A 73.8 MHZ Radio Interferometer Telescope for Intense Celestial Sources

William Charles Millar
A 73.8 MHZ RADIO INTERFEROMETER TELESCOPE
FOR INTENSE CELESTIAL SOURCES

by

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A 73.8 MHZ RADIO INTERFEROMETER TELESCOPE
FOR INTENSE CELESTIAL SOURCES

William Charles Millar, M.A.
Western Michigan University, 1985

A 73.8 MHz radio interferometer telescope was built, based on a published design. Although the design was proven, the telescope has thus far given no results on celestial sources. The electronics has been proven to be operational by testing them with hand-held dipole radio sources. Here, the electronics is evaluated with a discussion of possible reasons for the failure of the telescope in overall operation.
ACKNOWLEDGMENTS

I would like to thank professors L.D. Oppliger, G. Hardie, and M. Soga for their help and guidance during this project. As my thesis committee members they have given many suggestions and much encouragement in times of apparent failure. Many thanks go to Leo Parpart of the Physics Department for all the work he did in locating equipment and for research in antenna construction.

I would also like to thank Mr. Steven DeRyke for long hours of help in making the measurements shown in Figures 14 through 16. Mr. Richard Foster of the Grand Rapids Junior College, Technology Department was kind enough to loan some equipment necessary for the construction and testing of the radio electronics, and also offered advice in radio construction techniques.

Thanks go to the Physics Department and to The Graduate College for financial support for the project, and to the rest of the Faculty and graduate students of the Physics Department for their moral support during the project.

William Charles Millar
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INTRODUCTION

A Brief History of Radio Astronomy

James Clerk Maxwell published his theory of electrodynamics in 1864. (For all historical information in this chapter, see the book by J.S. Hey, listed in the bibliography.) This theory not only united the then separate disciplines of electricity and magnetism, but also made a prediction; light is an electromagnetic wave traveling at a constant velocity of $3 \times 10^8$ meters per second. But light is not the only kind of electromagnetic wave. Light comprises only a small range of the possible wavelengths. Maxwell predicted the existence of what are now called radio waves (radiation), infrared radiation, x-ray radiation and gamma radiation. All of these correspond to certain wavelength regions of the electromagnetic spectrum, and to new areas of astronomy opened up within the past 50 years.

A first confirmation of Maxwell's predictions came in 1888 when Heinrich Hertz discovered a method of producing and detecting radio waves. In the years that followed it was realized that the sun should be a source of not only visible light, but of radiation from the entire electromagnetic spectrum, including radio. Scientists made several attempts to detect radio waves from the sun, but all these early attempts were unsuccessful. By the turn of the century, the endeavor was all but forgotten.
Karl Jansky was a young engineer on the research staff of Bell Telephone Laboratories in New Jersey. In 1930 he was assigned to study the sources and directions of arrival of atmospheric static at wavelengths of about 15 meters. These wavelengths were to be used for ship-to-shore and transatlantic communications. To carry out this investigation, Jansky built a rotating aerial array about 30 meters long and 4 meters high which provided a beam width of about 30° (azimuth).

Jansky published a description of his investigations in 1932. \(\text{(Jansky, 1932)}\) In this paper he distinguished three types of static. First, the intermittent crashes from local electrical storms. Second, a steady weak static from a combined effect of many distant storms. And third, a steady but weaker hiss of unknown origin. This weaker hissing sound was like that of the thermal noise generated by the components of a radio receiver. At first, Jansky attributed this noise to manmade interference. But later he realized that the direction of arrival of the noise was moving each day in time with the stars. This was the clue that the source must be extraterrestrial. This observation marks the birth of radio astronomy.

Jansky spent another year recording data. In 1933 he published a second paper. \(\text{(Jansky, 1933)}\) The source was maintaining a constant celestial position, traversing the sky with a period of 23 hours 56 minutes, characteristic of stellar objects. He determined the approximate position of the source as right ascension 18 hours, declination 10° South. This is roughly the location of
the center of the Galaxy. Further analysis, in 1935, resolved that the source of the radio noise was indeed the center of the Milky Way.

There was some newspaper and radio publicity about the discovery, but this, along with Jansky's papers in scientific journals was not enough to prompt any universities or astronomical organizations to pursue the field. Bell Telephone Laboratories felt that any additional investigation was not worth the expense, since they now had the information they needed. Jansky stayed with B.T.L. but never again worked in radio astronomy.

Grote Reber realized that Jansky had made an important and fundamental scientific breakthrough. Reber was a radio engineer who was following these developments and decided to pursue radio astronomy as a hobby, in his spare time and at his own expense. Radio communications was his current hobby and he worked for a firm that built radio equipment, so he was knowledgeable in state-of-the-art radio electronics.

Reber decided to build a large parabolic reflector for his antenna since this would provide a symmetrical narrow width beam, with large collecting area and would allow changing the receiving wavelength by simply changing the receptor at the focus of the reflector. Two considerations guided his choosing an initial operating wavelength of about 10 centimeters. First, he could achieve good angular resolution using this antenna (see below) and second, if the radiation followed Planck's thermal radiation law, the radiation intensity would be greater at these shorter
wavelengths. In 1937 Reber began to build the first receiver specifically designed for radio astronomical observations. It was a meridian transit instrument steerable in elevation only, relying on the Earth's rotation to scan the sky. The reflector was 31 feet in diameter, made of 45 pieces of 26 gauge galvanized iron sheets screwed onto 72 radial wooden rafters cut to a parabolic shape. It cost $1300 (1937 dollars) and he built it in his back yard in Wheaton, Illinois.

Reber felt the two most crucial questions in radio astronomy were how to determine a detailed source distribution of the sky and how the radiation intensity depended on wavelength. His initial attempts to observe the sun, moon, planets and brightest stars at $\lambda = 9$ cm and $\lambda = 33$ cm produced no positive results. He concluded that the extraterrestrial noise did not follow Planck's blackbody law. In 1939 he started again with a new receiver at $\lambda = 1.87$ m and was successful at detecting emissions from the Milky Way. His first paper, (Reber, 1940) determined the radiation intensity at $\lambda = 1.87$ m and confirmed the source distribution as lying along the Galaxy. Reber then made important theoretical interpretations which attracted the attention of prominent astronomers. Finally, radio astronomy was given the attention it long deserved.

During World War II the British were constructing radar installations along the southern coast of England. These radar stations were to give early warning protection to the British Isles from German air raids, V1 and V2 rockets. However, the Germans were
capable of jamming the British radar. The Army Operational Research Group was commissioned to investigate the problem. They asked for the assistance of James Hey, a physicist, to organize the inquiry.

In February 1942, a series of reports from many of the radar sites described daytime occurrence of severe noise jamming at wavelengths of four and eight meters. The direction of maximum interference appeared to follow the sun. Hey contacted the Royal Observatory who informed him that there was a particularly large and active sunspot in transit on the solar disk. It was clear from the data that the active sun was the source of the radio noise jamming the British radar in those reports. For the first time the sun was detected as a radio source. It took about 50 years and an accident to find the sun's radio emissions.

These men were the principal pioneers and founders of radio astronomy. Their discoveries and contributions mark the birth and growth of radio astronomy into a major scientific discipline. Radio astronomy has been directly responsible for many of the great discoveries about the universe.

Discoveries Made by Radio Astronomy

These discoveries include the three degree background radiation predicted by the Big Bang theory. Flare, or radio stars like the sun, have been found in many locations in the Galaxy. Using the 21 cm spectral line of neutral hydrogen (HI regions), extensive and detailed maps of the Milky Way have been produced, giving us an understanding of the structure of our galaxy. The study of gaseous
nebulae with radio telescopes has uncovered their structural
dynamics and led to the detection of organic molecules in space.
Temperature measurements of the moon and planets made with radio
telescopes have increased our knowledge of our nearest neighbors in
space. Distance measurements to the planets made with radar give us
an accurate size of the solar system.

Two of the most important celestial objects discovered and
studied with radio telescopes are pulsars (1967) and quasars (1963).
Pulsars are generally accepted as being rotating neutron stars,
which confirms some theories of the end states of stars. Quasars
(quasi-stellar objects) are still not understood, although they may
be an early stage in the formation of galaxies. Radar has also
played a major role in the testing of general relativity and other
theories of gravity.

Solar activity is monitored daily by radio astronomers to help
effect a more complete understanding of the relationship between the
sun and Earth. Life on Earth is totally dependent on the conditions
of the sun. The more we understand the sun, the more we can
understand our home planet.

Radio telescopes have made possible the search for
extraterrestrial intelligence, a project being carried out by the
SETI group. There are about 100 billion galaxies in the visible
universe and each galaxy contains about 100 billion stars. We are
in a sparsely populated area of the Galaxy, but there are 40 stars
within 16 lightyears of the sun. It is not hard to convince oneself
that human beings may not be the only intelligent life. Thus we can
see that radio telescopes have become major research tools in astronomy.

Reasons for Constructing the 73.8 MHz Telescope

One of the principal duties of colleges and universities is to provide as broad and as full an understanding of the world and universe to students as is possible. For those engaged in the study of astronomy, optical telescopes provide only a relatively narrow view of the universe, even though they are the romance of astronomy. We must be able to present the most up-to-date information, views and observational experiences. Current electronic technology has made the construction of radio telescopes a viable endeavor for anyone with a few hundred dollars and the requisite skills. This enables institutions to expand both research and teaching facilities in astronomy.

In this thesis, the design and principles of operation of a 73.8 MHz radio telescope interferometer constructed at Western Michigan University are discussed. This radio telescope was built for use by astronomy students, to give them a feeling for, and an idea of the observational techniques of radio astronomy. An interferometer works best for discrete sources, like stars, as opposed to extended sources like the Galaxy. Discrete sources are the easiest to find and study. The students should find this telescope easy to use.

The interferometer telescope was developed in 1946–47 by two independent teams of scientists. Both teams, McCready, Pawsey and
Payne-Scott (1947) in Australia, and Ryle and Vonberg (1946) in England were attempting to prove that solar radio emissions are produced mainly in sunspot regions. A very narrow beam width was necessary in order to aim the telescope on and off the sunspots. The interferometer telescope produces this narrow beam width by creating an interference pattern between two or more sets of antennas, much the same way two slits produce an interference pattern for light. In 1946, the Pawsey team was the first to obtain positive results. However, the Ryle team was the first to publish in 1947. Ryle was awarded the 1974 Nobel Prize for his work in radio astronomy. Before discussing the 73.8 MHz telescope itself, we must first understand the sources of radio emissions that it will observe and record.
CELESTIAL RADIO SOURCES

The Optical and Radio Skies

Stars are hot blackbody radiators. They have strong emissions in the optical region and weak emissions in the radio region of the electromagnetic spectrum. Synchrotron radiation is emitted by relativistic electrons moving in magnetic fields and is typical of nonthermal celestial radio sources. Synchrotron radiation is strong in the radio region and weak in the optical region. Hence, essentially, a picture of the optical sky shows the position of the stars and a picture of the radio sky shows the position of clouds of relativistic electrons. This is an oversimplification, of course, and it depends upon the wavelengths used in the radio sky picture.

Sources in the radio sky can sometimes be linked to sources in the optical sky and vice versa. But the radio sky source distribution is quite different from the optical sky source distribution. For instance, there are objects called active galaxies. Some of these galaxies are of spiral type, but the strongest source of radio emissions come from jets of relativistic particles at the poles of the spiral, not from the spiral structure itself. Some of these jets are optically invisible and the existence of such galaxies would not be known if it were not for radio astronomy. In other cases, there might be a radio source at a position where there is no optical source. This is usually the case
when the optical emissions from the object are blocked by interstellar gas and dust. The spectrum of such a source can give valuable information about the properties and characteristics of the cloud. These clouds may be the source of materials for new stars and (maybe) solar systems. The next step to understanding radio astronomy and radio telescopes is to understand the physical mechanisms of the sources of celestial radio emissions.

Mechanisms

The physical mechanisms of radio sources can be broken into two kinds: thermal and nonthermal. At 73.8 MHz, celestial sources are nonthermal, except for the sun. The sun is practically a blackbody radiator. The thermal (blackbody) radiator will be discussed only briefly, for the purpose of contrasting its characteristics with the nonthermal radiation mechanisms that shall be discussed in more detail.

Thermal sources

Any body whose temperature is greater than absolute zero emits electromagnetic radiation. The intensity of the radiation follows Planck's blackbody radiation law. The wavelength of the radiation at maximum intensity is proportional to the temperature of the radiating body. For wavelengths above this maximum the intensity falls off at a uniform, moderate rate. For wavelengths below the maximum, the intensity falls off uniformly and quickly. A more complete discussion of blackbody radiation can be found in any upper
level physics text.

The radiation from thermal sources is not polarized. This important feature helps distinguish these sources from the (usually) polarized radiation of nonthermal sources. The radiation intensity for thermal sources falls off quickly with wavelengths greater than 3 meters. Hence, at 73.8 MHz (~4 meters) the radio sky is mostly a nonthermal source distribution.

**Nonthermal sources**

One form of nonthermal emission comes from ionized hydrogen gas clouds called H II regions. These clouds lie in the disk of the Galaxy and are considered to be the birth places of stars. The hot young stars in these regions, many of them being blue giants, are strong emitters of ultraviolet light which ionizes the hydrogen. Thus, an H II region is a thermally agitated plasma of protons and electrons. When an electron comes close to a proton, it can experience a free-free transition, resulting in the emission of a photon. In a free-free transition, the electron is free (not bound to any proton) before and after the interaction with the proton. The kinetic energy of the electron is reduced by the interaction and the energy of the photon is equal to the kinetic energy lost by the electron. The slow moving electron may then be struck by an incoming high energy photon from the hot star and gain more energy, or it may come close to another proton and suffer a free-bound transition. If the latter interaction occurs, a hydrogen spectral line will be created. The radiation spectrum of the cloud will be
the hydrogen spectrum superimposed on a continuous band of wavelengths through the radio and optical regions. Although the cloud's source of energy is thermal (the hot young star), the emissions from the cloud caused by the electron-proton interactions are nonthermal.

The mechanism of most nonthermal sources is the synchrotron mechanism. This mechanism and its corresponding radiation was first produced in a laboratory by the General Electric synchrotron in 1948, but its physics was understood as early as 1912.

A charged particle moving perpendicular to a magnetic field will describe a circle of calculable radius. The particle will absorb or emit radiation at a frequency called the gyro or cyclotron frequency, which is proportional to the magnitude of the magnetic field, and inversely proportional to the speed of the particle. A relativistic electron can be defined as one whose kinetic energy is comparable to or greater than its rest energy. The radiation from the relativistic electron moving in a magnetic field is concentrated in a cone of small solid angle centered on the direction of instantaneous velocity as it moves along the field line. The solid angle of the cone is inversely proportional to the particle energy. Since the magnetic field line has a definite direction, the radiation will be polarized. At very high energies, the radius of gyration approaches infinity, so the frequency of radiation tends toward zero. The maximum radiation intensity occurs at a frequency proportional to the magnetic flux density times the energy of the electron squared. The radiation spectrum from a cloud of
relativistic electrons is continuous, polarized and a function of the electron energy distribution.

Synchrotron radiation is linearly polarized with the electric field parallel to the orbital plane of the electron. However, the polarization is decreased by irregular magnetic field orientations in the cloud and by the Faraday rotation in the transporting (interstellar) medium.

The 21 cm line of the neutral hydrogen H I regions is also nonthermal. But this telescope is not able to observe this line so its mechanism will not be discussed here. Figure 1 shows a simplified comparison of the major source mechanisms.

Terminology used for Celestial Radio Sources

Radio astronomical observations from Earth can be made only in a limited range of wavelengths. The short wavelength limit of a few millimeters is caused by molecular absorption in the atmosphere. The long wavelength limit of 30-40 meters is caused by ionosphere reflection. The range of wavelengths where the atmosphere is relatively transparent is called the radio window.

The magnitude or strength of a celestial radio source is specified by the number of flux units at a specific frequency. For example, Cassiopeia A is rated at 11,000 flux units at 178 MHz. One flux unit is equal to \(10^{-26}\) watts per square meter per hertz. One jansky (after Karl Jansky) is one watt per square meter per hertz, so one flux unit is equal to \(10^{-26}\) jansky.
The intensity of radio radiation is the power passing through one square meter of an imaginary surface lying perpendicular to the direction of travel of the radio wave. The intensity, \( I \), at a particular frequency, is given by

\[
I = \frac{E^2}{R_r}
\]

where \( E \) is the electric field in volts per meter, and \( R_r \) is the free space radiation resistance at the frequency being considered.
The flux density (in flux units) of a source far from the Earth is the source's intensity per hertz. Thus the source intensity, i.e., the power per unit area being received from the source, is also proportional to the bandwidth of the radiation. This bandwidth is determined by the source or by the telescope, whichever has the smaller bandwidth. Therefore the received power at the antenna terminals is given by

\[ P = SAB \]  

(2)

where \( P \) is the received power, \( A \) is the antenna's effective aperture area (see below), \( B \) is the bandwidth and \( S \) is the flux density, or the rated number of flux units for the source.

A discrete radio source may be defined as a source that is separate or distinct from other sources. Cassiopeia A is a discrete radio source. Discrete radio sources can be of three types: point sources, localized sources and extended sources. A point source is an idealization. It is a source whose apparent size subtends an infinitesimal solid angle. A localized source is one of small, but finite solid angle, and may be looked upon as being a "real world" source. The difference between localized and extended source is arbitrary, but generally, an extended source is one that subtends an angle greater than one degree on its radio surface. The flux density is generally constant (except for periodic variable sources) for a localized source as viewed from the Earth. Users of the telescope discussed here will be working with discrete, localized sources.

The sensitivity of the telescope is one of the factors
determining how many sources the telescope will be able to detect. It describes the minimum amount of received power that is necessary for the telescope to detect a source. From Equation 2 it is easy to see how a telescope can be made more sensitive. Sensitivity can be increased either by increasing the effective area of the antenna, or by increasing the bandwidth of the receiver (if it is the limiting factor). However, there are practical limitations on how large we can make these factors. Money will usually limit the antenna size, and interference from broadcast transmitters or terrestrial noise will limit the bandwidth. Once these limitations have been reached, the only way to increase sensitivity is to increase the signal sensitivity of the receiver circuit and/or the receiver circuit gain. But money will usually limit this also.

Celestial Radio Source Objects

Actual radio sources can now be discussed, starting with the object closest to us, the moon. Then the planets, the sun, the stars, galactic objects and finally extragalactic sources will be discussed.

The flux density of radiation from the moon is about 85 flux units, and is detectable only by relatively large telescopes. At wavelengths of a few meters, the flux is constant in time. This makes the moon an easy object to find. However, the low flux density requires electronics that is too sensitive and sophisticated for the average amateur budget, and studies of the moon are best left to research institutions.
All of the planets, with the possible exception of Jupiter, have flux densities like that of the moon. They are too weak to be considered as sources for this telescope. Jupiter has strong emissions in the range of 5 to 40 MHz. These emissions are sporadic, and are apparently related to atmospheric disturbances on Jupiter and to the orbital motion of one of its satellites, Io. These emissions are nonthermal. However, at centimeter wavelengths, the emissions are thermal with a relatively constant intensity, and the upper layer cloud cover temperature may be measured. At the 73 MHz range, Jupiter could be an interesting subject of study, when the observer is well acquainted with the telescope's operation.

The sun is the most suitable source for small radio telescopes like the one presented here. It is a strong thermal radiator at all wavelengths and its intensity is highly variable in the regions where small amateur telescopes operate. The sun is actually a weak flare star, but it is close enough that the flare events can be studied in detail at radio and optical wavelengths. The solar flares also can be correlated with geophysical events. The sun's time varying output is extremely complex and may provide many opportunities for student study. Many amateurs use their telescopes exclusively for observation of solar flare events, or the time variable solar intensity.

Before 1967, radio stars were simply the small diameter radio sources. It was not until the discovery of pulsars that it was known that these small diameter sources were actually stars. In 1972, Algol was observed to be the first flare star other than the
sun. All radio stars except the sun are extremely faint and require the largest and most complex telescopes and data processing equipment. They are out of reach of this telescope.

Galactic radio objects are generally supernova remnants or nebulae. Supernovae are the spectacular death throes of very massive stars. The explosions create rapidly expanding gas clouds that are strong radio emitters. European and oriental history record three such events. The Crab exploded in 1054, Tycho's in 1572 and Keplers's in 1604. There have been no supernovae observed since Kepler's. However, the gas clouds of the known supernovae remnants continue to expand and emit all forms of electromagnetic radiation.

The strongest radio source in the northern hemisphere, other than the sun, is Cassiopeia A, another supernova remnant. Cassiopeia A exploded in about 1750. There is a large dense dust cloud between the Earth and Cassiopeia A thus explaining why the explosion was not observed optically. Cassiopeia A has a three meter flux density of 17000 flux units, and can serve as the calibration source for this telescope. Clouds of hydrogen gas, or nebulae, are weak emitters in the region of 73.8 MHz. To detect these clouds, shorter wavelengths should be used. With improvements in equipment and more careful observational techniques, more of these objects should become observable.

The center of the Milky Way is a strong radiator. This source is known as Sagittarius A. It is the strongest source in the constellation of Sagittarius. (This is the reason for the "A.") At
73.8 MHz, Sagittarius A is the dominant source in that area of the sky. This source should easily be found with this telescope.

Some of the most powerful radio sources are the farthest from Earth. These sources are called radio galaxies. Cygnus A is the next most powerful source after Cassiopeia A. Cygnus A is a galaxy believed to be between 500 and 700 million lightyears away. The structure of this source is extremely complex when observed with larger telescopes. To the 73.8 MHz telescope it will appear as an unresolved point. Several galaxies are in the source list and all of these galaxies will appear as point sources. The energy sources or mechanism that produce the intense radiation from these galaxies is unknown.

Table 1
Amateur Celestial Radio Sources, Epoch 1980.

<table>
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<th>Source</th>
<th>R.A.</th>
<th>Dec</th>
<th>Magnitude(fu)</th>
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<tr>
<td>Sun</td>
<td>variable</td>
<td>variable</td>
<td>100-10^9</td>
</tr>
<tr>
<td>Jupiter</td>
<td>variable</td>
<td>variable</td>
<td>100-10^5</td>
</tr>
<tr>
<td>Cass A</td>
<td>23h 21m</td>
<td>+59°</td>
<td>11,000</td>
</tr>
<tr>
<td>Sag A</td>
<td>18h 00m</td>
<td>-24°</td>
<td>9,000</td>
</tr>
<tr>
<td>Cyg A</td>
<td>19h 58m</td>
<td>+41°</td>
<td>8,100</td>
</tr>
<tr>
<td>Tau A</td>
<td>5h 30m</td>
<td>+22°</td>
<td>1,420</td>
</tr>
<tr>
<td>Vir A</td>
<td>12h 28m</td>
<td>+13°</td>
<td>970</td>
</tr>
</tbody>
</table>
There are essentially two kinds of radio telescopes: the large single dish and the interferometer. The large single dish, or LSD, is the kind of telescope that is usually thought of when the subject of radio astronomy is mentioned. Reber's telescope was an LSD. The interferometer telescope consists of two or more antennas, connected in or out of phase, or both. If the antennas are connected in phase, then it is an adding interferometer. If the antennas are connected out of phase then it is a subtracting interferometer. The last type, where the antennas are both in phase and out of phase (but not at the same time) is called a switching, or multiplying interferometer. Here, one of the antennas is switched in and out of phase with respect to the other antenna by a switcher circuit at the antenna's input.

The LSD telescope works best for observing faint sources, rapidly varying sources, or for doing source spectroscopy. This is because for weak or low flux sources, large collecting area, wide bandwidth and long integration times must be provided to obtain enough energy from the source to overcome the noise entering the detector at the same time. As the dish size (collecting area) is increased, the bandwidth or integration time may be decreased. This then allows source spectroscopy (narrow bandwidth) or observation of
variable sources (short integration time). The LSD can be of several types also, and are sometimes used as elements of larger interferometer telescopes, such as the Very Large Array (VLA) in New Mexico. An interferometer can produce high resolution using smaller antennas. Its output is easily recognized, compared to an LSD, in noisy records. The switching action of a multiplying interferometer gives even greater signal to noise performance to the simple interferometer. To understand the interferometer effect, one must understand antennas, and the interaction between sets of antennas in an array.

Basic Antenna Principles

The antenna's pattern is the response of the antenna as a function of direction. The pattern consists of a number of lobes. The largest lobe, usually lying on the antenna's receiving axis, is called the main lobe. The smaller lobes are called the side lobes, or back lobes. The pattern of an antenna is usually measured in the transmission mode using a field strength meter. A field pattern is the antenna's pattern expressed in terms of the electric or magnetic field intensity. If the pattern is measured at a sufficient distance such that a change in the distance does not change the pattern, then the pattern is called the far-field pattern. Measurements made at a closer range are called near-field patterns, and they are a function of both direction and distance. A power pattern is the antenna's pattern expressed in terms of the magnitude of the Poynting vector or radiation intensity. For most antennas,
the power pattern is similar to the field pattern.

If the pattern is symmetrical about the main lobe axis, then a figure of revolution of the antenna's planar pattern would provide a complete description of the antenna's pattern. This could be the case for a parabolic dish antenna. If the pattern is not symmetric, then a three dimensional drawing would be required. However, many antennas, particularly the Yagi type, are sensitive to field polarization: They are linearly polarized. Therefore, Yagi antenna patterns are given as E-field patterns and/or H-field patterns. The E-field plane is the plane of the elements of the antenna, and the H-field plane is perpendicular to that plane. These E-field and H-field patterns are called the principle-plane patterns.

Radio communications uses the terms vertical and horizontal polarization. These terms give the direction of the wave's E-field relative to the ground plane when the wave's direction vector is parallel to the ground plane. If the antennas are pointed close to the zenith, as they are (usually) in radio astronomy, these terms lose their meaning. Therefore, these terms should be slightly modified. Vertical polarization means that the E-field vector is parallel to the meridian. Horizontal polarization means the E-field vector is perpendicular to the meridian.

There are two useful numerical specifications for an antenna pattern made in terms of the width of the main lobe at particular response levels. One of these is the half-power beam width (HPBW) and the other is the beam width between first nulls (BWFN). The HPBW is 3 dB (half power) below the main lobe maximum, and the BWFN...
nulls are usually 10 or 20 dB below the main lobe maximum. Figure 2 shows the location of these quantities in a typical antenna pattern.

The next terms to be introduced are most easily understood if one considers them in terms of the antenna being an emitter, rather than a receiver of radiation. Since the patterns and properties of an antenna obey reciprocity, at least in the case where the antenna is being used in a radio telescope, the definitions will hold true when the antenna is used as a receiver.

![Figure 2. A typical antenna pattern.](image)

The **directive gain** of an antenna is defined as the ratio of the radiation intensity to the radiation intensity of a reference antenna, both measured in a given direction. The reference antenna
can be taken as an isotropic source (one which radiates equally well in all directions), or a simple dipole. Usually, for the statement of antenna characteristics, the reference is an isotropic source. But the measurement of those characteristics for most antennas is made in reference to a simple dipole. The reasons for this will be made clear later. The directivity of an antenna is the value of the directive gain in the direction of its maximum value. The directive gain and hence the directivity of an isotropic source is unity since all of its power is radiated equally well in all directions. For all other sources, the directivity will always be greater than unity, since there will always be one direction where the radiation intensity is greater than average. The directive gain will be greater than or equal to zero (there may be directions where no radiation is emitted) and less than or equal to the directivity (the directivity is the maximum value of the directive gain).

The reason for stating the characteristics of an antenna in terms of an isotropic radiator is to make easier the comparison of one antenna type with another antenna type. Unfortunately, an isotropic source has theoretical existence only, and cannot be built. However the simple dipole can be built and its characteristics in terms of an isotropic radiator are easily determined. The radiation from a simple dipole is approximately a donut shape with the dipole itself perpendicular to the plane of symmetry. The directive gain of the simple dipole anywhere in the plane of symmetry is 1.64. Its directivity is also 1.64.

Mathematically, directivity may be stated as
where $D$ is the directivity, $I_{\text{max}}$ is the radiation intensity in the direction of its maximum value and $I_{\text{ave}}$ is the average radiation intensity, or the intensity of the reference source in the same direction.

The gain of an antenna is approximately equal to the directivity. The directivity is dependent only on the shape of the antenna pattern, it does not take into account the losses in an actual antenna system. Therefore, the losses must be taken into account by the gain. This is done by a coupling constant with a value between zero and one inclusive. The gain is then

$$G = k I_{\text{max}} / I_{\text{ave}}$$

where $G$ is the gain and $k$ is the coupling constant. For most antennas systems, efficiency is quite high and this coupling constant can be taken as one. The radiation intensity of an isotropic source is $P_{\text{ave}} = 4\pi I_{\text{ave}}$. Thus,

$$D = 4\pi I_{\text{max}} / P_{\text{ave}}$$

where $P_{\text{ave}}$ is the average power radiated. From here we find that (Balanis, 1982a)

$$G = D = 4\pi / \Omega_A$$

where $\Omega_A$ is the solid angle of the antenna's aperture. For a Yagi type antenna, $\Omega_A$ is approximated by the product of the HPBW in the E-field and H-field planes. It can also be shown that (Balanis, 1982b)

$$\Omega_A = \lambda^2 / A$$

where $\lambda$ is the operating wavelength and $A$ is the antenna's...
An antenna has two kinds of resistance associated with the power radiated. The first is the real, or ohmic resistance and the second is an assumed resistance. This assumed resistance is the radiation resistance and represents the power lost due to the radiation of energy. The total power loss may be written as

\[ P = \frac{E^2_t}{R + R_r} \]  

(8)

where \( P \) is the power, \( E_t \) is the terminal voltage and \( R \) is the real resistance. Generally, the real resistance is on the order of one ohm and the radiation resistance about 300 ohms, hence, the real resistance may be neglected. Thus we find from Equation 2 and Equation 8 that

\[ E^2_t = S A R \]  

(9)

and the antenna terminal voltage may be approximated for any radio source.

The resolution of an antenna is approximately numerically equal to its HPBW. If \( \Omega_m \) is the solid angle of the main beam at the half-power locus, the number of discrete sources, \( N_r \), that the antenna can resolve is given by (Kraus, 1966)

\[ N_r = \frac{4\pi}{\Omega_m} \]  

(10)

where a uniform source distribution over the celestial sphere is assumed. Thus the number of discrete sources an antenna can resolve is approximately equal to its directivity. But this is an idealization because the distribution of sources is not uniform and the resolution also depends on the signal sensitivity of the receiver circuitry. Therefore the \( N_r \) of Equation 10 should be
regarded as an upper limit.

From Equations 7 and 10 it can be seen that one way of increasing the resolution of a telescope is to increase the antenna aperture. But increasing the aperture may have economic or physical limitations since it requires building a larger antenna. These limitations can be overcome by using an array of antennas. This array would use the interference between the antennas to create \textit{aperture synthesis}. The interference between the antennas reduces the HPBW, which is also the result of increasing an antenna's aperture. Hence the name, aperture synthesis. The result of reducing the HPBW is an increase in directivity and hence, an increase in the resolution of the telescope. This is the basis of the interferometer telescope. Two (or more) smaller, less expensive antennas can be set up as an array, synthesizing the result of one large expensive antenna.

\textbf{Principles of Interferometers}

Consider an array of two point sources. (Recall reciprocity.) If the distance between the antennas is $L$, and the phase reference point is taken between the antennas, then the far-field pattern is

$$E = E_2 e^{i\psi/2} + E_1 e^{-i\psi/2}$$

(11)

where $E_1$ and $E_2$ are the magnitudes of sources 1 and 2 respectively, and $\psi = 2\pi L/\lambda \sin \phi$. If the sources are of equal magnitude then $E_1 = E_2 = E_0$ and Equation 11 becomes

$$E = 2E_0 e^{i\psi/2} e^{-i\psi/2} = 2E_0 \cos(\psi/2)$$

(12)
For two isotropic sources separated by \( L = \lambda/2 \), the field pattern is shown in Figure 3.

If the two sources are not isotropic, then Equation 12 is still valid but \( E_0 \) becomes a function of \( \phi \) instead of being constant. In this case the pattern of each antenna, \( E_0(\phi) \) is called the primary pattern and the function \( \cos(\psi/2) \) is called the secondary pattern or array factor. It is the array factor that accounts for the increase in the telescope's directivity. Equation 12 is an example of the principle known as pattern multiplication.

Figure 3. Field pattern from array of two point sources separated by \( L = \lambda/2 \).

A line drawn between the antennas is called the interferometer baseline. The intention is to lay this baseline on a east-west line and use the rotation of the Earth to move the celestial radio source through the interference pattern of the antennas. Although it is not necessary to use an east-west baseline, doing so makes data
interpretation easier. Only the plane containing the antennas and
the source need be used for the antenna pattern.

From the previous discussion, the normalized far field pattern
of the antenna array is

\[ E(\phi) = E_n(\phi) \cos(\psi/2) \] (13)

where \( \psi \) is defined as \((2\pi s/\lambda)\sin \phi\), \( s \) is the separation of the
antennas in meters, and \( E_n(\phi) \) is the normalized field pattern of an
individual antenna. The relative power pattern is given by the
absolute square of \( E(\phi) \),

\[ P(\phi) = \left| E(\phi) \right|^2 = \left| E_n(\phi) \right|^2 \cos^2(\psi/2) \] (14)
\[ = \left| E_n(\phi) \right|^2 (1 + \cos \psi) \] (15)

For large spacing the pattern has many lobes, or fringes, in
reference to their counterparts in optics (see Figure 4). The
fringe spacing is the beam width between first nulls, which occurs
at \( \psi = \pi \). Thus, near the meridian so that the small angle
approximation for inverse sine can be used,

\[ \text{BFWN} = \lambda/s \text{ (radians)} \] (16)

At 73.8 MHz (approximately 4 meters), with \( s \) measured in
wavelengths, the fringe rate at the meridian is approximately \( s/4 \)
fringes per hour.

An interferometer obeying Equation 15 is a simple adding
interferometer. The subtracting interferometer obeys a similar
equation. The switching interferometer uses both these equations to
produce a new pattern that is very distinguishable in high noise
levels. When the antennas are in phase, the far field pattern is
given by
The element pattern (from Figure 1)

The array pattern ($1 = 10 \lambda$)

Figure 4. The simple adding interferometer pattern.
When they are out of phase the pattern is
\[ E(\phi)_o = E_n(\phi) \left[ e^{i\phi/2} - e^{-i\phi/2} \right] \]  
(18)

The relative power patterns are
\[ P(\phi)_i = |E_n(\phi)|^2 \left[ e^{i\phi/2} + e^{-i\phi/2} \right] \left[ e^{i\phi/2} - e^{-i\phi/2} \right]^* \]  
(19)

and
\[ P(\phi)_o = |E_n(\phi)|^2 \left[ e^{i\phi/2} - e^{-i\phi/2} \right] \left[ e^{i\phi/2} - e^{-i\phi/2} \right]^* \]  
(20)

The system output is proportional to the difference of these two patterns. Thus the output is
\[ P(\phi) = P(\phi)_i - P(\phi)_o = |E_n(\phi)|^2 2(e^{i\phi} + e^{-i\phi}) \]  
(21)

and when normalized,
\[ P_n(\phi) = \frac{|E_n(\phi)|^2 \cos \psi}{2} \]  
(22)

As can be seen the constant of Equation 15 is not present and the output has an average value of zero. Figure 5 shows the outputs of the different types of interferometers.

Theoretically, the same information about the celestial source is available from the simple interferometer or the multiplying interferometer. The advantages of the latter come from its relative insensitivity to power supply variations and other sources of instability in the receiver circuitry. The phase switching action causes the noise from the celestial source to be modulated at the switching frequency, thus making it easier to distinguish it from the receiver component noise. These two noise sources are statistically similar, and the two must be separated by the telescope.
Figure 5. Interferometer fringe patterns.
A 73.8 MHZ RADIO INTERFEROMETER TELESCOPE

Introduction

This section discusses a 73.8 MHz radio interferometer telescope that was built at Western Michigan University. This telescope is based on the design published by G. W. Swenson in a series of articles in *Sky and Telescope* magazine.

The Front End

A celestial source's emissions consist of incoherent radiation statistically similar to the background radiation and the thermal noise generated by the receiver components. The source's emissions are at a significantly lower power level than the background. It is the function of the receiver to separate, or distinguish between these emissions. Therefore, the receiver must have high sensitivity, selectivity, gain and stability. The type of receiver used almost exclusively in radio astronomy is the superheterodyne. This receiver uses a mixer and a local oscillator to change the incoming signal frequency to an intermediate frequency. It is a common (commercial) circuit. The receiver is built such that the majority of the receiver's amplification is at this intermediate frequency. This technique has two advantages. First, it is easier to construct high gain, high stability amplifiers at this intermediate frequency. Second, since the input of the receiver is
tuned to a different frequency, spurious emissions from the IF stage cannot be picked up by the receiver's input to be reamplified. Thus a feedback loop, which would turn the receiver into an oscillator, is avoided. The receiver is divided into two parts, the converter and the IF strip.

The front end, or the receiver, has seven stages and eight major sections. The block diagram of the front end is shown in Figure 6. The first stage is the antenna switcher and was built following Swenson's design (Swenson & Yang, 1978a). The RF amplifier, mixer and local oscillator are all part of the RF converter board. This circuit was published in a latter article from the telescope design (Swenson & Franke, 1979a). The circuit was laid out on a phenolic perf-board following the designer's description. The three IF amplifiers are based on the design published by Swenson, but were modified with information from the chip's data sheet to increase amplifier stability. The square law detector is located on the 3rd IF amplifier board and is the dividing point between the front end and back end of the telescope. The square law detector is actually a common AM radio detector consisting of a small signal diode and a capacitor. The converter circuit diagram (Swenson & Franke, 1979b) will not be reproduced here (it is copyrighted), but the IF amplifier diagrams will be shown since they are original.
Figure 6. Block diagram of the front end.
The converter consists of the RF amplifier, the mixer and the local oscillator. The RF amplifier is actually two stages. The first being made of two MPF-102 field effect transistors in cascode configuration and the second being a wide band hybrid amplifier chip. Cascode amplifiers are slightly noisier than other types but the noise figure, according to Swenson, was still low enough for this telescope. The most important advantage of using a cascode amplifier is that it does not require neutralization (for the Miller effect) and therefore its performance is not affected by parts interchange.

The input impedance is 50 ohms. The input transistor develops signal bias from the input tank circuit. The second transistor is biased by a pair of resistors, and sets the quiescent point for the amplifier. The amplifier load is a tuned circuit. The second stage of the RF amplifier is a Motorola MWA-110 hybrid amplifier. The term "hybrid" means that its bias circuitry is built into the chip, so it needs only an external load resistor and proper impedance matching. A coil provides the impedance matching between the cascode amp and the wide band amp. A tuned circuit forms the load and impedance match to the mixer. The description of coil requirements is made in Swenson's article and will not be repeated here.

The 63.1 MHz local oscillator is a common parallel-mode crystal oscillator described in any radio electronics book. Nothing needs to be said about this simple circuit except that it is tuned for maximum output. The mixer is an RCA 40673 dual insulated-gate field
effect transistor. The local oscillator is fed to gate 2 and the incoming signal to gate 1. The transistor is biased by a bypassed resistor on the source. Its load is a tank circuit. The output impedance of the converter is 50 ohms. The mixer is the heart of the superheterodyne action of this converter.

Tuning the converter was done with the usual procedure in RF circuitry; back to front. The local oscillator is first made to run and then set to maximum output using a RF probe into an oscilloscope. It was found that this circuit is very "touchy," and did not operate over more than a few degrees of rotation in the tuning capacitor. But once the oscillator started, its output was sufficient for operation, and consistently started on power up. Then, in turn, each of the tuned circuits was tuned for maximum output. The process was repeated until no further increase in sensitivity (gain) could be measured. The builder followed the designer's advice and opted for maximum gain since there was no way to make accurate noise figure measurements.

After tuning the circuit, it was found that the center of tuning was at 73.5 MHz, not 73.8 MHz. The difference could be accounted for by coil distortions in the tuned circuits. However, with the coils wrapped on nylon cores, the distortions could not be compensated for, and the telescope's frequency of operation is actually 73.5 MHz. Two attempts at building a printed circuit board for the converter failed. The final construction is on a phenolic perf-board. This turned out to be an advantage since it allowed for more experimentation with the circuit. It was Swenson's intention
to make this circuit as simple and as free from construction problems as possible. While he may have been successful, it took considerable effort to make this circuit operational.

The three intermediate frequency amplifiers are based on the MC1350 wide band video amplifier chip. They are built separate from the converter, in a sectionalized aluminum box. The input impedance of the IF strip is controlled by R1. Impedance matching between stages one and two is done by R2, and between stages two and three by R4. Gain is controlled by R3 and R5. The gain of the first stage is fixed at maximum. Tuning is done by the adjustable output transformers at each stage. The transformers are Miller type 5583. They are tuned for 10.7 MHz, and the Q factor of the transformers keep the bandwidth at about 300 KHz.

Again, tuning is done from back to front. Using a RF sweep generator at 10.7 MHz, make the adjustments for maximum output power. Initially, the adjustment resistors (R1 - R6) may be set at center range. When output (operation) is confirmed, tuning may begin. Turn R6 to minimum, there should be no output. Adjust R6 to maximum output and turn no further. The square law detector's output is a voltage whose square is proportional to the noise power of the predetection stages. (This includes the celestial source noise when present.) If the input impedance of the next amplifier stage is lower than the output impedance of the previous amplifier, current is transferred most efficiently. If the impedance of the next is greater than the previous, voltage is transferred most efficiently.
Notes: 1. All resistors in ohms, 1/4 watt, carbon film.
2. All capacitors in microfarads, except where noted.
3. Interstage connections made by coaxial cable.
4. All shielding is aluminum.
5. Power supply and ground connections made through binding posts.
6. Input and output connections made through f-connectors.
When the impedances are matched, power is transferred most efficiently. Since the output voltage of the detector is proportional to the power input, maximum power throughput is obtained when the detector is at maximum voltage output. Thus, all the stage matching resistors, R1, R2, R4 and R6 are set from minimum, for maximum voltage at the detector and turned no further. Resistors R3 and R5 control the gain of the IF strip and hence, the sensitivity of the telescope. They are set for best signal to noise performance while maximizing the gain. The IF amplifier was set to a gain of approximately 90 dB. The transformers are set to center frequency.

It is best, and advisable, that the receiver be tested and tuned as a whole unit. This allows matching between the converter circuit and IF strip. Figures 8 and 9 show the response curves for the receiver. The curves show the receiver's bandpass, image rejection and sensitivity measured at the detector. The area marked A in Figure 8 shows the bandpass curve. The curve shows the frequency response of the receiver from 73 MHz to 74 MHz, and shows that the receiver passband is about 300 KHz wide. The noise level is 10 millivolts and the output peaks at 73.5 MHz with 23 millivolts. The input signal level is 1 microvolt.

The area in Figure 8 marked B shows the sensitivity of the receiver. At 73.5 MHz the output changes from 12 millivolts to 27 millivolts with a change of input level from .18 microvolts to 1 microvolt. Since this is a clear, observable change in output level with an input level in the range expected from a source, the
receiver apparently has adequate sensitivity. Figure 9 shows the image rejection of the receiver. This curve shows how well the receiver rejects signals at frequencies outside of the passband at 73.8 MHz. This measurement was made with an input level of 3 microvolts, and even though it looks good, it may not hold true for some of the high power terrestrial noise sources.

All these measurements were taken using a radio frequency generator with a constant output over a range of 11 MHz to 111 MHz and plotting the output of the receiver on a chart strip recorder. The output of the generator was connected directly to the input of the receiver. The antenna switcher was not in the circuit. The output was taken from the square law detector in the IF amplifier, and connected to the chart strip recorder. The only correlation between the graph background and the plotted signal is in amplitude. There is no intended correlation between the graph background and frequency, and specific frequencies are marked by hand at the time of measurement. These curves indicate that the receiver is working within specifications required, for proper telescope operation.
Figure 8. Measurement of frequency response and sensitivity of the front end.
Figure 9. Measurement of image rejection of the front end.

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The Back End

The back end contains four stages and five major sections. The four stages are an a.c. amplifier, the phase detector, the integrator and the recorder driver. The back end also contains the switch signal generator that drives the phase detector and the antenna switcher circuit. For proper operation of the telescope, the antenna switcher and phase detector must be synchronized. This is one of the duties of the switcher generator. The back end is built on phenolic perf-board in its own aluminum box. The circuit diagram (Swenson & Yang, 1978b) is not reproduced here.

The first stage is an a.c. amplifier. This amplifier accepts the signal from the detector and passes only the a.c. component of the signal. There is a provision to bypass the a.c. coupling of this amplifier for testing purposes and to enable the back end to be used with a total power receiver. In this construction, an offset adjustment was added to the operational amplifier in the manner specified for this op-amp. This helped to decrease errors in the total power mode. The "total power switch" must be in the open position for operation as a switching interferometer. This stage has a voltage gain of approximately 30.

The phase-switch oscillator is 4/6 of a 7404 TTL hex-inverter driving a wave shaping 7473 TTL flip-flop. The output of the flip-flop drives a 741 op-amp amplifier whose output goes to the antenna switch and to a 2N4222 FET which drives the phase detector. When the antennas are in-phase, (1/2 cable out of the circuit) the
phase detector is a noninverting amplifier. When the antennas are out-of-phase, (\(\lambda/2\) cable in the circuit) the phase detector is an inverting amplifier. The state of the phase detector circuit is controlled by the voltage applied to the gate of the 2N4222 FET. When the transistor is turn on, the non-inverting input of the op-amp (IC III) is shorted to ground, making the circuit an inverting amplifier. The gain of the amplifier must be the same for the two states. This is the "gain equalization adjustment." A detailed adjustment procedure is given in the article. The second stage of the phase detector is a low cut-off frequency amplifier with provision for canceling any d.c. offset voltage added to the signal by the previous amplifiers. This is the "phase detector zero adjust."

The integrator is a very low slew rate d.c. amplifier. Its results can be duplicated by an overcompensated, externally compensated op-amp in a normal inverting amplifier configuration. However, in such a configuration the integration time would be op-amp dependent and difficult to control. The circuit here is based on the normal integrator circuit which has only a capacitor in the feedback loop. It allows op-amp independent control of the integration period. Above some frequency set by the time (integration) constant of the resistor-capacitor combination in the feedback loop, the output appears to be the integral of the input times the integration constant. The result is a statistical reduction in the data noise. The greater the number of samples (switching periods) in the sample time (integration period) the
lower the noise figure in the data. This is a result from statistics. However, one must be careful not to make the integration period so long that the fringes are eliminated also. The switching frequency of this telescope is about 360 Hz (1/360 second) and the integration time is about 120 seconds.

The last stage of the back end is a d.c. amplifier used to drive the chart strip recorder. It has variable gain and an offset adjustment. The builder found that a gain of one was useful and sufficient to run a Hewlet-Packard recorder.

Figures 10 and 11 show the signal waveforms at the input and at test points TP1, TP2 and TP3. (See the schematic, Swenson & Yang, 1978b) The output from the square law detector to the chart strip recorder is a d.c. voltage with noise riding on top. Figure 10 shows the case where the instantaneous voltage at the east antenna is twice that of the west antenna. Figure 11 shows the case where the reverse is true. The Figures do not show the noise that is seen riding on top of the signal when viewed on an oscilloscope. This is to simplify understanding of circuit operation.
Figure 10. Back end waveforms for the case where the output from the east antenna is twice that of the west antenna.

Figure 11. Back end waveforms for the case where the output from the west antenna is twice that of the east antenna.
The Antennas

The front end will work with any set of 300 ohm antennas that have the proper performance characteristics. The set used are Yagi type. There are four antennas, each of the same design. These antennas are in pairs with each pair mounted on separate poles. The five element antennas are made of aluminum. Figure 12 shows the design of each antenna. The dimensions are given in units of meters and wavelengths. The wavelength at 73.8 MHz is 4.02 meters. The antennas are built to have a characteristic impedance of 300 ohms. The Yagi design is preferred because these antennas are light, easy to build and easy to work with on site. They are also relatively inexpensive.

Yagi antennas are highly directional, end-fire arrays. Directivity can be controlled by the number of directors in front of the driven element and the spacing between those elements. The fact that they are end-fire arrays makes them easy to aim at the source. Just sight the source, or the meridian altitude of the source, down the spar of the antenna. Detailed discussion of the Yagi design can be found in the books and papers listed in the bibliography.

The poles are made of 6" O.D. PVC pipe, standing on plywood bases. The pair of antennas are separated by 3.8 meters on an aluminum arm mounted through the top of the 15 foot pole. The arm has a protractor at the pole mounting for measuring the altitude of the antennas' aim. The poles also have bubble levels to indicate plumb. The antennas are mounted and wired for vertical
polarization. Figure 13 shows a diagram of the poles.

The transmission lines are 300 ohm twin lead made by Channel Master (model 9555). The antennas and the transmission lines are all 300 ohms, but they cannot be directly connected. The antennas are 150 ohms when connected in parallel and the transmission line is 300 ohms, so there must be an impedance transformation made at the antenna poles. An impedance matcher is mounted on the poles with the antennas connected to the top by equal lengths of twin lead and the transmission line is connected to the bottom. The matcher consists of two aluminum rods, 6.3 mm (1/4") O.D., one meter long, separated by 2.5 cm center to center. They are mounted to the pole by Lucite stand-offs at the top, middle and bottom. The characteristic impedance of this matcher line is 212 ohms. A complete discussion of this matching technique (called Q-transformers) is given in the ARRL handbook.

The transmission lines are of arbitrary length limited only by the losses in the type of cable used. The 300 ohm twin lead used has a loss factor of 1.5 dB/100ft. The builders used approximately 150 feet of cable between the poles and the front end. These transmission lines must be of the same length to preserve phasing between the antenna signals.
Figure 12. The antenna design used for this telescope.
Figure 13. Diagram of the antenna pole and line impedance matcher.
The builders, as of this writing, have been unable to obtain data from a celestial source. The electronics, as shown from the previous data, is known to be working. Figures 14, 15 and 16 show data taken with the telescope using a hand-held dipole source that was walked through the antenna pattern for test purposes. Figure 14 shows the electronics working as a simple adding interferometer. The data were taken by walking the dipole on the base line between the two antenna poles. Some interference by large metal nearby machinery can be seen as the dipole approaches the west antenna, but clear interference effect fringes can be seen in the middle portion of the record.

Figures 15 and 16 show the telescope working in the switching mode. With the antennas pointing at the southern horizon, the dipole was walked through the pattern about 500 feet off the base line. Interference fringes like that of Figure 5 can clearly be seen.

The output from the dipole is estimated to be approximately twice that of a celestial source. It is currently believed that the antenna design as shown in Figure 12 has inadequate gain for use with this telescope. New antennas are being designed. An antenna was built to the same specifications with the elements insulated (a wooden spar was used) but there was no measurable difference in the performance. A new antenna with higher gain is being designed, using the guidelines of the National Bureau of Standards. Consideration has been given to the design discussed by Swenson in a later article on antennas for radio astronomy (Swenson, 1979).
The builders find they have a working telescope for sufficiently strong sources. Unfortunately, the source must be stronger than any possible celestial source. So far, the solution has been elusive. Improved antenna design may solve the problem. The new antenna will be "tunable," so the correct impedance at resonant frequency can be attained.
Figure 14. Telescope output from hand-held dipole walked along base line while in the adding mode, from east to west.
Figure 15. Telescope output from hand-held dipole walked 500 feet off the base line while in the switching mode, from east to west.
Figure 16. Telescope output from hand-held dipole walked 500 feet off the base line while in the switching mode, from west to east.
The telescope presented here is basic and contains only the essential components for operation. Many improvements can be made to the system. These improvements might be considered as projects for the future. This telescope is not a serious research tool. It is intended to be used only as an instrument for teaching the fundamentals of radio astronomy to students. The builder feels that knowledge about the design and construction of radio telescopes is just as important as the data interpretation. Future expansions and developments in the telescope architecture are important teaching tools and should not be neglected.

These improvements may include better construction techniques for the electronics. This means increasing the sensitivity of the receiver and/or increasing the amplification of the intermediate frequency amplifiers. Better circuitry in these areas will also improve the signal to noise performance of the telescope. The back end circuitry might include its own square law detector, removing the requirement for such from the IF strip. Also, the back end could provide jacks for direct connection to an oscilloscope with switches to select the point in the circuitry that the oscilloscope is displaying. Front panel (operator) switches to reset zeroing and integration, and ease back end test mode operation can be added. The overall performance might be improved with higher quality
operational amplifiers and passive components. The back end is the easiest part of the telescope to experiment with since it does not contain radio frequency signals.

One major project that may be carried out in the future is to interface the telescope with a microcomputer for automatic data recording and processing. The fast data processing capabilities of a computer can be used effectively for interpreting data collected from each observation, as well as a set of observations.

Other projects for the future would be the construction of electronics and antenna to operate at the higher frequency bands reserved for radio astronomy. Telescopes similar to this one could be built at these frequencies, at a cost less than this telescope, since some of the equipment has already been purchased or built. The back end can be used for any frequency of operation since it is independent of the RF circuitry. Specifically, the Physics Department would like to build a 406 MHz Telescope to operate in another reserved band. The same back end electronics could be used for both the 73.8 MHz and 406 MHz telescopes. With computer control, data could be collected from one source at both frequencies at the same time. The department would also like to build a 21 cm (1.42 GHz) telescope using four parabolic antenna dishes donated to the Department. The 21 cm line arises from electron spin-flip in neutral hydrogen. It has been used to map the position of hydrogen clouds in (and thus help determine the structure of) the Milky Way. Although this line is faint, there is possibility for work in this
band.

This construction project can be, and has been, a major project to be carried out by a small group. It should not be attempted by someone with no radio electronics experience. But for those who have the background, this is a good project and should be considered by any school with a serious attitude toward a major or minor program in astronomy.
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