DETECTION IN RADIO ASTRONOMY

The radio window runs from approximately 1 mm (set by atmospheric H₂O absorption) to tens of meters (set by ionospheric blockage). In this regime it is often possible, and sometimes necessary, to use phase-sensitive detection techniques, which make possible interferometry. For now, we consider only single antennae. For historical and operational reasons, the conventions in radio astronomy differ in marked ways from those in the optical regime. A particular example is the beam pattern or polar diagram of an antenna, completely analogous to the diffraction pattern but expressed as normalized response versus angle rather than intensity versus position. It has generally been the case in the radio regime that the detector is much smaller than the diffraction pattern, rather than the opposite as is usual in the optical. This accounts for some of the differences in units and usage, such as giving a map with intensity in units of flux per beam area.

Receivers are fed either by a dipole-style antenna at the focus of a large collector, or by a waveguide running from the focus. Strong amplification is required, along with extremely stable receivers since the signal is very much smaller than the thermal receiver noise. Switching techniques are often employed to monitor and correct for variations in the amplifier gain, either by switching between sky and a reference source, between object and ostensibly empty sky, or in frequency between a frequency of interest and a neighboring passband. Dicke switching, differencing signals between adjacent receivers, can be especially effective. The receivers themselves frequently employ heterodyne techniques, mixing the source signal with an attenuated signal from a source of controlled frequency (the local oscillator), and using the fact that the sum of waves with different frequencies is a superposition of waves with new frequencies at the sum and difference of the original ones; thus one of the new frequencies can be made conveniently small for electronic treatment.

Now for some specialized units and their relations in radio astronomy. Radiation intensity is given in Jansky's (Jy), with 1 Jy being defined as 10⁻²⁶ W m⁻² Hz⁻¹; we also deal in mJy, µJy, etc. This is a spectral flux, and must be integrated over frequency to arrive at a total received power. The power received from the sky is often expressed in terms of the brightness temperature
given by

\[ B_\nu(T) = \frac{2\nu^3}{e^2} \frac{1}{e^{\nu/kT} - 1} \]

goes to \( 2kT \nu^2/c^2 = kT/\lambda^2 \). This gives us the brightness temperature by matching the observed intensity \( S_\nu \) to the blackbody form: in the Rayleigh-Jeans limit, \( T_B = \lambda^2 S_\nu/2k \). For high frequencies, the rigorous Planck formula must be used. This is a restatement of what optical observers know as surface brightness - the intensity of radiation at a given frequency arriving per unit solid angle. Brightness temperature can tell immediately whether certain radiation mechanisms are operating. A blackbody has brightness temperature equal to its thermodynamic temperature if it fills the telescope beam, otherwise its brightness temperature is lowered by the ratio of its solid angle to that of the response (the beam dilution factor).

Explicitly, we can introduce the beam efficiency as the fraction of solid angle in the primary response lobe to the total. The gain of a system may be derived from its response pattern \( P(\theta, \phi) \) using

\[ \Omega_A = \int_0^{2\pi} \int_0^{\pi} P(\theta, \phi) d\Omega \leq 4\pi \]
and the gain is then $D = 4\pi/\Omega_A$, while the effective solid angle in the main lobe comes from integrating only to the first zero in the power pattern

$$\Omega_M = \int_{\text{first zero}} P(\theta, \phi) d\Omega \leq 4\pi$$

so that the beam efficiency is $\eta_B = \Omega_M/\Omega_A < 1$. This is so since the central peak in the diffraction pattern does not contain all the energy from a centered point source, while the receiver responds to the entire pattern. Using this quantity, we measure an antenna temperature $T_A$ related to the brightness temperature for a resolved source (larger than the beam pattern), by $T_A = T_B\eta_B$. For an unresolved source with solid angular extent $\Omega_S$, we have $T_A = \eta_B T_B (\Omega_S/\Omega_M)$.

All these quantities are functions of frequency. To do radio spectroscopy, one may scan the receiver in frequency by changing the local oscillator setting, use digital filters, or employ cross-correlation techniques. These last are more effective as they give a multiplex advantage in observing speed. Some frequencies are especially affected by interference. Certain bands are internationally protected (in a passive sense only) for radio astronomy, but satellite transmissions are notorious for having sidebands that are inadequately filtered, and even automobile spark plugs are strong sources at tens of cm. Thus radio observatories are often placed in remote valleys, and even so it is common to edit data so as to delete times of strong local interference. Altitude is only important at very short wavelengths, since from 3-10 cm atmospheric attenuation is typically 10%.

Dish antennae operate exactly like optical mirrors, and in fact come in prime-focus, Cassegrain, and more exotic folded designs. Experience shows that surface accuracy of 1/20 wavelength is needed to realize the full resolution of the system, not particularly difficult when the wavelengths is a meter or so. Wire mesh is a perfectly good reflector for wavelengths much longer than the mesh size, so many large dishes aren’t even solid. Even with such tolerances, the engineering to keep flexure under control can be formidable. The homologous principle has been especially powerful here, channeling flexure in the direction to change an antenna’s focal length but not shape with altitude.

Designs other than dishes have been used, exploiting the relationship between the shape of an aperture and its diffraction pattern to give maximum angular resolution at minimum cost. The Mills cross (see Kitchin page 99) is an interesting example, with a beam pattern changeable by adding cross-arm signals in or out of phase.

A peculiarity encountered most often with single-dish radio data (and now with IRAS and the deepest ground-based optical images) is confusion. This happens when the system is sensitive enough that it can detect more than one source per resolution element, setting a basic limit on how deep a map can be constructed and still distinguish individual sources. The effects of confusion can be subtle, and dealing with them adequately takes an understanding both of the detector and the source population. Interferometers are valuable in that they break the relation between sensitivity and gain (beam width), so that their results are seldom affected by confusion.