Observational Astronomy and Data Analysis
Astronomy 465, Fall 2024
Prof. Snezana Stanimirovic, Dr. Ralf Kotulla,
Hongxing Chen

Lecture: Tue 11-11:50 AM
(1335 Sterling Hall)
Labs: Tue & Wed 3:30-5:30 PM
(3521 Sterling Hall)

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Where are we up to with the labs?

- This week: work on the 1st optical lab
- Radio 1st lab due on Friday, Oct 4
- Weekly updates here: https://docs.google.com/document/d/10mH-rBTxGSY0CdmK4tlD1Y_73zJ4gzC9bV3AEiGnNws/edit

- A word about Python: give yourself some time, it's mostly trying things out (google for what you need to do and try some suggestions), reach out to classmates who have previous Python experience
- Reports and Overleaf?

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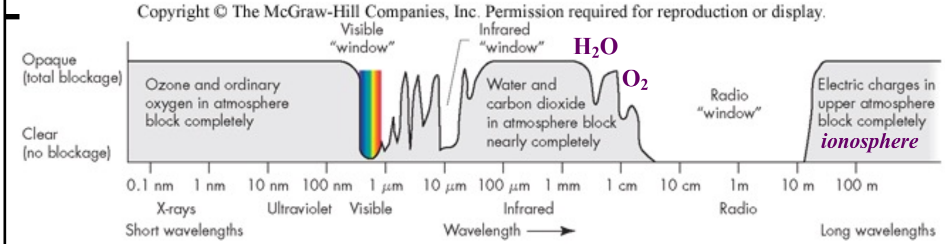
Lab schedule (dates may shift as we go)

- Lab 1: Characterizing a radio telescope - beam shape; due Oct 4
- Lab 4: Calibrating a CCD camera; due Oct 11
- Oct 8 - Lab 2: Characterizing a radio telescope - noise and temperature calibration
- Oct 15 – Lab 5: Stellar photometry - Age-dating a star cluster
- ~Nov 5 - Lab 3: Milky Way rotation curve
- (Lab 6: Surface photometry of nearby galaxies)
- Nov 26 – Prepare posters for the Undergraduate Symposium

Earth's atmosphere & radio window

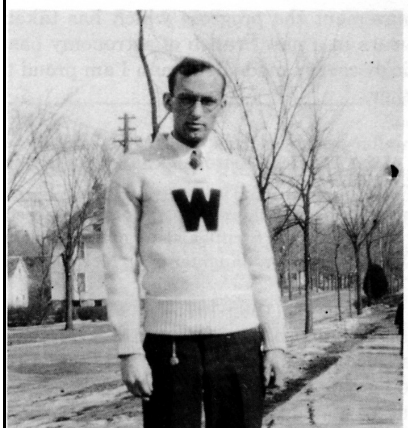


- Radio window is wider than the optical, but no attempts to do radio observations until 1932 and the accidental detection of radio signals by Karl Jansky.
- Reason: Expected flux density of thermal radiation for a Sun-like star at a distance of 1 pc is only 3×10^{-7} Jy. Too faint! Other emission mechanisms were not known at that time.
- Radio window:
  - Frequency: ~10 MHz to ~1000 GHz
  - Wavelength: ~30m to ~3mm

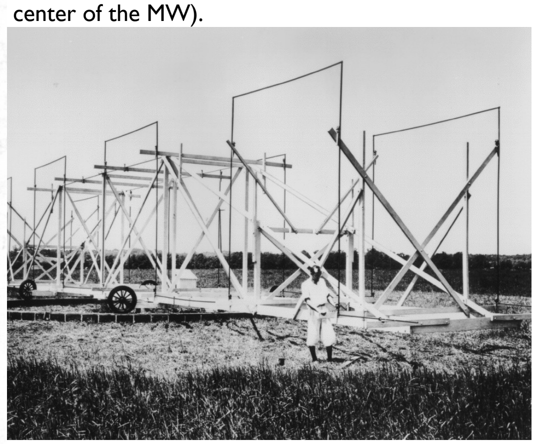
1 Jansky = 1 Jy = 10^{-23} erg sec^{-1} cm^{-2} Hz^{-1}

Long history of radio astronomy at UW: Karl Jansky (UW-Madison graduate!)

- Antenna at 20 MHz (14.5m) to investigate static that interfered with radio telephone transmissions.
- In 1933 found a faint signal of unknown origin that rose and fell once a day.
- Jansky thought this was the Sun (but it was the center of the MW).



Karl Jansky as University of Wisconsin student, wearing sweater with letter earned as member of university ice-hockey team.



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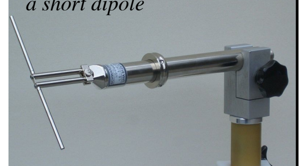
A wide range of radio telescopes…

- With the freq. range of 10 MHz to 1000 GHz there is a <u>great</u> variety of radio telescopes and observing techniques.
- All do the same job: convert EM radiation into electric current
- In a **radio receiver**, the incoming electromagnetic radiation exerts force on free charge inside a conducting antenna. This produces electric current which is being detected and amplified in the "receiver".
- In a **radio transmitter**, an oscillating electric current is applied to the antenna. This results in the motion of electric charge along the length of the conducting antenna, producing field disturbances and electromagnetic radiation.

Reciprocity theorem: can describe a telescope either as a receiver or a transmitter.

The simplest radio antenna: a short dipole



Very Long Baseline Array

Arecibo

LOFAR station

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SRT basic components and specs

1. **Parabolic, prime focus reflector** D = 2.3m
→ determines angular resolution = 6-7 degrees
2. Azimuth-Elevation Mount + Drive box
Az limit = 0 to 360 deg;
El limit = 2 to 90 deg
Pointing accuracy: ~1 deg
3. Feed horn + Receiver
Frequency range =
1400-1440 MHz
(several frequency modes)
4. Noise diode for calibration

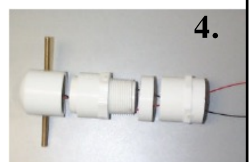
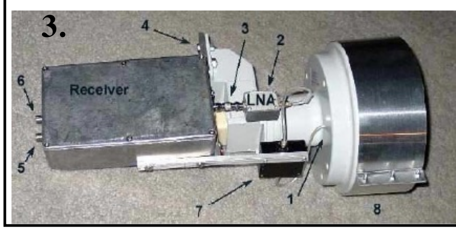


Figure 4 Noise Calibrator



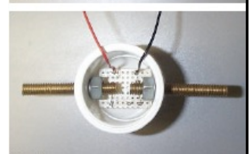


Figure 5 Cap

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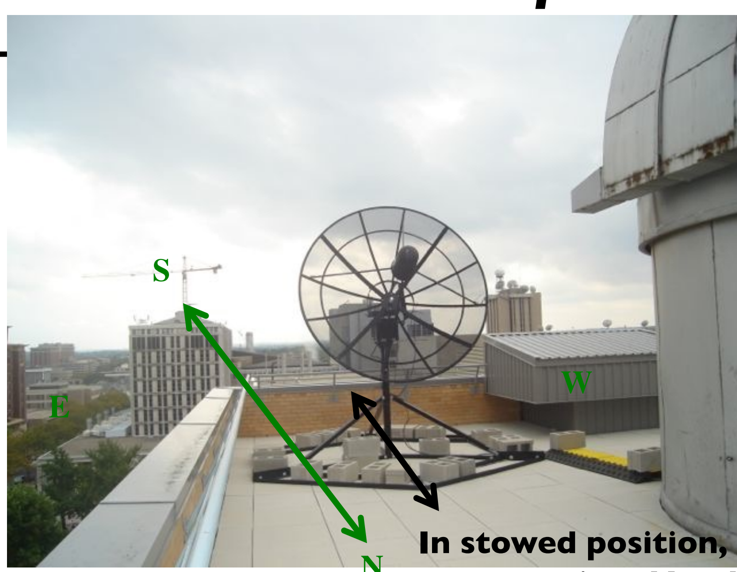
Radio telescope basics



In stowed position, the SRT points North (the receiver is lined up N-S)

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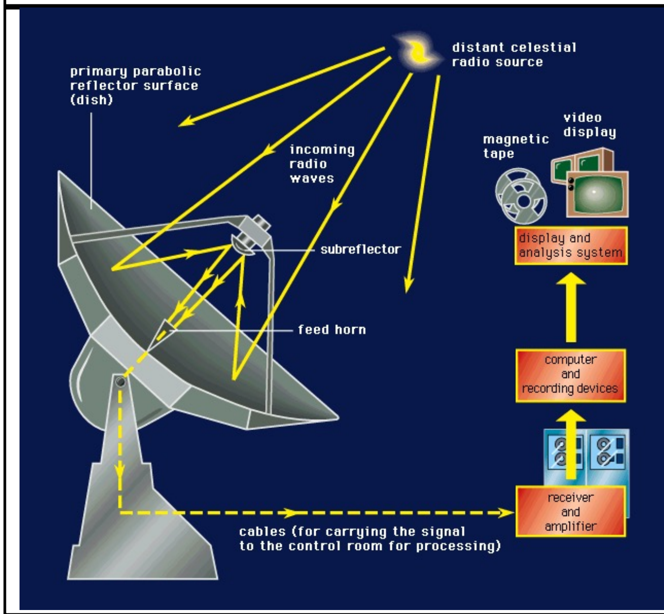
A simple schematic of a radio telescope



Reflector or antenna or dish collects and focuses radio waves into the feed. Sometimes telescopes have multiple reflectors.

Feed, usually a horn, guides waves to the probe and the receiver.

Probe (or transmission line) detects the signal and the **receiver** amplifies and further filters the signal.

Spectrometer or computer produces spectra.

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SRT's receiver

FIG. 2. A block diagram of the SRT Receiver

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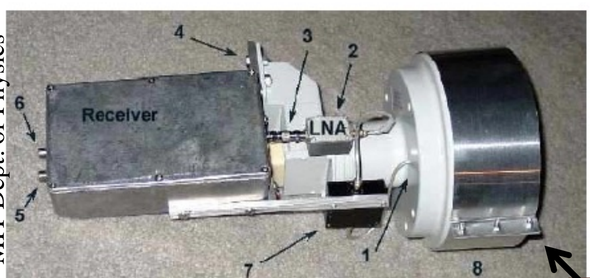

FIG. 3. A picture of the antenna feedhorn

1 - L-Band probe
2 - Low Noise Amplifier
3 - Universal Male F to F Coupler
4 - Receiver mounting bracket
5 - Video Port - Analog signal
6 - Power and Communication - Digital Signal
7 - Band Pass Filter
8 - Feed Horn Extension

"antenna" (short dipole) that detects radio waves. This is the probe (or transmission line)

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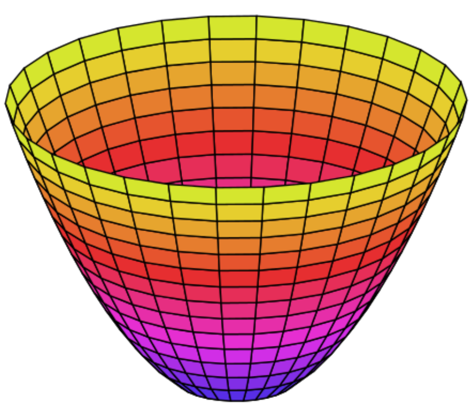
Few important concepts: Fundamentals, chapter 1.4.1

1. *Sensitivity*. As with optical telescopes, the light–gathering power of a radio telescope depends on the *effective collecting area* of the telescope, A_e.
   Larger dish → more sensitivity
2. Unlike optical telescopes, radio dishes do not need to have a highly polished surface.
3. *Directivity*. While the resolution of the optical telescope is limited by atmospheric turbulence, the resolution of a radio telescope is determined by diffraction. Building larger reflector → higher resolution

Radio telescopes are coherent detectors: as each photon carries very little energy, to detect EM we need large ensembles of photons and we need to detect them all *in-phase* so the signal does not cancel out.

Spectrometer is used to measure EM radiation or power of radiation across many narrow frequency bands (channels or bins)

What defines antenna design?

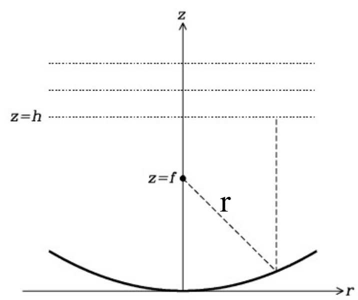


$$\frac{z}{c} = \frac{x^2 + y^2}{a^2}$$

Circular paraboloid

Requirements to focus light to a single point + bring on and off-axis rays to the focus at the same time, result in the need for a circular paraboloid. This is the most common shape for radio telescopes.
Fundamentals Chapter 3.1 + "Essential radio astronomy"

Circular paraboloid



- Both on and off-axis rays need to the arrive at the focus at the same time
- Requirement for a constant path length leads to:

$$(f+h) = \sqrt{r^2 + (f-z)^2} + (h-z)$$

- → $\boxed{z = \frac{r^2}{4f}}$

This is **the equation of a circular paraboloid** with f being the focal length.

- f/D = the focal ratio of the telescope, D is the diameter of the reflector. This is commonly used for optical telescopes and expresses how large is the field of view.

Reflector surface

- **How fine does the reflector surface need to be?**
  The “Ruze theory” can be simplified as: $\sigma \approx \frac{\lambda_{\min}}{16}$

  sigma = surface error, λ_{min} is the minimum usable wavelength of operation.

  (3.1.4 in Fundamentals or Chapter 3 in “Essential radio astronomy”)

- Example: Green Bank Telescope in West Virginia was made to operate at a frequency of up to 100 GHz (3 mm). To meet this requirement, the rms surface deviation from a perfect paraboloid must not exceed σ~3mm/16 = 200 μm.

- At 1420 MHz or 21cm the requirement is only σ~21cm/16 = 1.3 cm → a simple mesh surface is fine

- Mesh color: most radio telescopes are painted white to reflect sunlight and avoid deformation due to solar heating. SRT has an aluminum frame. The surface holes are <lambda/10

NOEMA (French Alps) antennas

Surface rms: 30 μm
Prime focus telescopes like the SRTs

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Antenna-sky coupling
(Fundamentals, Chapter 3.1)

- Radio receivers use a single-mode transmission lines and only a single polarization state is handled at the time.
- Power received (or collected from a source) by the telescope is (I = specific intensity, Ω = solid angle, ν = frequency, A_e = effective area):

$$P_{\rm rec} = \frac{1}{2} A_e I_\nu \; d\Omega d\nu$$

- A_e (or A_{eff}) is the **effective area of the telescope**. $A_e = \eta A_p$
  It is related to the telescope physical (or geometric) area A_p through the **aperture efficiency η.** This accounts for all losses due to blockage of the surface by the feed and feed support, over/under illumination of the surface by the feed, surface irregularities etc.

- Telescopes's ability to differentiate emission from objects at different solid angles determines its resolution and is described with the beam pattern. Directivity is governed by diffraction. We define this with a (antenna or beam) normalized power pattern (optical telescopes: Point Spread Function): $P_n(\theta, \phi)$

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Cont. [Lab 1: Theory]

- This means that our measurements in any direction are affected by the telescope's beam pattern:

$$\boxed{P_{rec} = \frac{1}{2} A_e I_\nu(\theta,\phi) P_n(\theta,\phi)}$$

- The total power received per unit frequency is then:

$$P_{\mathrm{rec}}(\nu) = \frac{A_e}{2} \int\int P_n(\theta,\phi) I_\nu(\theta,\phi)\ d\Omega$$

- If we observe a point source (*angular size of source << the beam*), which can be described as a delta function, the result is just the power or beam pattern.

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How can we measure P_n ?

2012 Astro 510 class work.

Observed Sun and measured telescope's response in Az and El.

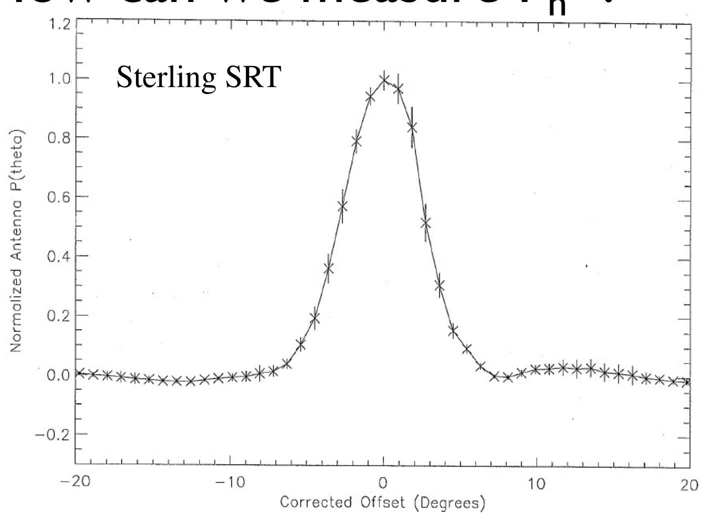

Fig. 1.— Normalized Average Emission Spectrum for Antenna Beamwidth of SRT using Sun Scans in Azimuth with 1-Sigma Error Bars (X - plot symbol). Noise was fit with second order polynominal and subtracted from RAW data. The spectrum was obtained form SRT observations taken on February 3, 2012.

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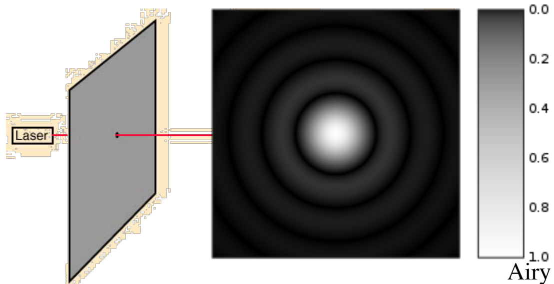
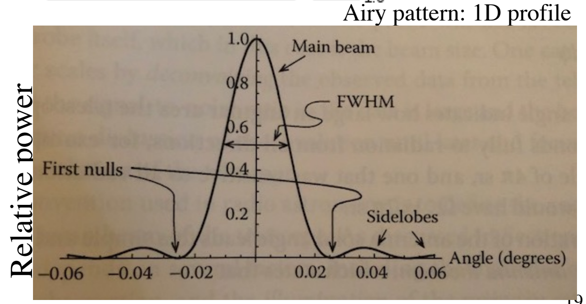
Airy pattern = diffraction pattern = power (beam) pattern of a uniformly illuminated circular aperture



Airy pattern: 1D profile

The **power pattern** is the angular distribution of radiated/received power, often normalized to unity at the peak.
Tells us in which directions (solid angles) is the telescope sensitive to receiving or transmitting radiation.



Distance from the center in degrees

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Cont.

- The Airy pattern assumes uniform illumination of the slit or telescope's primary reflector.

- Mathematically, the normalized power pattern for a uniformly illuminated circularly symmetric aperture is expressed with:

$$P_n(\theta) = [\frac{2J_1(\pi\theta D/\lambda)}{\pi\theta D/\lambda}]^2$$

- Antenna pattern also tells us what is the resolving power or angular resolution of the telescope. Essentially any two points closer than the Half Power Beam Width, HPBW = 1.02λ/D radians (D is aperture size, λ observed wavelength), will not be resolved.
- As HPBW depends on the aperture size, larger apertures result in higher angular resolution.
- J_1 is the Bessel function
- **HPBW = FWHM = full width at half maximum**

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Illumination of radio telescopes is never uniform

- However, most radio feeds do not have uniform illumination. Often illumination tapers or drops off close to the edges of the primary reflector. This results in the final power pattern being close to a Gaussian function with its Half Power Beam Width in radians being given as:

$$\boxed{\theta_{\mathrm{HPBW}} \approx 1.2\lambda/D}$$

- Notice that this is slightly broader than

what the diffraction-limit (Airy function) will have.

Literature: “Fundamentals of radio astronomy” Chapter 3.1+4.2, also “Essential Radio Astronomy”

Another useful book: “Single Dish Radio Astronomy and Applications”
http://aspbooks.org.ezproxy.library.wisc.edu/a/volumes/table_of_contents/?book_id=389

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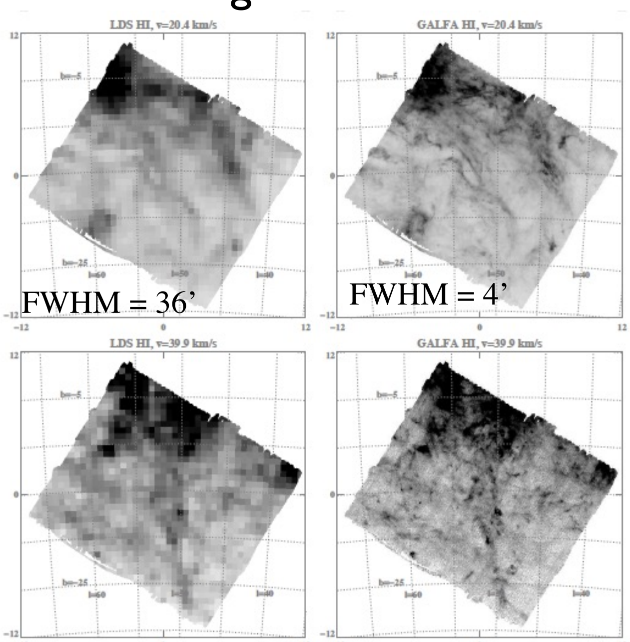
Example: different angular resolution

- Higher resolution observations always show more structure, both in images and spectra.
- Any telescope or spectrograph always has limited resolution and we need to keep this in mind when preparing and interpreting observations.



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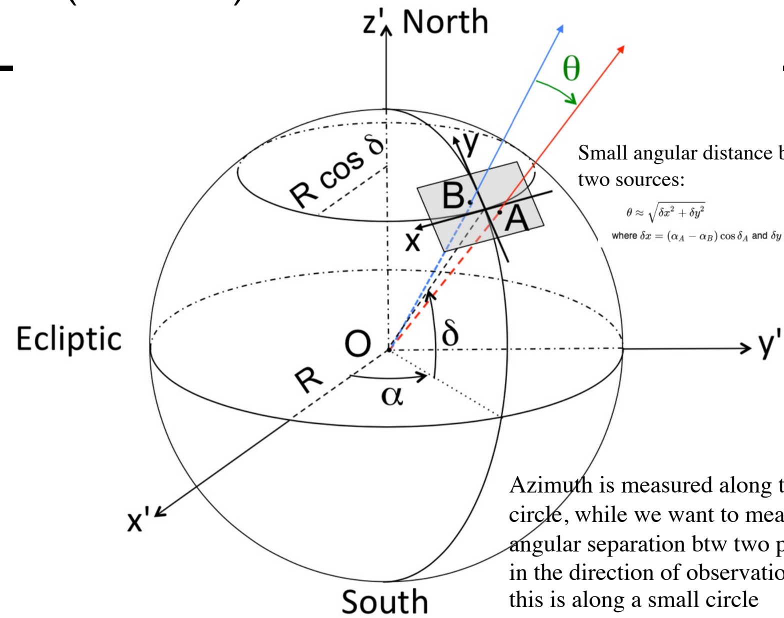
Cos(Elevation) correction for Az beam scans



Small angular distance between two sources:

$$\theta \approx \sqrt{\delta x^2 + \delta y^2}$$

where $\delta x = (\alpha_A - \alpha_B)\cos\delta_A$ and $\delta y = \delta_A - \delta_B$.

Azimuth is measured along the great circle, while we want to measure angular separation btw two pointings in the direction of observation and this is along a small circle

Few problems

Q1:

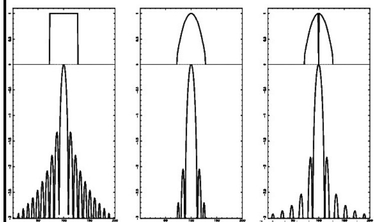
- The Haystack SRT has a diameter of 2m, and can observe at a wavelength of 21cm with a maximum bandwidth of 1.50 MHz. What is the angular resolution of the SRT in degrees?

Q2:

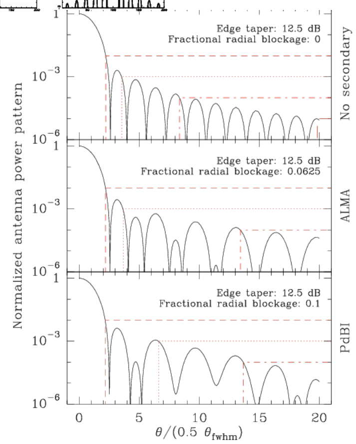
- The Haystack SRT has a diameter of 2m, and can observe at a wavelength of 21cm with a maximum bandwidth of 1.50 MHz. Assuming that the SRT has the optimum edge taper, calculate the following:

1. The angular resolution in degrees
2. The maximum collecting area
3. The maximum detected power from a 1-Jy source located at the peak of the first sidelobe

Tapering and aperture illumination affect telescope's beam shape



Top: tapered illumination function;
bottom: resulting power pattern



The illumination or edge taper that maximizes the effective collecting area, provides a good compromise between sidelobe levels and angular resolution is called: **optimum (10-dB) taper** (power transmitted at the center is 10x larger than at the antenna edge:

$$\theta_{fwhm} = 1.15\lambda/D$$

First sidelobe is at 0.4% of the main beam. Maximum collecting area is 82% of reflector's physical collecting area.

dB????