Fundamentals of Radio Astronomy

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ALFALFA Undergraduate Workshop
Arecibo Observatory, 2008 Jan. 13
Outline

• Sources in brief
• Radiotelescope components
• Radiotelescope characteristics

Useful Texts

Burke & Graham-Smith, *An Introduction to Radio Astronomy*
Rohlfs, *Tools of Radio Astronomy*
Stanimirovic et al., *Single-dish Radio Astronomy: Techniques and Applications*
Sources of Radio Emission

- Blackbody (thermal)
- Continuum sources
- Spectral line sources
Blackbody Sources

- Peak in cm-wave radio requires very low temperature: $\lambda = 0.2898 \text{ cm} K$
- Cosmic Microwave Background is about the only relevant blackbody source
- Ignored in most work – essentially constant source of static (same in all directions) and much weaker than static produced by instrumentation itself
Continuum Sources

• Due to relativistic electrons:
  Synchrotron radiation
  Bremsstrahlung

[Bremsstrahlung diagram]

[Synchrotron radiation diagram]
Continuum Sources

- Quasars, Active Galactic Nuclei, Pulsars, Supernova Remnants, etc.
- Used by ALFALFA for calibration
• Neutral hydrogen (H I) spin-flip transition
• Recombination lines (between high-lying atomic states)
• Molecular lines (CO, OH, etc.)
• Doppler effect: frequency shift of spectral line due to relative motion of source and observer
• Closely related: redshift due to expansion of universe
• Customarily report “velocity” as
\[ cz = c(f_o - f)/f_o \]
• H I spectral line from galaxy shifted by expansion of universe ("recession velocity") and broadened by rotation
Radiotelescope Components

- Reflector(s)
- Feed horn(s)
- Low-noise amplifier
- Filter
- Downconverter
- IF Amplifier
- Spectrometer
Feedhorns

Typical cm-wave feedhorn

4 GHz feedhorn on LCRT
Signal Path

Low-Noise Amplifier → Filter → Down-converter

IF Amplifier

Spectrometer

Local Oscillator
Autocorrelation Spectrometer

• Special-purpose hardware computes autocorrelation function:

\[ R_n = N^{-1} \sum_{1}^{N} [v(t_j)v(t_j+n\delta t)] \]

where \( \delta t \) is lag and \( v \) is signal voltage; integer \( n \) ranges from 0 to \( (\delta t \delta f)^{-1} \) if frequency channels of width \( \delta f \) are required.

• Power spectrum is discrete Fourier transform (FFT) of \( R_n \)
• Nyquist theorem: must sample at rate $2B$ to achieve spectrum of bandwidth $B$ without aliasing

Diamonds: samples at rate $\sim B$ give aliassed signal near 0 Hz
Ovals: samples at rate $>2B$ give $\sim$correct period
Radiotelescope Characteristics

- Gain & effective area
- Beam, sidelobes, stray radiation
- Sensitivity, noise & integration time
- Polarization & Stoke’s parameters
Gain & effective area

- Received power $P_{\text{rec}}$
- Flux (energy per unit area per unit time) $S$
- Effective area $A_{\text{eff}} = \frac{P_{\text{rec}}}{S}$
- Gain $G$ for transmitter is ratio of emitted flux in given direction to $P/(4\pi r^2)$
- Most emitted (received) within central diffraction max, angle $\sim \frac{\lambda}{D}$
- So $G = 4\pi A_{\text{eff}} / \lambda^2$
Beam & sidelobes

• Essentially diffraction pattern of telescope functioning as transmitter
• Uniformly illuminated circular aperture: central beam & sidelobe rings
• Obstructions, non-uniform illumination by feedhorn → asymmetry and alter strengths of sidelobes vs. central beam
• Emission received from pattern outside first sidelobe ring often called *stray radiation*
• FWHM of central beam is *beamwidth*
• Integrated solid angle of central beam is $\Omega_o$
• Gain related to beam via $G = \frac{4\pi}{\Omega_o}$
Sensitivity

- Limited by noise – mostly thermal noise within electronics but also from ground reflected off telescope structure into feedhorn and CMB
- System temperature: temperature of blackbody producing same power as telescope + instrumentation produces when there is no source in beam
• Often give brightness of source in temperature units: difference in effective blackbody temperature when source is in beam vs. when no source is in beam – even when source is spectral line or synchrotron radiation and brightness has little to do with actual temperature of the source

• Preferred unit (requires calibration) is Jansky:

\[ 1 \text{Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \]
• Limiting sensitivity for unpolarized source set by requiring signal added by source to equal rms uncertainty in $T_{sys}$:

$$\Delta S = 2kT_{sys} A_{eff}^{-1} (B\tau)^{-1/2}$$

($k$: Boltzmann’s constant; $\tau$: integration time)

• For spectral line work, $B$ is set by velocity resolution required; $T_{sys}$ and $A_{eff}$ set by telescope and instrumentation → increase sensitivity by integrating longer – but need 4 times integration time to increase sensitivity by factor of 2
Polarization

- H I sources unpolarized, but synchrotron sources are often polarized to some extent – $E$ in plane of electron’s acceleration
- Single receiver (LNA) can respond to only single polarization at any instant– either one component of linear polarization or one handedness of circular polarization
- So two receivers required to receive both polarizations
• Linear $E_x$ and $E_y$ with phase difference $\phi$
• Stokes’ parameters:

$$I = E_x^2 + E_y^2$$

$$Q = E_x^2 - E_y^2$$

$$U = 2E_xE_y \cos \phi$$

$$V = 2E_xE_y \sin \phi$$
• Unpolarized source: $E_x = E_y$ and $\phi = 0$
• So $Q = 0$, $V = 0$, and $I = U$ for H I; usually report only Stokes’ I or total flux = sum of fluxes of x and y polarizations