Haystack Observatory is an interdisciplinary research center of the Massachusetts Institute of Technology (MIT) focused on radio astronomy, geodesy, and atmospheric science.

Haystack's radio astronomy program is conducted under the auspices of the Northeast Radio Observatory Corporation (NEROC).

Our Mission:

- Study the structure of our galaxy and the larger universe.
- Advance scientific knowledge of our planet and its atmosphere.
- Develop technology for radio science applications.
- Contribute to the education of future scientists and engineers.

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The History of Radio Astronomy - MIT Haystack Observatory

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1. Introduction

People have looked at the night sky since the very beginning of human existence on this earth. Their view has, however, been limited to the very narrow range of wavelengths that the eyes are capable of detecting. Imagine what the night sky would look like if our eyes were sensitive to other parts of the electromagnetic spectrum.

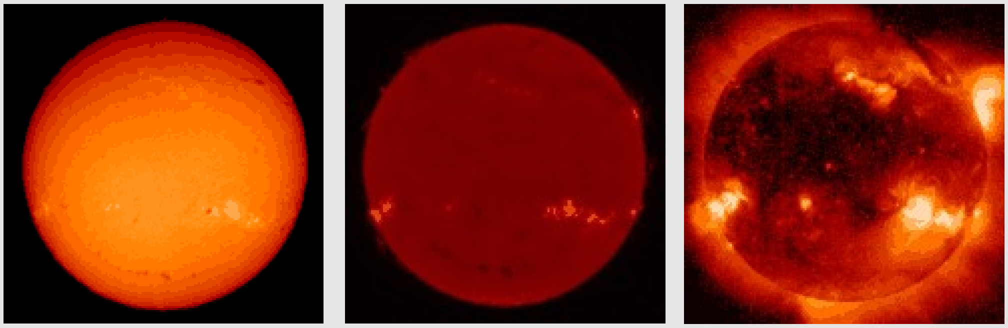
There are certain wavelengths that would not be visible from the earth's surface because of the atmosphere. If we look for the part of the spectrum that is most accessible from the ground we would arrive at the radio regime. This spans wavelengths ranging from less than a millimeter to several meters as compared to the optical wavelengths which range from 400 to 700 nanometers. Our view of the universe with eyes sensitive to the radio regime would look very different from our current view.

Since our eyes are limited to the optical regime we have to use other means of detecting the rich store of information that is available in a radio view of the skies. This branch of astronomy is known as radio astronomy.

The goals of radio astronomical observations are similar to those at optical or any other wavelength astronomy - to study the characteristics of an object emitting these waves. The methods used in radio astronomy are the same as those used in any branch of science - testing a hypothesis with experiments and observations.

Many objects in the universe emit radio waves. The "view" of an object as seen in the radio wave region can be quite different from what is seen in the visible light region. This points to different mechanisms causing the radio emission as compared to the optical emission. Comparative studies of objects in the emission from different wavelengths can teach us a lot about the processes that go on in the universe.

As an example, here are three images of the sun made at three different wavelengths:



H-alpha image (optical wavelengths - 6563 Angstroms) on 3/30/98

H-alpha image (optical wavelengths - 6563 Angstroms) on 3/30/98

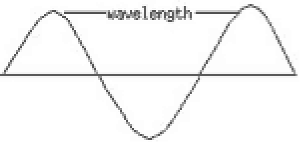
Soft X-ray image on 3/30/98

Daily images of the sun at various wavelengths such as the ones above can be obtained from a NASA web site.

It is immediately obvious that the above images show the sun as being very different at the three wavelengths. By combining the information obtained from the three images astronomers can study many aspects of the sun, the sunspots, the solar flares and prominences and all the other kinds of activities on the surface of the sun.

The aim of this tutorial is to provide an introduction to the basics of radio astronomy and introduce you to the techniques that allow radio astronomers to obtain and analyze data from radio telescopes.

2. Basics



We will now talk about some basic concepts that are needed to understand emission from astronomical sources. We will also cover some radio astronomy fundamentals and terms that are needed to understand the language radio astronomers speak.

2.1 Wave Basics

Electromagnetic Radiation

Electromagnetic radiation comes from the acceleration of charged particles. A stationary charged particle has a *field* associated with it. We cannot see a field but can infer it from the reaction of other particles around the charged particle (for example - the action of a magnet on iron filings). As you move away from the particle the field goes down in strength. Now, if you move the charged particle, this field moves with it and changes. This change in the field causes some energy to be carried away from the particle. It is this energy that we call electromagnetic radiation.

Electromagnetic Spectrum

Electromagnetic radiation is characterized by a *wavelength.* This concept is easily understood if we think about the radiation being in the form of a wave.

The wavelength is defined as the distance between two peaks or two troughs of the wave. The wavelength is inversely proportional to the frequency - which essentially defines how many repetitions of the wave there are in a given intervals. So, as the wavelength increases, the frequency decreases and vice versa.

The different "types" of electromagnetic radiation are defined by their wavelengths:

Type	Wavelength Range
Gamm rays	<0.01 nanometers
X-rays	0.01 - 10 nanometers
Ultraviolet	10 - 300 nanometers
Visible	0.3 - 0.8 micrometers
Infrared	1 - 1000 micrometers
Radio	0.001 - 30 meters

These names are largely historical in origin and are often separated by the techniques used to detect the particular kind of radiation and by the transmission characteristics of the earths atmosphere.

The "radio" regime of the spectrum is further subdivided into several categories that are wavelength dependent.

"Classical radio" wavelengths: The first astronomical detection was made at a wavelength of 14.6 meters. These long wavelengths are what people usually think of as radio wavelengths. The wavelengths at which FM and AM radio and TV signals are sent are also around these wavelengths:

FM radio (and TV): ~ 3 meters

AM radio : 300 meters

Microwaves: These are wavelengths between 1cm and 30 meters. Many of the communication links around the country are at these wavelengths (around 15 cm). Microwave ovens also cook food with radiation at these wavelengths. The important radio emission from neutral atomic hydrogen occurs at a wavelength of 21 cm.

Millimeter waves: Wavelengths from 1 mm to 10 mm. The rotational spectra of molecules occur in this wavelength range.

Submillimeter waves: Wavelengths < 1mm. Radio detection techniques are used to wavelengths of about 0.4mm. This wavelength range overlaps with the far-infrared portion of the electromagnetic spectrum.

2.2 Astronomy Basics

The basics of all astronomical observing is essentially the same. One needs to know where the source is in the sky and how to best use the instrument to get the information required to solve the problem. In general, it is important to know the source position to know whether it is visible at a particular time of day and whether it is in an optimum position for observations. The instrument parameters are different for each telescope although there are some general rules in determining the characteristics of the emission. This will be discussed in the section on calibration.

Coordinate systems - In order to know the source position in the sky one needs to define a coordinate system. Astronomers use the right ascension and declination system which can be compared to the latitude and longitude system on the earth's surface. This system is defined on the "celestial sphere" which is the two dimensional projection of the sky on the sphere around the earth. In this system the zero point of the declination is the "celestial equator" which is parallel to the earth's equator. So, in other words, if you were standing at a spot on the equator you would "see" the celestial equator as an arc passing directly overhead. The declination is 0degrees for a source on the celestial equator and is 90degrees for a source at the north pole. Sources below the equator would have negative declinations. The zero point of the right ascension is the vernal equinox which is the point at which the sun moves into the northern celestial sphere and marks the position of the sun on the first day of spring. The right ascension increases to the east and is measured in units of time.

The next concept we want to define is that of an hour angle. For this, we first define the hour circle as a great circle on the celestial sphere that passes through the north and south celestial poles (which are directly above the north and south geographic poles of the earth). Then, the angle measured westward along the celestial equator from the local meridian to the hour circle that passes through the source is defined as the hour angle of the source.

While making an observation at a telescope we not only want to know the right ascension and declination of the source but also the elevation and azimuth. These parameters will depend on the latitude and longitude of the observatory. If you go outside at night and look for the Pole star (which is situated very close to the north celestial pole), you will see that it is definitely not overhead. The height (in angular units) of the Pole star above your horizon corresponds to the latitude of the place you are standing. The angular distance above (or below) the horizon of any celestial source is called the elevation (or altitude) of the source. The azimuth is defined as the angle along the celestial horizon, measured eastward from the north, to the intersection of the horizon with the great circle passing through the source.

More detailed explanations of these coordinate systems can be found in any basic astronomy textbook.

Time - There are several times that can be defined using the celestial sources. We will only define those that are used actively in observing at the telescope. Universal Time is defined as the local time (defined by the sun) at 0degrees longitude. This is also called Greenwich Mean Time. The local sidereal time is defined as the hour angle of the vernal equinox. From the definition of the hour angle given above we can see that the local time (NOT the standard or zone time) and the local sidereal time will be equal on the day of the vernal equinox.

Doppler motion - This phenomenon describes the effect on the frequency of emission from a source when the source is moving relative to an observer. As the source moves away the wave emitted by the source gets stretched out - this causes the wavelength to increase and the frequency to decrease. It is usally called a "redshift". On the other hand, if the source is moving toward the observer the wave gets compressed causing the wavelength to decrease and the frequency to increase. This is called a "blueshift". The frequency can then be associated with the velocity of the source using the following relationship:

(change in frequency)/(original frequency) = velocity/speed of light

Radio astronomers often use frequency and velocity interchangeably.

Source velocity - The velocity of a given source is an important number in radio astronomy - especially when looking at spectral line emission from molecules. This velocity is defined as a relative velocity - relative to the motion of the "local standard of rest (or LSR)". The LSR is the velocity of the sun and the local group of stars in the Galaxy. So, depending on where the source you are looking at is in the Galaxy relative to the sun, it will either be moving toward the sun or away from the sun. Such a relative motion causes a Doppler effect on the light (or radio waves) coming into the telescope. This can cause the frequency of the emission (or absorption) line that you are looking at to shift. If the shift is greater than your observing frequency window (or bandwidth) then you might miss seeing it altogether. So we want to be sure that the receiving equipment can correctly take this frequency shift into account.

3. Differences between Optical and Radio Astronomy

There are many differences between optical and radio astronomy. The three main differences are the design of the instruments, the resulting data that is found, and the different sources that are seen.

Both optical and radio astronomy use telescopes; however, there is a big difference in the design between an optical telescope and a radio telescope.

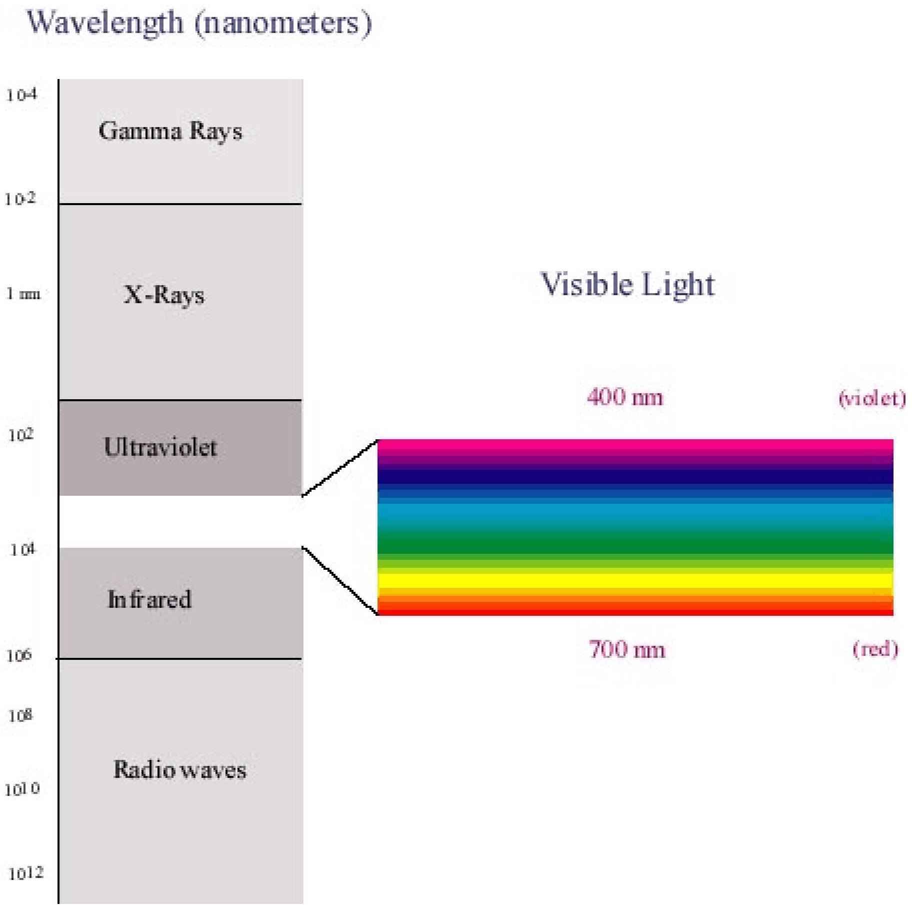
Optical astronomy is the study of the visible part of the electromagnetic spectrum, that is wavelengths of approximately 400 nm (purple) to 700 nm (red).

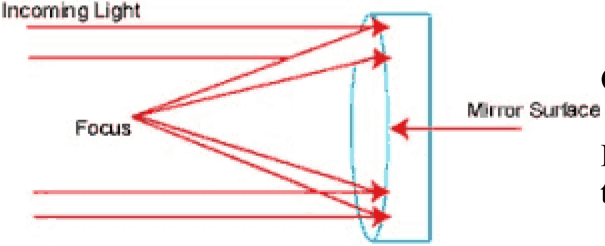
Radio wavelengths are much longer; the radio spectrum ranges from approximately one millimeter to hundreds of meters. This means that optical photons have much higher energies than radio photons. This property of photons affects the way one would detect them.

Optical detectors such as charge coupled devices (CCDs) detect the individual photons that strike the detector surface. The photon strike creates a response in the detector - this response is proportional to the number of photons striking the surface. In some cases, one can count the photons. The result is a measure of the intensity of the source that is generating the photons. Such a detection mechanism (called "coherent detection") will not work on radio photons. The energy carried by these photons is much too low to cause a reaction in a detector.

So in radio astronomy "incoherent" detection techniques are used. In simple terms, the receiver will now detect the wave nature of the radio wave rather than the photon nature. This means that one cannot count radio photons but rather get information about the phase and amplitude of the wave.

Electromagnetic Spectrum Diagram





Optical Telescopes

In optical astronomy there are three basic types of telescopes; the***refractor***, the ***catadioptric*** and the ***reflector***.

The ***refractor telescope*** receives light through the objective lens (the large lens closest to the subject being viewed) and sends it to the eyepiece for magnification. The image below shows a schematic diagram of a refractor telescope.

The second type of optical telescope is the ***catadioptric***. This type of telescope is similar to the Cassegrain reflector. It uses both mirrors and lenses, as the light entering the tube changes its direction twice. The tube length is shorter than its focal length. Focal length is the distance between the optical center of the objective lens and the optical center of the eyepiece. The longer this distance, the greater the magnification.

The basic ***reflector*** telescope uses a concave mirror as its objective lens to collect light from distant objects and then reflects that light up the tube to an overhead diagonal mirror. The diagonal mirror redirects the light into the eyepiece for magnification. The image below is a diagram of a reflector telescope.

There are four basic types of reflecting telescopes; they are the prime focus (as shown here), Newtonian, cassegrain, and the Schmidt. In the prime focus, the detector lies in front of the mirror. The Newtonian has a small mirror that reflects the light off the side of the telescope tube. The cassegrain utilizes a subreflector to reflect the light back through a hole in the primary mirror, and the detector can be placed behind the mirror. The Schmidt reflector, uses both a mirror and a correcting lens to produce a perfect image over a wide field.

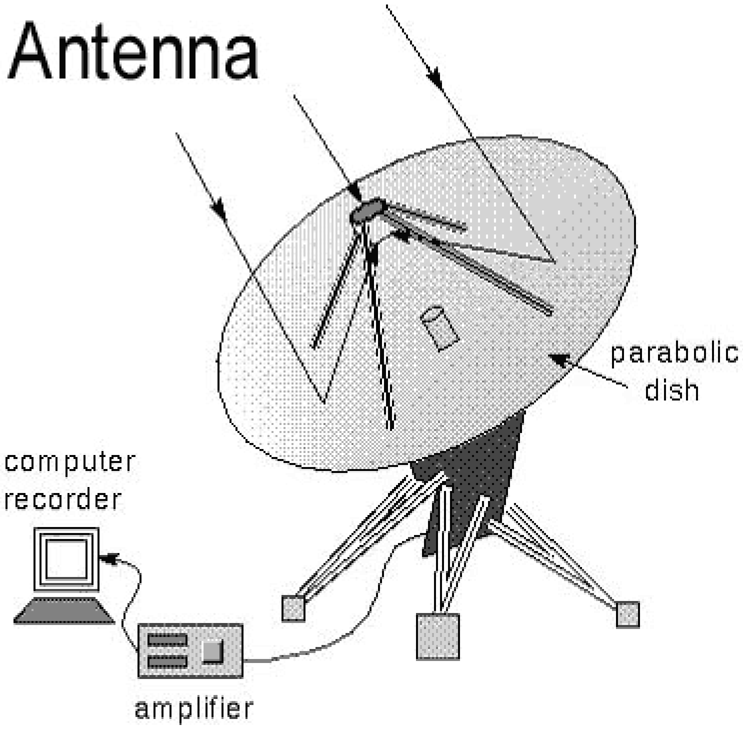
Radio Telescopes

Radio telescopes are mainly either prime focus or Cassegrain reflectors. However, the radio telescope looks very different from the optical telescope; radio telescopes are much larger than optical telescopes. The reason for this is that the angular resolution (or the angular area of the sky from which the telescope can collect emission) of a telescope is proportional to the wavelength divided by its diameter. So in order for a radio telescope to be able to detect the same angular resolution as an optical telescope the radio telescope has to be much larger. In addition, the sensitivity of the telescope or the ability to detect weak emission is also related to the area of the reflecting surface.

There are four basic elements to a radio telescope, the ***reflector,*** the ***subreflector***, the ***feed and transmission line*** and the ***receiver.***

The ***reflector*** collects power from astronomical sources. The ***subreflector*** is a surface that directs the radiation to the ***feed*** at the center of the reflector. Behind the feed is the ***receiver*** system (at the cassegrain focus). The receiver amplifies the radio signal, selects the appropriate frequency range that detects the signal.

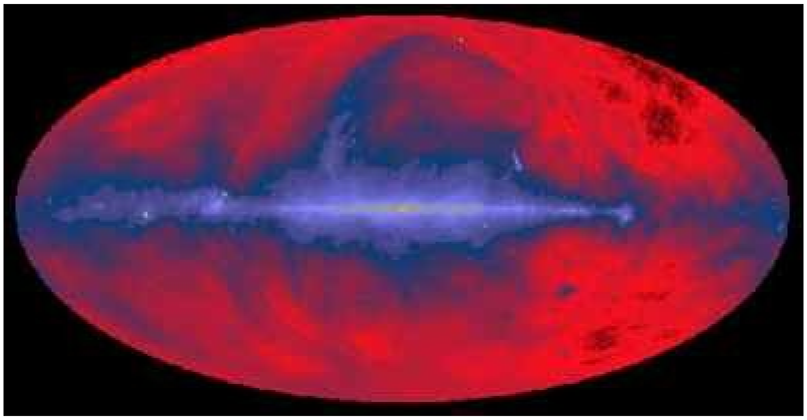
Radio telescopes use a large metal dish, usually parabolic, to reflect radio waves to the subreflector situated close to the prime focus. The signal from the antenna is sent to an amplifier, which magnifies the faint radio signals. The amplified radio signal is then processed by a computer. The receiver is configured in such a way that throughout the amplification process, the signal remains directly proportional to the strength of the incoming radiation. So the resulting image or spectrum is a true representation of the emission from the astronomical source. The following image is a schematic diagram of a radio telescope.



A radio telescope reflects radio waves to a focus at the antenna.

The resulting images from the radio telescope are very different from the optical telescope. These difference are mainly due to the different mechanisms that cause the emission. For example, here is an image of the Milky Way using an optical telescope (photo courtesy of APOD). At visible wavelengths, the sky is dominated by thermal emission from the visible surface of the stars. Optical astronomers measure the brightness of objects by measuring the apparent magnitude, or the flux density of the object. The flux density is a measure of the power received from the object per unit frequency, per unit area.

Here is the Milky Way using a radio telescope tuned to 408MHz.
(image courtesy of APOD 12/14/97)

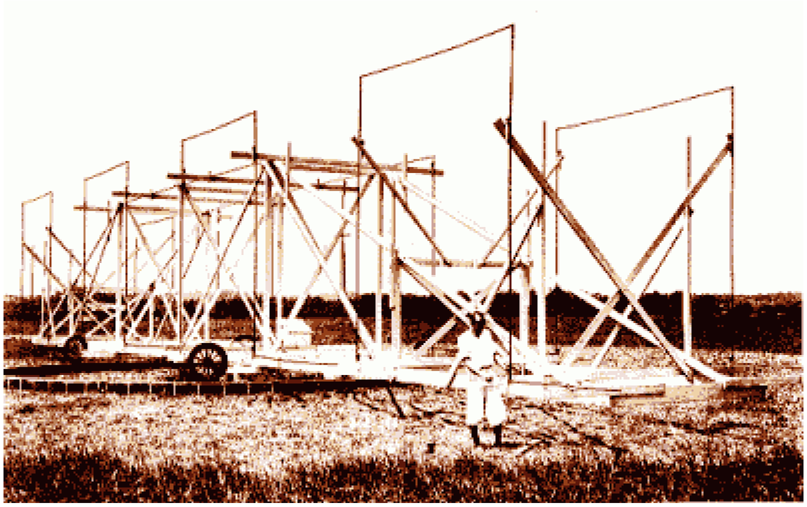


None of the bright stars in the night sky are prominent radio emitters. The emissions that are measured in radio astronomy come not from the stars, but from the gasses, etc. It can be seen that these views are very different from one another. The radio sky is not dominated by the light from stars and, depending on the wavelength, may not be dominated by thermal radiation. At short radio wavelengths thermal emission sources dominate the sky, and at long radio wavelengths the sky is dominated by non-thermal emission sources. In the radio sky there are also sources of both continuous emission and line emission. An example of radio line emission is the 21-cm line of neutral atomic Hydrogen. At long wavelengths the emission occurs primarily from synchrotron emitting sources such as pulsars, supernovae remnants, radio galaxies, and quasars. At short wavelengths the emission is dominated by thermal sources. Small, hot sources such as stars can be detected but are not an important part of emission. Large, cold sources such as the gas and dust clouds of interstellar medium and hot, large sources such as HII regions are important sources of emission.

4. The History of Radio Astronomy

The early history of radio astronomy begins in 1894, with Sir Oliver Lodge. Lodge attempted detection of radiation from the sun at centimeter wavelengths. Unfortunately over the next forty years, further attempts also failed due to inadequate detection techniques.

The more recent history of radio astronomy begins in 1931 when an American engineer named Karl Jansky, while working for Bell Telephone Laboratories, conducted experiments on radio wavelength interference. Jansky detected three separate groups of static; local thunderstorms, distant thunderstorms and a steady hiss-type static of unknown origin. The unknown source that Jansky found is the center of the Milky Way as he was able to show by determining its position on the sky.



Jansky was the first to detect radio emission from the Galaxy. The image above shows Jansky standing with his antenna (Photo courtesy of Bell Laboratories). This rotatable antenna looks similar to a merry-go-round; the rotation allowed it to move along with the static. The work done by Jansky included receiving frequencies in the range of 15 to 30 MHz (approximately 15-m wavelengths). Jansky published three reports on his findings, which were largely ignored for many years to come. The field of radio astronomy would eventually recognize him with a unit named for him; the Jansky is equivalent to 10^(-26) watts per m^2 per Hz.

In 1937 Grote Reber, also a radio engineer, read about Jansky's work. Reber built a parabolic, 9.5-m diameter, reflector dish in his backyard. This was the first radio telescope used for astronomical research. Reber spent years studying cosmic radio waves at various wavelengths, while other astronomers still didn't get involved. He finally detected celestial radio emission at approximately 2-m. The image below shows Reber with his telescope, the prototype for modern radio telescopes (courtesy of NRAO). Reber continued his investigations of radio sources and confirmed that radio emission arose from the Galactic plane. Reber, in 1944, published the first radio frequency sky maps. Reber's telescope is displayed at the National Radio Astronomy Observatory (NRAO) in Green Bank West Virginia.

The first observation of radio emission from the sun was made in 1942, by J.S. Hey. Hey was working with the British Army Operational Research Group analyzing all occurrences of jamming of Army radar sets. A system for observing and recording jamming was organized. This eventually led Hey to conclude that the sun was radiating intense radio emission. Later that same year, G.C. Southworth made the first successful observations of thermal radio emission from the sun; he did this at centimeter wavelengths. The next important discovery regarding radio waves from beyond the solar system were discrete sources of emission. In 1946, J.S. Hey, S.J. Parsons, and J.W. Phillips observed fluctuations in the intensity of cosmic radio waves from the constellation Cygnus. In the next ten years thousands of discrete sources were identified, including galaxies and supernovae.

Most gases in galaxies are invisible to optical telescopes but can be seen by radio telescopes. Fast moving electrons, neutral atoms and molecules generously emit at radio wavelengths. In 1951, H. I. Ewen and E. M. Purcell, detected the spectral line emission from neutral Hydrogen that fell into the radio spectrum. For the first time, astronomers could determine the shape of our own home galaxy.

In 1963 Bell Laboratories assigned Arno Penzias and Robert Wilson the task of tracing the radio noise that was interfering with the development of communication satellites. Penzias and Wilson discovered that no matter where the antenna was pointed there was always non-zero noise strength, even where the sky was visibly empty. A simple solution would have been to reset their receivers to zero, but they persisted in tracing the source. This major discovery made by Penzias and Wilson was the cosmic background radiation and the strongest evidence for the big bang. Penzias and Wilson won the Nobel Prize in physics for their discovery in 1978. The image to the left shows Penzias and Wilson with their 6m horn antenna (Photo courtesy of Lucent Technologies, Bell Labs Innovation). The horn shape was used because the field of view remains unobstructed allowing for a precise measurement of the effective collecting area of the antenna.

In the late 1960's, radio pulsars, predicted only by theories of stellar evolution, were discovered by Jocelyn Bell-Burnell and Anthony Hewish. Bell-Burnell and Hewish were working at what is now called the Nuffield Radio Astronomy Observatory at Cambridge, England. Pulsars are very strongly magnetized, spinning neutron stars. Neutron stars are so dense that one teaspoon of this star would weigh as much as all the cars and trucks in the U.S. put together. Anthony Hewish and Martin Ryle won the Nobel prize for this discovery in 1974.

5. Radio Astronomy Basics

This section contains some basic terms and concepts that are important in understanding radio emission measurement techniques.

5.1 Characteristics of the Signals

5.1.1 Electromagnetic Radiation: Rays, Waves, or Photons?

Wavelength and frequency ranges; what's λ , what's ν ?

The radio-frequency range is arbitrarily defined to be from frequencies (ν) beginning at the super-sonic, meaning just above the range of sound waves that humans can hear, 20 kHz or so, up to about 600 GHz, where the far infrared begins. The corresponding wavelength (λ) range is from many kilometers down to about 0.5 mm or 500 microns. Frequency and wavelength are related, as for any conventional wave phenomena, by:

$$\nu = c/\lambda$$

where c is the speed of light, 299792.5 km/s.

Over this frequency range and at moderate equivalent temperatures, we can usually ignore photons; that is, we need not quantize the electromagnetic field. In most cases, this results in both simplification and insight that is lacking if one thinks photons instead of waves.

Many formulas used in radio astronomy (and electrical engineering) are based on the Rayleigh-Jeans approximation to the Planck black-body law. If, furthermore, the antenna structures are large compared to a wavelength, as is usually the case at centimeter and millimeter wavelengths, then we can often ignore waves also and use just ray-trace optics.

5.1.2 Law of large distances

Another helpful simplification involves the large distances and small angular sized of most astronomical objects. Angles in radians are, then, just the linear sizes divided by the distances.

5.1.3 Noise-like signals

A. Law of large numbers

Most astronomical sources are large in physical size, even though small in angular size, and radiation is emitted by a large number of statistically independent sources– atoms, molecules, or electrons. The resulting signals are noise-like, that is, the electric fields are Gaussian random variables with spectra that depend on the details of the emission mechanisms. Laboratory laser and maser oscillators are usually coherent because of the cavity in which they oscillate. Astronomical masers have never been found to have non-Gaussian statistics.

For similar reasons, many radio-astronomical sources are unpolarized; that is, signals in one polarization are statistically independent of signals in the orthogonal polarization. But some sources, especially those involving magnetic fields that extend over a significant part of the spatial extent of the source, can be polarized, and studying such polarization sometimes leads to significant insights.

B. Law of large sizes

As a rough rule with some exceptions, an incoherent source that is not resolved in angle can be seen to vary only on time scales long compared with the light travel time through the length of the emitting region. A black sphere with cyclic temperature variations, for example, will have these variations smoothed over as seen from a large distance if the cycle time is comparable to or less than the light travel time across a radius of the sphere. Some astronomical sources vary, and the time scales of the variations can sometimes be used to infer maximum sizes.

C. Significance for measurement techniques

Some of the techniques used in radio astronomy depend on these characteristics of the sources. One-bit autocorrelation spectroscopy, for example, depends on the signal voltage being a Gaussian random variable. And many-hour-long interferometry depends on the source being stable over that time.

5.2 Spectra

5.2.1 Continuum sources, black body or ν^n?

A black body at temperature T in the radio-frequency range has a specific intensity given by the Raleigh-Jeans approximation to the Planck black-body law:

$$I=2kT/\lambda^2$$

where I is the specific intensity in, for example, watts/(m^2Hz ster), k is Boltzman's constant, 1.380×10^{-23} watts/Hz/K and λ is wavelength.

The proportionality to temperature allows us to talk about intensities and powers in temperature units, K or Kelvins. If a source really were thermal emission from a black or gray body, then this radiation temperature would be independent of wavelength. More typically, however, sources are "colored", that is, radiation temperatures vary with wavelength and are not necessarily related to physical temperatures of the sources. A synchrotron-emission source, for example, has a spectral index n, usually defined by $I \propto \nu^{-n}$, that is related to the energy distribution of the emitting electrons. Regardless of the emission mechanism or spectrum, we can use the Rayleigh-Jeans equation above to define a brightness temperature, T_b, proportional to intensity, but then T_b will be, in general, a function of frequency. Even in the high-frequency low-temperature range where Rayleigh-Jeans is no longer useful, we can use this equation to define a convenient fake brightness temperature. Figure 1 is a cartoon example of such spectra.

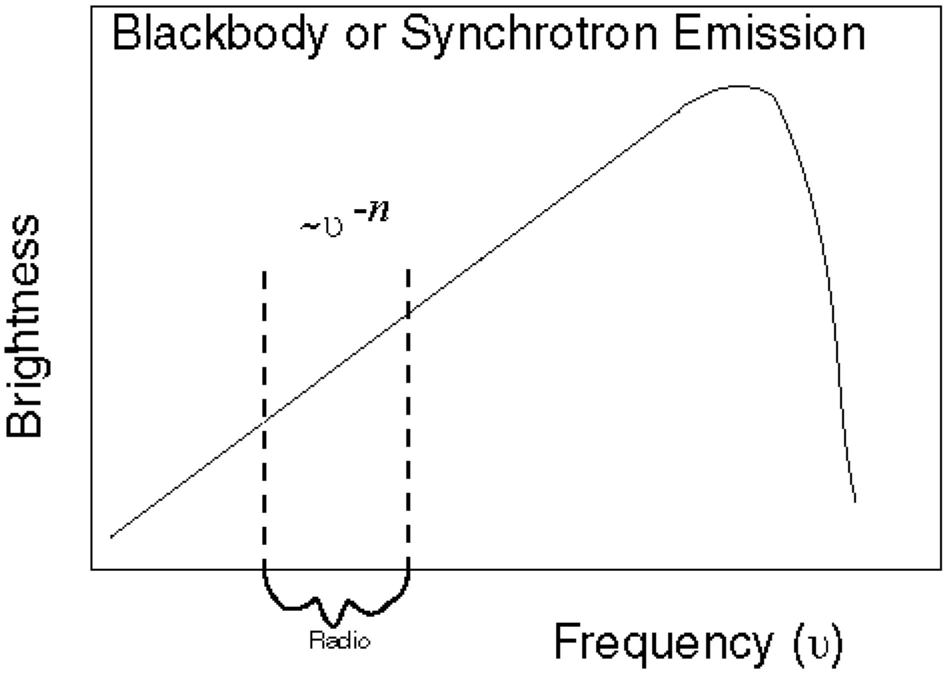


Figure 1

Electrical engineers implicitly use the Rayleigh-Jeans approximation also. The noise power per unit bandwidth from a warm resistor into a matched load is just *kT* provided that the frequency and temperature are in the range for which Rayleigh-Jeans is precise. To see this, imagine a resistor coupled to a feed looking at a black body. Even in the range where Rayleigh-Jeans is no longer useful; in thermal equilibrium, equal power must flow each way.

5.2.2 Atoms and molecules– emission and absorption lines

Emission and absorption lines in radio astronomy usually originate from atoms and small molecules or molecular ions in gaseous form, and molecular transitions at radio wavelengths are usually rotational. Emission lines result from warm gas overlying a cold background so that the intensity (or flux or radiation temperature) at the line frequency is sharply higher compared to nearby wavelengths. If such a gas cloud is optically thick (opaque), the specific intensity or "brightness" at the line frequency is given by the state temperature of the corresponding transition, which, at thermodynamic equilibrium, would be just the temperature. Thermodynamic equilibrium is, however, not very common in radio astronomy. Absorption lines result from cool gas overlying a hotter background source so that the intensity at the line frequency is sharply lower compared to nearby wavelengths. If such a gas cloud is optically thick, then the line center again gives the state temperature. Figure 2 is a cartoon of such spectra.

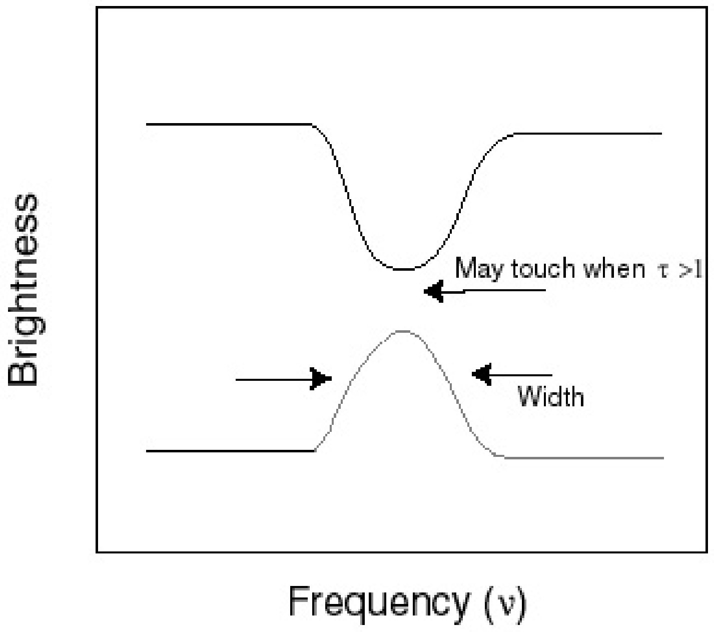


Figure 2

5.2.3 Doppler shifts and kinematics

Doppler shifts are very important in spectral-line radio astronomy. The non-relativistic form is usually written as

$$\Delta \nu / \nu = -v/c$$

where $\Delta \nu$ is the change in frequency ν due to the Doppler velocity v, defined as the rate of change of distance from source to observer (hence the minus sign), and *c* is the speed of light.

Even when speeds are relativistic, this non-relativistic formula is sometimes still used to define a convenient fake velocity.

Line widths and line shapes are influenced by several line-broadening mechanisms including *a*) natural line widths related to the lifetimes of the states involved in the transition, *b*) kinematic temperatures characterizing the small-scale random motions of the atoms or molecules, *c*) turbulence or larger-scale random motions, and *d*) kinematics, by which we mean large-scale ordered motions such as expansions, contractions, or rotations. A useful exercise is to estimate the spectrum that would be seen from some simple kinematic models such as a circumstellar shell or sphere that is expanding, contracting (infalling), or rotating and is unresolved in angle. In some cases the central star ionizes nearby gas, which makes a central continuum source. Such an object can then show both emission and absorption lines.

5.3 Antennas at Radio Wavelengths

5.3.1 Parabolic¥why?

Radio-astronomical sources are far away, so incoming signals often look like plane waves from a specific direction (*point sources*), and the first goal of a radio telescope is to catch as much energy as possible from such a wave and avoid as much as possible any other signals, especially local interference. The signal at the antenna in this case can be characterized by a flux density in Janskys (1 Jy = 10^{-26} w/m^2/Hz), so the bigger the antenna, the more watts (well, pico-pico watts) we collect. A parabolic antenna (i.e., a parabola of revolution), which puts all this energy into a small spot where a *feed* can be placed, is usually an engineering optimum for centimeter and millimeter wavelengths.

5.3.2 Aperture efficiency and K/Jy

Consider a black sphere with diameter d and temperature T at a distance r from a circular receiving antenna with diameter D. Assume that r is much larger than either d or D. Figure 3 is a cartoon of this situation.

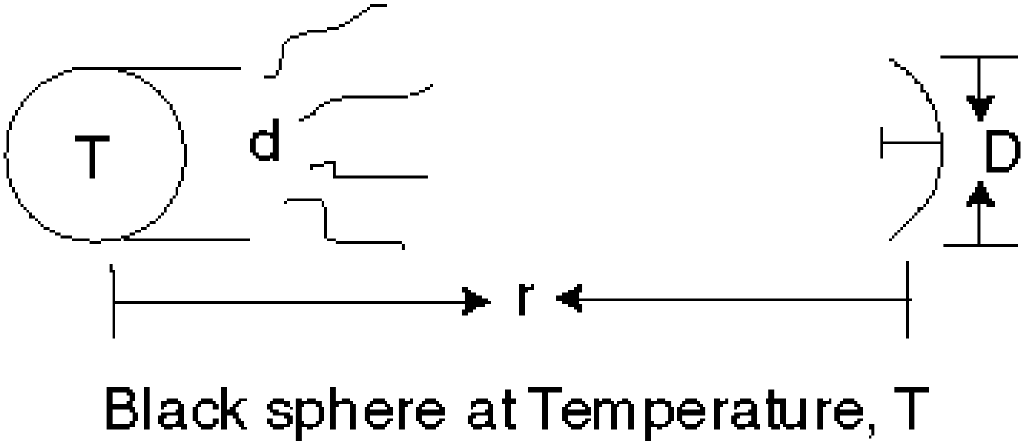


Figure 3

Then the power density (power per unit frequency interval) received by the antenna, P, can be calculated as its collecting area times the flux from the source at the antenna or as the specific intensity of the source times the solid angle of the antenna as seen from the source. Either way gives the same formula, namely,

$$P=I(\pi d^2/4)(1/r^2)(\pi D^2/4)$$

The first three terms on the right are the source flux density, F, and $A = \pi D^2/4$ is the antenna collecting area, which is usually smaller than its physical area due to various losses. If we characterize P in temperature units, $P = 2kT_R$, as usual, then

$$T_R/F=A/2k$$

is a figure of merit, sometimes called *sensitivity*, in Kelvins per Jansky for the antenna. That extra 2 is because the flux density refers to the total in both polarizations, but a single receiver can only receive one polarization.

The ratio of the antenna collecting area from this formula to its physical area is called *aperture efficiency* usually expressed as a percentage and usually 60% or less.

5.3.3 Beam efficiency and beam dilution

Another figure of merit, appropriate for sources extended in angle, is the *beam efficiency*, crudely defined as the ratio of T_R to the brightness temperature of the source. (There are more precise but less useful definitions.) Beam efficiency by this definition is, however, a function of the source angular size and shape, alas. A more useful parameter is the *beam dilution*, defined in the same way but for an assumed circular source with a specified diameter in beamwidths and as a function of this diameter. Planets with known brightness temperatures and angular sizes are candidate calibration sources for measuring aperture efficiency when they are small in angle compared with a beamwidth or points on the beam-dilution curve when they are larger in angle. Figure 4 is a cartoon of this situation.

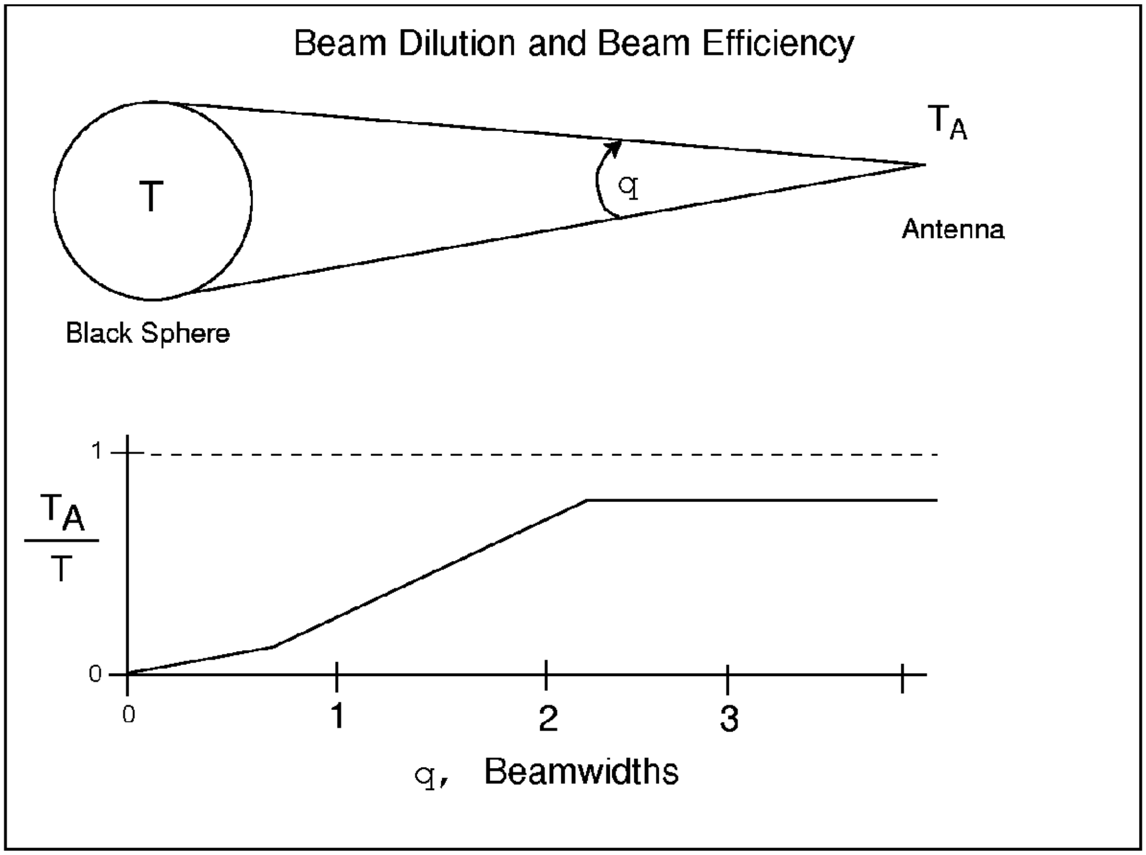


Figure 4

5.3.4 Cassegrain¥why?

A Cassegrain antenna comprises a parabolical main reflector and a concave hyperbolical *subreflector* near the *prime focus* of the main reflector to reflect incoming signals back to a spot near the center of the main reflector, the *secondary focus*, where the feed is placed. This feed is usually mounted on the front of a receiver box that fits through a hole in the center of the main reflector. This arrangement trades a little additional aperture blockage (the subreflector is larger than a prime-focus feed would be), for the ability to place additional equipment, such as a cryogenic refrigerator, near the secondary focus.

5.3.5 Beamwidth: λ *D*

The *beamwidth* (full width to half power) of the radiation pattern of a circular antenna is approximately 1.2 λ /*D* in radians, where λ is the wavelength and *D* is the diameter of the antenna in, of course, the same units. The 1.2 factor depends somewhat on the feed illumination pattern, that is, on the pattern of the feed as seen from the main reflector. A circular antenna with circular illumination gives a circular beam.

When a finite antenna is used to map extended sources over a range of angles one can show the resulting maps are *band limited* in the sense that they contain no angular frequencies above a maximum (called the Nyquist limit) that depends only on the wavelength and the antenna diameter. Band-limited maps are, then, smooth continuous functions of two angles on the sky, but they can be specified or measured at a finite grid of evenly spaced points provided that these points are no farther apart than a Nyquist step, which is λ /(2*D*) in radians. A Nyquist is typically a little less than half a beamwidth. Smooth maps can be obtained from finite grids of points by convolution.

5.3.6 Requirements for surface precision

The effective area of an antenna is less than its physical area because of various losses, one of which is due to the departure of the surface from an ideal parabolic shape. An antenna with a surface that is rough on the scale of a wavelength will be almost useless because of low aperture efficiency and also susceptibility to interference scattered into the feed. An ideal antenna would have at least so-called 1/20-wave optics, meaning that the surface is within a 1/20 of a wavelength of perfect. We must sometimes make do with antennas less than ideal; all antennas have some short-wavelength limit based on this criterion.

5.4 Interferometers

5.4.1 Why? Resolution: λ /*D*

Two or more antennas looking at the same source at the same time can have their signals combined into an interferometer to give some of the information that would be obtained from a single antenna with a diameter equal the spacing between the interferometer antennas. The resolution of a two-antenna interferometer is approximately λ/*D* (no 1.2), where *D* is now the spacing between antennas, but this resolution is only in the direction parallel to a line connecting the antennas and only for sources in a plane perpendicular to this line. A single measurement with a single pair of antennas gives a single datum to be placed in the so-called *uv*plane, which is the Fourier-transform plane of the angular distribution of the source on the sky. The *uv*plane is roughly comparable to the plane of the surface of an equivalent single antenna. Even with only two antennas, because of Earth§s rotation, data can be obtained over time along two elliptical arcs in the *uv* plane. More antennas give more elliptical arcs, often crossing, but unless the antennas actually touch or overlap, there will always be gaps with no data in the *uv* plane. The corresponding synthesized antenna beam has side-lobes because of the missing*uv* data. There are helpful data-reduction techniques that amount to model fitting or to interpolating or extrapolating across these gaps.

5.4.2 Connected vs VLBI

Interferometers with antennas spaced up to, say, a few kilometers usually have cables or fibers connecting the antennas to a central site where the cross correlations are done in real time. With wider spacing, including transcontinental and intercontinental interferometers, the techniques of tape-recorder or very-long-baseline interferometry (VLBI) are used. At each antenna, data and microsecond timing information, usually derived from atomic clocks, are recorded on magnetic tapes to be shipped to a central site for cross correlation at a time that may be weeks or months later. This delay is a disadvantage, especially for troubleshooting, but there is almost no other way to do large data rates on megameter baselines with their milliarcsecond resolutions. Figure 5 is a sample uv coverage plot of 3C84 for a realistic VLBI experiment.

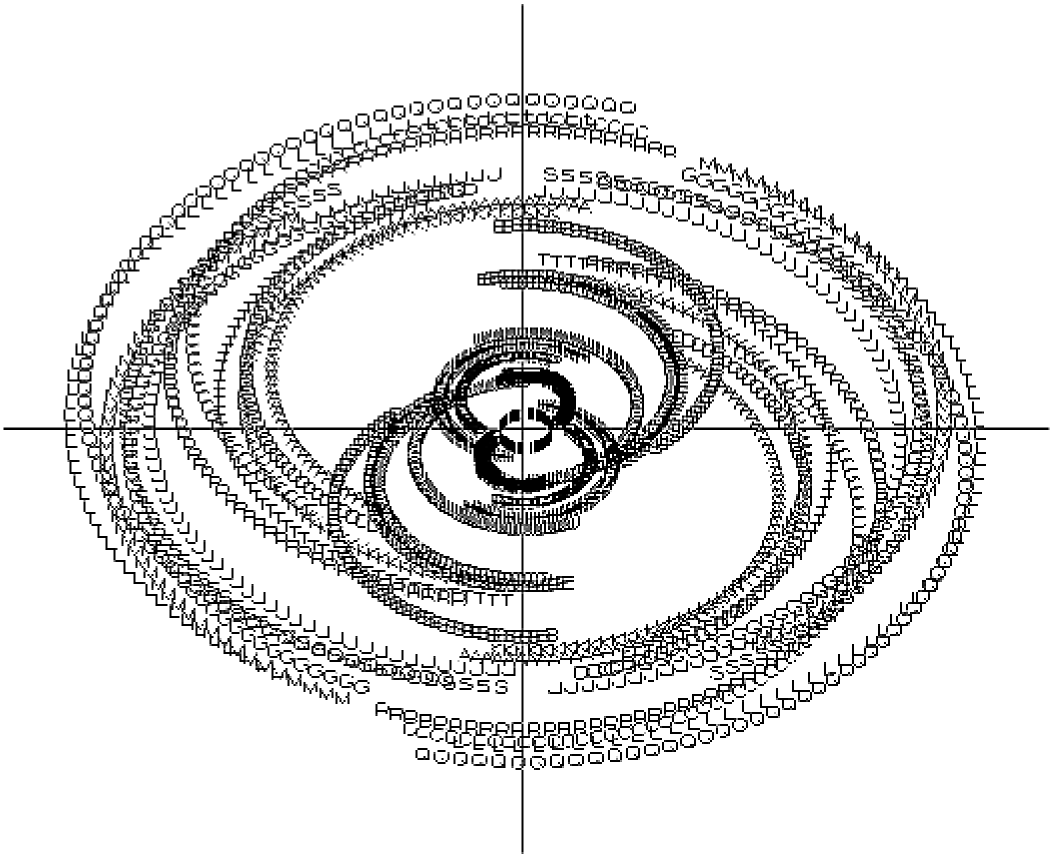


Figure 5.

6. Radio Wave Detection Techniques

6.1 Introduction

This chapter describes the various components of a radio telescope and outlines the various detection mechanisms for the radiation.

6.2 Antennas

6.2.1 Introduction

The elements of a standard radio telescope are the reflector, feed, transmission line and receiver. We will first discuss the reflector, which collects power from an astronomical source and provides directionality. The terms antennas and reflectors are often used interchangeably. However, there is a difference–an antenna is a device that couples the waves in free space to the confined waves in a transmission line while reflectors concentrate the radiation. The reflector or antenna has two purposes, first they collect power and second they provide directionality. The power collected by an antenna is approximately given by

$$P=S\nu A\ \Delta\nu$$

where $S\nu$ is the flux density at the earth from some astronomical source, A is the area of the antenna and $\Delta\nu$ is the frequency interval or bandwidth of the measured radiation.

So, the larger antennas collect more power. The antenna also has the capability of discriminating the signals coming from different directions in space.

6.2.2 Diffraction and reciprocity

The operation of antennas, and telescopes in general, are governed by electromagnetic theory and diffraction theory plays an important role. In order to understand this, one first needs to know the reciprocity theorem. This theorem states that the telescope operates the same way whether it is receiving or transmitting radiation. So the response pattern of an antenna that is receiving radiation is the same as the pattern produced when the same antenna is transmitting. A schematic of a response pattern of an antenna is given in Figure 6.1.

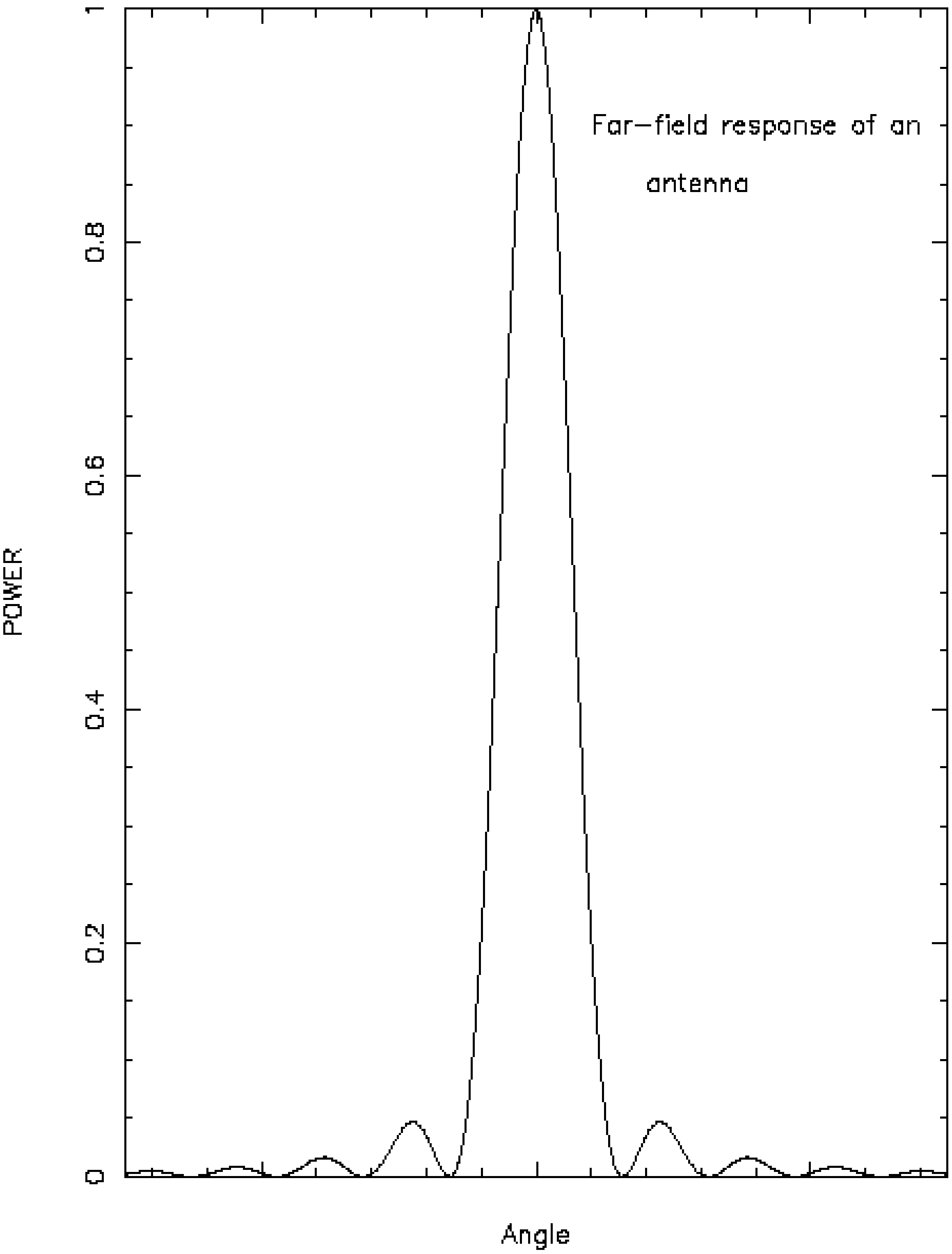


Figure 6.1

A telescope’s response pattern is then the same as the far-field diffraction pattern produced by the aperture. In general, when radiation of wavelength λ passes through an aperture of diameter *D,* the radiation diffracts into a beam with angular size $\theta = \lambda / D$. At large distances (or the far-field response), the pattern is given by Fraunhofer diffraction theory and the pattern looks like that in Figure 6.1, where the beamwidth is the full width at half power of the main beam. The beamwidth θ is also a measure of the directivity of the antenna. A more precise statement that can be made (and will not be derived here) is that the angular pattern of the electric field in the far-field is the Fourier transform of the electric field distribution across the aperture.

6.2.3 Parabolic Antennas

Parabolic antennas (or reflectors) are common to both radio and optical astronomy. The reflector focuses plane waves to a single point, or in other words, converts plane waves into converging spherical waves. In a radio telescope these spherical waves are then coupled to a transmission line using a feed horn, which is a horn antenna. The feed horn can be placed at the prime focus or at a secondary focus using a Cassegrain design (Figure 6.2).

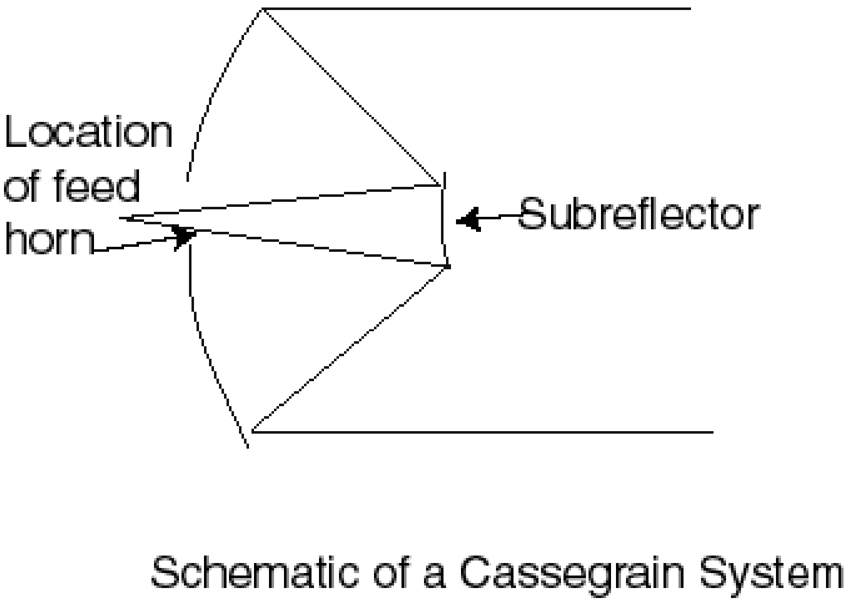


Figure 6.2

Most radio telescopes have a Cassegrain design since placing the feed horn at the prime focus will block more of the surface. Small telescopes (such as the SRT) have a prime-focus arrangement in which the reflector is illuminated by the feed placed at the focal point on the axis of the parabola. The geometry of a parabola is given by

$y=x^2/(4F)$

where y is the distance from plane, x is the distance from the vertex, and F is the focal length as shown in Figure 6.3.

Figure 6.3

The reflector surface must follow a parabola to within a small fraction of a wavelength. An imperfect surface scatters some signal away from the focus and produces a loss known as the *Ruze* loss after John Ruze, who first derived the expression

$L = exp(-(4\pi d/\lambda)^2)$

where *L* is the loss factor, *d* is the root-mean-square (rms) deviation from a parabola,and is λ the wavelength.

For most random distributions, the rms is about one quarter of the peak-to-valley variations. Figure 6.4 shows the Ruze loss in dB as a function of surface quality.

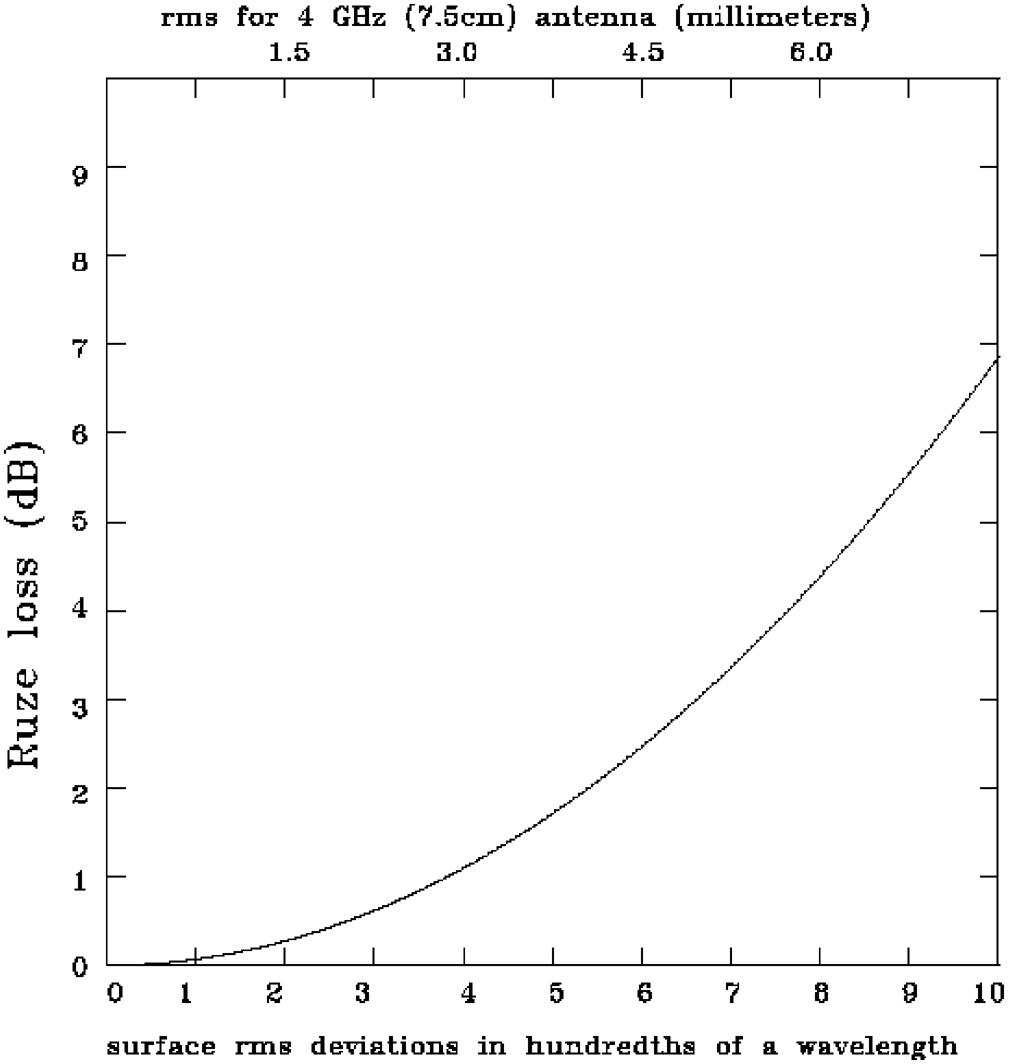


Figure 6.4

The angle subtended by the reflector, as seen by the feed, is determined by the ratio of focal length to diameter or *F/D*. Most dishes have a *F/D* ratio close to 0.4. A Radio Shack 9-foot satellite TV dish has an *F/D* of 0.38. For this *F/D*, the edge of the dish is about 64° out as seen by the feed. The feed should ideally be an antenna with a uniform beam that illuminates only the reflector surface. The efficiency in this case would be close to 100%. In practice, a good feed provides about 60 to 70% efficiency, so that the gain of this 9-foot antenna is 39.6 dB at 4.1 GHz. A very popular feed design is a *scalar* feed, which consists of a probe in a circular waveguide surrounded by choke rings as illustrated in Figure 4. The beam of the feed, which usually tapers down by about 10 dB at the edge of the dish, can be adjusted to some extent by the choice of opening size and location of the choke rings. Figure 5 shows the effect on efficiency of varying this taper. The beamwidth of a dish illuminated with such a scalar feed is approximately

$$\theta = 1.22\ \lambda/D$$

6.2.4 Gain

Radio and radar engineers normally speak about antennas in terms of their gain in dB referred to a half-wave dipole (dBd) or referred to an ideal isotropic antenna (dBi). A half-wave dipole has a gain of 2.15 dBi. Radio astronomers prefer to talk of size and efficiency or effective collecting area The gain, G, of an antenna relative to isotropic is related to its effective collecting area, A, by

$$G = 4\pi A/\lambda^2$$

where is the λ wavelength

The gain is also related to the directivity of the antenna: An antenna with a smaller beam will have a higher gain. If we think of the antenna as a transmitter, as we can do owing to reciprocity, then if the transmitted energy is confined to a narrow angle, the power in this direction must be higher than average in order for the total power radiated in all directions to add up to the total power transmitted.

To achieve an effective area or aperture of many square wavelengths (gains of more than, say, 26 dBd), a parabolic reflector is the simplest and best approach. For long wavelengths, for which an antenna with more than 26 dBd would have enormous dimensions, other approaches are more appropriate. As radio amateurs doing Moon-bounce know, it is hard to beat an array of Yagi antennas for simplicity and minimum wind loading. A single 20-wavelength-long Yagi can give a gain of 20 dBd. Stacking 2 Yagis adds 3 dB and another 3 dB for every doubling. The effective aperture of a 20 dBd Yagi, however, is only 13 square wavelengths, so that stacking 50 Yagis to get 37 dBd of gain at, say, 4 GHz doesn't make much sense when you can do as well with a 9-foot-diameter dish of 60% efficiency. At UHF frequencies around 400 MHz, the choice between Yagis and a dish is not so clear.

With the availability of excellent LNAs, optimizing the antenna efficiency is less important than optimizing the ratio of efficiency to system noise temperature or gain over system temperature, G/T_s. This means that using a feed with low sidelobes and slightly under-illuminating the dish may reduce T_s by more than it reduces G and so improve sensitivity.

6.2.5 Spillover

With advent of superb Low Noise Amplifiers (LNAs), the antenna noise is also a very important performance parameter along with the gain or equivalent effective aperture. Antenna noise originates from the sky background, ohmic losses, and ground pickup or *spillover* from sidelobes. While the sky noise is fundamental, the losses and sidelobes can be made small by a good design. Sky noise is frequency dependent but never gets any lower than the cosmic 3-K background. The minimum is near 1.4 GHz, where Galactic noise has declined and atmospheric attenuation, due primarily to the water line at 22 GHz, is still low. The lowest system noise achievable is about 18 K. At the NASA deep space network (DSN), where every fraction of a dB of performance is worth $millions, the S-band (2.3 GHz) system budget is approximately 3 K from cosmic background plus 7 K spillover plus 3 K atmospheric plus 5 K LNA. At 408 MHz, galactic noise will dominate, and system noise will be at least 50 K increasing to over 100 K toward the Galactic center. Figure 6.5 shows the relative system-noise contributions as a function of frequency.

Figure 6.5

6.3 Receivers

6.3.1 Introduction

Radio telescope receivers filter and detect radio emission from astronomical sources. In most cases the emission is incoherent radiation whose statistical properties do not differ either from the noise originating in the receiver or from the background radiation that is coupled to the receiver by the antenna. In addition, these signals are extremely weak, so amplifiers have to be constructed in order to increase the signal to a detectable level.

Figure 6.6 is a schematic of a minimalist receiver for continuum radio astronomy.

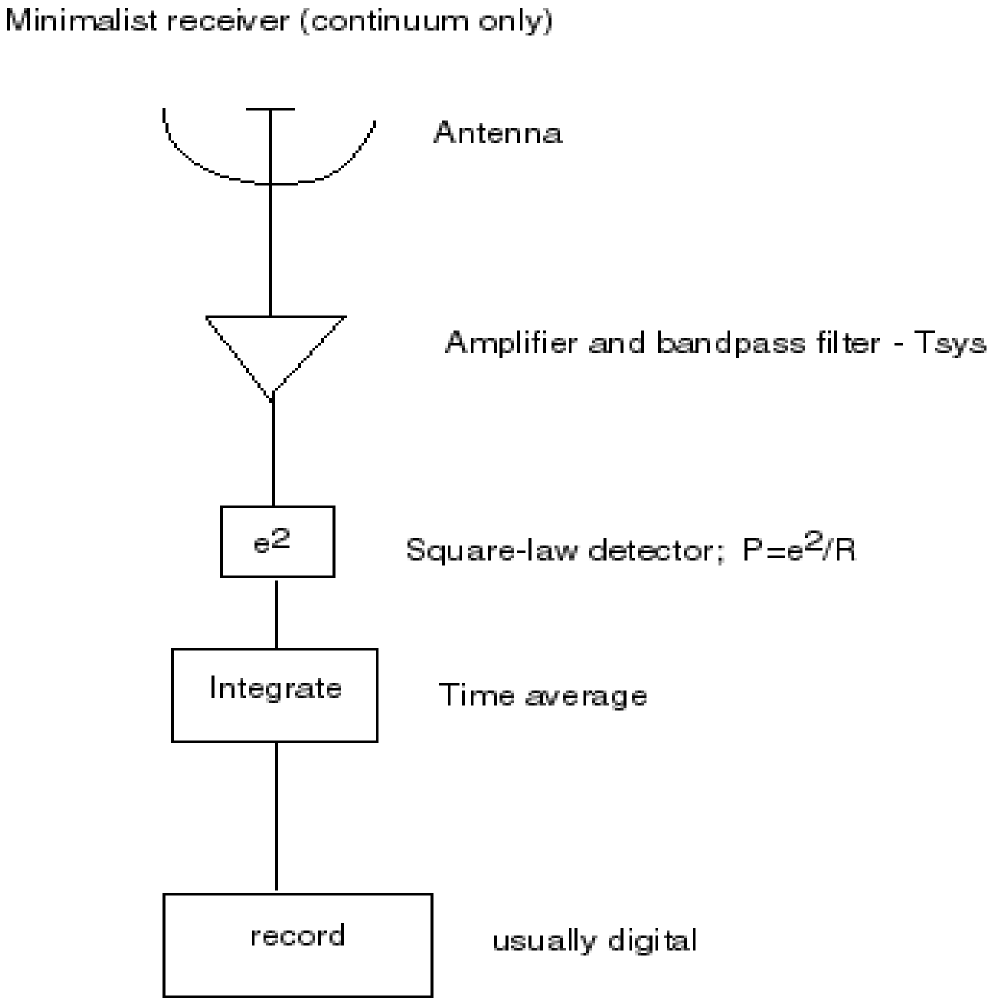


Figure 6.6

After the antenna, the first stage of the receiver, the low-noise amplifier (LNA), is probably the most important component of a radio telescope. Since the signals are so weak, the noise performance of the receiver is crucial, and this leads to extraordinary efforts, such as cryogenic cooling, to reduce noise in the LNA. The noise performance of radio-astronomy receivers is usually characterized by an equivalent system temperature, T_{sys} (in Kelvins), referred to the feed or even to outside Earth's atmosphere. Using temperature units for the system allows direct comparison with source temperatures. Typical system temperatures are ten to a hundred K for centimeter wavelengths or up to several hundred K for millimeter and sub-millimeter wavelengths. These numbers should drop as technological progress is made.

A. The noise equations

The usual root-mean-square (rms) noise calculations in radio astronomy are based on

$$\Delta T = \frac{\alpha \gamma T_{sys}}{\sqrt{\beta t}}$$

where T_{sys} is the system temperature in Kelvins, β is the noise bandwidth,

which is only approximately equal to the resolution in spectroscopy or the total usable bandwidth in continuum, and t is the total integration time (on plus off) for normal switched observing. Set α to 2 for ordinary single switching where 2 is the product of two $\sqrt{2}$, one for spending half the time on source, another for differencing two equally noisy measurements. The correlation quantization correction γ is approximately 1.16 for Haystack's spectrometer with its modified 3×3 multiplication table. Set γ to 1 for continuum. Then ΔT is the rms fluctuation in the corresponding measurement. The βt in the denominator of this equation is, in effect, the number of samples averaged to make the measurement.

B. Why heterodyne?

Most receivers used in radio astronomy (all receivers used for spectroscopy) employ so-called superheterodyne schemes. The goal is to transform the frequency of the signal (SF) down to a lower frequency, called the intermediate frequency (IF) that is easier to process but without losing any of the information to be measured. This is accomplished by mixing the SF from the LNA with a local oscillator (LO) and filtering out any unwanted sidebands in the IF. A bonus is that the SF can be shifted around in the IF, or alternatively, the IF for a given SF can be shifted around by shifting the LO.

C. Why square-law detectors?

Inside radio-astronomy receivers, a signal is usually represented by a voltage proportional to the electric field (as collected by the antenna). But we normally want to measure power or power density. So, at least for continuum measurements and for calibration, we need a device that produces an output proportional to the square of the voltage, a so-called square-law detector, and also averages over at least a few cycles of the waveform.

6.3.2 Extracting weak signals from noise

As mentioned above, radio-astronomy systems usually operate close to the theoretical noise limits. With a few exceptions, signals are usually extremely weak. One such exception is the Sun. Depending on frequency, Solar cycle, antenna size, and system noise temperature, pointing an antenna at the Sun normally increases the received power several fold. Toward other sources, it is not unusual to detect and measure signals that are less than 0.1% of the system noise. The increase in power, measured in K, due to the presence of a radio source in the beam is given by

$$T_a = AF/(2k)$$

where A is the effective aperture (m^2) or aperture efficiency times physical aperture, F is the radio flux density in watts/m^2/Hz, and k is Boltzmann's constant, 1.38×10^{-23} w/Hz/K.

The factor of 2 in the denominator is because radio astronomers usually define the flux density as that present in both wave polarizations, but a receiver is sensitive to only one polarization. Radio telescopes use linear or circular polarization depending on the type of observations being made, and with two LNAs and two receivers, one can detect two orthogonal polarizations simultaneously. In order to detect and measure signals that are a very small fraction of the power passing through the receiver, signal averaging or *integration* is used. If the receiver gain were perfectly stable, our ability to measure small changes in signal is given by the noise equation in the previous section. There ΔT is the one-sigma measurement noise.

If the receiver bandwidth is 1 MHz and T_{sys} = 100 K, for example, then we can measure down to 0.013 K in one minute. For a sure detection, we need to see a change of 10 sigma or about 0.1 K change. The receiver gain in practice is seldom exactly constant, and the additional spillover noise and atmospheric noise may also be changing, so it will be difficult at this level to distinguish a real signal from a change in gain or atmospheric noise. There are several solutions to this problem, depending on the type of observing, all of which rely on some way of forming a reference. If we are making spectral-line measurements, the reference is often just adjacent frequencies. If we scan the frequency or simultaneously divide the spectrum into many frequency channels, then the gain or atmospheric noise changes will be largely common to all frequencies and will cancel with baseline subtraction in the final spectrum. In making measurements of broadband or *continuum* radio emission, we usually use a synchronous detection technique known as *Dicke* switching after its inventor Robert Dicke. An example of Dicke switching is the use of a switch to toggle the input of the LNA between two antenna outputs that provide adjacent beams in the sky. If we switch fast enough in this case and take the difference between the power of the two outputs synchronously with the antenna switch, then receiver gain changes will largely cancel. Furthermore, if the two antenna beams are close together on the sky, then changes in the atmospheric noise will tend to be common to both beams and will also cancel. Since we are taking a difference and spending half the time looking at the reference, the ΔT given above will have to be doubled.

Another powerful technique for extracting weak signals from noise is correlation. The radio telescope in this case has two or more receivers either connected to the same antenna, or, more often, two or more separate antennas. The signal voltages are multiplied together before averaging instead of multiplying the signal voltage by itself to obtain the power. With separated antennas, the correlation output combines the antenna patterns as an interferometer, which generates lobes on the sky that are separated in angle by the wavelength divided by the projected baseline between the antennas. Correlation techniques are common in radio astronomy, and they are becoming popular also in communications. Correlation is used, for example, to detect and demodulate spread-spectrum signals as in code-division multiple-access (CDMA) digital cellular telephones.

6.3.3 An analog-to-digital converter (ADC)

Since all the final processing of a radiometer output is done with a computer, we need to convert analog voltages from the detector to numbers that can be processed in software. A very accurate and effective ADC is a voltage-to-frequency converter followed by a counter. This ADC provides integrated power with as many bits as are needed to represent the count over the integration interval. If reading the output of the counter at perfectly regular intervals is difficult, then another counter can be used simultaneously to count the constant-frequency output of a crystal oscillator. The integrated power is then proportional to the ratio of the counts from the voltage-to-frequency converter to the counts from the crystal oscillator.

6.3.4 Interference

Radio astronomy is often limited by interference especially at low frequencies. The spectrum is overcrowded with transmitters: Earth-based TV, satellite TV, FM, cellular phones, radars, and many others. Radio astronomy has some protected frequency bands, but these bands are often contaminated by harmonics accidentally radiated by TV transmitters, intermodulation from poorly designed transmitters, and noise from leaky high-voltage insulators and automobile ignition noise. Some of the worst offenders are poorly designed satellite transmitters, whose signals come from the sky so that they effect even radio telescopes that are well shielded by the local terrain. Radio telescopes and their receivers can be made more immune to interference by:

a. Including a bandpass filter following the LNA to prevent interference from being generated inside the receiver by intermodulation.
b. Placing the telescope in a location with as much shielding as possible from the local terrain. Low spots (e.g., valleys) are good for low-frequency radio telescopes because they reduce the level of interference from ground-based transmitters. (Prefer a dry mountain-top to reduce atmospheric attenuation at millimeter and shorter wavelengths.)
c. Tracking down interference and trying to reduce it at the source.
d. Designing and using an antenna with very low sidelobes.
e. Using an interferometer and correlation processing, which is far more immune to interference.
f. Using data editing to remove data corrupted by interference.

6.4 Spectrometers and Spectroscopy

A source of electromagnetic radiation that is in a solid form, such as the surface of a planet or a small grain of dust in interstellar space, has a very smooth spectrum, that is, the intensity of the emission varies quite slowly with frequency. Such emission is called continuum emission−the spectrum is a continuous function of frequency without sharp features. In this case there is not much restriction on the bandwidth that can be used to detect the radiation. One can use the largest bandwidth permitted by the radiometer to obtain the highest sensitivity.

However, in the case of atoms and molecules in a gaseous state, the emission is discrete. A gas does not produce continuous emission but rather the emission is over a small range of frequencies. The spectrum consists of narrow "spikes" of emission whose width is determined primarily by the motions of the emitting atoms or molecules.

In this case one needs to have much narrower bandwidths which decreases the sensitivity. In order to detect these spectral lines spectrometers are used.

6.4.1 Scanning filter

To measure spectral-line emission or absorption from molecules or atoms, we need a device to measure power spectra−a spectrometer. An intuitive method to measure power spectra is to scan a narrow tunable bandpass filter across the frequencies to be measured and record its power output as a function of frequency. A variant of this scheme, actually used in spectrum analyzers, has a fixed filter in the IF that is scanned, in effect, by scanning an LO in a heterodyne configuration.

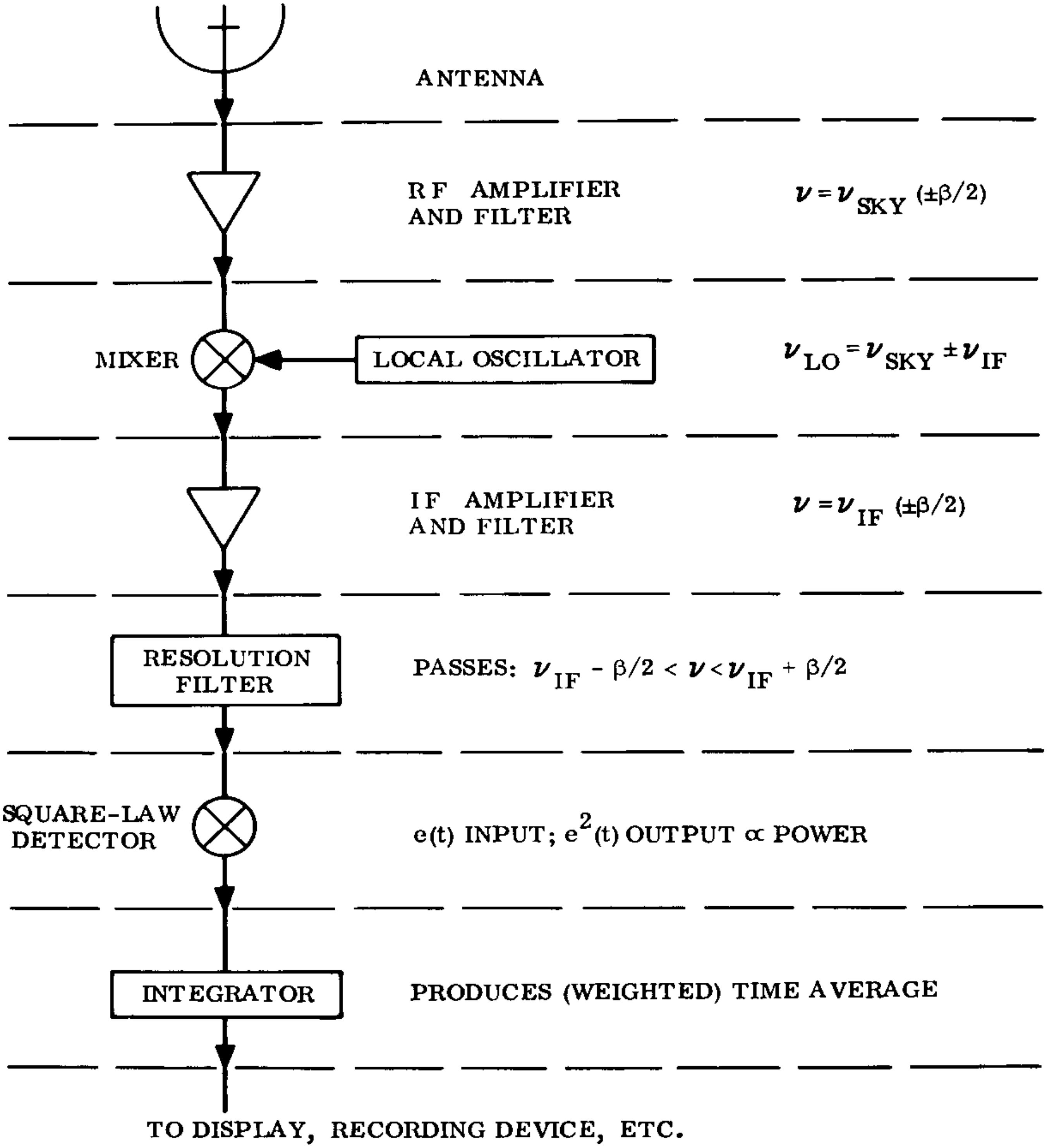


Figure 6.7

Figure 6.7 shows an example of a scanning filter receiver. Variations in the power spectrum narrower than the width of the scanning filter are smoothed over and lost. The width and shape of this filter characterize the spectrometer's resolution. This scheme works but is wasteful because all the information outside the instantaneous position of the filter is ignored.

6.4.2 Comb of filters–filter bank

A significant improvement in observing efficiency results from having a comb or bank of bandpass filters placed side-by-side in frequency and recording all their outputs simultaneously. Figure 6.8 shows an example of such a filter bank. Choosing filter shapes and spacing for such a spectrometer is, however, not intuitive. The popular almost-square filters placed just touching, for example, give spectra that are difficult to interpret whenever spectral features are comparable to the filter widths. With today's technology, filter banks are expensive and troublesome compared to various digital alternatives.

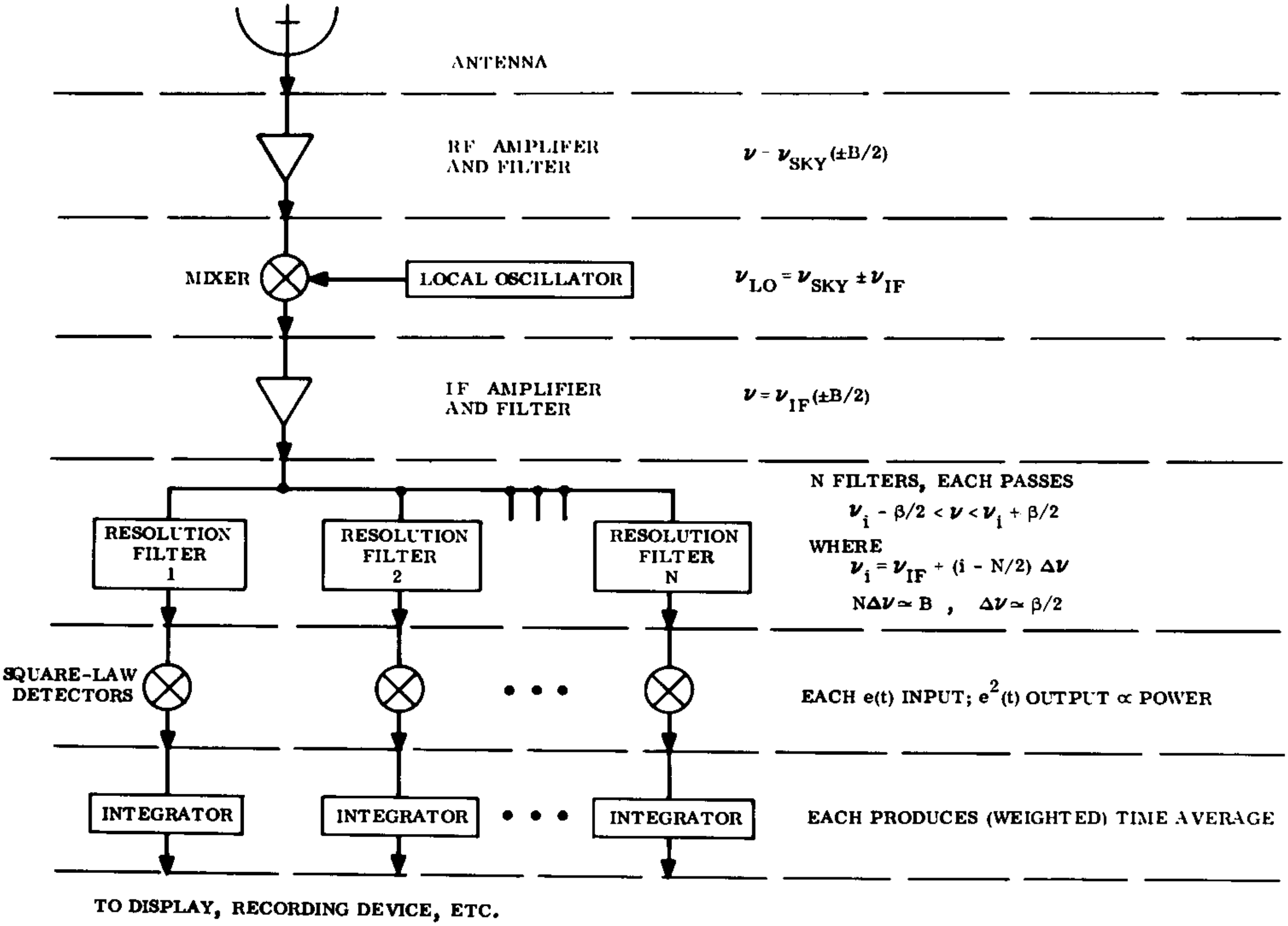


Figure 6.8

6.4.3 Autocorrelations and Fourier transforms

A. Why?

Some authors define the power spectrum to be the Fourier transform of the autocorrelation of the voltage and then show that this definition accords, at least approximately, with the intuitive scanning filter. If autocorrelations are done for lags, τ , up to some maximum, τ_{max}, and Fourier transforms are done with no weighting, then, except for noise considerations, the resulting power spectra will be the same as would be obtained with a scanning filter whose shape is $\sin(2\pi\nu\tau_{max}) / (2\pi\nu\tau_{max})$. If the spectra to be measured are band limited, perhaps by a preceding low-pass filter, then, by the Nyquist theorem, autocorrelations can be done at uniform finite lag steps, $\tau_S=1/(2\nu_{max})$, where ν_{max} is the maximum frequency of this band. This sampling corresponds to two data per cycle of ν_{max}. The resulting spectra are also band limited because they contain no lags above τ_{max}, which is the Nyquist limit. The band-limited spectra from an autocorrelation spectrometer are, then, smooth continuous functions of frequency, and they can be specified at a finite set of evenly spaced points provided that these points are no farther apart than a Nyquist step, $\nu_{step}=1/(2\tau_{max})$. The number of these frequency steps is the same as the number of lag steps, namely $2\nu_{max\tau max}$, which sometimes leads to confusion. Smooth continuous spectra can be obtained from finite sets of points by convolution by the same $\sin(2\pi\nu\tau_{max})/(2\pi\nu\tau_{max})$.

The point of using autocorrelations to get power spectra and of quantizing both autocorrelations and spectra is to allow these operations to be done digitally. The autocorrelations are usually done in hardware, the Fourier transforms in software. This is usually a significant simplification compared to a filter bank.

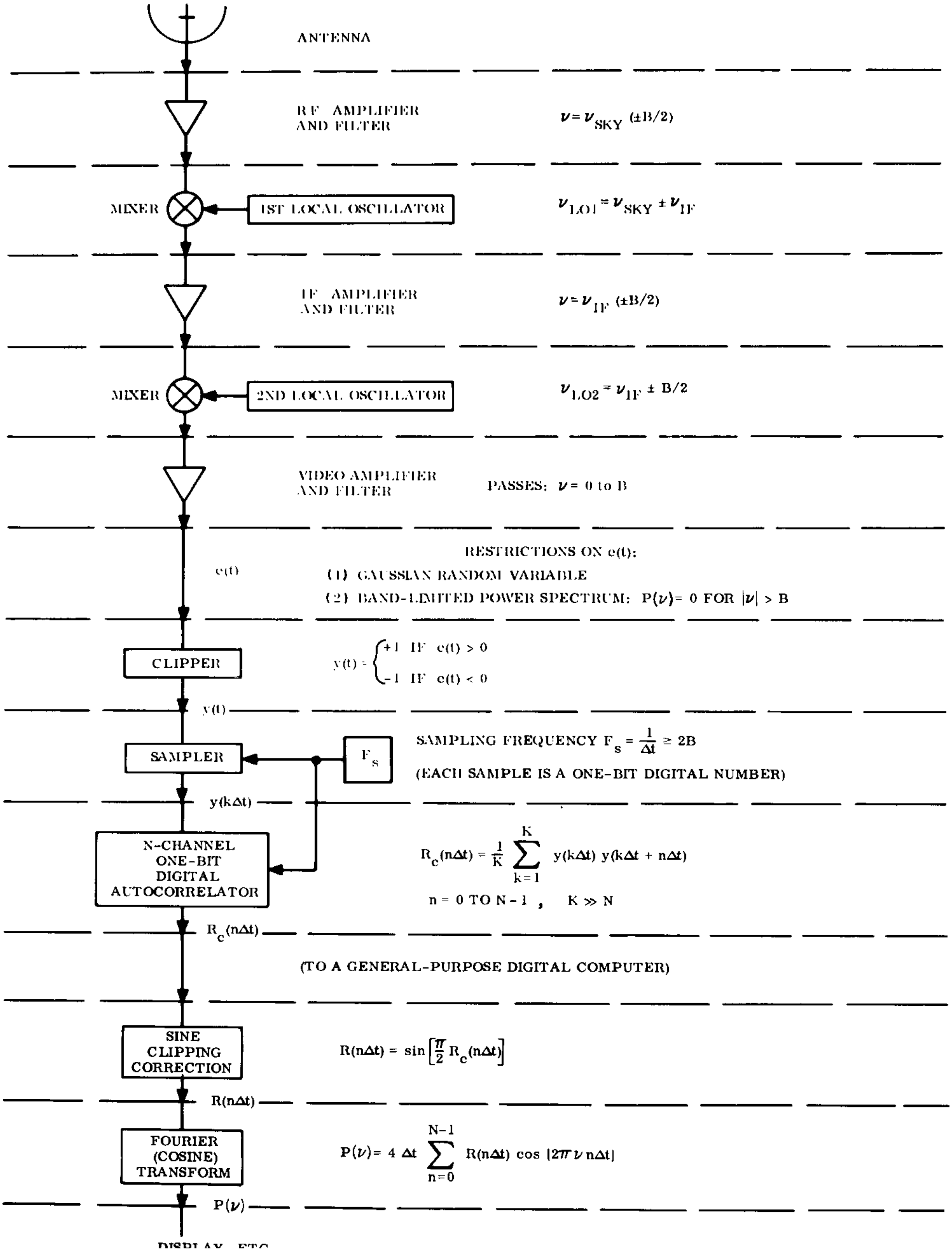

ANTENNA
RF AMPLIFIER AND FILTER
$\nu = \nu_{SKY}$ (±B/2)
MIXER
1ST LOCAL OSCILLATOR
$\nu_{LO1} = \nu_{SKY} \pm \nu_{IF}$
IF AMPLIFIER AND FILTER
$\nu = \nu_{IF}$ (±B/2)
MIXER
2ND LOCAL OSCILLATOR
$\nu_{LO2} = \nu_{IF} \pm B/2$
VIDEO AMPLIFIER AND FILTER
PASSES: $\nu = 0$ to B
e(t)
RESTRICTIONS ON e(t):
(1) GAUSSIAN RANDOM VARIABLE
(2) BAND-LIMITED POWER SPECTRUM: $P(\nu) = 0$ FOR $|\nu| > B$
CLIPPER
$y(t) = \begin{cases} +1 & \text{IF } e(t) > 0 \\ -1 & \text{IF } e(t) < 0 \end{cases}$
y(t)
SAMPLER
F_s
SAMPLING FREQUENCY $F_s = \frac{1}{\Delta t} \geq 2B$
(EACH SAMPLE IS A ONE-BIT DIGITAL NUMBER)
$y(k\Delta t)$
N-CHANNEL ONE-BIT DIGITAL AUTOCORRELATOR
$R_c(n\Delta t) = \frac{1}{K} \sum_{k=1}^{K} y(k\Delta t)\, y(k\Delta t + n\Delta t)$
$n = 0$ TO $N-1$, $K \gg N$
$R_c(n\Delta t)$
(TO A GENERAL-PURPOSE DIGITAL COMPUTER)
SINE CLIPPING CORRECTION
$R(n\Delta t) = \sin\left[\frac{\pi}{2} R_c(n\Delta t)\right]$
$R(n\Delta t)$
FOURIER (COSINE) TRANSFORM
$P(\nu) = 4\,\Delta t \sum_{n=0}^{N-1} R(n\Delta t) \cos\left[2\pi \nu n\Delta t\right]$
$P(\nu)$
DISPLAY, ETC.

Figure 6.9

B. Multi-bit vs. one bit

A further simplification is possible because of the nature of the signals to be measured. For Gaussian random noise, autocorrelations and power spectra can be computed from one-bit (just sign) samples of the voltage. Figure 6.9 shows an example of such a configuration. The price to pay for this simplification is about 31% additional noise and a little more computer arithmetic to correct the one-bit autocorrelations before the Fourier transform. Haystack now uses 1.5-bit (i.e., three-level) sampling, which adds about 16% additional noise (γ in the noise equation above) and is only a little more complex than one-bit.

6.4.4 Switching schemes and baselines−Why switch?

One of the most persistent and difficult problems in spectral measurements in radio astronomy involves the difficulty of obtaining good flat baselines−the parts of spectra with no signal. The corresponding baseline problem with continuum measurements involves stable measurements off source (cold sky) to subtract from on-source measurements. There are numerous instrumental effects that contribute to bumpy baselines, and many of the effects are a substantial percentage of the system temperature and are typically much larger than the signals to be measured. To reduce the severity of such instrumental effects, almost all radio-astronomy measurements are made using one of several possible switching schemes. The ideal switching scheme would have the source itself turn off and on synchronously with a prescribed periodicity and with nothing else changing. Then the difference between signal and comparison is precisely the desired measurement. Provided that T_s does not change between the on-source and off-source observations, it can be shown that noise is minimized by spending half the observing time on-source and half the time off-source.

Among practical switching schemes, we can move the antenna pointing on and off the source either by actually moving the antenna or by offsetting the effective pointing by moving the feed or its image. But this works only if the source is confined in angle. Or we can move the source in and out of the pass-band by moving the LO frequency. But this works only if the source is confined in frequency. Or we can switch the input to the receiver alternately from the feed to an absorber or load. This last scheme is less good because many of the instrumental effects to be ameliorated are in the feed and beyond.

Switching schemes are needed for either continuum or spectral measurements. A price to be paid for switching is increased noise. There are two contributions to the added noise: The receiver spends only half the time looking at the signal, and the result is the difference between two equally noisy measurements. The result is twice the noise compared with not switching for the same integration time (this is αin the noise equation above), or four times the integration time to achieve the same noise.

7. Calibration of Data

A signal from an astronomical source can be reduced by absorption in the earth's atmosphere. Depending on the wavelength, the atmosphere acts as a very extended source and can diminish the signal from the astronomical source as well as add noise. The noise contribution is then the sum of the receiver noise and the atmospheric noise and is given by

$$T_N = T_{rcvr} + T_{atm}(1 - e^{-\tau})$$

Here τ is the atmospheric opacity. It is possible that at certain frequencies the noise contribution from the atmosphere is larger than that from the receiver. In order to properly calibrate the data one needs to measure the total noise and determine the loss due to absorption in the earth's atmosphere.

In order to do this one first measures an ambient temperature load. The voltage measured is given by

$$V_1 = K(T_{AMB} + T_{rcvr})$$

where K is a constant. Then one measures the sky at the same elevation as the source. The voltage from this measurement is given by

$$V_2 = K[T_{rcvr} + T_{ATM}(1 - e^{-\tau})]$$

The system temperature, T_{sys} is defined as

$$T_{sys} = \frac{T_{AMB}}{y - 1}$$

where y = V_1 / V_2 Substituting for V_1 and V_2, and assuming that T_{ATM} is approximately equal to T_{AMB}, one can express the system temperature as

$$T_{sys} = [T_{rcvr} + T_{ATM}(1 - e^{-\tau})]e^{-\tau}$$

This expression is the total noise times $e^{-\tau}$ and this is what needs to be applied to the data to calibrate it. Once the system temperature is measured, the voltage on and off the source can be measured and the antenna temperature can be expressed as

$$T_A = \frac{V_{ON} - V_{OFF}}{V_{OFF}} T_{sys}$$

The system temperature depends on the elevation and has to be measured for each source, when the source changes in elevation and when the atmospheric conditions change.

8. Sources of Radio Emission

8.1 Radio Emission from Solar System Objects

At visible wavelengths all the emission seen from these objects is due to light reflected from the sun. However at radio wavelengths there is very little reflected sunlight so the radio emission observed from the planets is dominated by thermal emission. This emission is related to the surface temperature of these bodies. Figure 1 contains a measurement of Venus made with the Haystack 37-m telescope. The first one shows scans of the planet made in azimuth and elevation. The peak of the scans corresponds to the antenna temperature of the planet. This temperature can be converted to a brightness temperature by scaling it with the aperture efficiency of the system at this frequency.

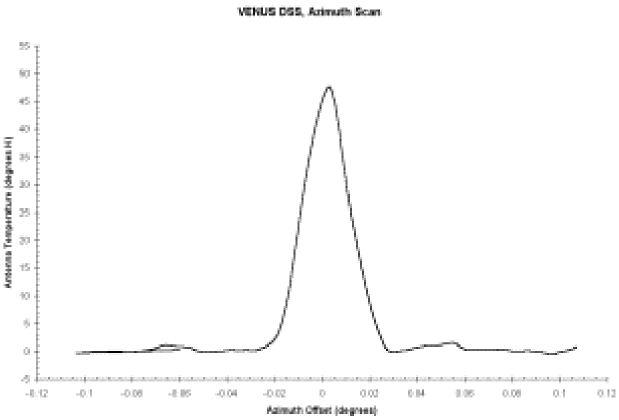


Figure 1

Venus has thick cloud layers that reflect light very well. At infrared wavelengths these clouds are opaque and the temperature measured at these wavelengths is only about 225K. However measurements at radio wavelengths imply a surface temperature of about 700 K. At the shorter radio wavelengths (< 3 cm) the atmosphere becomes opaque again and the measurements result in lower temperature determinations.

The emission from the moon is also thermal. At infrared wavelengths there are variations correlated to the lunar phase which are due to solar heating. At centimeter wavelengths this variation is much less. This is because the radio emission (which is still thermal) arises from below the surface. The material below the surface is heated by conduction and the variations lag behind the solar heating. The variations are also not as extreme. Figure 2 is a beamswitched observation of the moon made with the Haystack Small Radio Telescope (SRT).

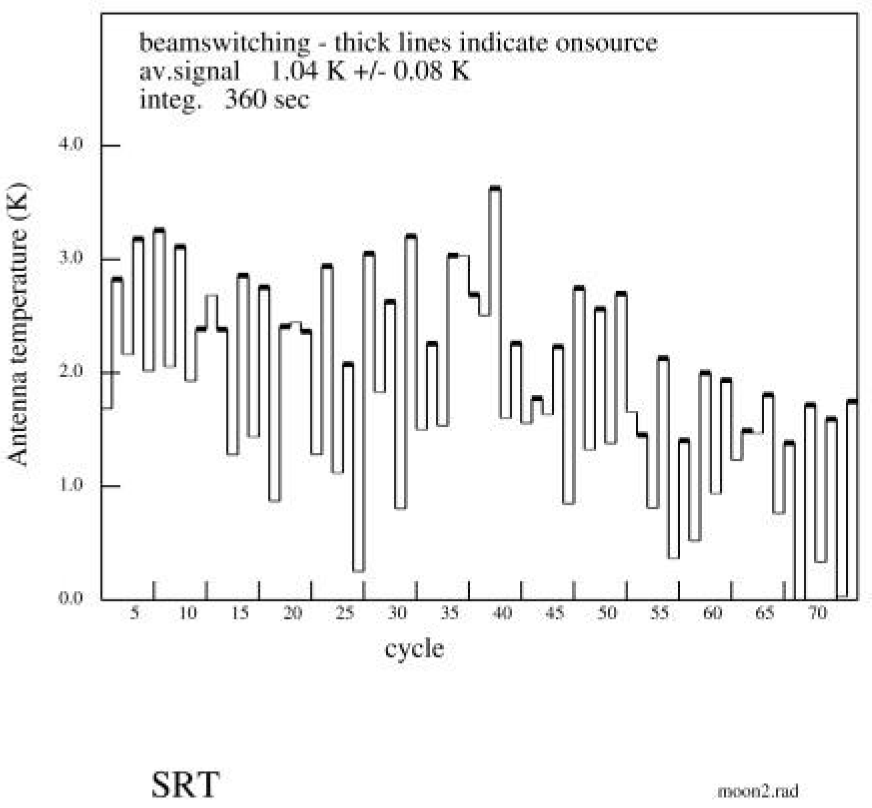


Figure 2

8.1.2 Jovian planets

The Jovian planets are much further from the sun and consequently are colder. Jupiter, however, is a strong radio emitter at the long (> 10cm) radio wavelengths. At shorter wavelengths (around 3 cm) Jupiter has a brightness temperature of around 140 K which is consistent with infrared measurements. However at longer wavelengths the temperature are of the order of a few thousand degrees. These high temperatures come from a non-thermal source namely synchrotron emission from the strong magnetic field of the planet. Jupiter also has some strongly varying radio emission at long radio wavelengths. The source of this emission has been found to be non-thermal cyclotron emission. This arises from electrons spiraling in Jupiter's magnetic field. The variation is caused by the fact that the origin of these electrons are volcanoes and geysers on the surface of Io.

Radio emission from the other Jovian planets has been found to be mainly thermal. The emission arises mainly from the cloud tops of the planet atmospheres and shows that the temperatures drop the farther the planet is from the sun.

8.1.3 The Sun

Radio emission from the sun arises from several different phenomena and can be divided into three main components – 1) the quiet sun component, which is always present, 2) the slowly varying component and 3) the active sun component which is caused by sunspots and flare activity.

The quiet sun component of the radio emission is from thermal emission from the hot ionized gas. In order to understand from which part of the sun's atmosphere this emission arises, one needs to understand the main opacity source at radio wavelengths. (The opacity is a measure of how much a wave gets absorbed as it travels through a medium). The main source of opacity in the sun's atmosphere (the photosphere, chromosphere and corona) at radio wavelengths comes from electrons. The bulk of the emission arises from the region where the opacity, τ, is near 1, since at higher optical depth regions cannot be penetrated and the low optical depth regions do not produce enough emission. At visible wavelengths this happens at the photosphere where the temperature is about 6000 K and hence the sun appears as a blackbody with that temperature. At a frequency of 100 GHz (wavelenth 0.3cm) the emission originates at the same height in the photosphere and the sun appears as a 6000 K blackbody. But at a frequency of 1.4 GHz (wavelength of 21 cm) the emission originated from the top of the chromosphere and is seen as a blackbody of temperature of about 100,000 K. And at longer wavelengths (300 cm or frequency of 0.1 GHz) the emission arises from the corona and is a 2 million K blackbody. All this also means that the size of the sun measured at the different wavelengths will vary.

The other two components are related to the sunspot activity on the sun. The slowly varying component is also thermal in origin and arises from the region above the sunspots where the electron density is higher. The blackbody temperature of these regions can be as high as 2 million K. Thus the regions above the sunspots can contribute more radio emission than the total area without sunspots and increase the total radio flux relative to the quiet sun. So the change in the total radio flux is dependent on the total number of sunspots. The radio flux density then follows the 11 year sunspot cycle. Figure 3 shows an image of the sun made with the Haystack 37—m telescope at a frequency of 21 GHz (wavelength of 1.3 cm).

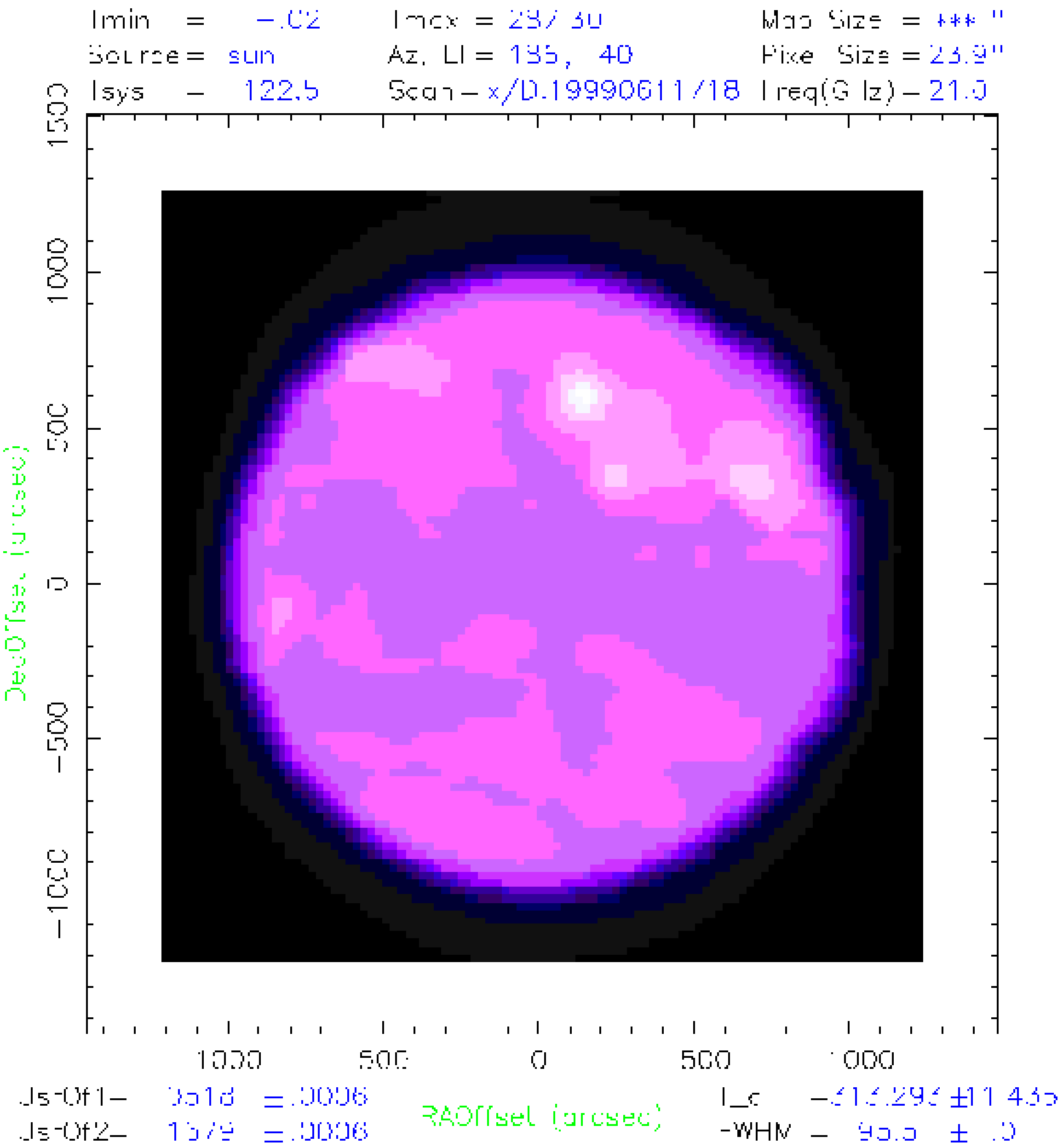


Figure 3

8.2 Stars

The sun is a star and a strong source of radio emission. Most ordinary stars are expected to emit radio waves since they are thermal sources. However, the majority of the radio emission from stars is undetectable since they are far away and the signals are too faint. There is a class of objects known as “radio stars” that emit radio waves although all radio stars do not fall into one category. Many of these stars generate radio emission in strong winds of gas blowing out of the star or in ejected spherical envelopes expanding out from the star’s surface. There is also a class of binary stars that have radio emission arising from the interaction of their magnetic fields. There is also a category of stars that show flare behavior. It is thought that these are very young stars that are ejecting matter in the form of minor jets.

Most of the strong radio emission comes from stars that are either very young or very old. When stars form they go through phases of mass ejection and interaction with the surrounding medium. One such example are HII regions. These are not direct observations of the star but of the region of ionized hydrogen that is caused by UV radiation from the young star ionizing the gas around it. In many cases, the radio emission from the HII region is the only way of detecting these young stars since they are embedded deeply in the gas clouds from which they are born and hence the optical emission cannot get out. Figure 4 shows an example of an HII region. The grey scale image is an infrared image of an HII region that has a bow-shock appearance. The overlaid contours in the first and third panels corresponds to emission from the molecules CS and C18O. The second panel of contours corresponds to continuum emission at a frequency of 97 GHz.

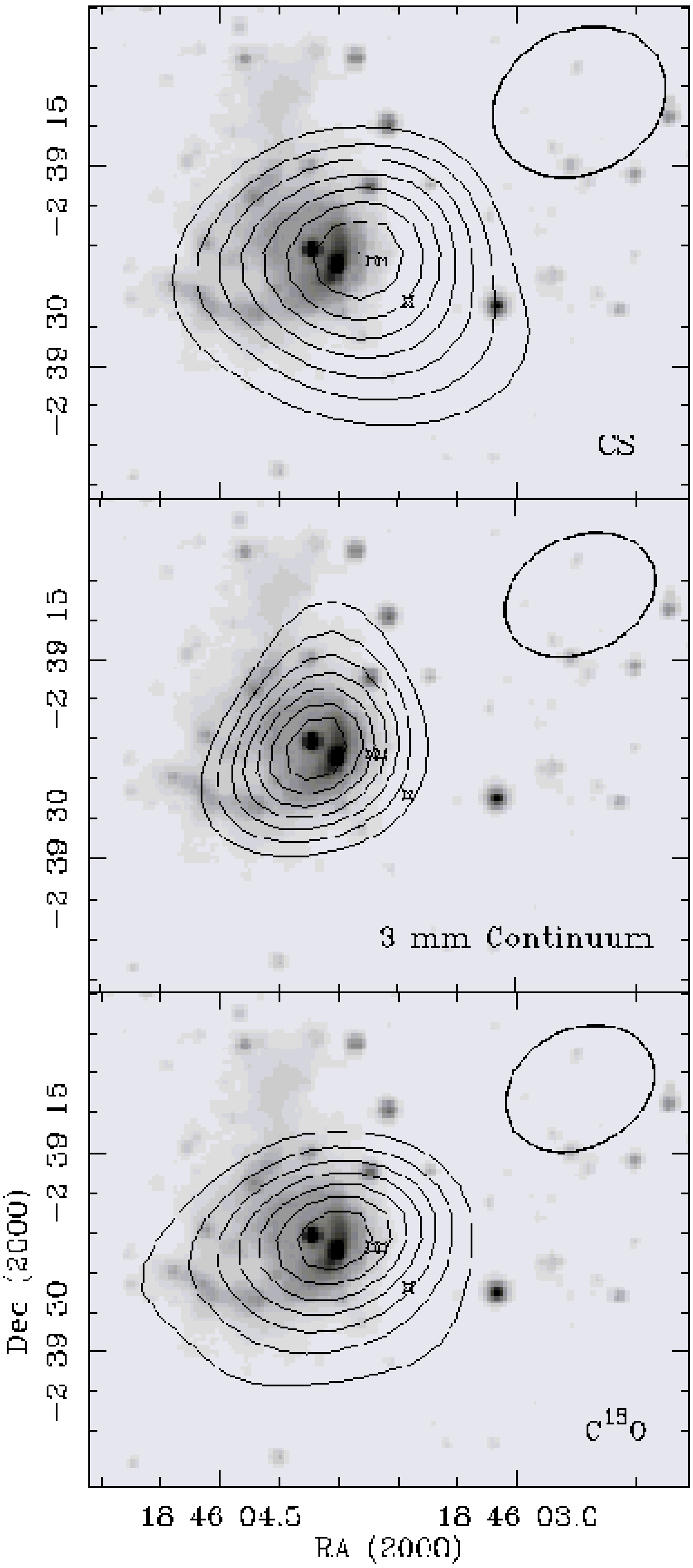


Figure 4

Stars at the end of their life emit radio emission in various ways. One of the exciting discoveries in radio astronomy came from the discovery of pulsars. Pulsars are now known to be neutron stars that spin rapidly and emit radio signals in highly directed beams. As these beams sweep across the direction of the earth, radio telescopes pick them up as a repeating signal. The radio emission mechanisms for these pulsar beams is related to synchrotron emission which is caused by the acceleration of relativistic electrons by a magnetic field. The periodicity is caused by the fact that the magnetic field axis is not coincident with the rotation axis.

When large stars reach the end of their life, they can explode in supernova events. The ejected material then interacts with the surrounding medium. This leads to the formation of "supernova remnants" which also are strong sources of radio emission. What is left behind is a neutron star. An example of a supernova remnant is the Crab nebula (Figure 5).

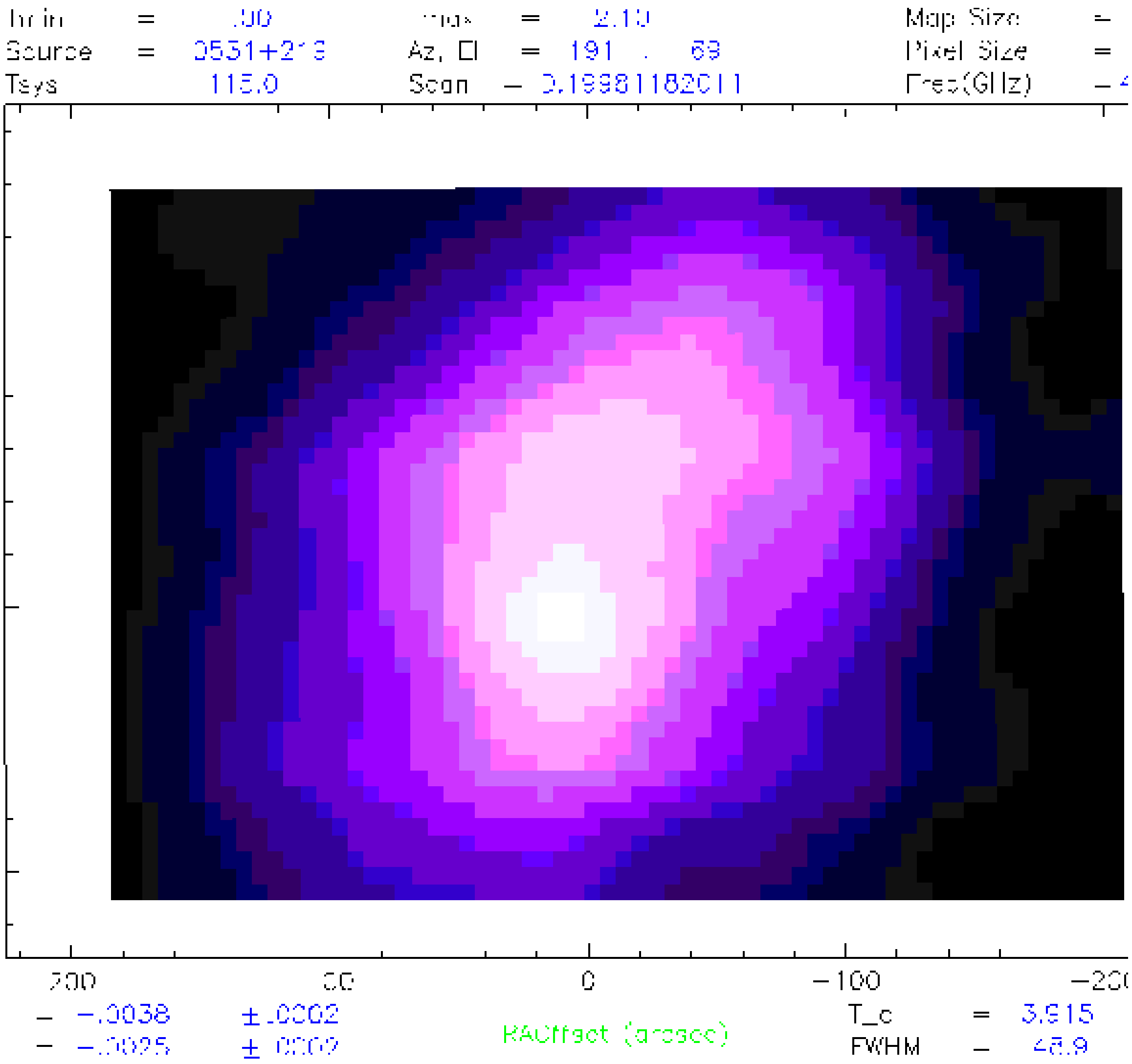


Figure 5

8.3 Interstellar Clouds

A substantial fraction of the gas in the interstellar medium is in molecular form. This gas is in the form of dense, cold "molecular clouds". This component of the interstellar medium is very closely connected with star formation. The molecules in these clouds are excited by collisions and they spontaneously emit producing spectral lines. These spectral lines occur at discrete frequencies that, at radio wavelengths, are governed by the

rotation of the molecule.
Radio astronomy was instrumental in the discovery of more than a 100 interstellar molecules and more and more complex molecules are still being discovered. The reason that complex molecules can exist in these molecular clouds without being destroyed by UV radiation from stars is that the clouds contain large amounts of dust grains that absorb the UV radiation and shield the molecules from photo-destruction. Molecules from simple diatomic ones such as CO, CS, SiO, SO etc to more complex ones such as ethanol, methanol, cyanoacetelyne, etc have been detected toward these molecular clouds. The molecular spectra contain substantial information about the physical and chemical environment of these clouds. The velocity of the lines gives information about the motion of the clouds with respect to the solar neighborhood. The line widths measure the internal motion of the gas within the clouds from Doppler motions. The strength of the line and the ratio of information from several different transitions can be used to measure the column density of the gas, the temperature and the density. The density of molecular hydrogen, whose rotation cannot be measured directly, can be calculated from the strength of the spectral lines. Finally, the size and mass of the molecular cloud can be derived by mapping the extent of the molecular emission. Figure 6 shows the emission from a cold, dark cloud in the Taurus region (called TMC-1) in three transitions of the HC3N molecule. Combining the information from these three transitions can be used to derive the molecular hydrogen density in the cloud.

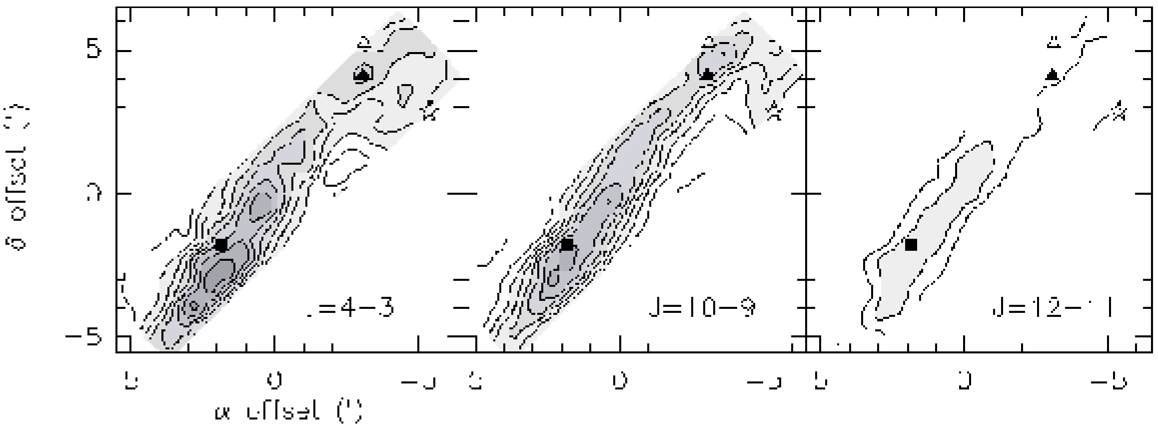


Figure 6

Combining the information from several molecular species one can also study the chemical processes in these clouds. Hence molecules are a powerful tool that is available to scientists to study molecular clouds and through them the process of star formation.

8.4 Milky Way

A component of the radio emission from the Milky Way comes from the spin flip transition of the hydrogen atoms in the interstellar medium. This spectral line arises from the fact that the electron and the proton in the hydrogen atom have a particular direction of spin. The energy of the situation where the spins are aligned is different from that when the spins are in opposite directions. This difference in energy is emitted when the atom goes from one state to the other and has a wavelength of 21cm (or a frequency of 1420 MHz.

Since the emission comes from the hydrogen atoms in the plane of the galaxy, the velocity of the line with respect to the solar neighborhood (or the local standard of rest) can be used to study the structure of the galaxy and its rotation. A map of the galaxy in the emission of the HI line made with the Haystack small radio telescope is shown in Figure 7.

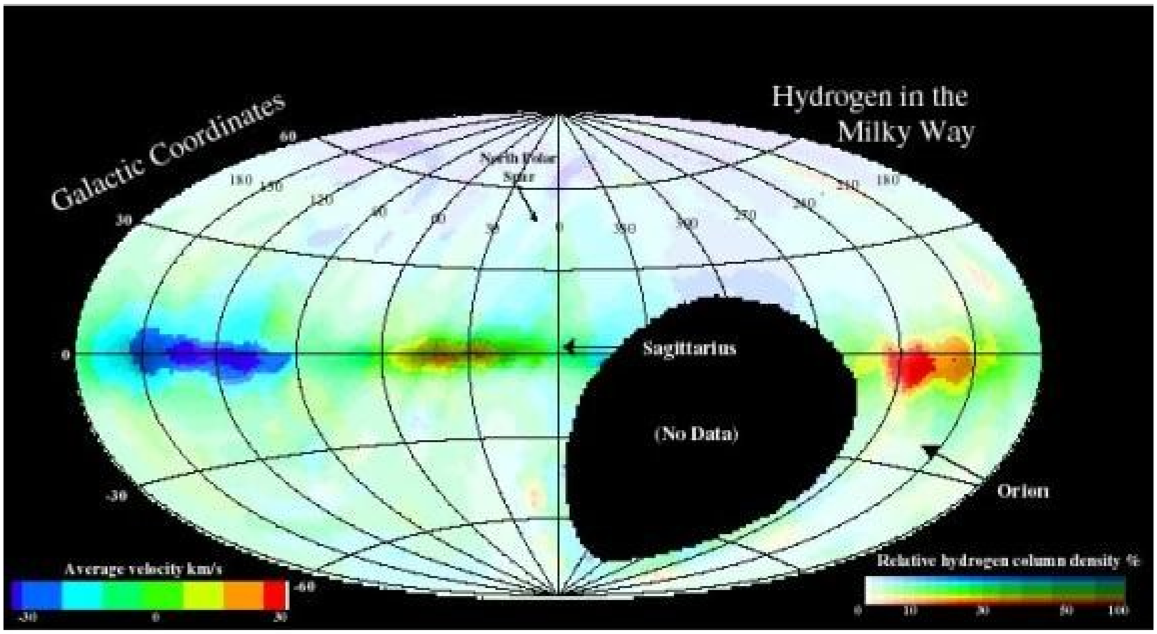
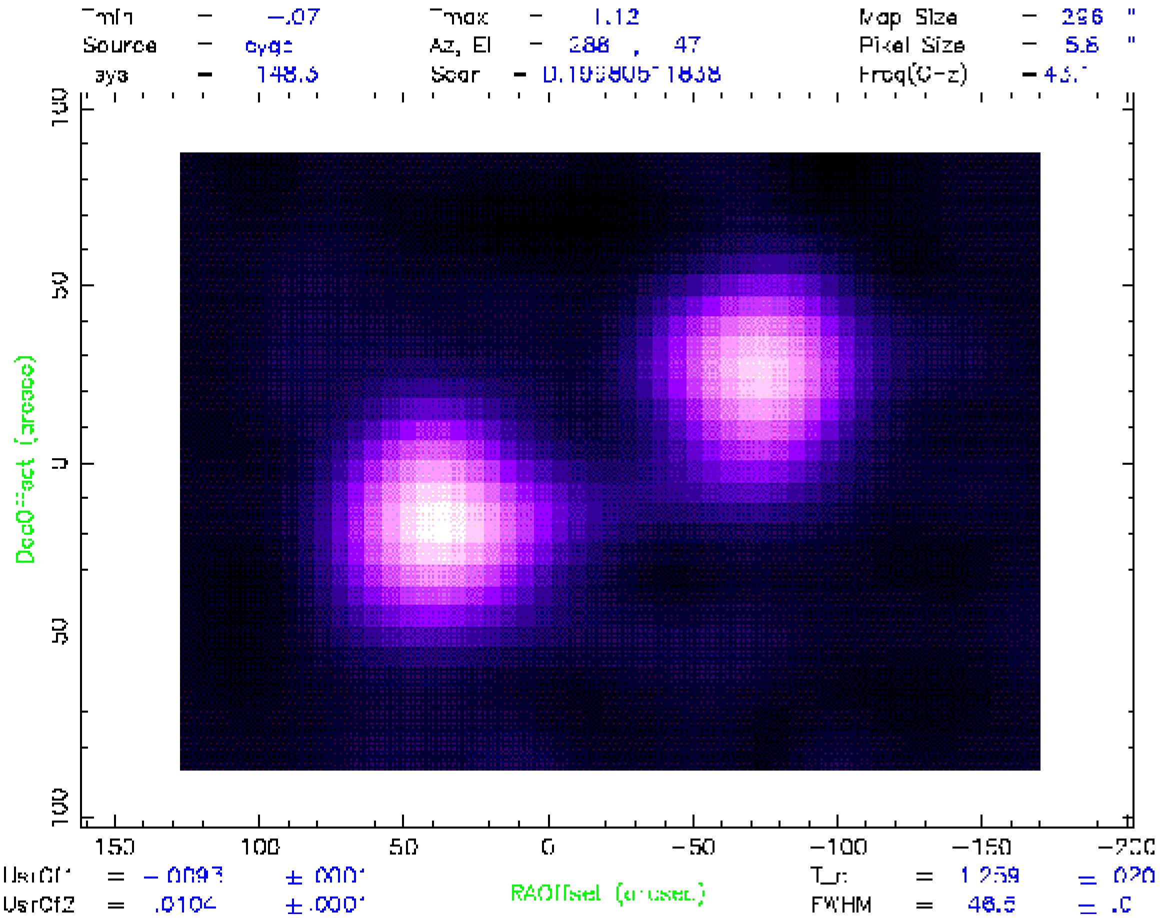


Figure 7

8.5 Extragalactic

One of the most striking discoveries of radio astronomy has been the spectacular jets from active galaxies. These jets have structures that are extremely complex. Jets from the galaxies have been imaged with extremely high resolution using Very Long Baseline Interferometric techniques. These images show that the jets are highly collimated very close to their origin. One famous example of such a jet is the source Cygnus A. Figure 8 shows an image of this source made with the Haystack 37-m telescope at a frequency of 43 GHz. The image does not show much detail of the jet because the resolution of the system at this frequency is about 45”. However, the two lobes of the jet are clearly seen. Note that the jets are much brighter than the galaxy from which they originate, which is situated at the center of the image.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Tmax = 1.12
Map Size = 296 "
Source = cyg
Az, El = 288 , 47
Pixel Size = 5.6 "
Tsys = 148.5
Scan = 0.193805 1838
Freq(GHz) = 43.
DecOffset (arcsec)
100
50
0
-50
-100
150
100
50
0
-50
-100
-150
-200
RAOffset (arcsec)
UsrCf1 = -.0093 ± .0001
UsrCf2 = .0104 ± .0001
T_r = 1.259 ± .020
FWHM = 46.5 ± .0

Figure 8

9. Glossary

Angstrom

An angstrom is a unit of length that is equivalent to 10^-10m or 0.1nm. Used mainly to specify the wavelength of radiation.

Electromagnetic spectrum

definition

Emission

The release of a photon from an atom when an electron in the atoms jumps from a higher to a lower energy level.

Interference

Unwanted radio signals received by a radio telescope that originate in human activity rather than natural phenomena.

Light Year

The distance traveled by light, or other electromagnetic radiation,in one tropical year through space. One light year is equivalent to 9.4607 x 10^12 km, or 63,240 astronomical units, or 0.3066 parsecs.

Nebulae

definition

Radiation

Energy propogating in the form of electromagnetic waves or photons.

Radio astronomy

The study of the Universe in the radio part of the electromagnetic spectrum.

The radio spectrum ranges from approximately 1mm to 30 meters, almost all of it accessible from ground-based observatories, day and night.

Radio telescope

definition

Star

definition

Haystack Upgrade Program

Massachusetts Institute of Technology (MIT) has recently initiated a major upgrade of the Haystack Radar in Tyngsborough, Massachusetts. The upgrade program is jointly sponsored by the United States Air Force and the Defense Advanced Research Projects Agency and is being executed by Lincoln Laboratory, a federally funded research and development center of MIT.

MIT Lincoln Laboratory developed the Haystack facility in the 1960s as a step in the technological evolution of high-performance microwave systems. Haystack is now used for two purposes. Part of the year it is used by the MIT Haystack Observatory as a radio-telescope to conduct research and for education activities. As a radio-telescope, the Haystack antenna is used to conduct single-dish radio astronomy in the 22-25 GHz, 35-50 GHz and 85-115 GHz frequency bands, and for Very Long Baseline Interferometry experiments. The Haystack research facilities are also used in various education programs for graduate, undergraduate, and pre-college students. The pre-college outreach programs for the local middle and high school students enhance their interest in science, engineering, and mathematics, and contribute to the neighboring towns, the Commonwealth, and the Nation.

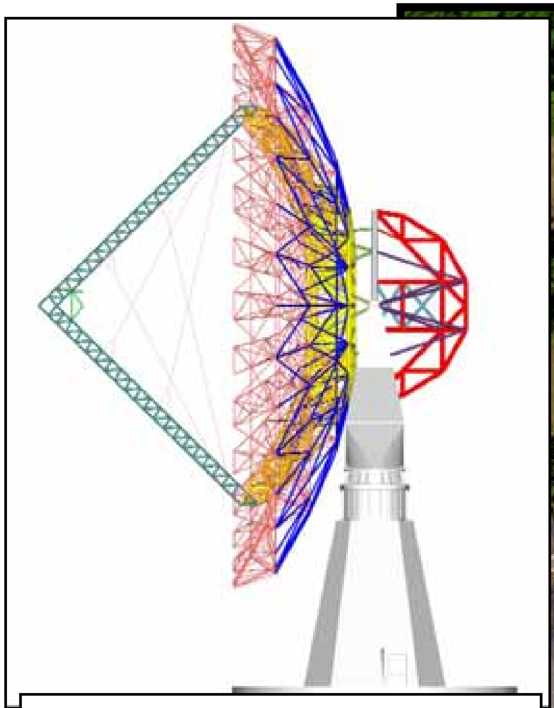
Haystack is also used by MIT Lincoln Laboratory as a radar which acts as a contributing sensor to the United States Space Surveillance Network and as a radar technology testbed. The Haystack Radar utilizes the 37 m Haystack antenna to generate radar images of satellites orbiting the Earth. These images are used by the United States Strategic Command to assess satellite structure, mission, and status. The radar is also used to collect data on orbiting space debris. Orbiting debris could be a threat to the International Space Station, the Space Shuttle, and other satellites. The Haystack Radar has been the major contributor to understanding the space debris environment in the 1-10 cm size regime.

The Haystack Radar currently operates in the 9.5 GHz to 10.5 GHz frequency band. As part of the upgrade, a millimeter-wave radar that operates in the 92 GHz to 100 GHz frequency band will be added to the system. The new radar will use an innovative transmitter design and signal processing to achieve image resolution that is about 10 times better than what is currently available. The existing 37 meter (120 foot) antenna will be replaced by a new dish, accurate to 0.1 millimeter (0.004 inch) over its entire surface, which is a factor of 3 better than at present. The new antenna will permit the Haystack radio-telescope to operate in the 150 GHz range or higher, making it a premier radio-astronomy facility. L-3 ESSCO of Concord, MA, has been selected to design, fabricate, and install the new antenna.

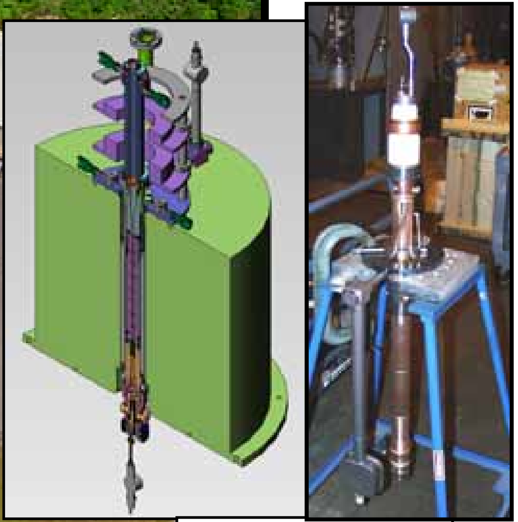
The upgrade program is currently in the design stage and will be completed in 2009. In 2006, the 150 foot diameter Haystack radome will be temporarily lifted and set aside to permit the removal of the existing antenna and the installation of the new antenna. The new radar transmitter and processing system will be integrated and tested in 2007-2009. The final testing of the new radar will be completed in 2009. These modifications and upgrades will dramatically advance the state of the art in space surveillance technology and will allow Haystack to remain at the forefront of radio astronomy research facilities.

HUSIR

Haystack Ultra-wideband Satellite Imaging Radar

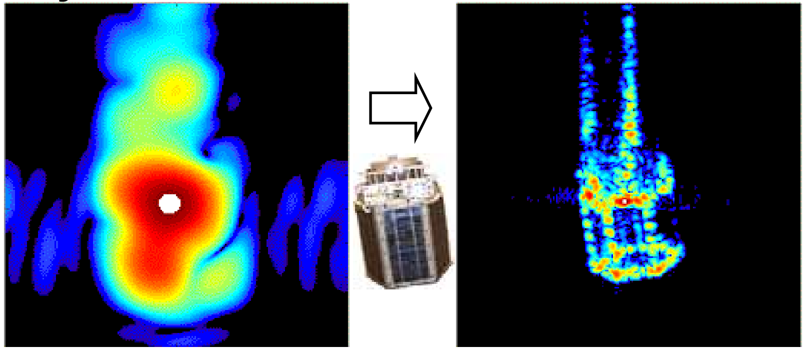


100 micron rms surface
120’ diameter



92-100 GHz High Power Transmitter

Haystack X-Band* **HUSIR W-Band***



9.5-10.5 GHz

92-100 GHz

Order of magnitude improvement in Haystack imaging resolution

* ISAR images of a satellite model using compact range data