Introduction to Radio Astronomy I
-- Instrumentation and Techniques
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I. General Comments

Radio Astronomy is the study of naturally occurring radio emission produced by objects in the universe. It may be considered either the astronomy of a specific frequency range or the branch of that science which uses the heterodyne technique of electromagnetic wave measurement. By the first definition, radio astronomy studies electromagnetic radiation in the frequency range 5 MHz (frequencies below this are absorbed in the ionosphere) to about 300 GHz (frequencies above this are absorbed by neutral gas in the atmosphere). This frequency band is then the "window" in which radioastronomical observations are made. Turning to the second definition, we may consider radio astronomy to be the investigation of objects in a frequency range in which it is possible to measure the complex electric field in an electromagnetic wave. In optical astronomy, only the intensity of electromagnetic radiation may be measured. This capability of radio astronomy allows the use of powerful techniques in spectral measurement, polarimetry, and interferometry.

Radio astronomy may be classified according to the nature of radiation being detected (spectral line or continuum), or the type of object being studied. In spectral line astronomy, transitions of atoms and molecules are used either as diagnostics of physical conditions in astrophysical media such as dark clouds, or as tracers of large scale motions such as galactic rotation. Continuum observations determine (potentially) the character and morphology of thermal and nonthermal radiation sources. The second type of classification distinguishes between objects in our galaxy (supernova remnants, pulsars, OH masers, etc.) and those which lie beyond (radio galaxies, quasars, etc.).

II. Basic Hardware

A. Antennas.

The main function of an antenna is to increase the strength of an electromagnetic signal incident on the Earth prior to presenting it to the receiver. Below we will consider some of the more important figures of merit of a radioastronomical antenna. The beam pattern, $P(\theta,\phi)$, is the response of the antenna to a point source at coordinates θ, ϕ . The beam pattern may be used to calculate the beam solid angle, Ω_A, which is defined as;

$$\Omega_A \equiv \int_{4\pi} d\Omega \, P(\theta,\phi) \qquad (1)$$

The directivity, or gain, of an antenna is;

$$D \equiv 4\pi/\Omega_A \qquad (2)$$

It is useful to speak also of the forward gain, which is the increase in signal strength observed for a point source (over what the signal would be if we did not have the antenna) at $\theta=\phi=0$. The forward gain is given by an equation identical to equation (2), only with substitution of a solid angle Ω_M, which is the main beam solid angle,

$$\Omega_M \equiv \int_{\text{MAIN BEAM}} d\Omega \, P(\theta,\phi) \qquad (3)$$

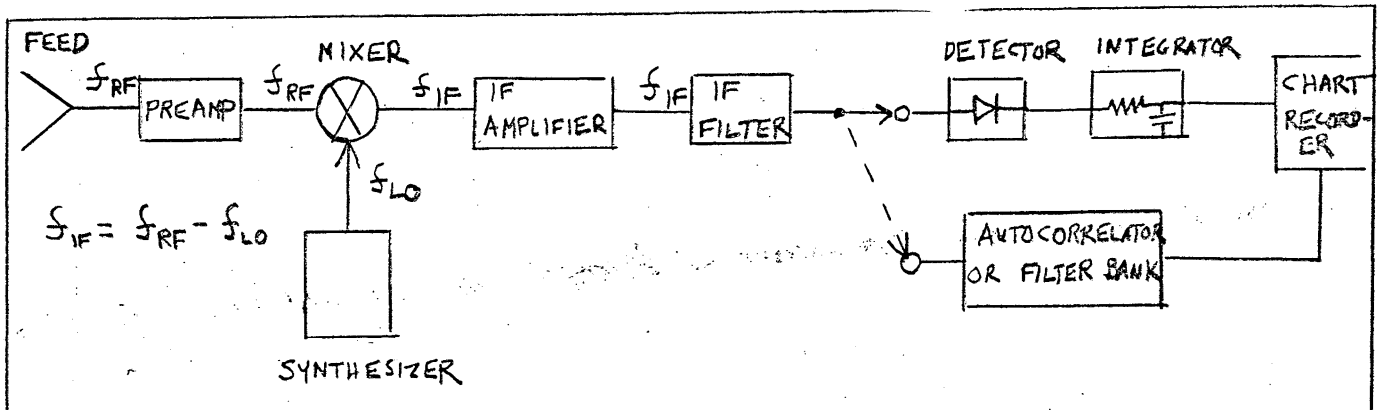
The beam efficiency, ε_B, is defined as;

$$\varepsilon_B \equiv \Omega_M/\Omega_A \qquad (4)$$

and is a measure of how efficiently the antenna response is being put into the main beam (as opposed to sidelobes and grating lobes). The aperture efficiency, ϵ_A, is the ratio of the actual forward gain to that of an ideal antenna of the same physical size. For large parabolic dishes, ϵ_A is in the range 0.5 to 0.6. The greatest aperture efficiency I know of is the 430 MHz system of the Arecibo 1000' telescope for which an aperture efficiency of nearly 80 percent exists. The antenna temperature, T_A , is a measure of the power delivered by the antenna to the feed terminals, and is defined as the amount of power delivered if the feed were in an isothermal cavity of temperature T_A. A very useful figure of merit for an antenna, related to the parameters defined above, is the antenna sensitivity (directly proportional to the gain) which is the increase in antenna temperature per flux unit of a point source in the main beam. It is essentially another measure of the forward gain.

B. Receivers

The purpose of a radioastronomical receiver is to amplify the very weak signals at the feed terminals to levels suitable for measurement. The type of receiver used almost exclusively in radio astronomy is the superheterodyne receiver, shown in the figure below.



SUPERHETERODYNE RECEIVER

Receivers add noise to signals input to them, which tends to mask the signals coming from the antenna. In this regard they are somewhat analogous to studying gamma rays with a radioactive detector. The amount of noise internally generated in the receiver (almost exclusively in the preamplifier) is characterized by the system temperature. This is the amount of noise which would be observed by a perfectly noiseless receiver connected to a load having the physical temperature of the system temperature. It is obviously the foremost goal of receiver engineering to make the system temperature as low as possible. The type of receiver shown above is susceptible to gain changes in the preamplifier. For precise intensity measurement, one needs to control the gain variations. The two most commonly employed varieties are the Dicke radiometer and the noise-adding radiometer.

C. Comments on Types of Astronomical Measurement.

In contrast to experimental physics, astronomy is a passive science, and there are a relatively small number of observables which can be measured. These are the time of observation, the position in the sky of the object (and also angular extent), the frequency of observation, and the four Stokes parameters I,Q,U, and V. From such measurements must come all astrophysical inferences. In what is given below, we describe how some of these quantities are measured.

III- Total Power Measurement

A. The Radiometer Equation

The most common type of measurement is of the total power, or Stokes parameter I. The relevant equation in discussing radioastronomical total power measurements is the radiometer equation.

$$\Delta S = \underbrace{\frac{2k_B}{A_e}}_{G} \underbrace{\left\{ \frac{T_{sys}}{\sqrt{\beta\tau}} \right\}}_{o} \qquad (5)$$

k_B = Boltzmann constant
A_e = effective aperture of the antenna
T_{sys} = receiver system temperature
B = IF bandwidth
τ = postdetection time constant

The quantity ΔS is the RMS of the noise fluctuations in the detected signal. Big G is totally a property of the antenna, little o is totally a property of the receiver. The radiometer equation tells us what is the minimum signal strength detectable with a given radiometer configuration.

B. Beyond the Radiometer Equation.

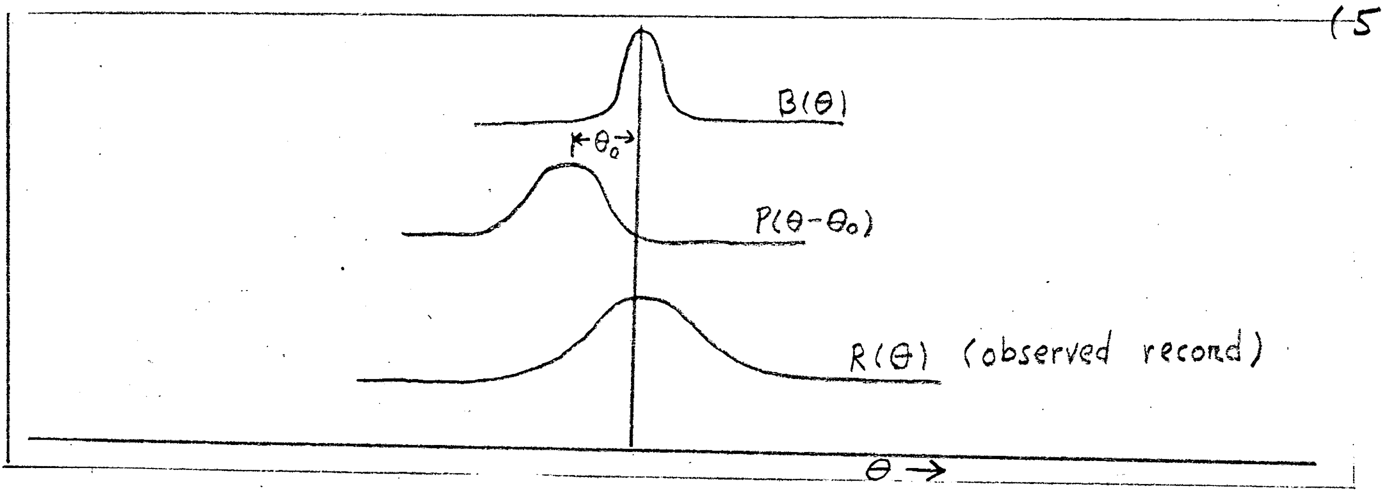
In both line and continuum observations, the level of sensitivity practically achieved often does not reach the level indicated by the radiometer equation. In continuum measurements this limitation is usually due to the phenomenon known appropriately as confusion, and in spectral line observation one often encounters an effect known as standing waves. Confusion limited observations occur when the strength of the signal due to weak sources in the main beam exceeds the radiometer noise. Confusion is an unwanted signal which cannot be eliminated. In spectral line observations, standing waves refer to interference between the direct signal from the source and reflected signals, LO leakage, etc. In the frequency domain, these standing wave patterns may often mimic spectral lines.

IV. Angular Size Measurements.

A. Single Dish Measurements.

Assume a source of brightness distribution $\beta(\theta)$ is observed in drift scan mode with an antenna having a beam shape $P(\theta-\theta_0)$, as shown below. Clearly, the observed record, $R(\theta_0)$, will be;

$$R(\theta_0) = \int_{-\infty}^{+\infty} P(\theta-\theta_0)\, \beta(\theta)\, d\theta \qquad (6)$$



or the convolution of the source brightness distribution and the antenna pattern. Clearly if the beam shape is well known, the source brightness distribution may be retrieved from the observed record. This process is known as restoration. One way would be to fit model brightness distributions using equation (6). Another method would be to use the fact that the Fourier transform of a convolution is the product of the Fourier transforms of the convolved functions. Let ~ indicate a Fourier transform, and $\mathcal{F}$ denote the Fourier operator.

Then,

$$\left.\begin{aligned} \tilde{R}(K) &= \mathcal{F}\int_{-\infty}^{+\infty} d\theta\; P(\theta-\theta_0)\, B(\theta) \\ &= \tilde{P}(K)\,\tilde{B}(K) \\ \tilde{B}(K) &= \tilde{R}(K)/\tilde{P}(K) \end{aligned}\right\} \qquad (7)$$

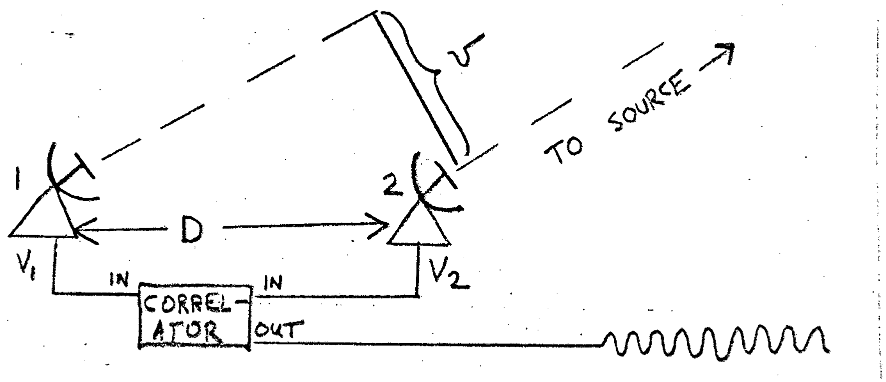
In real life, noise and uncertainty regarding the beamshape limits the use of this technique to angular scales not greatly smaller than the beamwidth.

B. More Clever Techniques

The "clever" techniques described below have one important feature in common. They all are essentially diffraction phenomena and utilize the fact that the observed diffraction pattern is the convolution of the ideal (point source) pattern with the brightness distribution of the source.

1. Interferometry

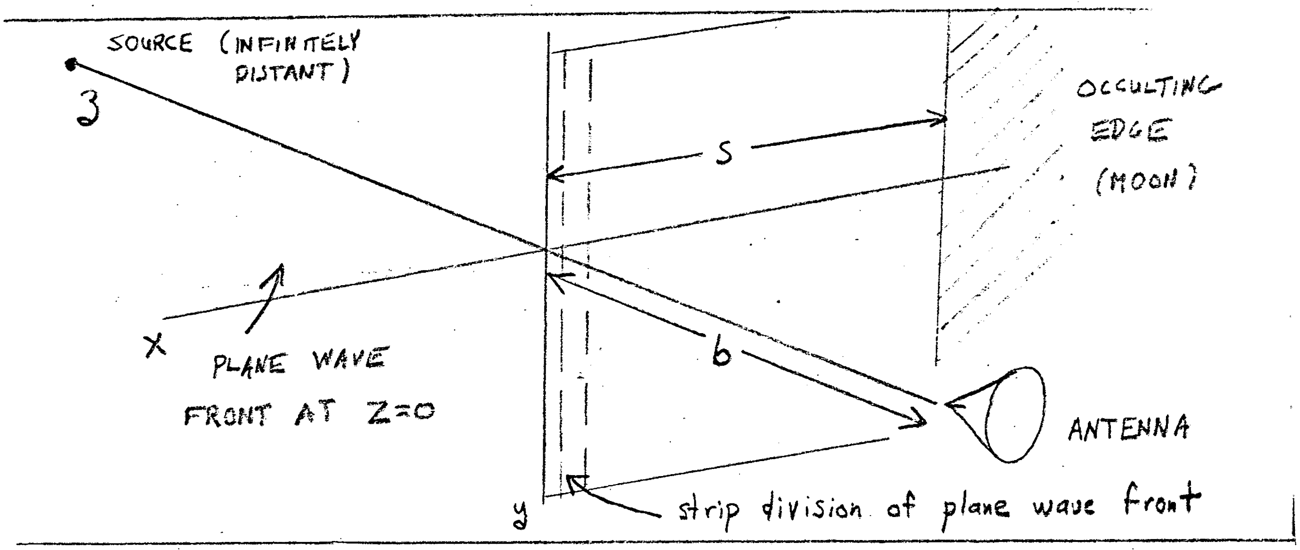
The most widely used, and if applicable, best technique is that of radio interferometry. Consider two antennas observing a source as shown below.



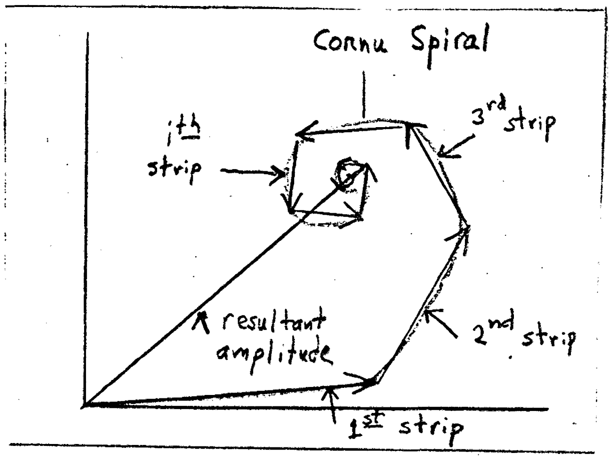
Let the projection of the baseline on the sky in the East-West direction be defined as u and the projection in the North-South direction be v. If the voltages (undetected) from the two antennas are multiplied togeather, a sinusoidally varying signal will be produced as voltages add alternatively in and out of phase. The amplitude and phase of this signal are measured, and comprise a complex number termed the visibility, $V(u,v)$. The two-dimensional Fourier transform of the visibility gives the brightness distribution of the source.

2. Lunar Occultations

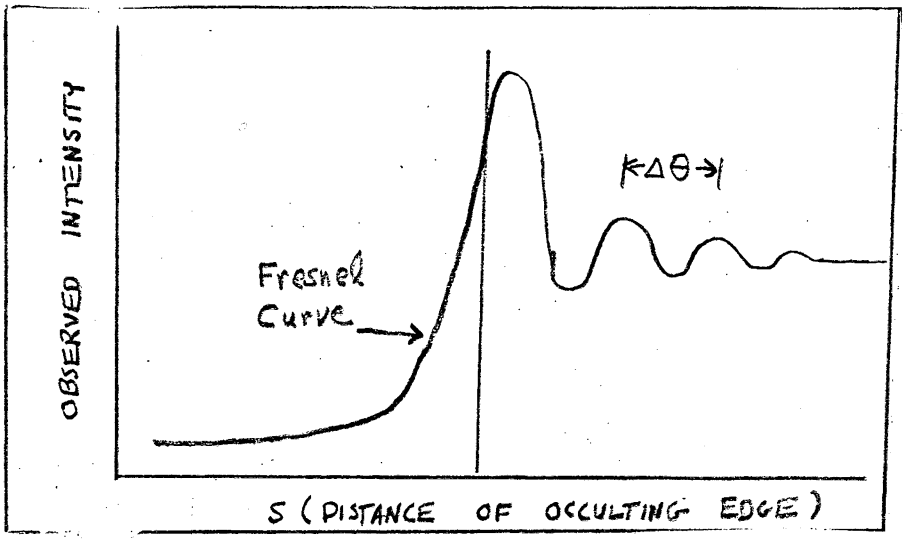
A technique which was more widely used ten years ago is that of lunar occultations. Consider the geometry shown below.



We can divide the plane wave front into small strips of equal width. Let the amplitude of the electromagnetic wave at a point z=b, x=x due to a strip at z=0, x=x be denoted by A . The resultant wave amplitude at the antenna is due to the vector sum of all strips on the wave front. Let the phase of the wave from the strip at x=0 define phase zero. The effect of summing contributions from the remaining strips is illustrated in the vibration curve, or Cornu spiral.



It is clear that as the occulting edge moves in from x=+∞, it will begin knocking out strips. The expected behavior of the observed intensity will then be as shown below.



The angular size of the "bumps" of the Fresnel curve is roughly;

$$\Delta\Theta \approx \sqrt{\frac{\lambda}{2b}} \qquad (8)$$

which would be of the order of a few arcseconds at 10 cm.

3. Scintillations

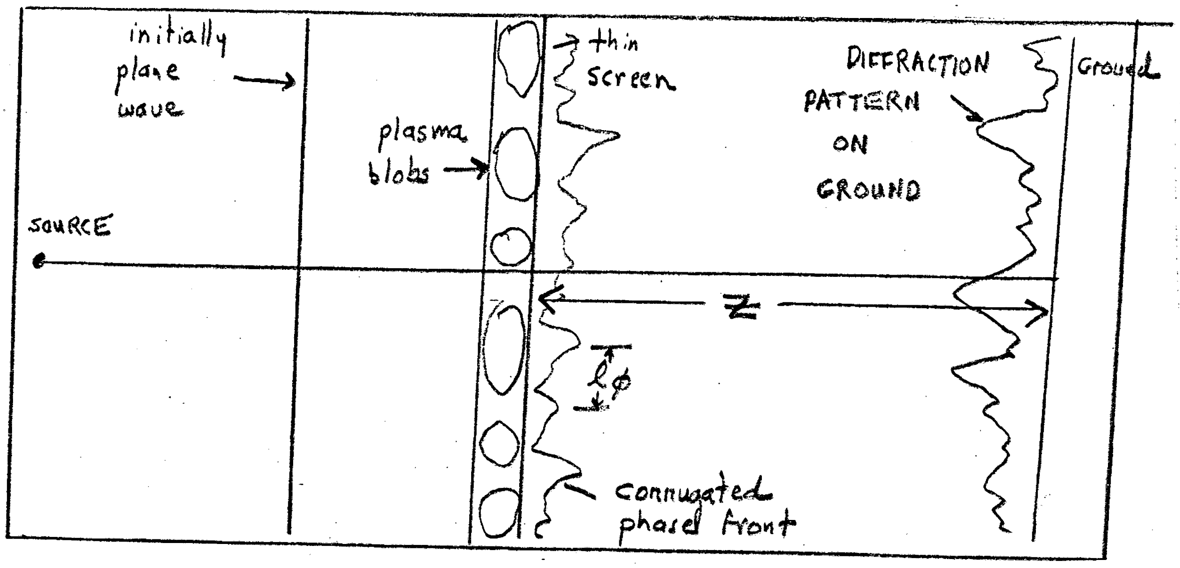
The interplanetary medium is a nonuniform plasma. Since the index of refraction in an electrostatic plasma is;

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2} \qquad (9)$$

ω_p = electron plasma frequency

ω = wave frequency

the index of refraction in the interplanetary medium is a stochastic function of position. On Earth we therefore see a complicated diffraction pattern. Since the solar wind moves, the diffraction pattern moves too, so as a result radio sources seen through the solar wind close to the Sun appear to "twinkle". This may be more clearly seen by reference to what is known as the "thin screen" formalism for scintillations. This assumes that the entire influence of the medium may be attributed to a thin, phase changing screen located a distance z from the observer (see Figure below).



Consider an initially plane wave incident on the screen. Since the index of refraction varies irregularly along the screen, so will the phase of the output wave. By Huygen's principle each point on a wave front may be considered a source for a new spherical wave. Since the new sources no longer have the same phase-relationship, they will interfere on a distant screen. The screen moves, therefore so does the diffraction pattern, resulting in intensity variations on the ground. The crucial parameters in the specification of the scintillation phenomenon are the distance to the screen and the phase decorrelation length, $l\phi$, which is a measure of the distance over which the phase of the output wave is correlated. The phase decorrelation length may be thought of as the slit spacing in a diffraction grating It is intuitively clear than a diffraction pattern will be washed out if the angular size of a light source subtends an angle greater than the angle between grating slits as seen by an observer at the observing screen. Similiarly, the scintillation pattern begins to be washed out if the source subtends an angle larger than θ_c, where θ_c is given by;

$$\theta_c \cong l\phi / z \qquad (10)$$

For interplanetary scintillations, the phase decorrelation length has been determined to be of the order of 100 km. Since the distance to the thin screen is of the order of 1 astronomical unit, we see that scintillations WIll only be prominent in sources smaller than a few tenths of an arcsecond.

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4. Summary of Angular Size Techniques.

A summary of the angular sizes to which various methods of measurement are sensitive is summarized below.

Largest single dish methods (Arecibo at 10 cm, NRAO 300' at 6 cm): roughly 1 to 2 arcminutes.
Small baseline interferometers (NRAO 3 element interferometer, Cambridge 5 km synthesis telescope): a few arcseconds to tens of arcseconds.
Long Baseline, coherent LO interferometers (NRAO Green Bank to Huntersville at 3 and 11 cm, Jodrell Bank to Defford at 70 cm): a few tenths of an arcsecond

Lunar Occultations: of order a few arcseconds at all frequencies.

Interplanetary Scintillations: signal to noise dependent, but typically a few tenths of an arcsecond to of the order of .01 arcsecond.
Very Long Baseline Interferometry: intercontinental VLBI at wavelengths of 2-3 cm (best resolution presently available) gives information down to the level of tenths of a milliarcsecond.
Interstellar Scintillation (ISS): resolution dependent on frequency, but is of the order of 1 microarcsecond or less.