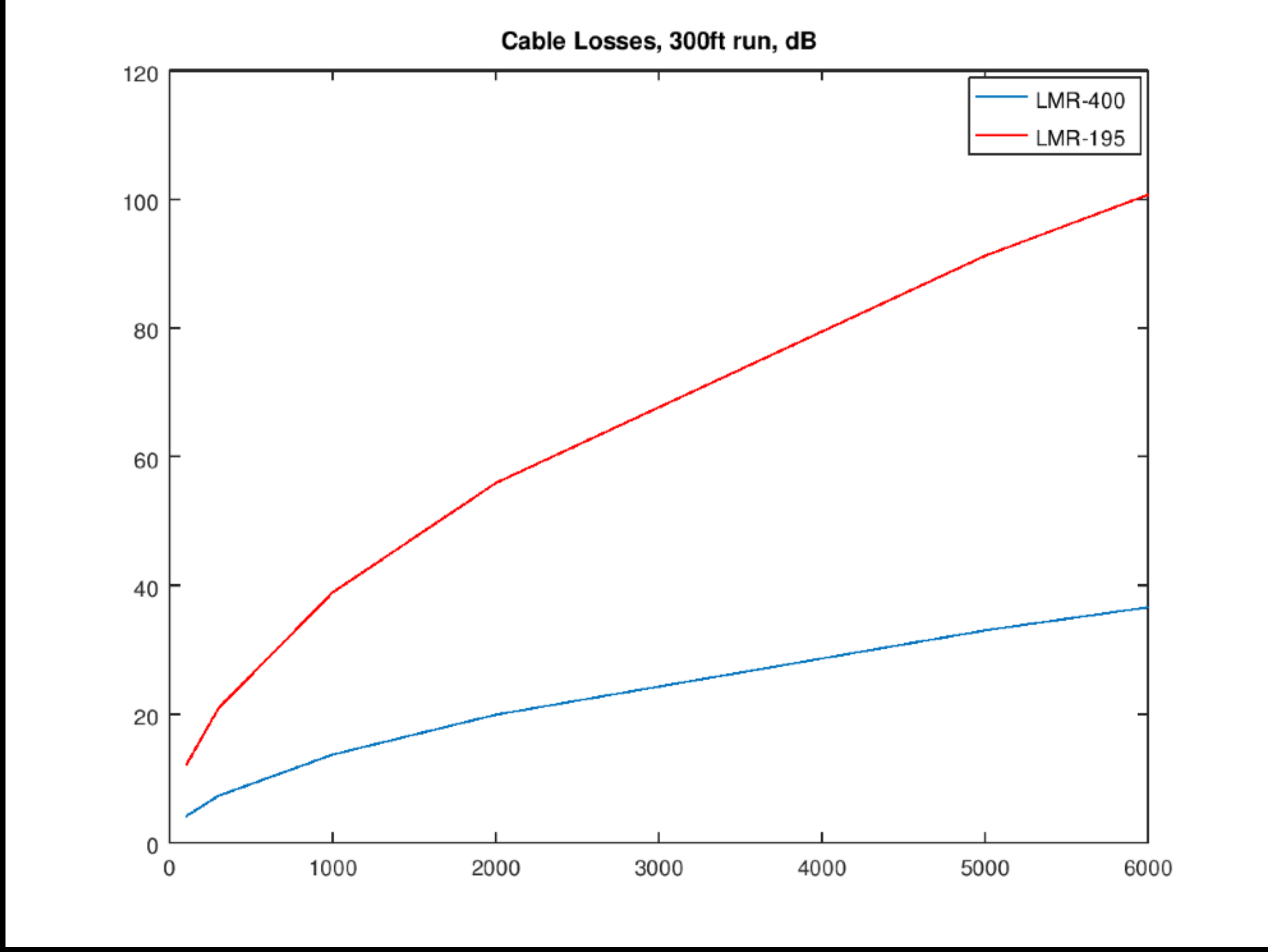
- Radio waves come into detector.
- Something needs to measure them - usually an ADC (analog to digital converter)
- ADCs are noisy, and we may have signal loss en route through cables.
- So, usually amplify signal as soon as it comes in.
- Amplifiers usually quoted in logarithmic dB, 10 dB a factor 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.

Mixing

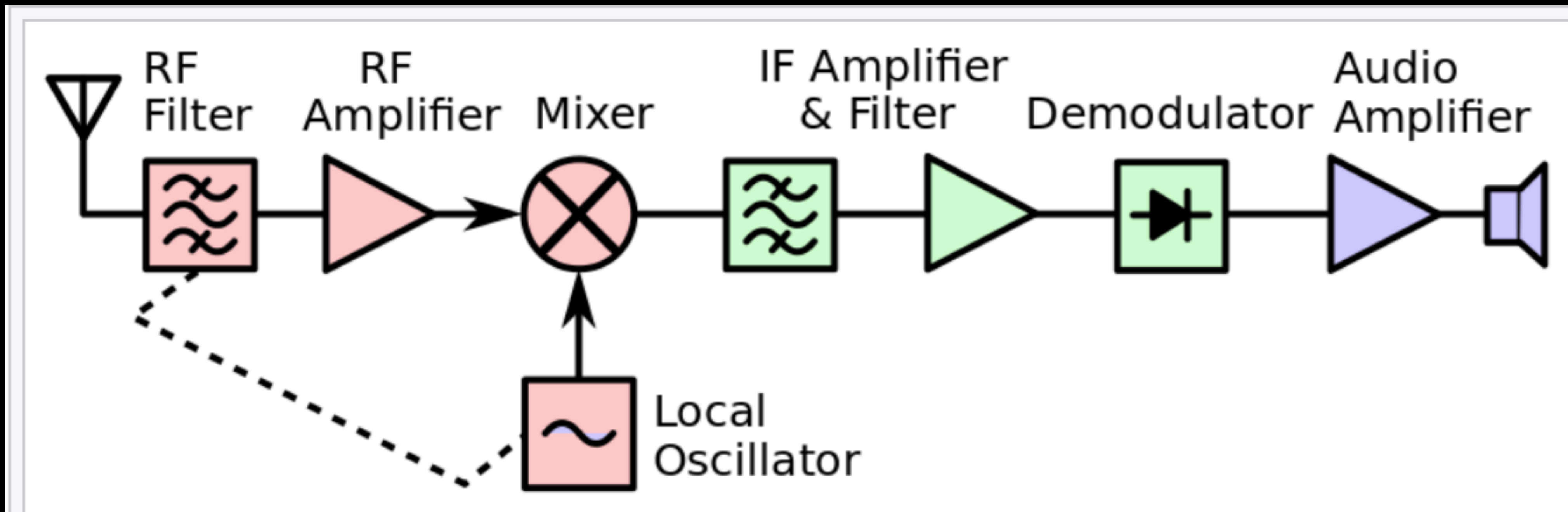
- We'd like to be able to observe at any frequency.
- ADCs will only work at some frequency. Usually (but not always) lower than frequencies we care about.
- Sending high frequencies along cables is also challenging. Cable loss grows quickly with frequency.
- Getting signal down from GBT at 5 GHz could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



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.

Super Heterodyne Receiver



- Signal comes in. Gets amplified/filtered (often amplified before the filter. Why?)

- Separate signal 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 second Nyquist zone.