A6525
Radio Astronomy
(m-cm wavelengths)

Lecture plan

1 Single element radio telescopes (optics and radiometry)  JMC
2 Noise, radio sources, and source confusion  JMC
3 Radiation fields, propagation, polarimetry  JMC
4 Time domain (transient detection, pulsar timing)  JMC
5 Interferometry and aperture synthesis I  JMC
6 Synthesis imaging  SC
7 Source detection  SC
8 Surveys, VLASS, new instrumentation  SC
9 Radar astronomy/phased-arrays  DBC
10 Spectroscopy and HI surveys  RG
11 Spectroscopy and HI surveys  RG
12 Spectroscopy and HI surveys  RG

Reference Books

- Rohlf & Wilson
  *Tools of Radio Astronomy*
- Thomson, Moran & Swenson
  *Interferometry and Synthesis in Radio Astronomy*
- Smolders & van Haarlem
  *Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays*
- Kraus
  *Radio Astronomy*
- Lorimer & Kramer
  *Handbook of Pulsar Astronomy*
- Born & Wolf
  *Principles of Optics*
- Bracewell
  *The Fourier Transform and its Applications*
Some Classic Papers

- *Thermal Agitation of Electricity in Conductors*, J.B. Johnson, Phys Rev, 32, 97 (1928)

Radio Telescopes

- Antennas
  - Dipoles and resonant antennas:
    - Select components of the radiation field $E(x,t)$
    - Directions, frequencies, polarization
  - Reflectors:
    - Direction selectivity (PSF)
    - Frequency selectivity from
      - Surface Imperfections $\rightarrow \lambda_{\text{min}} \sim \sigma_s / 16$
      - Diffraction: $\lambda >$ size of structural elements
    - Designed to collect radiation at a focal point that by definition is in phase
- Measurements are often of fields, not just power
- Manipulation of fields is a key difference between optical and radio telescopes although in principle, all telescopes manipulate fields before power is measured
- Modern radio telescopes digitally sample fields and manipulate them to achieve specified optical performance (coherent dedispersion [pulsars], correlators, aperture synthesis)
### Comparison of Radio and Optical Components

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<td>1 $\mu$as (SIM)</td>
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### Components of a Radio Telescope System

- **Antenna (Reflector System)**
  - A phase transformer
  - Spherical wave $\rightarrow$ plane wave
- **Feed System (Horn)**
  - Launches spherical wave front
  - Dictates amplitude distribution over the primary reflector (sometimes in conjunction with secondary reflector)
- **Receiver system (radiometer)**
  - Measures power in a specified bandwidth
  - Preserves amplitude and phase relationships (for heterodyne systems)
### Antennas as Concentrators and Detectors

- Reflector antennas concentrate EM energy
  - But think coherent summation of electric fields
- Metal probes or terminals of a dipole antenna provide a voltage proportional to the electric field selected by the antenna

→ Electric field components (amplitude and phase) are directly accessible to digital sampling

  e.g. LOFAR, LWA, MWA, PAPER, HERA, SKA-low ...

### Apertures and Diffraction

- Topologically a reflector antenna (no matter its detailed optics) is the same as a single slit in a screen.
  - The reflector maintains coherent phase in the aperture plane
- In the far field at distance $D >>$ aperture size, the angular response ($PSF =$ antenna power pattern) is the Fourier transform of the aperture
- In practice, the field in the aperture is not uniform (deliberately) so the “illumination” pattern is also included in the Fourier transform
- The PSF can therefore be shaped to control sidelobe levels, width, etc.
Fresnel Diffraction

Huygens’ principle says that each point within an aperture \( A(x) \) illuminated by a plane wave radiates spherical waves. At a position \( x \) the scalar electric field is given by the Kirchoff Diffraction Integral (KDI),

\[
\varepsilon(x, \lambda) = \frac{1}{i\lambda D} \int dx' A(x') e^{i\Psi(x, x')}
\]

\[
\Psi(x, x') = \frac{k}{2D} |x - x'|^2
\]

\[
k = \frac{2\pi}{\lambda}
\]

\[
\frac{k}{D} = \frac{2\pi}{\lambda D} = \frac{1}{\frac{\lambda D}{\lambda}} = \frac{1}{(\text{Fresnel scale})^2}
\]

Can be recast as a convolution problem:

\[
\varepsilon(x, \lambda) \propto A(x) \ast K(x)
\]

\[
K(x) = e^{i \left( \frac{\lambda x}{D} \right)^2} = \text{Fresnel function}
\]

- Locations near the aperture: Fresnel diffraction
- Far from aperture: Fraunhofer diffraction
- Transition distance = Fresnel distance = \( D_F \sim \frac{\text{(size of aperture)}^2}{\lambda} \)
Radio Telescopes

The first 50 years: experimentation, discovery and striving for sensitivity + angular resolution, time resolution

Now: Experiments, precision cosmology and astrophysics, a new era of exploration: sensitivity + resolution + high time and frequency resolution
Lecture 1: Introduction to Radio Astronomy

Karl Jansky
Bell Telephone Laboratory 1933
Reber Telescope (1940s)

Figure 1.3: The 85-foot Horned E. Tietel radio telescope used by Frank Drake at the National Radio Astronomy Observatory in Green Bank, West Virginia, for Project Ozma in April 1960. Part of the image reassembled for the 75th anniversary of the project, including Drake, standing second from the right.
Nancay Radio Telescope

Molonglo Observatory Synthesis Telescope
Parkes (CSIRO/ATNF)

Effelsberg
MPIfR, Bonn
Green Bank Telescope

Ryle Synthesis Telescope (Cambridge)
VLBI / VLBA

VLBA Astrometry

PSR B0919+06
S. Chatterjee et al. (2000)
μ = 88.5 ± 0.13 mas/yr
π = 0.83 ± 0.13 mas

D = 1.2kpc
V = 505 km/s
Proper Motions of Pulsars

- Interferometry (VLA, MERLIN, VLBA)
  - mas/yr - arcsec/yr
- Timing
  - microsec - ms
- Interstellar Scintillation
  - intensity (t, ν) (minutes, MHz)

Maser emission from water molecules orbiting a central black hole in NGC5258

VLBA
Ray tracing vs Diffraction

• Ray tracing has its uses in radio astronomy but diffraction almost always has to be included in a detailed analysis

• Why different from OIR?
  Because $\lambda$/optical-element sizes) are larger

Beam Patterns and Pixels

• All telescopes have an angular response to radiation
• Optical/IR/X-ray/Gamma-ray: point spread function (PSF)
• Radio: antenna power pattern $P_r(\theta)$
• A single reflector with a single feed antenna at the focus has one pixel
Getting Multiple Pixels

1. Use multiple feed antennas (feed clusters)
   e.g. ALFA = Arecibo L-band Feed Array (7 pixels)

2. Use a phased-array feed system
   Difficult, R&D now a major part of SKA efforts

3. Use arrays of antennas as interferometers and synthesize an aperture

Innovations in Radio Telescopes

• Where needed?
  • High angular resolution with high sensitivity
  • Wide overall field of view for
    – Fast surveys of the sky (large numbers of objects)
    – Time variable sources (bursts)

• Challenges:
  • Building collecting area cheaply
  • Exploiting Moore’s law in digital electronics
  • i.e. steel/aluminum vs. silicon/germanium
Points

• Beamwidths: $\theta \approx \lambda / D$
  – Applies to all detectors of wavelike phenomena
  – Optical/IR telescopes, radio telescopes, our eyes
• Effective temperatures (pretend radiation is blackbody in the Rayleigh-Jeans regime)
• Unit for flux density: the Jansky, used to characterize radio sources
• Radiometer noise: analogous quantity to readout noise + photon counting noise in CCDs (with different statistics)

Nomenclature

• Antenna beam pattern = point spread function (PSF)
  – Beam FWHM = full width at half maximum
  – Beam solid angle $\sim (\pi/4) \text{FWHM}^2$
  – Beam = diffraction effect
  • For aperture of size D, radiation is diffracted into an angle $\lambda/D$
  • The solid angle is then $\sim (\pi/4) (\lambda/D)^2$
  – Sidelobes of the beam pattern
• Radiometry and radiometer equation; radiometer noise; radio source confusion
• Effective temperature of radiation
• System temperature of radiometer
• Heterodyned receiver system, local oscillator, sidebands, baseband
Effective Temperatures

- Radio telescope measurements can be calibrated into temperature units
- Examples:
  - Cosmic microwave background: 2.7 K it is a bb!
  - Clouds in the interstellar medium: HI, HII
    - HI: temperatures 10s of K up to ~ 10^3 K
    - HII: 5000 – 12000 K
  - Sun: 6000K at some λ, 10^6 K at others ???
  - Interstellar masers: up to ~ 10^{14} K
  - Pulsars (rotating neutron stars): up to 10^{41} K !!!

Flux Densities

- The Jansky unit of flux density was invented in the 1960s and was chosen to be ~ 1 for radio sources detectable then.
- Today (better receivers) we can detect ~ 10^{-6} Jy sources
- Energy in 1 sec in a 1 Hz bandwidth through a 1 cm^2 area:
  - ΔE = Fν Δt Δν ΔA = 10^{-23} erg or 10^{-26} Joule
- All the energy collected by all the radio telescopes ever ~ 1 erg.
Extended Sources

- Definition: Source much larger than antenna power pattern main lobe: $\Omega_s >> \Omega_A$
- Then the measured power is $P_v = kT \Delta v$
- So what?
  - The measured power is independent of the telescope size
  - Why is this useful?

Basic Lessons: A Minimalist View

- Phase, phase, phase
  - Imaging, polarization, dedispersion, radar
  - Phase restoration w.r.t. propagation and instrumentation
- Noise, noise, noise
  - All celestial signals are statistical in nature
  - High photon number $\Rightarrow$ Gaussian statistics (with a notable exception)
- Waves and fields, not photons
- Nonthermal, thermal radiation
- Incoherent, coherent radiation
- RFI: a low/high tech nuisance needing high-tech solutions
- Array telescopes: the future
- Computational astronomy and datamining:
  - Massive data sets
  - Virtual Observatories (National, International)
**Diffraction**

The narrower the slit, the wider the diffraction pattern.

Telescope analog: Slit $\rightarrow$ lens or mirror size.

The wider the slit separation, the closer the spacing of fringes in the diffraction pattern.

Telescope analog: Slit separation $\rightarrow$ baseline of interferometer.

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**Radio Antenna Power Patterns**

http://www.haystack.edu
Optical Point Spread Function

http://zeiss-campus.magnet.fsu.edu/articles/basics/images/

Diffraction Point Spread Function (PSF): The PSF is calculated by FFT from the wavefront aberration. The ray density in the pupil may be increased to improve the accuracy of the PSF. The PSF may be displayed as perspective wire-grid plot, gray-scale intensity plot, false color plot or "true" color plot.

Not included in OpTalIX-LT
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3.8 m Space Sciences Radio Telescope

3.8m diameter
f/0.4 prime focus optics
Single polarization channel
RF = 1.4 GHz
Three mixing stages
Can detect the 21 cm atomic hydrogen line as well as with the Green Bank Telescope (100m) and Arecibo (305m)
Why?
Direct Baseband Recording and FFTs: Access to phase

\[ S(v) = \left| \int_{-\nu_0/2}^{\nu_0/2} x(t) e^{-i2\pi vt} dt \right|^2 \]

For “normal” computer hardware, current sampling and storage rates < ~100 MHz

Current GUPPI (Green Bank Ultimate Pulsar Processing Instrument) or Arecibo version (PUPPI) can sample a 800 MHz bandwidth at 8-bits, and do spectral/deg-
dispersion analysis in real time using 2048 spectral channels. 40 usec minimum sampling interval for direct sample and record on disk.

VLBI recorders: 1 Gbit/s, 2 polarizations, 128 MHz, 2 bits
Soon 4 GHz, increasing bandwidth to 512 MHz for 2 polarizations

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Block diagram of “front-end” receiver

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Figure 1: Diagram of three panels
Digital “back end” receiver

Figure 3: Overview of RF/IF path and iBOB block diagram

Two examples of the power of phase

- Imaging with aperture synthesis = manipulation of the correlation function between fields measured between multiple pairs of antennas

- Dedispersion of a pulsar signal to remove the effects of propagation through the ionized interstellar medium (deconvolution of digital data)
Cygnus A

Radio image
Very Large Array
Aperture Synthesis

Sub-nanosec shot pulse from the Crab Pulsar

Requires digital filtering of the electric field components selected over a 2.5 GHz bandwidth to remove phase wrapping imposed by dispersive propagation through the interstellar medium.
Radiometry

- Radio telescopes are used as **radiometers** to measure power incident on an antenna
  - A single reflector antenna + single “feed” antenna at the focal point = a single pixel
  - Significant (Nobel prize) single-pixel science:
    - Discovery of the Cosmic Microwave Background
    - Discovery of Pulsars
    - Indirect detection of gravitational waves from a pulsar binary

- Spectroscopy = frequency resolved radiometry
- Sensitivity of a radiometer is characterized in terms of the **system temperature**:
  - \( T_{\text{sys}} = T_{\text{sky}} + T_{\text{receiver}} + T_{\text{spillover}} + \ldots \)
- m wavelengths: Galactic noise from synchrotron radiation dominates
- cm wavelengths: receiver + thermal Galactic noise
- mm wavelengths: receiver + atmospheric noise

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Background Sky Noise

![Background Sky Noise Diagram](image)
Radiometry Fundamentals

In contrast to optical and infrared astronomy where it is natural to think of photon detection, radio astronomy generally involves signals formed from large numbers of photons that are, hence, well within the classical regime. Radio signals from natural sources are inherently random, and this randomness determines (i.e. limits), in part, the ability of a radio telescope to discriminate individual radio sources.

A single-antenna radio telescope with standard receiver is a radiometer that measures the power level of the radiation at the frequency $\nu$, in the polarization, and in the solid angle to which the telescope is sensitive. The ability of the telescope to identify an individual radio source depends on:

1. Radiometer noise: noise produced by the sky background and by the telescope itself. The sky background consists of an isotropic 3 Kelvin ‘cosmic’ background (the blackbody radiation left over from the big bang); a broadly distributed synchrotron background from galactic cosmic ray electrons; and a thermal background from plasma in the galactic disk. The relative contributions of these backgrounds and instrumental noise depend strongly on radio frequency.

2. Radio source ‘confusion’; radiometer variations caused by the ensemble of sources that are in the telescope beam at any instant. For a fixed antenna, as the Earth rotates, individual sources pass through the beam and the number of sources in the beam is a Poisson random variable; thus the radiometer output varies with time. To single out any given source, its flux density must be greater than the root-mean-square variation due to confusion.

3. Gain variations: All real world amplifiers and detectors have output levels that vary with time due to various macroscopic (e.g. temperature) and microscopic (1/f noise) causes.

4. Radio frequency interference (RFI): Sources of RFI range from the ridiculous to the sublime, being caused by car ignitions; arcing in motors and relays (e.g. the Space Science Bldg. elevator); lightning; aircraft and police transmissions; satellites. RFI is noticeably less at night and on weekends, as well as at remote locations and, generally speaking, at higher frequencies ($f \geq 30$ GHz).
Blackbody Radiation. Radiation from a blackbody source is described by a brightness distribution (a.k.a. specific intensity; units = energy/time/area/ frequency/solid angle)

\[ B_\nu = \frac{2\hbar\nu^3}{c^2} \frac{1}{e^{\frac{\hbar\nu}{kT}} - 1} \]  

(1)

where \( \hbar = \) Planck's constant, \( \nu = \) frequency, \( c = \) speed of light, \( k = \) Boltzmann's constant, and \( T = \) temperature. At radio frequencies, \( \hbar \nu \ll kT \), so expanding the exponential into a Taylor series of two terms, we get the Rayleigh-Jeans approximation

\[ B_\nu = \frac{2kT}{\lambda^2} \]  

(2)

where \( \lambda \equiv c/\nu \). It is therefore conventional to refer to radiation intensities in terms of an effective radiation temperature. This is done even in cases where the radiation mechanism is known to differ from blackbody radiation.

\[
T_b = \frac{\lambda^2 B_\nu}{2k} \approx \frac{\lambda^2 F_\nu}{2k \Omega_s} \quad \text{Brightness temperature}
\]

\[
\Omega_s \approx \frac{\pi \theta_s^2}{4}
\]

\[
\theta_s = \text{angular diameter}
\]
Radio Telescopes as Radiometers: A radio telescope used as a single antenna with a radiometer measures power, not brightness or specific intensity. The power level for a radio telescope may be expressed as an integral
\[
P_\nu = \frac{1}{2} A_e \int d\Omega d\nu B_\nu(\Omega) P_\nu(\Omega),
\]
where
1. The factor of 1/2 accounts for the acceptance by a single antenna of only a single polarization whereas the radiation field from the source is assumed to be unpolarized (equal power in two opposite or orthogonal polarizations).
2. \( A_e \) = effective area of antenna \( \equiv \eta \times \text{geometric area} \approx 0.6 \pi R^2_\text{s} \), where \( \eta \) is the aperture efficiency of the telescope that measures the uniformity by which the main reflector is illuminated by the feed antenna at the focus.
3. \( B_\nu = \text{brightness distribution of the sky as a function of frequency } \nu \text{ and direction solid angle } \Omega \).
4. \( P_\nu(\Omega) \) = the antenna power pattern. This is the response of the antenna as a function of direction, normalized so that the maximum response is 1 in the boresight direction and \(<1\) in other directions. The width of the ‘main lobe’ of the power pattern is \( \theta_\text{A} \equiv \text{FWHM (full width at half maximum)} \approx \lambda/D_\text{A}, \) \( D_\text{A} \) = antenna diameter. The solid angle of the main beam is \( \Omega_\text{A} = \int_{\text{beam}} d\Omega P_\nu(\Omega) \approx \pi (\theta_\text{A}/2)^2 \).
5. \( \Delta \nu = \text{receiver bandwidth = range of frequencies centered on some frequency } \nu \). We always have \( \Delta \nu < \nu \).
6. Equation 3 can be viewed as a convolution integral of the antenna power pattern with the sky. In a drift scan of the sky, the measured width of the response will be a combination of the beam width and the source size.

Extended Sources: For a source with extent \( \Omega_s \gg \Omega_\text{A} \) (such as the 3K cosmic background), the brightness distribution is constant over the telescope beam and over the receiver bandpass, so
\[
P_\nu \approx \frac{1}{2} \Delta \nu A_s \Omega_s B_\nu.
\]
Recall that \( A_s \propto D_\text{s}^2 \) while \( \Omega_\text{A} \propto (\lambda/D_\text{A})^2 \). Their product is therefore independent of the telescope diameter; moreover, it can be shown that \( A_s \Omega_\text{A} = \lambda^2 \). Using this fact and assuming that the extended source radiates as a blackbody, we get
\[
P_\nu \approx kT \Delta \nu.
\]
Thus (1) measurement of the power level of an extended source determines the radiation temperature of the source (the radiation temperature may or may not be related to the physical temperature in the source); (2) the ability to measure the temperature is just as good for a small antenna as a large one, to the extent that the source is extended for both. For example, extended 21 cm emission from the Galaxy is as easily detected with a 4 meter antenna as with a 300 meter antenna (Arecibo).
Point Sources: If $\Omega_s \ll \Omega_A$, the source is said to be a point source, since it is unresolvable with the telescope beam. Now, assuming the antenna power response $P_n$ to be constant over the source (and that the beam center points directly at the source $\rightarrow P_n = 1$), we have

$$P_\nu \approx \frac{1}{2} \Delta \nu A \Omega_s B_\nu(\text{max}). \quad (6)$$

Flux density: Another useful quantity is flux density $F_\nu$ (flux = rate at which energy passes through a surface; ‘density’ refers to flux per unit frequency). Flux density has units of energy/time/area/frequency. A useful unit of flux density is the Jansky (named after Karl Jansky who, for Bell Labs in the early 1930’s, discovered radio emission from the Galactic center while investigating sources of noise in trans-Atlantic radio communications):

$$1 \, \text{Jy} = 10^{-26} \text{Watts m}^{-2} \text{Hz}^{-1} = 10^{-31} \frac{\text{erg}}{\text{s cm}^2 \text{Hz}}. \quad (7)$$

The flux densities of thousands of radio sources are tabulated, having been determined in sky surveys made at frequencies from about 25 MHz up to 100 GHz (a range of 4000:1).

The relationship between flux density and brightness distribution is

$$F_\nu = \int d\Omega B_\nu(\Omega). \quad (8)$$

We can rewrite this expression as

$$F_\nu \equiv \Omega_s B_\nu(\text{max}), \quad (9)$$

where we effectively define the solid angle of the source $\Omega_s$.

Returning to the telescope response for a point source and using the flux density, we have

$$P_\nu = \frac{1}{2} \Delta \nu A F_\nu. \quad (10)$$

Note that, unlike an extended source, the power measured from a point source scales linearly with the telescope area; bigger antennas measure more power.
Telescope Response in Terms of Effective Temperature: Suppose we assume that the power level we measure is due to an extended source at temperature $T$ whereas it actually is due to a point source of flux density $F$. Equating equations (1) and (2) and solving for temperature gives

$$T = \left(\frac{A_e}{2k}\right) F_e.$$  \hfill (11)

The quantity $A_e/2k$ serves as a conversion factor from flux density to temperature:

$$G = \frac{A_e}{2k} = 2.7 \times 10^{-3} \text{ K/Jy} \quad D_A = 4 \text{ m}$$

$$= 1.5 \times 10^{-1} \text{ K/Jy} \quad D_A = 300 \text{ m} \quad \text{(Arecibo)}$$  \hfill (12)

As an example, a 1 Jy source produces a 15K deflection at Arecibo compared with a system temperature that is 40K at 1.4 GHz or 100K at 0.4 GHz. This is a very large deflection.

System Temperature and the Radiometer Equation: It is convenient to describe the properties of the receiver system as well as the radiation field in terms of temperature. The system temperature measures the power level when the telescope is pointed at ‘blank’ sky and includes contributions from the sky background and noise in antenna, cable, and receiver components. The system temperature quantifies the mean power level. All contributions to the radiometer temperature are random in nature, so the receiver output is actually noiselike. This is easily demonstrated by viewing the signal on an oscilloscope or listening to the signal through a loudspeaker. (You can demonstrate this with your FM stereo by listening to the hiss when it is tuned in between two stations; some of this hiss is due to synchrotron radiation from cosmic ray electrons in our galaxy’s magnetic field).

Radiometer noise in a receiver behaves according to the familiar $1/\sqrt{N}$ law from statistics. That is, if we have a receiver with bandwidth $\Delta \nu$ and if we average the signal output over a time $\tau$, the number of independent fluctuations that is summed is $N = \Delta \nu \tau$. The root mean square fluctuation $\sigma_T$ of the radiometer divided by the mean temperature $T_{sys}$ is the radiometer equation:

$$\frac{\sigma_T}{T_{sys}} = \frac{1}{\sqrt{2\Delta \nu \tau}}$$  \hfill (13)
**Detectability of sources:** The level of radiometer noise determines how well we can measure the system temperature. More importantly, it determines how well we can determine that, rather than looking at just blank sky, the telescope is pointed towards an actual source. In order to be detectable, the source must increase the system temperature by an amount that is distinguishable from the noise. A useful rule of thumb is that a source must increase the temperature by an amount that is 5 times the statistical variation; i.e.

\[ T_{\text{source}} = G F_{\nu} \geq 5\sigma_{\nu} = \frac{5T_{\text{sys}}}{(\Delta\nu\tau)^{1/2}} \]  

(14)

Equivalently, the flux density must satisfy:

\[ F_{\nu} \geq \frac{5T_{\text{sys}}}{G(\Delta\nu\tau)^{1/2}} \]  

(15)

Clearly, if we maximize the product of bandwidth and time constant, we can measure weaker sources. For \( T_{\text{sys}} = 100\,\text{K}, \Delta\nu = 40\,\text{MHz}, \) and \( \tau = 1\,\text{sec}, \) and using the above values for \( G, \) we find detection levels

\[ F_{\nu} \geq \frac{0.079\,\text{Jy}}{G} = 30\,\text{Jy} \quad 4\,\text{m} \]

\[ = 0.0053\,\text{Jy} \quad 300\,\text{m}. \]  

(16)

The way sources are detected is by performing a differential measurement on and off the source (e.g. measure the radiometer level when the telescope beam is pointed toward the source; subtract from this the level when it is pointed at one or more adjacent positions) and testing whether the difference is larger than the noise fluctuations. Alternatively, sometimes drift scans are performed by pointing the telescope to a position through which the source will drift due to Earth’s rotation. A point source will produce a response that is proportional to a one-dimensional cut through the beam \( P_{\theta}(\Omega). \) Drift scans are useful for 1) discovering new sources; 2) mapping out the beam; and 3) testing the pointing of the telescope.
Other factors: There is a limit to how well one can increase the time-bandwidth product as opposed to increasing \( G \propto A_{\ell} \). This is because other factors come into play, especially source confusion, which results from there being multiple sources within the telescope beam at a given sky position. Moving from one sky position to another, these sources change, thereby producing a radiometer fluctuation that can exceed that produced by radiometer noise alone. If so, measurements are said to be 'confusion limited' rather than radiometer noise limited. Telescopes with larger beams (i.e. small antennas at large wavelengths) have larger confusion variations. The rms confusion fluctuation is roughly

\[
\sigma_c \approx 3700 \left( \frac{\nu}{1 \text{ GHz}} \right)^{-0.7} \Omega_{\text{d}} \text{ Jy}.
\]  

(17)

For the Arecibo telescope at 1.4 GHz, \( \sigma_c \approx 2\text{mJy} \). A source must be stronger than \( 5\sigma_c \approx 10 \text{ mJy} \) to be convincingly detected.

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**Figure 6.** Confusion profile. This profile plot shows the 3 GHz confusion amplitude in an 8 arcsec FWHM beam, truncated at \( \mu\text{mJy beam}^{-1} \).

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**Importance of the Antenna Elements**

- Antenna amplitude pattern causes amplitude to vary across the source.
- Antenna phase pattern causes phase to vary across the source.
- Polarization properties of the antenna modify the apparent polarization of the source.
- Antenna pointing errors can cause time varying amplitude and phase errors.
- Variation in noise pickup from the ground can cause time variable amplitude errors.
- Deformations of the antenna surface can cause amplitude and phase errors, especially at short wavelengths.
Types of Antennas

- Wire antennas \((\lambda > 1\text{m})\)
  - Dipole
  - Yagi
  - Helix
  - Small arrays of the above
- Reflector antennas \((\lambda < 1\text{m})\)
- Hybrid antennas \((\lambda = 1\text{m})\)
  - Wire reflectors
  - Reflectors with dipole feeds

Basic Antenna Formulas

Effective collecting area \(A(\nu, \theta, \phi)\text{ m}^2\)

On-axis response \(A_0 = \eta A\)
\(\eta\) = aperture efficiency

Normalized pattern (primary beam)
\(A(\nu, \theta, \phi) = A(\nu, \theta, \phi)/A_0\)

Beam solid angle
\(\Omega_A = \int\int A(\nu, \theta, \phi) \, d\Omega\text{ all sky}\)

\(A_0 \Omega_A = \lambda^2\)
\(\lambda\) = wavelength, \(\nu\) = frequency
What determines the beam shape?

\[ f(u,v) = \text{complex aperture field distribution} \]
\[ u,v = \text{aperture coordinates (wavelengths)} \]

\[ F(l,m) = \text{complex far-field voltage pattern} \]
\[ l = \sin \theta \cos \phi, \ m = \sin \theta \sin \phi \]

\[ F(l,m) = \int \int \text{aperture} f(u,v) \exp(2\pi i(ul + vm)) \, du \, dv \]

\[ f(u,v) = \int \int \text{hemisphere} F(l,m) \exp(-2\pi i(ul + vm)) \, dl \, dm \]

For VLA: \( \theta_{3\text{dB}} = 1.02/D \), First null = 1.22/D,
\( D = \text{reflector diameter in wavelengths} \)

---

**Antenna Mounts: Altitude over Azimuth**

- **Advantages**
  - Cost
  - Gravity performance
- **Disadvantages**
  - Zone of avoidance
  - Beam rotates on sky
Antenna Mounts: Equatorial

• Advantages
  – Tracking accuracy
  – Beam doesn’t rotate
• Disadvantages
  – Cost
  – Gravity performance
  – Sources on horizon at pole
Reflector Optics: Limitations

- **Prime focus**
  - Over-illumination (spillover) can increase system temperature due to ground pick-up
  - Number of receivers, and access to them, is limited
- **Subreflector systems**
  - Can limit low frequency capability. Feed horn too large.
  - Over-illumination by feed horn can exceed gain of reflector’s diffraction limited sidelobes
    - Strong sources a few degrees away may limit image dynamic range
- **Offset optics**
  - Support structure of offset feed is complex and expensive

Reflector Optics: Examples

- **Prime focus** (GMRT)
- **Cassegrain focus** (AT)
- **Offset Cassegrain** (VLA)
- **Naysmith** (OVRO)
- **Beam Waveguide** (NRO)
- **Dual Offset** (GBT)
Antenna for Square Kilometer Array
Feed Systems

On axis response: $A_0 = \eta A$

Efficiency: $\eta = \eta_{id} \cdot \eta_{bl} \cdot \eta_{s} \cdot \eta_{t} \cdot \eta_{misc}$

$\eta_{id} =$ Reflector surface efficiency
Due to imperfections in reflector surface
$\eta_{id} = \exp\left(-\frac{(4\pi\sigma/\lambda)^2}{4}\right)$  e.g., $\sigma = \lambda/16$, $\eta_{id} = 0.5$

$\eta_{bl} =$ Blockage efficiency
Caused by subreflector and its support structure

$\eta_{s} =$ Feed spillover efficiency
Fraction of power radiated by feed intercepted by subreflector

$\eta_{t} =$ Feed illumination efficiency
Outer parts of reflector illuminated at lower level than inner part

$\eta_{misc} =$ Reflector diffraction, feed position phase errors, feed match and loss
Surface of ALMA Vertex Antenna

- Surface measurements of DV02 made with holography
- Measured surface rms = 10um

Antenna Performance: Aperture Efficiency

Primary Beam

$P = \sin(\theta), D =$ antenna diameter in contours: $-3, -6, -10, -15, -20, -25,$ wavelengths

$\text{dB} = 10\log(\text{power ratio}) = 20\log(\text{voltage ratio})$

VLA: $\theta_{3\text{dB}} = 1.02/D$, First null = 1.22/D

Voltage radiation pattern, $|F(l,m)|$

$\approx -30, -35, -40 \text{ dB}$
Far-out Sidelobes of Antennas

Diffraction effects cause there to be non-zero gain even from behind a telescope.

Receivers: Noise Temperature

- Reference received power to the equivalent temperature of a matched load at the input to the receiver.
- Rayleigh-Jeans approximation to Planck radiation law for a blackbody:

\[ P_{\text{in}} = k_B T \Delta \nu \quad (W) \]

\( k_B = \text{Boltzman's constant} \quad (1.38 \times 10^{-23} \text{ J}/\text{K}) \)

- When observing a radio source, \( T_{\text{total}} = T_A + T_{\text{sys}} \):
  - \( T_{\text{sys}} = \text{system noise when not looking at a discrete radio source} \)
  - \( T_A = \text{source antenna temperature} \)
Receivers: SEFD

\[ T_A = \eta AS/(2k_B) = KS \]

\[ S = \text{source flux (Jy)} \]

SEFD = system equivalent flux density

SEFD = \( T_{\text{sys}}/K \) (Jy)

<table>
<thead>
<tr>
<th>Band (GHz)</th>
<th>( \eta )</th>
<th>( T_{\text{sys}} )</th>
<th>SEFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>.50</td>
<td>21</td>
<td>236</td>
</tr>
<tr>
<td>2-4</td>
<td>.62</td>
<td>27</td>
<td>245</td>
</tr>
<tr>
<td>4-8</td>
<td>.60</td>
<td>28</td>
<td>262</td>
</tr>
<tr>
<td>8-12</td>
<td>.56</td>
<td>31</td>
<td>311</td>
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<tr>
<td>12-18</td>
<td>.54</td>
<td>37</td>
<td>385</td>
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<tr>
<td>18-26</td>
<td>.51</td>
<td>55</td>
<td>606</td>
</tr>
<tr>
<td>26-40</td>
<td>.39</td>
<td>58</td>
<td>836</td>
</tr>
<tr>
<td>40-50</td>
<td>.34</td>
<td>78</td>
<td>1290</td>
</tr>
</tbody>
</table>

The two largest radio telescopes

Green Bank Telescope
West Virginia
100 meter diameter

Arecibo Observatory
Puerto Rico
305 meter diameter
**Implementations**

\( A_{\text{effective}}: \) Large single apertures
- Large-N arrays* (dipoles, dishes)

\( T_{\text{system}}: \) Low-noise devices
- Receiver integration (MMICS)
- Computer-aided EM design

Quiet sites: Radio quiet zones + mitigation

Frequency coverage and Field of View (FoV):
- Broadband feeds (10:1)
- Phased-array feeds
- Radio cameras multiple-pixel feeds

Digital: Networking, DSP, software telescopes

---

**Astronomical Implications/Specifications**

- **High Redshift Coverage ⇔ Wavelength/Frequency Coverage**
  - Hydrogen \( \lambda 21 \text{ cm}, 1.4 \text{ GHz} \)
    - Epoch of Reionization: \( z \sim 13 \) to \( z \sim 6 \) or 100 to 200 MHz
  - Carbon monoxide \( \lambda 3 \text{ mm}, 115 \text{ GHz} + \) other transitions
    - First galaxies: \( z \sim 10 \) or 12 GHz and higher
  - Water \( \lambda 1.3 \text{ cm}, 22 \text{ GHz} \)
    - Precision determination of Hubble constant to \( z \sim 1 \)
  - Other molecules:
    - to submillimeter wavelengths
  - Continuum observations: all wavelengths

- **Radio astronomy requires observations outside narrow, protected bands defined long ago**
  - More reason to go to remote sites (including the Moon)
EXPReS
Express Production Real-time e-VLBI Service

Global Real-time VLBI

Allen Telescope Array: 11:1 frequency range (1-11 GHz)
Log periodic; Cryo-cooled receiver integrated into tip
(UC Berkeley/SETI Institute)

Quasi-self complementary feed
(10:1) (Cornell University)

Quad-ridge (10:1)
(Lindgren/Caltech)
Phased Array Feeds

Challenges:
• Digital beam forming with wide bandwidth
• Low system noise with uncooled systems
• Weight and cost

Vivaldi structures (ASTRON)

Checkerboard feed (ATNF)

Lunar Arrays

• Parallel design studies
  – Dark Ages Lunar Interferometer (DALI) - NRL
  – Lunar Array for Cosmology (LARC) - MIT

• Tsiolkovsky
LOFAR: Low Frequency Array

- LOFAR-configuration compatible
- LOFAR antenna layout

Antenna field
High speed data network
Central super computer

Low Frequencies
Big Bang

Classic Radio Interferometer Array

- The Karl G. Jansky Very Large Array in 1km D-configuration
  - Resolution of 1000-m aperture, area of 130m aperture

Field-of-view is diffraction limit of element apertures
(25m at 30cm = 45')

VLA configuration D
(1km at 30cm = 69'')
VLA configuration A
(36km at 30cm = 2'')

cf. Green Bank Telescope
(100m Off-axis Gregorian)
λ/D = 10' at 1GHz (30cm)
Future Radio Interferometer Array

- Science observing since March 2010 – a Laboratory on the Sky!
- Future possibilities – the road towards the Square Kilometre Array and the LSST next decade – the Jansky VLA is a SKA Science Proving Ground!

The VLA Sky Survey (VLASS) Initiative

- Announced 11 July 2013: Community-led Program to define a new radio sky survey using the upgraded Karl G. Jansky VLA
  - Previous centimeter-wave VLA Surveys: NVSS & FIRST 1993-2002
  - Open international participation, public data and products
  - VLASS data public from start (no proprietary period)
- Fall 2013: Issued a call for White Papers - 21 Papers!
- AAS workshop 5 January 2014 (~50 attendees, see online)
- 2014: Survey Science Group (SSG), working groups formed
  - survey proposal developed, drafts posted, comments, refined
  - technical implementation plan (TIP: Myers et al.)
- Jan 2015: Final Proposal posted ALL-SKY + DEEP
  - ~9000 hrs. over 7 years (6 config. cycles, A+B config.)
  - [https://science.nrao.edu/science/surveys/vlass](https://science.nrao.edu/science/surveys/vlass)
Key Science Cases – Highlights

• Medium/Deep Fields for Galaxy Evolution & Cosmology
  – AGN and Clusters of Galaxies, Feedback
  – Star-forming Galaxies
  – Weak Lensing

• Large Area Survey for Transients & Faraday Tomography
  – Full Polarimetry for B-field Studies
  – EM Counterparts to GW events (LIGO/VIRGO)
  – Radio Bursts on timescales from 1ms to >1 year

• Galactic Plane and Center
  – Atomic and Molecular Lines from 0.2-50 GHz
  – Stars and Stellar Systems

### VLASS Future Milestones

**Notional schedule (as of July 2015)**

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 March 4 – 6</td>
<td>External Community Review (Socorro)</td>
</tr>
<tr>
<td>2015 March – 2015 Aug</td>
<td>Set up Project Office, draft workplan, allocate resources</td>
</tr>
<tr>
<td>2015 March – 2016 May</td>
<td>Test &amp; Development Program carried out</td>
</tr>
<tr>
<td>2015 November</td>
<td>VLASS Preliminary Design Review (PDR)</td>
</tr>
<tr>
<td>2016 May 27</td>
<td>Start of 2016A B-config (VLASS pilot observations possible)</td>
</tr>
<tr>
<td>2016 June</td>
<td>VLASS Critical Design Review (CDR), final go/no-go</td>
</tr>
<tr>
<td>2016 Aug 29</td>
<td>End of 2016A B-config (nominal, without VLASS)</td>
</tr>
<tr>
<td>2016 Oct 3</td>
<td>End of 2016A B-config (with a 1 month extension for VLASS)</td>
</tr>
<tr>
<td>2017 Apr 3</td>
<td>Delivery of B-config Epoch 1 (6 months: ALL-SKY I only)</td>
</tr>
<tr>
<td>2017 Oct 3</td>
<td>Delivery of B-config Epoch 1 (12 months: Pol.)</td>
</tr>
<tr>
<td>2017 Sep</td>
<td>VLASS Cycle 2 observations commence (B-config)</td>
</tr>
</tbody>
</table>