Radio Astronomy Techniques

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Characteristics of radio signals

- Radio frequency range: 20 kHz-600 GHz, wavelengths: kms - 0.5mm
- Ignore photons - i.e. need not quantize EM field
- Rayleigh-Jeans approximation to Planck black body law
- At cm and mm wavelengths antenna structures are large compared to wavelength so use ray trace optics
- Most astronomical objects are at large distances and of small angular size. So the angles are a ratio of the linear size and the distance.
- Astronomical sources are large in physical size and the radiation emitted from them comes from a large number of statistically independent sources => resulting signals are noise-like - so spectra depend on the emission mechanism.
- Variation in sources is only on the light travel time scale

**Implications for measurement techniques:**
- One bit autocorrelation spectroscopy depends on signal voltage being a gaussian random variable
- Many hour interferometry depends on the source being stable over that time
Continuum Sources

Brightness of a blackbody at temperature $T$ is given by

$$B_\mu(T) = \frac{2\hbar \mu^3}{c^2} \frac{1}{(e^{\hbar \mu/kT} - 1)}$$

Rayleigh-Jeans approximation ($\hbar \mu/kT \ll 1$) is almost always true in radio astronomy implies

$$B_\mu(T) = \frac{2\mu^2 kT}{c^2}$$

The thermal noise power per unit frequency interval from a resistor for the R-J approx. is

$$P_\mu = kT$$

This proportionality allows us to talk about intensities and power in temperature units.

Sources are typically “colored” - radiation temperatures vary with frequency - not necessarily related to physical temperatures.

e.g. Synchrotron emission source: $I_\mu \propto \mu^{-n}$ where $n$ is related to the energy distribution of the emitting electrons

- typically $0.5 < n < 1$

Blackbody - $n = -2$

Can use R-J equation to define a brightness temperature that is proportional to intensity, $T_b$ will be proportional to frequency
Atoms and Molecules: emission and absorption lines

Emission and absorption lines originate from atoms, molecules or small ions in a gaseous form. Molecular transitions are usually rotational (and sometimes vibrational).

**Emission lines:** Warm gas in front of a colder background so the intensity at line frequency is sharply higher compared to nearby frequencies.

**Absorption lines:** Cold gas in front of a warmer background source.

The brightness temperature at antenna is given by:

\[ T_a = T_c e^{-\tau} + T_g (1 - e^{-\tau}) \]

where \( T_c \) is the background temperature, \( T_g \) is the temperature of the gas, and \( \tau \) is the opacity of the gas.
Doppler shifts and kinematics
Doppler shifts are very important in radio astronomy. Non-relativistic form is given by:

\[
\frac{\Delta \mu}{\mu} = -\frac{v}{c}
\]

where \(\Delta \mu\) is the change in frequency due to the Doppler velocity \(v\)

Line widths and line shapes are influenced by several mechanisms:
1. Natural line widths related to the lifetimes of the states involved in the transition
2. Kinematic temperatures characterizing small scale random motions of atoms or molecules
3. Turbulence or larger-scale random motions
4. Kinematics - large scale ordered motions such as expansions, contractions, rotations or outflows
Parabolic antennas - why?
Sources are so far away that incoming waves are plane waves from a specific direction. Need to catch as much energy from the source while avoiding local interference. Signal is characterized by a flux density in Janskys (1 Jy $= 10^{-26}$ w/m²/Hz) so the bigger the antenna the more watts we collect. A parabolic antenna puts all the energy at the focus where a feed (a small antenna which “feeds” radiated power to the main antenna - radar analogy) can be placed.

Aperture Efficiency and K/Jy
Black sphere with diameter $d$ and temperature $T$ at a distance $r$ from a circular receiving antenna with diameter $D$. $r \gg d$ or $D$.
Power per unit frequency interval received by this antenna can be given by

$$P = I \left( \frac{od^2}{4} \right) \left( \frac{1}{r^2} \right) \left( \frac{OD^2}{4} \right)$$

The first 3 terms combine to make flux density $F$ and the other term is the antenna collecting area.
If $P$ is characterized in temperature units (=$2kT_R$), then $T_R/F = A/2k$ is the sensitivity.
Beam efficiency and Beam dilution

*Beam efficiency* is defined as the ratio of $T_R$ to the brightness temperature of the source. However, it is a function of the shape and angular size of the source.

*Beam dilution* is defined the same way but for an assumed circular source with a specified diameter in beamwidths and as a function of this diameter. Can calibrate these quantities with planets - known brightness temperatures and angular sizes.

**Beamwidth - $1.2\kappa/D$**

Full width to half power of radiation pattern of a circular antenna. The 1.2 factor depends on feed illumination pattern.
Elements of a radio telescope

- Reflector - collects power, provides directionality
- Feed - couples the radiation to the transmission line
- Transmission line
- Receiver - filters and detects the emission
Reflector (Antenna)

- Reciprocity theorem
- Beamwidth $\eta = \kappa/D$
- Far-field response
- $\eta$ also defines directivity
- Angular pattern of the electric field in the far field is the FT of the electric field distribution across the aperture
Most radio antennas have a Cassegrain design - feed horn is at the secondary since less of the surface will be blocked. Small telescopes such as the SRT have a prime focus arrangement.

Reflector surface must follow a parabola to a fraction of a wavelength. An imperfect surface scatters some signal away from the focus.
SRT antenna characteristics

- Diameter 2.1m
- Focal length - 32”
- F/D ratio - 0.38
- Four piece quad antenna from Kaul-Tronics Inc.
- Quad feed supports to ensure the feed is accurately centered at the focus
- C/Ku mesh - reflects waves where the holes are less than 1/10th of the wavelength
Picture of an SRT mounted on a trailer
SRT mount

- Fully automated AZ/EL mount constructed from two horizon to horizon mounts
- Controlled by a STAMP microprocessor
- Operates on 24-36 voltsDC at 2.5 amps and will move the antenna 150 degrees(set by limits switches) in 70-80 seconds
- Motor drives a large worm gear which drives a large sector gear attached to the antenna mounting ring.
Feeds

• Ideal feed - antenna with a uniform beam that illuminates only the reflector surface
• In practice - a good feed provides 60 - 70% efficiency
• SRT feed - probe in a circular waveguide surrounded by choke rings
• Beam of this feed - adjustable by choice of opening size and location of choke rings
• Beamwidth of an antenna with such a feed is $1.22\kappa/D$
Gain and Spillover

- Gain of an antenna relative to an ideal isotropic antenna is $G = 4\sigma A/\kappa^2$ where $A$ is the effective collecting area.
- Gain is also related to the directivity - larger antenna, smaller beam, higher gain
- Antenna noise - from sky background, ohmic losses and ground pickup or spillover
- Losses and spillover - minimized by good antenna design
System noise contribution as a function of frequency
Receivers

- First stage - low noise amplifier (LNA)
- Noise performance given by $T_{sys} (K)$ provides direct comparison to source
- Heterodyne receivers - transforms the signal to lower frequency - mix SF from the LNA with local oscillator and filtering unwanted sidebands
- Square-law detector - produces output proportional to the square of the voltage
- Integrating signals improves the noise and the ability to detect extremely weak signals
- Analog signals from the detector are converted to digital - voltage to frequency converter followed by a counter
- Interference
SRT Receiver - block diagram
SRT Receiver

- First stage - LNA (also called pre-amp) provides a nominal 22 dB gain
- Image rejection mixers - pair of mixers with 90° quadrature phased L.O. drive followed by a 90° I.F. to make a single sideband receiver.
- 10 dB attenuation for observing strong sources like the sun
- Pair of IF amplifiers which provides 53 dB of gain and high/low pass filtering
- The conversion of the I.F. frequency voltage waveform to a voltage which is proportional to the I.F. signal power uses a back-diode or Schottky diode in the "squaring" region (square law detector)
SRT Analog Receiver

- Analog to digital converter - I.F. power is an analog signal which is converted to a pulse whose duration is inversely proportional to the average power present during the pulse period
- Local Oscillator synthesizer - allows frequency coverage to reach the OH line at 1665 MHz
- Serial communication
- Stamp communication
- Motor control
- More details on web page
SRT Digital Receiver

- Uses digital electronics
- Software spectrometer - no scanning needed
- Higher sensitivity, spectra in shorter time
- Currently uses same pre-amp as analog system which limits frequency to 1400-1440 MHz