A SEARCH FOR EXTRATERRESTRIAL RADIO BEACONS AT THE HYDROGEN LINE

A Thesis

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by

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CHAPTER I

INTRODUCTION

In recent years the topic of communication with extraterrestrial intelligent life has gained increasing popularity within the scientific community as well as elsewhere. The birth of this era of respectability was around the year 1960 and was witnessed by the famous Cocconi and Morrison paper (Reference 1) and by Project Ozma which was a pilot search conducted by Drake (Reference 2). Since that time there has been a considerable amount of work done concerning the probability of the existence of a communicative civilization and the best techniques to employ in bringing about communication with any such extraterrestrial intelligence. These speculations have been accompanied by some actual attempts at detecting signals sent by an extraterrestrial intelligence. This is a description of my participation in one such attempt.

A short summary of other observational work, both completed and in progress, is given. A theoretical search strategy is discussed. The degree to which we are able to follow that strategy is described. After establishing a criterion for selection, I thoroughly searched 3.3% of the sky for extraterrestrial radio beacons.

CHAPTER II

PREVIOUS AND CONCURRENT SEARCHES

There have been several small scale attempts to detect, in the microwave region, signals originating from an extraterrestrial civilization. This "microwave window" is thought by many scientists to be the optimum region of the electromagnetic spectrum in which to conduct interstellar communication.

The first known attempt at detecting radio signals from extraterrestrial civilizations beyond the solar system was the previously mentioned Project Ozma conducted by F. D. Drake, then of the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia. During the months of May, June, and July of 1960, a search was made in the vicinity of the hydrogen line for signals from Tau Ceti and Epsilon Eridani, two stars about 11 light years away. Drake used the 85 foot Tatel radio telescope at Green Bank (Reference 2).

During the fall of 1968 and 1969, a group headed by V. S. Troitsky conducted a search in the vicinity of 970 MHz using a 15 meter radio telescope near the Gorky State University in the USSR. Troitsky looked at 11 nearby stars (including Tau Ceti and Epsilon Eridani) and one nearby galaxy (Reference 3).

During the summer of 1972, G. L. Verschuur, then of NRAO, conducted a search for artificial signals in the vicinity of the hydrogen line using the 140 foot and 300 foot radio telescopes at Green Bank. Verschuur looked at 10 nearby stars including Tau Ceti and Epsilon Eridani (Reference 4).

Since 1970 V. S. Troitsky has been conducting a search for pulsed signals from the entire sky at 16, 30, 50 centimeters. He uses a network of near isotropic antennas in the USSR (Reference 5).

Since 1972 B. Zuckerman and P. Palmer have been conducting a search for signals at the hydrogen line from about 600 nearby, sunlike stars. They assume that the beacon is transmitting at the rest frequency of neutral hydrogen. They doppler correct for the relative velocity between each star and the Earth. They are using the radio telescopes at Green Bank (References 6 and 7).

Since 1972 N. S. Kardashev of the Institute for Cosmic Research in the USSR has been conducting a search for pulsed signals from the entire sky at several wavelengths. He is using a network of antennas in the USSR (Reference 7).

Since 1974 A. Bridle and P. Feldman have been conducting a search for signals from several nearby stars at the water line (22.2 GHz). They are using the 150 foot radio telescope of the Algonquin Radio Observatory in Canada (Reference 7).

Since 1975 F. D. Drake and C. Sagan have been conducting a search for signals from several nearby galaxies at 1420, 1653, and 2380 MHz. They are using the 1000 foot radio telescope at the Arecibo Observatory in Puerto Rico (Reference 7).

CHAPTER III

THE SEARCH STRATEGY

At this point, I would like to discuss a search strategy developed by R. S. Dixon (Reference 8). The reason for this is that the beacon search being conducted at the Ohio State University Radio Obervatory (OSURO) follows this strategy to the fullest extent allowed by our equipment. Although Dixon's paper cited in Reference 8 describes this strategy in detail, I would like to encapsulate the relevant parts of it here and emphasize some of its unusual points.

Dixon states that there are two types of signals that would originate from an extraterrestrial civilization. The first type is that known as leakage signals. Leakage signals are those that a civilization generates for its own internal purposes. The assumption is that some of this radiation will escape into space and will thus be detectable by us. Dixon says that these signals will be relatively weak because the sender will see them as wasted power. He also says that we will be unable to make many assumptions about the form of these signals.

Our civilization already produces this type of electromagnetic pollution in the form of television, radar and other signals that escape into interstellar space. We can presumably be detected out to about 20 light years, already. However, since the future of this type of radiation from our own planet is uncertain, it seems difficult to make assumptions about leakage signals from elsewhere.

I would like to interject here a comment about another possible type of signal. That is the signal resulting from actual communication between two civilizations. This signal would probably be strong enough to detect if we could intercept it. Unfortunately this type of signal may be tightly beamed and the probability of our lying within that beam diminishes correspondingly. However, if interstellar communication is widespread, the probability of our intercepting this type of signal may be higher than we would at first assume. At any rate, the existence of this type of signal would tend to increase our chances of detecting a civilization while looking for leakage signals.

The second type of signal mentioned by Dixon is the beacon. A beacon is a signal sent by a civilization to attract the attention of another civilization. Dixon implies that more can be safely assumed about the form of the beacon signal than the form of a leakage signal. Specifically, he assumes that the beacon signal will be of a form that maximizes the probability of its discovery, either accidentally or intentionally, by another civilization. As a part of this general assumption, Dixon uses a rule of picking one of two extremes in a set of choices rather than picking an indefinite middle choice. Using these assumptions, he proceeds to consider the many dimensions that need to be searched in this type of endeavor. They are; distance, direction, time, polarization, frequency, signaling rate, bandwidth, and modulation.

For several reasons, a distance limit is somewhat arbitrarily set at 1000 light years. Dixon points out that candidate stars (usually F, G, and K types) are individually searchable out to about 100 light years. Beyond that our knowledge of individual stars is poor. This, coupled with the large number of candidate stars per area of sky at that range, leads Dixon to conclude that an all-sky survey is in order.

For example: at 1000 light years there are an average of 4 candidate stars in the beam of the OSURO telescope in any direction.

I would like to point out here an argument presented by Drake in Reference 5 that seems to do away with the idea of searching candidate stars in an outward going spiral. Drake shows how a more powerful, yet more distant civilization may be more detectable, than a less powerful yet nearer civilization. This idea is of course trivial on the surface. The strength of Drake's presentation is that his simple mathematical model shows how much more distant a stronger beacon can be, and still compete successfully with a weaker beacon that is relatively nearby. It is my opinion that Drake's argument alone is sufficient to make a continuous survey the better strategy for finding beacons.

Under the time dimension, Dixon discusses very briefly the so called time strategies. One is for the beacon to transmit coninuously and omnidirectionally. The other is for the beacon to beam its signal in a certain direction for a certain period of time. In the absence of additional information it seems obvious that either the beacon or the beacon searcher should operate in the continuous omnidirectional mode in order to make eventual success more certain. Dixon assumes that the beacon will be the continuous omnidirectional end of the operation.

Dixon concludes that the signal bandwidth will be "near" zero. Since narrow-band signals are inherently polarized, the polarization dimension is very important. For example: if the receiving antenna receives vertically polarized radiation and the beacon signal arrives horizontally polarized, then no signal will be detected. Dixon concludes that right or left circular polarization is appropriate.

Related to the bandwidth is the signaling rate which Dixon assumes will be relatively slow. Also related to the bandwidth is the modulation. Dixon concludes that the optimum modulation for a beacon signal is binary polarization modulation using right and left circular polarization as the two states.

The choice of frequency in Dixon's search strategy has some very interesting features. He picks the hydrogen line for the classical reasons (Reference 1), but adds a new twist that overcomes some of the usual arguments against using the hydrogen line.

The relative motion between a beacon and a receiving station produces a doppler shift in the frequency of the beacon signal. Because we do not, in general, know the relative motion between ourselves and any beacon, a wide range in frequency must be reached unless a common frame of reference for this motion is chosen. Dixon says that the nearest reference point that we have in common with the beacon operators is the center of our galaxy. In this thesis, I consider the center of our galaxy to be at rest with respect to the intergalactic medium and that this medium forms a frame of reference called the galactic standard of rest. Since the beacon operators only know their motion with respect to the galactic standard of rest (GSR) and we only know ours, it is assumed that each compensates for its own doppler shift. The result of this is that the frequency chosen is the hydrogen line doppler shifted to the GSR. What is involved in finding this frequency will be discussed later.

One advantage of this scheme is that this frequency is largely removed from the region where hydrogen emission interference and hydrogen absorption present a problem. Another advantage is that an interferring terrestrial signal will most likely not have a frequency that is the same function of time as the predicted beacon frequency. This may be a great aid in recognizing terrestrial interference. Still another advantage is that mutual interference between two communicating civilizations will in general be absent. In other words, by using this scheme we could receive messages from another civilization while simultaneously sending messages to that civilization. A beacon operator could then listen for replies from emerging civilizations without turning off his beacon.

In summary, Dixon concludes that a beacon will transmit a narrow band, circularly polarized signal omnidirectionally and continuously at the frequency of the hydrogen line doppler corrected to be at rest with the intergalactic medium. The modulation will be binary with right and left circular polarizations as the two states. The signaling rate will be on the order of one bit per second. He sets a distance limit to this strategy of about 1000 light years and in view of this, concludes that an all-sky survey is in order.

CHAPTER IV

THE ATTEMPT TO FOLLOW THE SEARCH STRATEGY

As previously stated our search strategy conforms to Dixon's strategy to the fullest extent that our equipment allows. From his range limit of 1000 light years, Dixon concludes that an all-sky survey is needed. This is indeed fortunate for us, because the OSURO radio telescope is an instrument that is specifically designed for survey work. At 1000 light years the distribution of stars is till relatively isotropic so the survey should be made over the entire sky. We plan to search all of the sky that is observable with the OSURO radio telescope ($+63^{o} \geq \delta \geq -36^{o}$). Observations are made every 20'in declination. Because of the 40' half-power beam width in declination of our radio telescope, we consider this to be continuous sky coverage.

Our system temperature T_{sys} is about 100 ^{o}K. The narrowest channel has a bandwidth B of 20 KHz. The integration time t is 10 seconds. An estimate of our systems minimum detectable received power P_r is (Reference 5)

$$P_r = k\, T_{sys} \sqrt{\frac{B}{t}}$$

or about 6 x 10^{-20} watts. In order for an omnidirectional beacon located at the 1000 light year range limit to be detectable by us, it will need a transmitted power P_t of

$$P_t = \frac{4\pi R^2 P_r}{A_e}$$

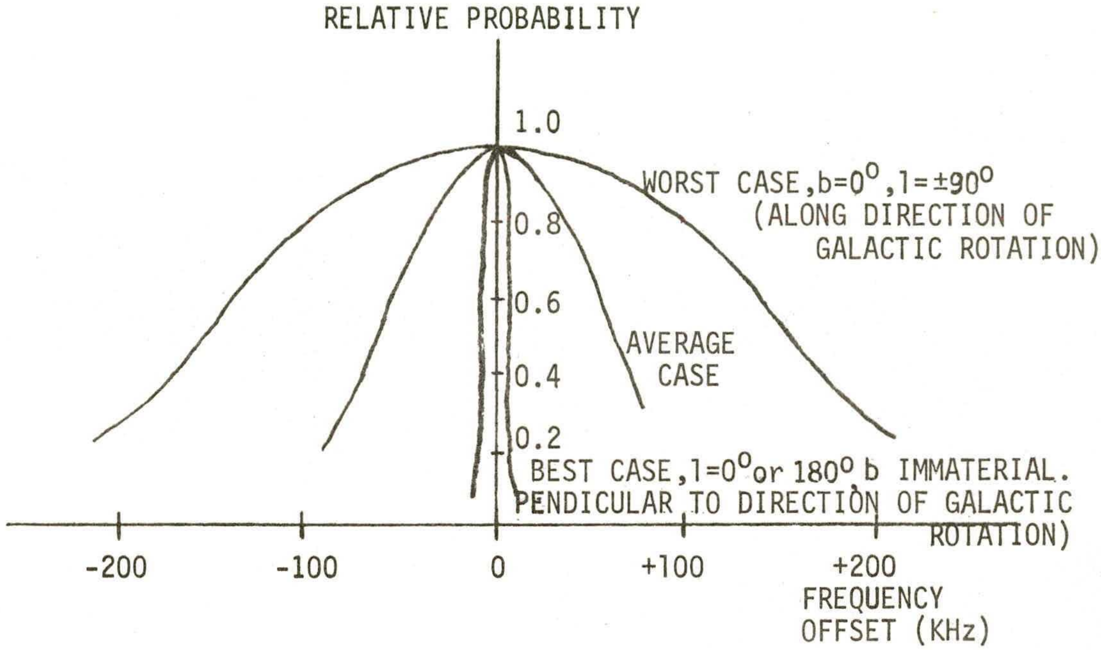
where R is the range (1000 light years) and A_e is the effective aperture of our receiving antenna (1100 square meters). This results in a minimum transmitted power of 6 x 10^{16} watts.

For the time dimension, Dixon assumes that the beacon will be transmitting continuously. This means that there are no preferred times to look for the signal. The fact that our radio telescope is a meridian transit instrument, is then no disadvantage in searching this dimension.

For the polarization and modulation dimension an antenna system that receives both right and left circular polarization is needed. The OSURO antenna receives vertically polarized radiation so we will get half of the signal strength of the circularly polarized signal of either hand. Also the assumed binary modulation will go unnoticed. We would see a signal that seems to be unmodulated or always "on." This situation may not be as unsatisfactory as it first seems. Dixon assumes a signaling rate that is on the order of one bit per second. This borders being high enough for the beacon signal to change state (i.e., go from left circular to right circular or vice versa) while the beacon is still within the beam of most transit telescopes. If the radio telescope receives only one of the two orthogonal polarizations and the signaling rate is lower than Dixon's estimate, the beacon could be in the other polarization state when it transits. If this happens there will be no detection regardless of the strength of the beacon signal. However, since our antenna receives the vertical polarization, we will always receive the signal at half strength, independent of the signaling rate. Thus, with our equipment the dimension of signaling rate becomes unbounded toward the low end. The signaling rate is still bounded on the high end by the constraint that the bandwidth be "near" zero. As far as the loss of modulation is concerned, once a signal is found that seems to be of the form predicted by Dixon any modulation that it may contain can be studied at another observatory.

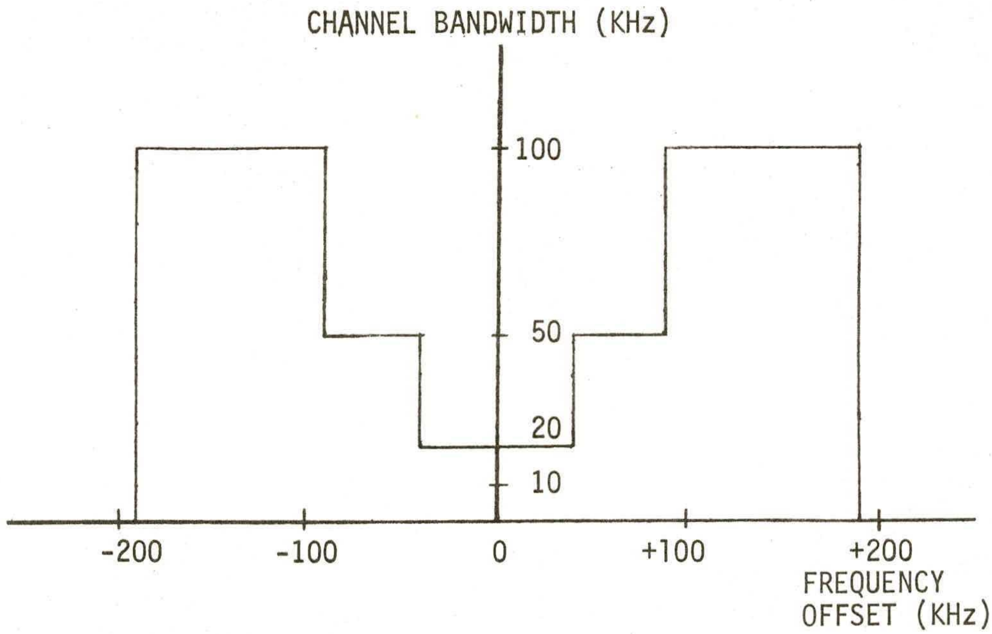
Dixon's strategy calls for a beacon signal to have a bandwidth that is "near" zero. We have at present an 8 channel filter bank. Due to the uncertainty in the current knowledge of our galactic rotation velocity (±25 km/sec), we need to compensate for the corresponding uncertainty in frequency by covering at least 250 KHz. A probability distribution of the galactic rotation velocity is shown in Figure 1, p. 12 (Reference 9). However, frequency offset is plotted along the abscissa instead of velocity. The filter bank was tapered to fit this probability distribution as can be seen in Figure 2, p. 12 (Reference 9).

This narrow-band signal is assumed to be centered at the hydrogen line doppler corrected to be at rest with respect to the intergalactic medium. Our filter bank is centered on this frequency. This frequency is a sinusoidal function of time due to the Earth's rotation. This sinusoidal function is in general different for different days of observation at the same declination because of the Earth's orbit and solar motion. A program that is run on the observatory's IBM 1130 computer calculates this frequency at several points and is thought to be of sufficient accuracy. However, some error is incurred in our attempts to make the receiver follow this function. Our motor driven primary local oscillator is able to provide a sawtooth approximation to this sinusoidal function. Unfortunately the motor runs at a slightly different rate when going in one direction than it does when going in the other. Also the mechanical controls used to set the speed of the motor (and thus the slopes of the sawtooth) and its reversal points (and thus the peaks of the sawtooth) are such that we are able to achieve only limited accuracy in controlling the sawtooth function. There also were errors in the program



A probability distribution of the galactic rotation velocity.

Figure 1



The tapered filter bank.

Figure 2

that calculates the frequency of the primary local oscillator before January 10, 1975, when they were found and corrected. The difference between the actual primary local oscillator frequency f_1 and the desired frequency $\overline{f}_1$ is plotted in Figure 22 on page 48 for 11 sources that were found in the search records. Since 2/3 of this sample fall within 125 KHz of the desired frequency, I estimate our error in tracking the search frequency to be ±125 KHz before January 10, 1975.

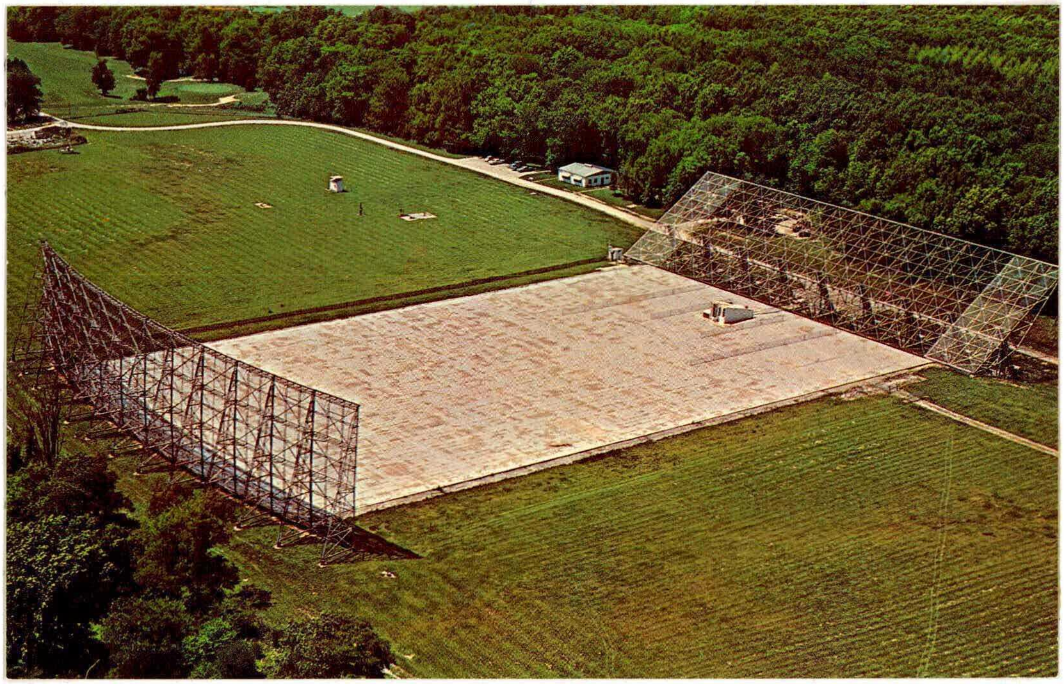
CHAPTER V

INSTRUMENTATION

ANTENNA

The radio telescope used in the search is made up primarily of the antenna and the receiver. The antenna (Reference 10) is a meridian transit instrument that is specifically designed for survey work. A meridian transit telescope has its main beam on the meridian. Such a telescope uses the Earth's rotation to point it to different right ascensions. Of course, since the Earth turns continually, this results in a continual scanning across the sky in right ascension. The telescope is steerable in declination by the moving of a 340 foot by 100 foot flat relector. The incoming rays are deflected by the flat reflector across a 3 acre aluminum covered ground plane and onto the 350 by 70 foot parabolic section. The parabola focuses the rays into the horns which are housed in a radome on the ground plane (Figure 3).

The antenna is fed by two such horns in a beam switching technique. Basically this involves subtracting what is seen in one beam from what is seen in the other. A point source is a radio source whose angular extent is small compared to the beam of the radio telescope. It is the point source that is of primary interest in this thesis. It also provides the simplest example of how beam switching effects an observation. As the Earth rotates the two beams caused by the two horns drift across the sky. The first beam drifts across the point source while the second beam is still seeing blank sky. The observed response is the beam shape (i.e., the antenna pattern) convolved with a point minus the antenna pattern (due to the second horn) convolved with nothing. The result is, of course, the antenna pattern due to the first horn. Later when the second beam sweeps



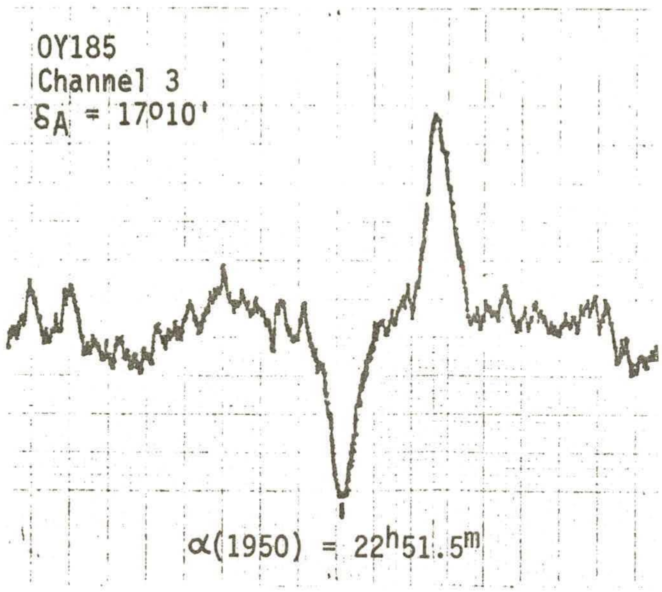
The Ohio State University radio telescope.

Figure 3

across the point source, the first beam is seeing blank sky. The observed response is then nothing minus the antenna pattern due to the second horn. The result is similar to the antenna pattern due to the first horn, only it is inverted. Figure 4 shows the observed response of the radio telescope due to the radio source OY185. This is obviously the simplest possible example of the effect of beam switching. Complication arises when a source is extended so that it is in both beams simultaneously. However, the principle illustrated by this simple example holds throughout.

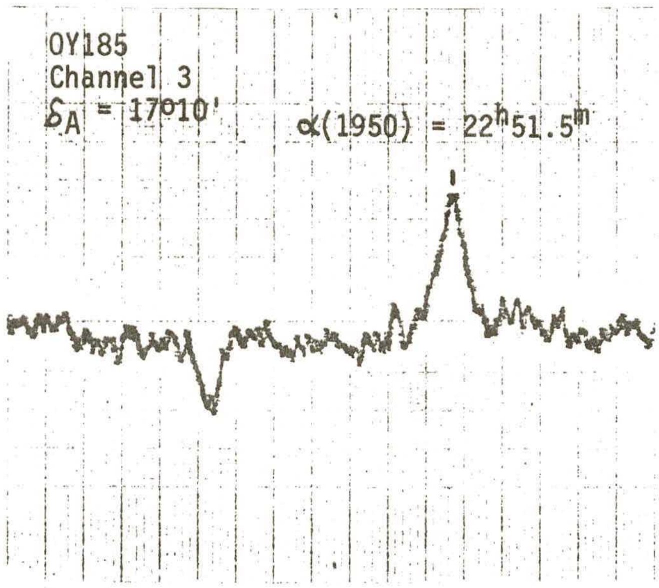
During the search phase and the initial part of the study phase, an older horn was resurrected and used as a second horn. Being able to switch the main horn against even this old one vastly improved the records. It helped to cancel terrestrial interference and gave us two passes at a source per day. However, this older horn was less efficient than the main horn. The response due to that was, in general, not as strong as was the response of the main horn, as can be seen in Figure 5. This tended to keep the system unbalanced, thus creating records that were a little more noisy than they could have been. At the end of the summer of 1975, a new horn was completed and installed to replace the old one. This further improved the situation and gave us two good passes at a source per day (Figure 4).

The antenna has a physical aperture of 2211 m^2. Measurements at 21 cm with both the main horn and the new horn indicating aperture efficiencies of about 50%. This results in an effective aperture of about 1100 m^2 at 21 cm. This is for declinations south of $+40^{\circ}$. Higher declinations introduce an aperture vignetting effect which reduces the effective aperture. The half-power beam width (HPBW) in declination is about



Observed response of OY185 using the new horn. The squint is applied to the main horn (down response) to get the true position.

Figure 4



Observed response of OY185 using the old horn. The squint is applied to the main horn (up response) to get the true position.

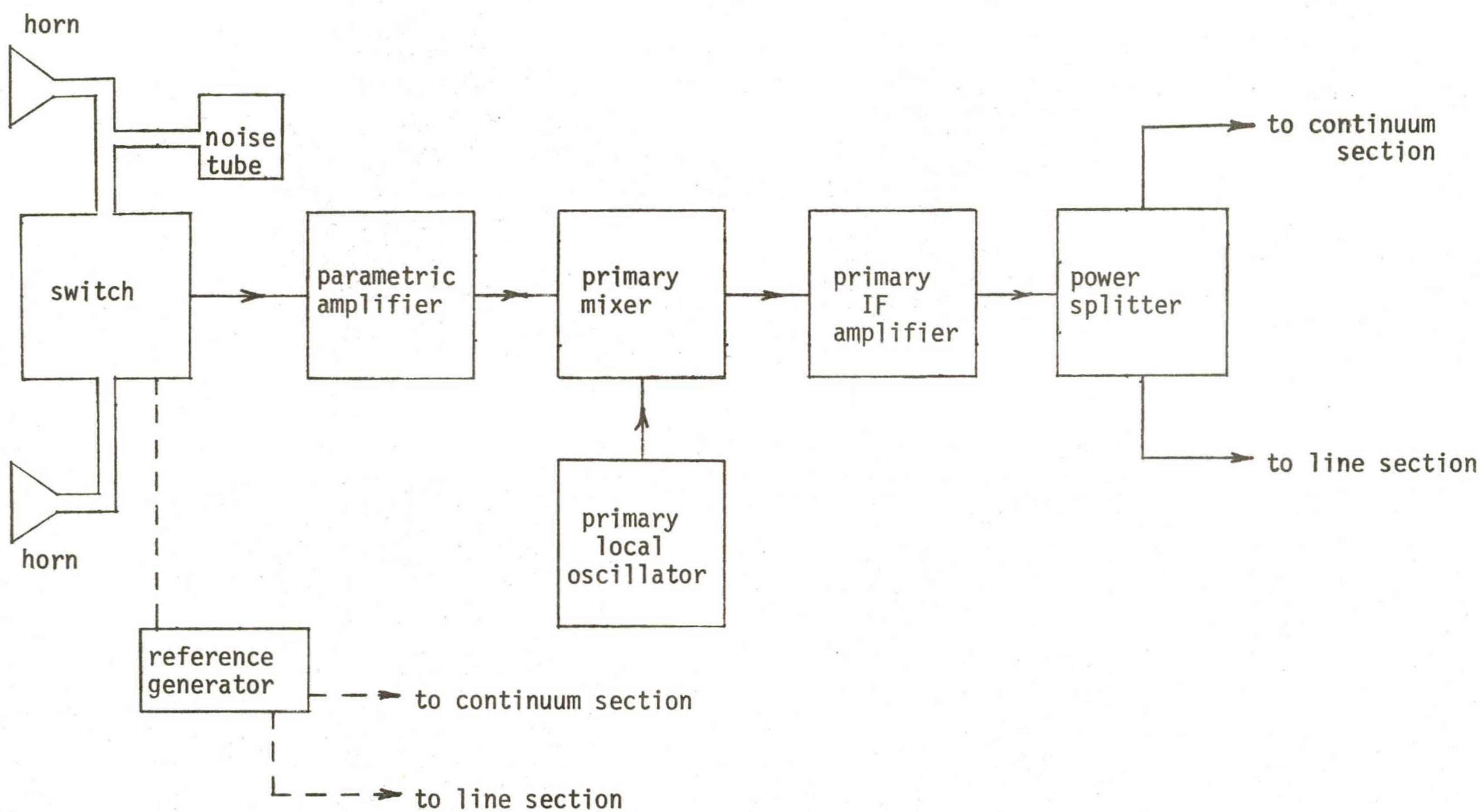
Figure 5

40' (minutes of arc) at 21 cm. The HPBW in right ascension is about 8' at 21 cm. The spacing between the main horn and the old horn responses is about 100'. The spacing between the main horn and the new horn responses is about 39'.

Since all of the feed horns cannot be placed on the axis, the beams are, in general, not exactly on the meridian. There is then a difference between the apparent position of a source and its true position. This is called a squint. The true position is equal to the apparent position minus the squint. The squint in declination is about 1^{o}. The squint in right ascension is about $\frac{-2.0^{m}}{\cos \delta}$ where δ is the declination of the source.

RECEIVER

The receiver used was basically the multichannel hydrogen line radiometer described in Reference 11. A block diagram of the front section of the receiver is shown in Figure 6. Dual beam switching was used as described previously. A noise tube with attenuators injects a 5 ^{o}K calibration signal into the waveguide ahead of the switch. The switch is a low loss device employing Varctor diodes and is described in Reference 12. The switching frequency is 80 KHz and is controlled by the reference generator described in Reference 11. The liquid nitrogen cooled parametric amplifier (Reference 13) was designed and built by the Bell Telephone Laboratories. It is tuned to 1420 MHz and has a half-power bandwidth of 8 MHz. The primary local oscillator is described in Reference 12 as the multichannel local oscillator. It is variable over the region 1385 to 1393 MHz. This is the oscillator that is scanned in order to enable the receiver to track the search frequency. The primary mixer is the Empire Device 107B broad-band, crystal mixer that is described in



Front section of the receiver.

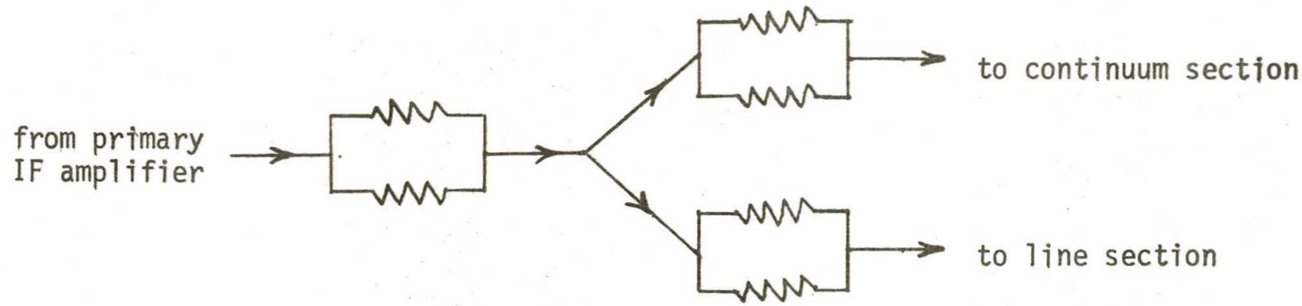
Figure 6

Reference 14. The primary IF (intermediate frequency) amplifier is described in Reference 15 as the LEL IF preamplifier. It has a bandwidth of 8 MHz at half-power points that is centered at 30 MHz.

The power splitter designed by R. S. Dixon consists of three 16 ohm resistances connected in a "Y" configuration (Figure 7, p.21). The power splitter had to be matched to the 50 ohm impedances presented by the coaxial lines that carry the power to and from the splitter. It was this matching condition that brought about resistances of 16 ohms. Each 16 ohm resistance is made by connecting two 33 ohm metal film resistors in parallel.

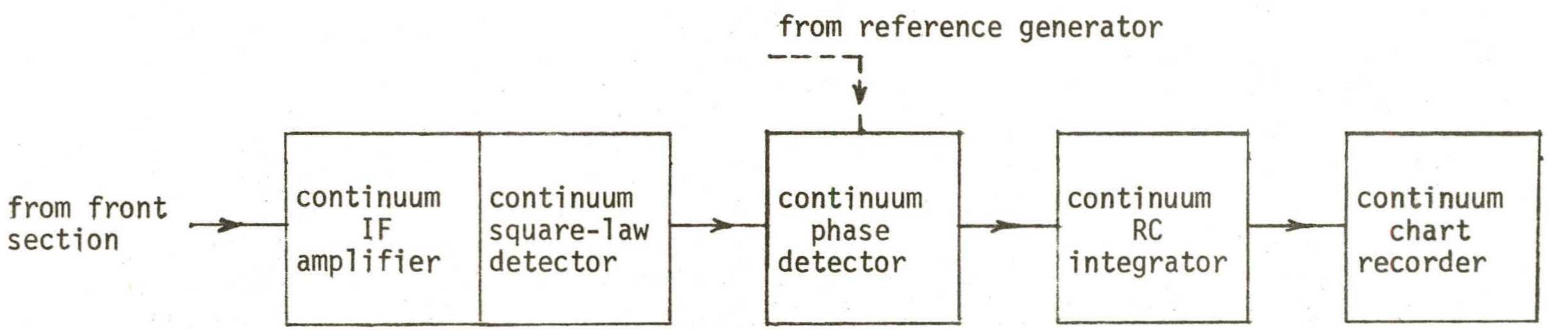
The continuum section of the receiver (Figure 8, p.21) is used to monitor the performance of the line receiver. The continuum IF amplifier and continuum square law detector are contained in one unit and are described in Reference 14. The IF amplifier (LEL - IF20B) also has half-power bandwidth of 8 MHz centered at 30 MHz. The continuum phase detector is also dexcribed in Reference 14 as the Sanborn phase sensitive demodulator. The continuum RC integrator and the continuum chart recorder (as the Honeywell strip chart recorder) are also described in Reference 14.

A block diagram of the hydrogen line section of the receiver is shown in Figure 9. The first line IF amplifier is described in Reference 11 as the 30 mc/s preamplifier. It too has a half-power bandwidth of 8 MHz centered at 30 MHz. The line local oscillator is described in Reference 11 as the switch-selected, crystal oscillator along with the line mixer. Together, they convert the 30 MHz spectrum down to the 19 to 21 MHz range. The line local oscillator is tuned to 49.9 MHz. The second line IF amplifier is described in Reference 11 as the 20 MHz postamplifier. It



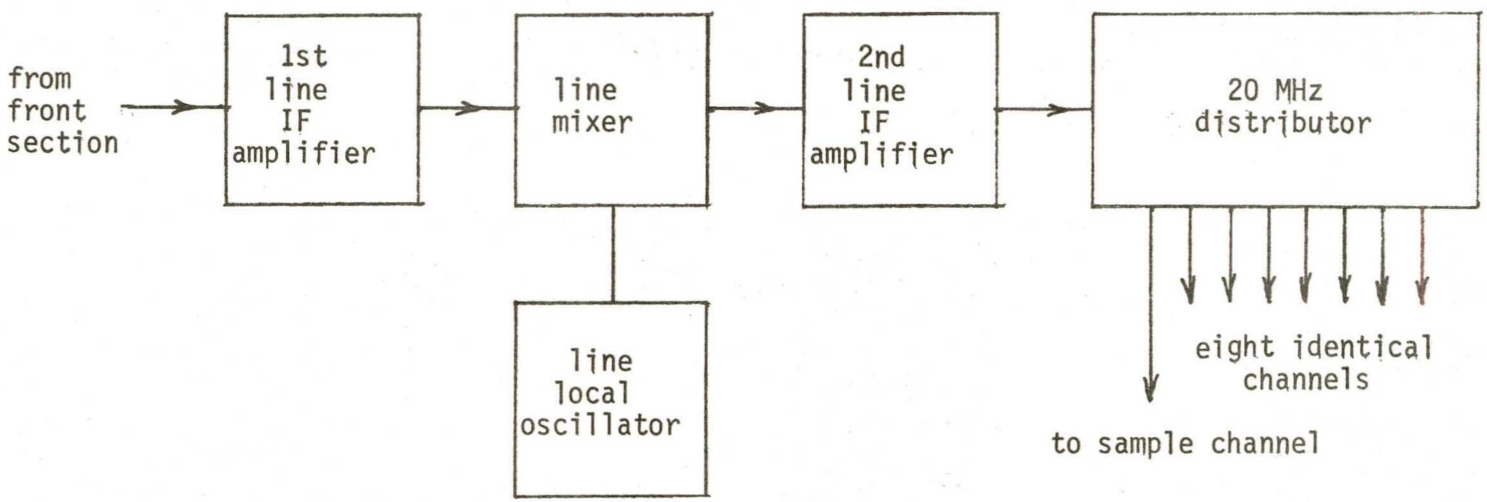
Power splitter. All resistors are 33Ω.

Figure 7



Continuum section of the receiver

Figure 8



Line section of the receiver.

Figure 9

has a 2 MHz bandwidth at the 1 db down points and is centered at 20 MHz. It is at least 30 db down at 30 MHz.

The 20 MHz distributor, also described in Reference 11, divides the spectrum into eight, narrow-band, video channels providing isolation between each. A block diagram of a sample channel is shown in Figure 10. All of the components are described in Reference 11, except for the DC amplifier. It was built by E. Teiga in the summer of 1975. A schematic diagram is shown in Figure 11. The DC amplifiers are housed in two boxes, one for each of the two 4-channel, chart recorders. Each narrow-band video channel is housed in its own box.

DOPPLER PROGRAM

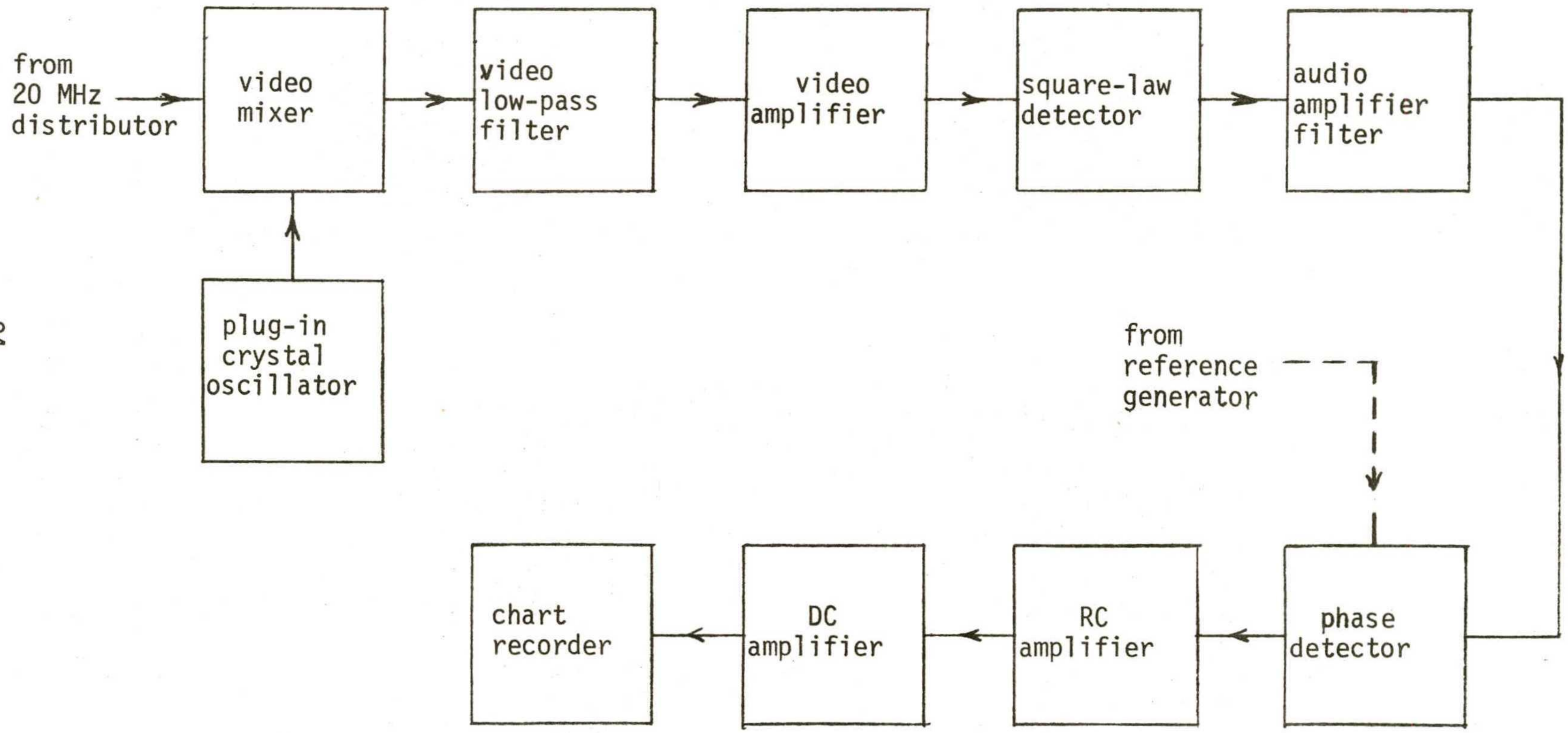
Our search strategy calls for the receiver to be tuned to the rest frequency of neutral hydrogen doppler corrected to the galactic standard of rest (GSR). To achieve this, we need to know the component of our velocity with respect to the GSR in the direction that the radio telescope is pointing at any given time. Knowing this velocity v allows us to calculate the amount of frequency shift that must be introduced in order to keep the receiver tuned to the desired frequency. This is obtained from the basic doppler relation for v<<c the velocity of light.

$$\pm\Delta f = \mp v\frac{f_h}{c}$$

where f_h = 1420.406 MHz is the rest frequency of neutral hydrogen. The desired search frequency is then

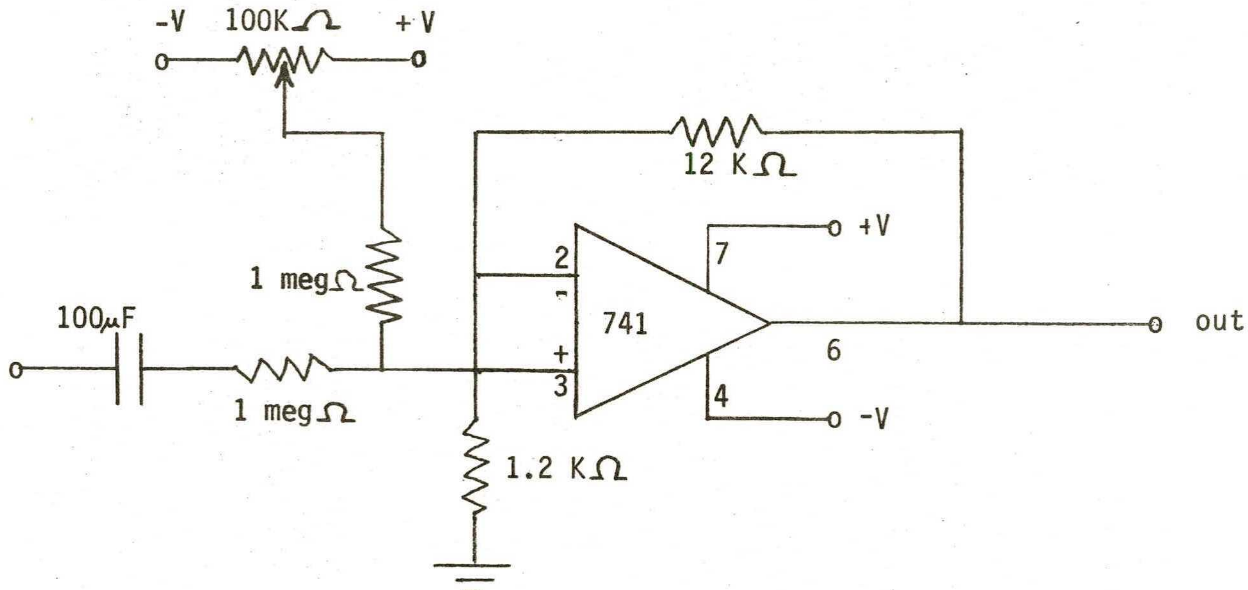
$$f = f_h\ (1 - \frac{v}{c}).$$

It is obvious that as the velocity changes the frequency will change. In general, the velocity component changes because of the Earth's rotation,



Sample channel.

Figure 10



DC Amplifier

Figure 11

the Earth's orbit about the Sun, the Sun's motion with respect to the local standard of rest (LSR), and the motion of the LSR about the galaxy. Since the OSURO radio telescope is a meridian transit instrument, the diection that it is pointing is always perpendicular to the direction of the Earth's rotation. So the velocity component due to the Earth's rotation falls out. The fact that the telescope is a meridian transit instrument also means that the direction in which it points is constantly changing due to the Earth's rotation. For each different direction that the telescope points, the velocity component of our receiver with respect to the GSR in that direction is in general different.

A program run on the observatory's IBM 1130 computer is used to calculate our velocity component with respect to the GSR in any given direction at any given time. It also calculates f_1, the frequency that our primary local oscillator should be, in order to enable the receiver to be tuned to the search frequency f. The search frequency differs from the primary local oscillator frequency by a constant of 29.770 MHz.

$$f = f_1 + 29.770$$

The program contains some subroutines written by J. A. Ball of Lincoln Laboratory (Reference 15) and some written by R. S. Dixon of OSURO.

When I first arrived at the observatory in October of 1974, the program had not yet been checked for errors. It was among the first of my duties to make this check. I first checked the part of the program that was to calculate the velocity of our receiver with respect to the LSR. A comparison of our program's output with an output from an NRAO program that employed some of the same subroutines showed some discrepancy. I then made some rough manual checks on several of our outputs and again found discripancies. A close examination of our program revealed that a few errors had been made in the keypunching. When these were corrected our program agreed much better with the rough manual calculations. Later, repeated observation of a couple of hydrogen regions that I used as standards indicated that the program was sufficiently accurate for my degree of precision. These corrections to the program were made by January 10, 1975 and all observations before then may be off some in frequency. An examination of the equations used in the program to calculate the velocity of the LSR with respect to the GSR showed that they were at least mathematically correct.

CHAPTER VI

THE ANALYSIS OF THE SEARCH DATA FOR BEACON CANDIDATES

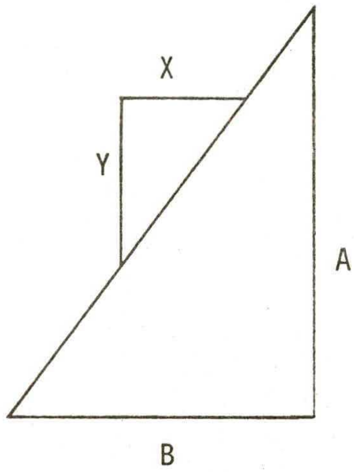
The first step in trying to pick beacon candidates from the data is, of course, to choose a criterion for selection. For us this criterion tended to float somewhat. At first when I did the analysis, I looked only for narrow-band sources (i.e., sources with a half-power bandwidth of less than 20 KHz). If a narrow-band source showed some extension to our beam, I still considered it a candidate. Later R. S. Dixon explained that we should use only point sources of narrow bandwidth as candidates for the following reason. If a source is of large angular extent, then it must either be a natural source or a result of astroengineering activity. If it is natural then it is not a beacon. If it is a beacon built by astroengineering, such as an extraterrestrial civilization that is controlling the emission of a natural hydrogen cloud and using it as a beacon, then the only way that it could be ascertained as such, is by some time variation. And we are not set up to study time variation. From that time onward, I used the criterion of a narrow-band, point source for selecting beacon candidates. Still later (Appendix), I realized that there was at least one way, other than time variation, to detect astroengineering acitivity. If a neutral hydrogen source is detected with a bandwidth of less than 1.75 KHz, then it is peculiar and possibly the result of astroengineering, even if it is extended.

A point source is relatively easy to pick out. A point source convolved with our antenna beam will be observed to have the shape of our beam. To determine whether a source is extended to our beam in declination, is more difficult than finding the extent in right ascension. Measurements must be made of the source intensity at several nearby declinations. This data must be plotted and compared to the declination beam shape. However, our declination beam width is so wide that most sources appear as point sources in declination.

The usual situation is one of determining whether or not a source is extended to our beam in right ascension. One way of determining whether a source is extended or not, is to make templates of known point sources that are near the declination of the source in question. Comparing the source with the templates should quickly reveal obvious extension. If the extension is not so obvious then one must consider the effect of vertical fluctuation noise on horizontal measurements.

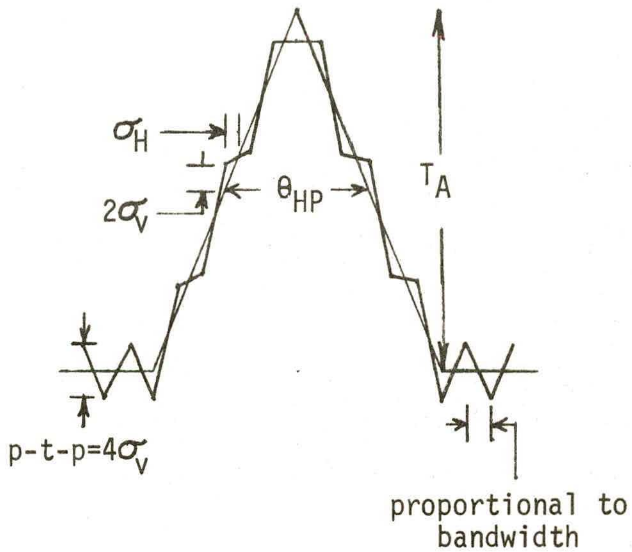
To determine in the more difficult cases whether a source is extended or not, I measured its extent at the half intensity point and compared that to the HPBW. However, the vertical fluctuation noise that leads to error in the intensity measurement also gives rise to error in horizontal measurements such as the angular extent. There is a very simple way of determining the magnitude of these errors. This is an adaptation of the idea described in Reference 16, where Carlson discusses noise in pulse position modulation. That idea is very simply that the base to height ratio of the two triangles shown in Figure 12 is the same.

A method of calculating this error is the following: Assume that the response due to the source is triangular. A triangle approximates our beam shape well enough for this purpose. The source is already assumed to be nearly a point source, so the response to it should approximate the beam shape. Let σ_V, the error in the vertical measurements be defined as 1/4 the peak to peak (p-t-p) noise.



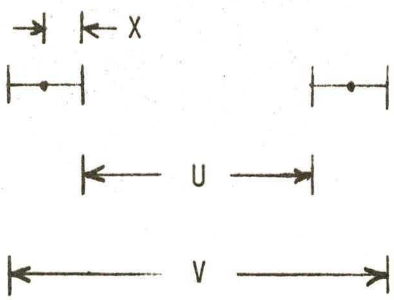
Two triangles having an equivalent base to height ratio.

Figure 12



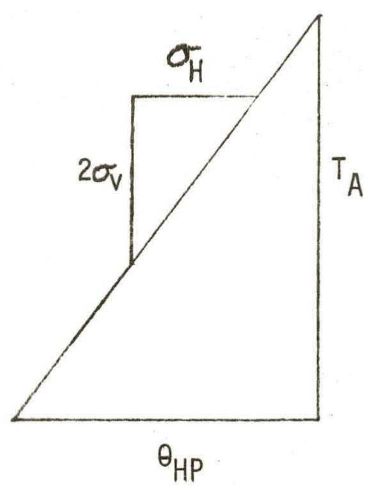
A triangular response corrupted by vertical fluctuation noise.

Figure 13



Error in measuring the distance between two points.

Figure 14



The two triangles again.

Figure 15

$$\sigma_V \equiv \frac{\text{p-t-p}}{4}$$

This p-t-p value should preferably be measured where the baseline is straight (i.e., source free) as shown in Figure 13, p. 30. Incidentally, σ_V is the same error that is associated with flux density and antenna temperature measurements. Let A be the intensity (height) of the source. Let B equal one-half the width of the base or the width at half intensity. These two measured widths should be close, since a triangular response is assumed. Let Y be defined as 1/2 the p-t-p or $2\sigma_V$ (Figure 13). Let X be the distance shown in Figures 12 and 13, p.30. Since a horizontal measurement is the distance between two points, the position of these two points is crucial. From Figure 13 and Figure 14 it can be seen that the measured distance can be anything from V to U. The difference V - U = 4X is then the peak to peak noise for the horizontal distance measurement. Let σ_H be defined as 1/4 of this p-t-p or σ_H = X. Since

$$\frac{X}{Y} = \frac{B}{A}$$

and from Figure 15, it can be seen that

$$\frac{\sigma_H}{2\sigma_V} = \frac{\theta_{HP}}{T_A}$$

where T_A = A the antenna temperature due to the source and θ_{HP} is the extent of the source at half intensity. Therefore, the error in measuring θ_{HP} is

$$\sigma_H = \frac{2\sigma_V \; \theta_{HP}}{T_A}$$

Ascertaining whether a source is narrow-band or not is relatively straight forward. In this thesis, I consider a source to be narrow band if it drops below the spectal resolution limits of our receiver (i.e., 20 KHz or less. If a source is observed simultaneously in 3 channels, then it is obviously greater than 20 KHz. If a source is observed simultaneously in 2 channels, then it could be either greater or less than 20 KHz. We know that a source is less than or equal to 20 KHz in bandwidth only when it is observed in one 20 KHz channel.

The output of the radio telescope is in analog form. Chart recorders display the output on rolls of chart paper. The multichannel hydrogen line receiver has two chart recorders, which display four channels each. There is a separate chart recorder for the continuum receiver. There are about 24 feet of paper outputed from each line recorder every day. This results in about 190 feet of data to analyze each day, including weekends. Since the data is analyzed manually and not by machine, the time that the analysis takes is directly proportional to how careful one decides to be. As a result there is a tendency to either fall behind, or to examine the data in what may be too hasty a manner.

Observations are made every 20' in declination. At least two days are spent at each declination setting. These two-day outputs are not averaged together, but are used to hedge against missing a section of the sky, due to poor records that occur from time to time. The beam is moved from the northerly declinations toward the southerly ones. This is because when moving down in declination the top edge of the flat reflector moves toward the parabolic section. This does not require the use of the brakes, which have a tendency to jam, especially in cold weather.

Since the search began in December, 1973, data has been taken over the region $48^{o}30' \geq \delta \geq 06^{o}50'$. The data covering $48^{o}30' \geq \delta \geq 20^{o}50'$ has been analyzed by R. S. Dixon. Using the early criterion for beacon candidates, I went through the notes that Dixon kept from the data that he had inspected. I found roughly 15 possible narrow-band sources for a yield of about 0.5 possible candidates per degree of declination. There were also many peculiar responses that were probably due to the terrestrial interference problems that were experienced before dual beam switching was implemented in March of 1974.

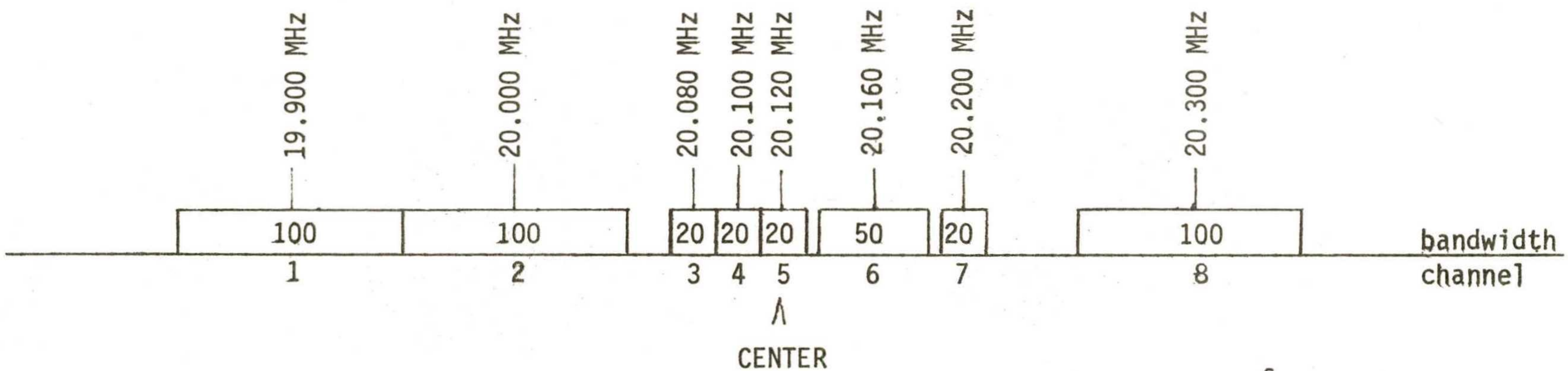
Since these sources could not be ruled out as beacons, I decided to try and reobserve them in order to ascertain whether or not they met the criterion that I was then using for beacon candidates (i.e., a half-power bandwidth of 20 KHz or less). In the early summer of 1975, I started the reobservation attempts beginning at $\delta = 48^{o}30'$. I tried to work my way through the sources going down in declination, but quickly became aware of a major problem. The frequency marker, that indicates the points where the primary local oscillator frequency scans across a 100 KHz interval, had not yet been installed. In order to reobserve a source, its velocity with respect to the local standard of rest is needed. Among the items needed in order to determine this velocity is the frequency that the receiver is tuned to at the time the source transits. (I will go into how this is done in detail later.) I could only estimate what this frequency should have been from the output of the computer program. The telescope operator later explained to me that this estimated frequency was probably very different from the actual frequency. Another difficulty was that at the time of these first search observations dual beam switching had not yet been installed. Terrestrial interference was apparently in wide evidence. Also, one pass per day made it difficult for me to distinguish weak sources from noise. Since the other day's observations at the same declination may have been at different frequencies, comparing two records in order to overcome this last difficulty was not feasible. During this same period we began to experience severe problems in the DC gain of the system. It was at this time that the DC amplifiers were built and installed in the line system. I failed to reobserve any of the sources during this first attempt.

I have analyzed data covering $20^{o}30' \geq \delta \geq 15^{o}30'$. I went through my notes from the region $20^{o}30' \geq \delta \geq 16^{o}30'$ and found approximately 24 possible narrow-band sources for yield of about 6 possible sources per degree of declination. Because dual beam switching and the 100 KHz frequency marker were in operation at the time this region was searched, I thought that I could get enough information from the search records to enable me to reobserve these sources if they were real. Also, I had analyzed the search records for this region myself and consequently, felt more confident about the results of the anlysis. I consider the study of this declination band of four degrees to constitute the core of my thesis.

CHAPTER VII

THE REOBSERVATION METHOD

In order for a source to be reobserved it is necessary to know its velocity component in our direction with respect to some reference frame. The reference frame that I used is the local standard of rest (LSR). This velocity component of the source V_s can be obtained from the search records in the following way. Our search strategy calls for the center frequency of our filter bank to be set at the rest frequency of neutral hydrogen (1420.406 MHz) doppler corrected to the galactic standard of rest. A beacon following this strategy will not necessarily fall at the center of our filter bank. This is because of the uncertainty of the galactic rotation velocity and of the error incurred in our attempt to track the theoretical search frequency. A linear interpolation between 100 KHz markers will give the frequency of the primary local oscillator f_1 at the right ascension of the observed source. The source will appear in only one or two channels it it is to qualify as narrow band. The peak of the velocity profile of a source is assumed to be at the center of the channel or channels in which it appears. The frequency of the plug-in crystal oscillator f_3 that is associated with each channel can be found from the so-called frequency plan. The interim frequency plan that was in use before January of 1974 is shown in Figure 16, p.36. The optimized frequency plan, implemented in January of 1974, is shown in Figure 17, p. 37. The optimized frequency plan was in use during the initial search of this region. So the appropriate f_3 can be obtained from Figure 17. If the source appears in two adjacent channels, then a frequency at the midpoint of the combined channels is used in place of f_3. The frequency f_2 of



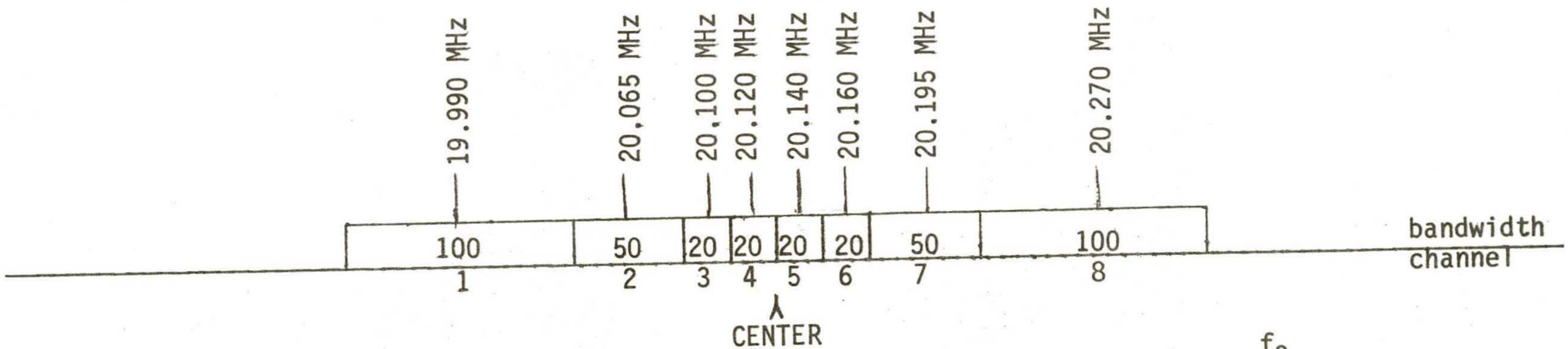
CHANNEL	BANDWIDTH	f_3 CENTER FREQUENCY
1	100 KHz	19.900 MHz
2	100 KHz	20.000 MHz
3	20 KHz	20.080 MHz
4	20 KHz	20.100 MHz
5	20 KHz	20.120 MHz
6	50 KHz	20.160 MHz
7	20 KHz	20.200 MHz
8	100 KHz	20.300 MHz

$$f_0 = f_1 + 49.900 - f_3$$

Implemented in November, 1973

INTERIM FREQUENCY PLAN

Figure 16



CHANNEL	BANDWIDTH	f_3 CENTER FREQUENCY
1	100 KHz	19.990 MHz
2	50 KHz	20.065 MHz
3	20 KHz	20.100 MHz
4	20 KHz	20.120 MHz
5	20 KHz	20.140 MHz
6	20 KHz	20.160 MHz
7	50 KHz	20.195 MHz
8	100 KHz	20.270 MHz

$$f_0 = f_1 + 49.900 - f_3$$

IMPLEMENTED IN JANUARY, 1974

O P T I M I Z E D F R E Q U E N C Y P L A N

Figure 17

the line local oscillator shown in Figure 9 is 49.900 MHz. It is used along with the appropriate f_3 and the measured f_1 to calculate the observed frequency f_0 in MHz.

$$f_0 = f_1 + 49.900 - f_3$$

From the basic doppler relation

$$f_0 = f_h \left(1 - \frac{V_R}{c}\right)$$

where f_h is the rest frequency of neutral hydrogen (I used $f_h = 1420.406$ MHz), c is the velocity of light ($c = 3 \times 10^5$ km/sec), and V_R is our velocity with respect to the source.

$$V_R = V_{LSR} - V_S$$

where V_S is the velocity component in our direction of the source (presumably a hydrogen cloud) with respect to the LSR and V_{LSR} is our velocity component in the direction of the source with respect to the LSR. V_{LSR} changes with time due primarily to the Earth's orbital motion and solar motion. V_S on the other hand should be constant if the source is a hydrogen cloud or a beacon that has been doppler corrected to be at rest with the intergalactic medium or GSR. The doppler program and a linear interpolation gives V_{LSR} at the date of observation. Solving for V_S gives

$$V_S = \frac{c}{f_h} \left(f_0 - f_h \left[1 - \frac{V_{LSR}}{c}\right]\right).$$

V_S is the source velocity component in our direction with respect to the LSR. For this thesis negative velocity corresponds to decreasing distance between source and observer.

Once V_S is known the source can be reobserved at a later time. For the date of reobservation V_{LSR} is computed in the direction of the source.

Then the observed frequency f_0 can be calculated from

$$f_0 = f_h \left(1 - \frac{(V_{LSR} - V_S)}{c}\right).$$

Next a choice must be made as to where to put the source in the filter bank. I usually chose channel 3 because it was one of the narrowest channels and it had the least noise. The corresponding f_3 of the desired channel is obtained from Figure 17. The primary local oscillator frequency in MHz is then found from

$$f_1 = f_0 - 49.900 + f_3.$$

The primary local oscillator is then tuned to this frequency. The primary local oscillator is not usually put into the scanning mode for the observation of a single source but is fixed at f_1. Then as the source transits the meridian it should appear in the desired channel.

If the source is detected, then its velocity can be measured more accurately. Its bandwidth can be examined to see if it is 20 KHz or less. The angular extent of the response due to the source can be measured to see if it is a point source. If it still looks promising, further information such as the antenna temperature and a more accurate position can be obtained.

CHAPTER VIII

A THOROUGH SEARCH OF THE REGION BETWEEN 20°30' AND 16°30' NORTH DECLINATION

I have chosen the region $20^{\circ}30' \geq \delta \geq 16^{\circ}30'$ for a more thorough study. My reasons for picking this particular declination band, as mentioned previously, are somewhat arbitrary in that the region has no special significance. This is congruent with Dixon's search strategy which assumes a relatively isotropic distribution of candidate stars at the 1000 light year range limit. What does have some significance is that now, following Dixon's search strategy to the fullest extent allowed by our current equipment, a small region of the sky has been thoroughly searched for extraterrestrial radio beacons.

In addition to considering sources predicted by Dixon's strategy, I also investigated responses that appeared to be due to narrow-band point sources that were being pulsed in amplitude at a low bit rate. These responses usually appeared to be due to only one of the two beams (i.e., an "up" response or a "down" response was present, but not both). These responses are most likely some type of statistical apparition.

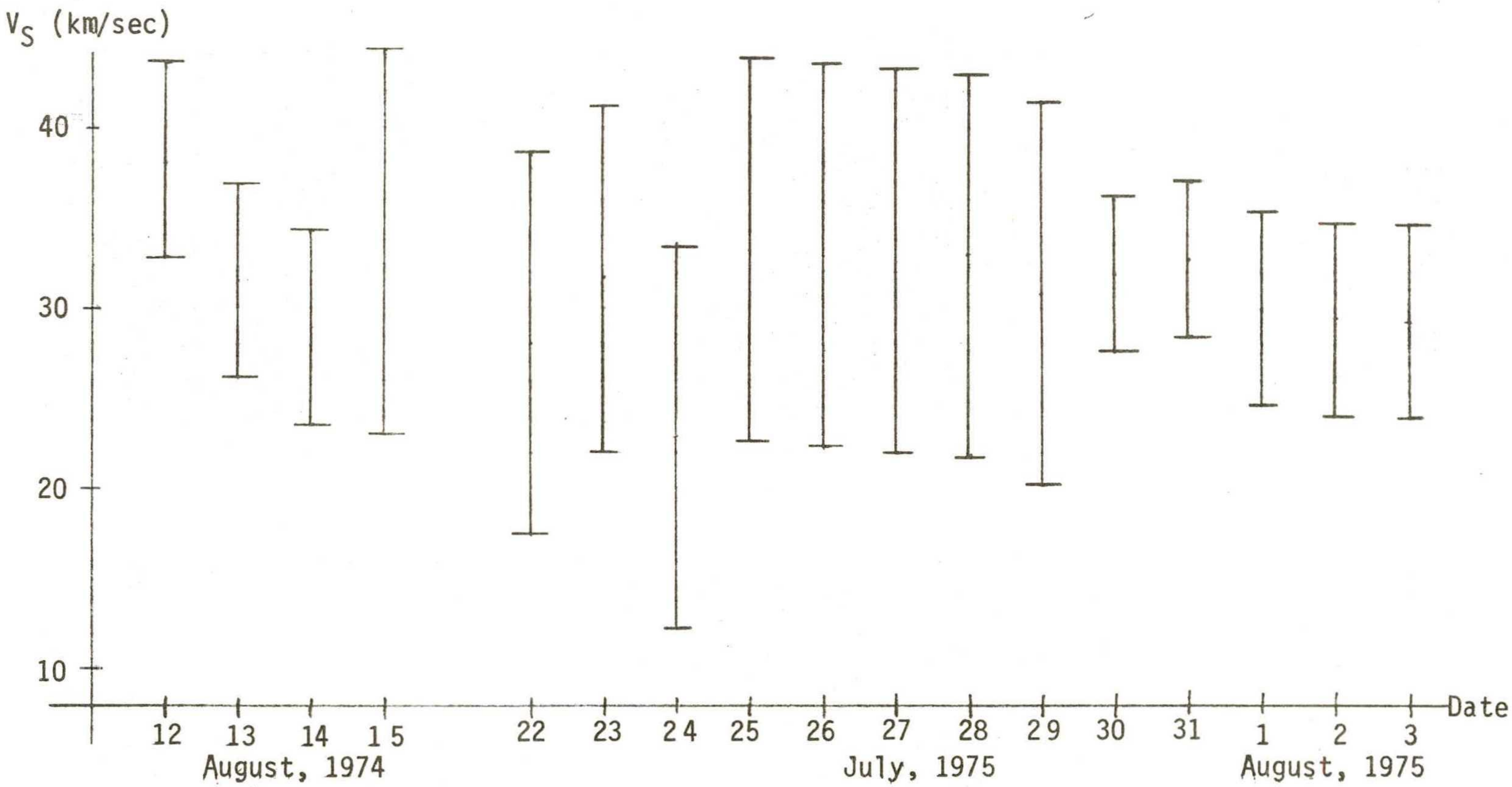
From the notes that I had taken during my analysis of the search records covering this region, I found several possible sources that may have had bandwidths of less than 20 KHz. Since I had no lower limit on the bandwidths of these objects, I could not exclude them from the class of objects for which I was searching (i.e., anomalously narrow-band radiation). I then attempted to reobserve these sources in order to determine whether or not they fit the criterion for beacon candidates.

Sources OM282L and ON242L were studied before the current criterion of selecting only point sources of narrow bandwidth was chosen. Their names are derived using the standard method of naming OSURO sources. The suffix L designates it as a line source. Since these sources are both extended to our beam, further study of them was discontinued after the adoption of the current criterion. However, I am including some mention of them because they serve as standards in that the successful reobservation and study of these sources tend to confirm the validity of my technique.

Sources OM282L and ON242L were both seen in the search records of August 12, 1974 at $\delta_A = +21^{o}30'$. They appeared in several of the records following August 12. They were reobserved beginning on July 22, 1975. A plot of the component of these objects' velocity V_S with respect to the LSR in our direction appears in Figures 18 and 19, p.42, 43. Since I do not know where inside of a channel the peak of the velocity profile occurs, I have plotted the entire velocity bandwidth of the channel. Approximations of their positions, angular extents θ_{HP}, antenna temperatures T_A, velocities V_S, and bandwidths BW appear below.

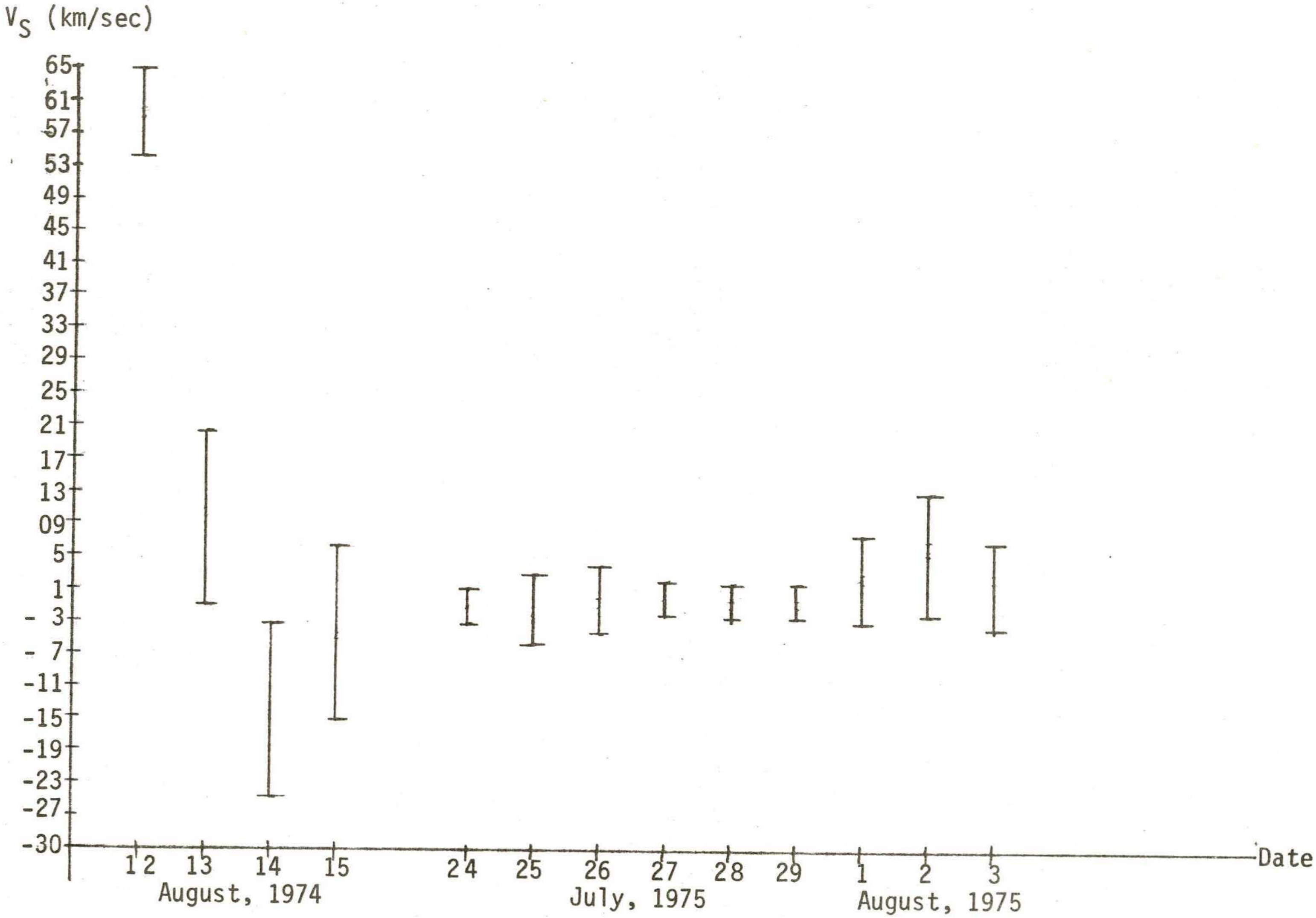
Source Name	α(1950)	δ(1950)	θ_{HP} (arc min.)	T_A (^{o}K)	V_S (km/sec)	BW (KHz)
OM282L	11^h49^m	$20^{o}39'$	39±07	3.6±0.3	32	40
ON242L	12^h25^m	$20^{o}39'$	49±15	4.5±0.7	0	15

The estimates of V_S and BW given above were made from the observations of 1975 because the system was in the study mode at that time (i.e., the primary local oscillator was fixed in frequency and not scanning), and as a result I have a little more confidence in the results. If the 1974 observations are included, the velocity V_S of OM282L is around 33 km/sec and its bandwidth BW appears to be less than 30 KHz.



The velocity component of OM282L in our direction with respect to the LSR.

Figure 18



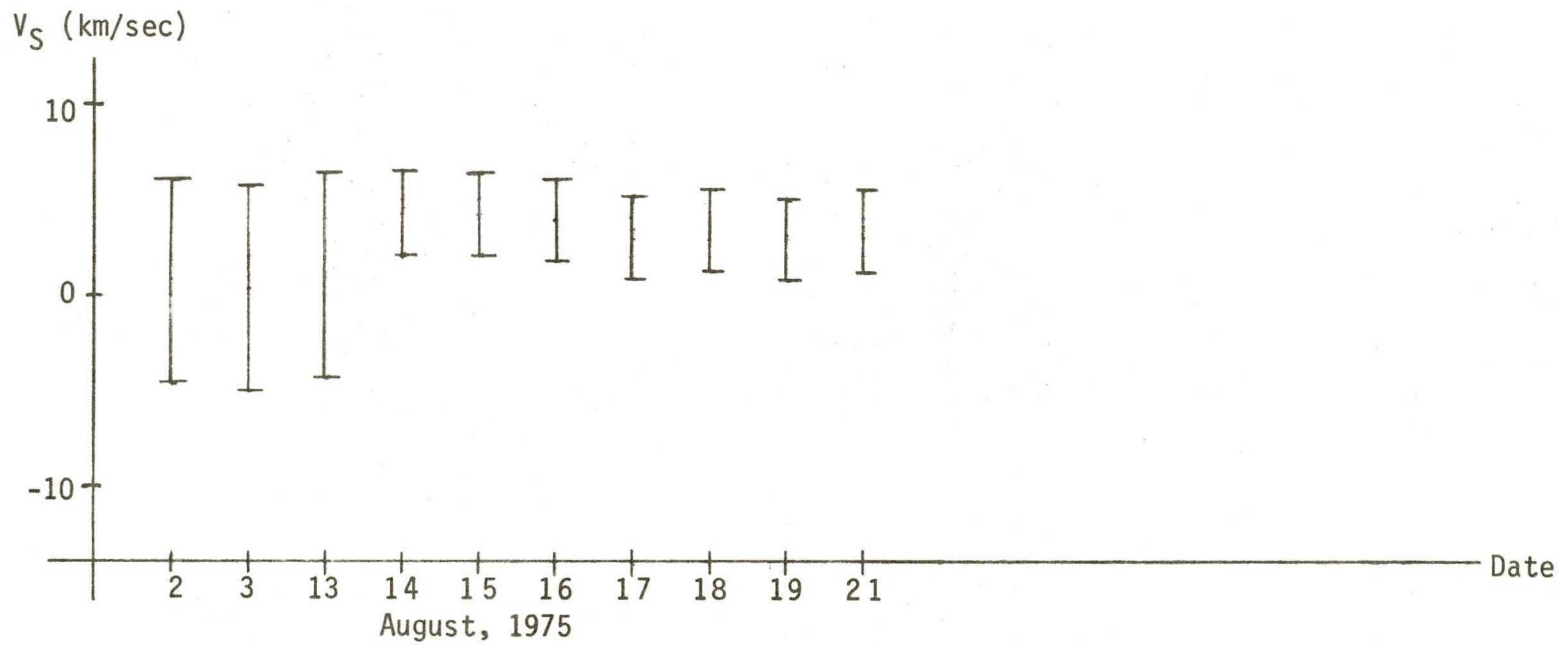
The velocity component of ON242L in our direction with respect to the LSR.

Figure 19

Similarly, the velocity of ON242L is around -1 km/sec and its bandwidth seems to be 12 KHz or less.

The anomlous data point for August 12, 1974 has been excluded from the velocity and bandwidth estimates, because it is completely disjoint from the others. It is difficult for me to discredit this data point for two reasons. The August 12 response was the first response seen for ON242L. The other data points were taken from a source at the same position that was observed on later days. Also any error in measuring f_1, from which V_S is calculated, should have been noticeable in calculating V_S for OM282L because the two sources appear on the same record only 36^m apart. Yet, V_S for OM282L for August 12 is not so unusual. I failed to detect a 60 km/sec velocity feature at the position of ON242L on any other day. The most plausible conclusion seems to be that the weak response seen on August 12 was noise and that seeing a real source at that position the next day was coincidental.

While studying OM282L and ON242L, I discovered OL275L at $\alpha(1950) = 10^h45.2^m$, $\delta(1950) = 20^o38'$. It seemed to be narrow band and a possible point source, so I decided to study it even though it was not found in conjunction wtih the search phase. A plot of the velocity V_S measured before the new horn's installation is seen in Figure 20, p.45. From the plot it appears that an upper limit on the source's bandwidth could be set as low as 12 KHz. OL275L was also included in the reobservation attempts that took place after the new horn's installation. Since the records of the observations made with the new horn are much better, I used that data to determine the source's extent. The source is extended



The velocity component of OL275L in our direction with respect to the LSR.

Figure 20

in right ascension ($\theta_{HP} > 8'$), as can be seen below. A plot of the

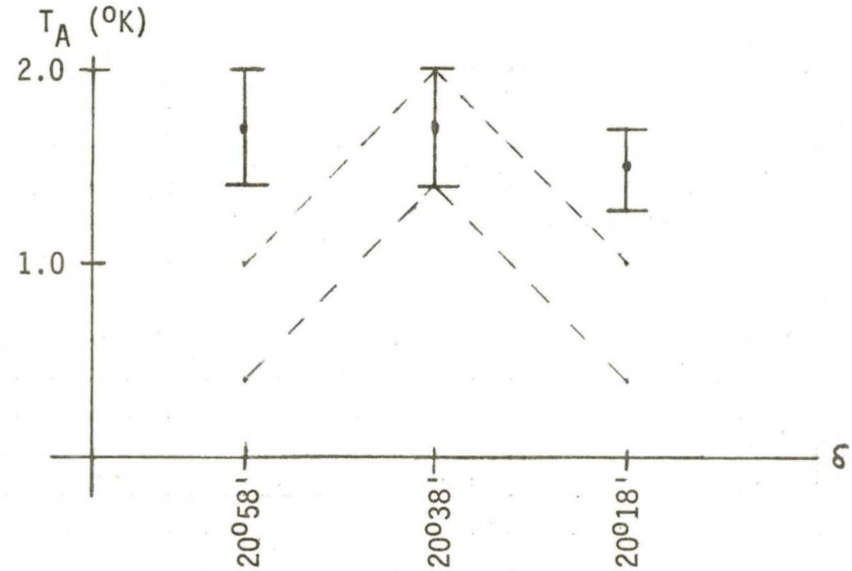
δ(1950)	T_A (^oK)	θ_{HP} (arc min.)
20 58'	1.7 ± 0.3	42 ± 17
20 38'	1.7 ± 0.3	18 ± 6
20 18'	1.5 ± 0.2	22 ± 6

antenna temperature T_A versus the declination is shown in Figure 21, p. 47 shows that the source is not down to half power soon enough to fit the declination half power beamwidth ϕ_{HP}. So the source is apparently extended in declination also (ϕ_{HP}>40'). It appears to be part of a more complex region rather than an isolated cloud. However, it does have a bandwidth of 20 KHz or less and a velocity V_S of about 3.7 km/sec.

When the current criterion for beacon candidates was adopted, I went back through the list of sources that I had selected for reoberva-tion and removed the extended ones. The remainder of the sources are listed in Figure 22, p. 48. Reobservation attempts of these 11 sources began on January 1, 1976.

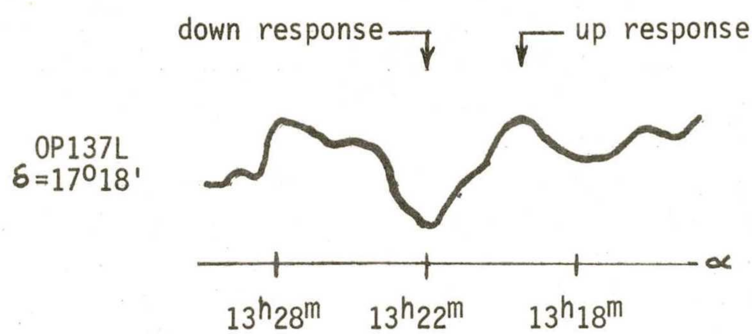
Source OE193L appeared in three channels and is in excess of 20 KHz. A manual average of two days observations at the position of OP137L revealed what appears to be an extended source (Figure 23, p.47). The source is too weak to get an estimate of its bandwidth, but its velocity peak seems to be around V_S = 0 km/sec. The extent in right ascension appears to be about 25' ± 12'.

None of the other 9 sources were reobserved. Of this 9, 4 appeared on the search records as weak sources seen in both horns. The remaining 5 responses appeared in one horn only. None of these 9 responses were seen twice.



A plot of the antenna temperature versus declination for OL275L. A triangular approximation to the declination beam shape is shown with a dashed line.

Figure 21



The result of manually averaging two days of observation.

Figure 23

SOURCE	α(1950)	δ(1950)	V_S (km/sec)	f_1 (MHz) measured primary local oscillator frequency	$\bar{f}_1$ (MHz) desired primary local oscillator frequency	$f_1-\bar{f}_1$ (KHz) difference	f_o (MHz) actual frequency observer	f (MHz) theoretical search frequency	f_o-f (KHz) difference
OE179L	$03^h47.1^m$	$17^o25'$	+ 7.8	1390.730	1390.819	- 89	1420.470	1420.589	-119
OE193L	03^h56^m	$19^o26'$	+ 12.0	1390.744	1390.853	-109	1420.524	1420.673	- 99
				1390.900	1390.851	+ 49	1420.530	1420.621	- 91
OI172L	07^h43^m	$18^o33'$	- 61.1	1390.400	1390.303	+ 97	1420.200	1420.073	+127
OI173L	07^h44^m	$17^o34'$	-140.2	1390.086	1390.288	-202	1419.826	1420.058	-232
OJ118L	$08^h10.5^m$	$17^o15'$	- 99.6	1390.112	1390.252	-140	1420.022	1420.022	0
OK114L	$09^h08.1^m$	$17^o56'$	-159.1	1389.908	1390.242	-334	1419.743	1420.012	-269
OK154L	$09^h32.5^m$	$17^o57'$	0164.3	1389.979	1390.248	-269	1419.719	1420.018	-299
OP136L	$13^h21.3^m$	$18^o18'$	- 13.4	1390.700	1390.623	+ 77	1420.405	1420.393	+ 12
OP137L	13^h22^m	$17^o18'$	+ 0.6	1390.743	1390.619	+124	1420.483	1420.389	+ 94
OR162L	15^h37^m	$17^o15'$	+ 92.2	1391.141	1391.015	+126	1420.881	1420.785	+ 96
OZ150L	23^h30^m	$18^o02'$	+203.3	1391.517	1391.513	+ 4	1421.352	1421.283	+ 69

The 11 responses found in the search records of $20^o30' \geq \delta \geq 16^o30'$ for which reobservation attempts were made.

Figure 22

Error bars of position, velocity and bandwidth are not set by a criterion such as 1/4 the peak-to-peak fluctuation. Positions in right ascension should easily be within $1/2^m$. The given positions in declination indicate where the center of the beam was pointing during the observation. If the sources are discrete, or nearly so, their position in declination should be within about 20' (1/2 the HPBW) of the given position. Velocites should be easily within 1/2 the bandwidth of the channel in which the source is observed (i.e., within 2 km/sec. for channel 3). Measurements of bandwidth upper limits are more uncertain but they should not be more than 10 KHz greater than the given upper limit.

CHAPTER IX

CONCLUSION

I have described the search for extraterrestrial radio beacons that has been in operation at OSURO since December of 1973. This search is based on the strategy developed by R. S. Dixon of OSURO. Data has been taken covering the region $48^{o}30' \geq \delta \geq 06^{o}50'$. A criterion of point sources with bandwidths less than 20 KHz was adopted for beacon candidates. This criterion goes beyond looking only for sources predicted by Dixon's strategy in that all responses that seem to be point sources of narrow bandwidth are investigated. This includes, for example, studying responses that could be due to a low bit rate signal that is being pulsed in amplitude rather than using polarization modulation. I arbitrarity chose a declination band of 4^{o} covering the region $20^{o}30' \geq \delta \geq 16^{o}30'$ for a thorough study. This amounts to 3.3% of the sky. My purpose was to establish a lower limit, if possible, to the dimensions of bandwidth and angular extent for any source within this region. From the search records, I selected all sources of unknown lower limits and attempted to reobserve them to enable me to establish such limits. Although some of the sources had bandwidths of 20 KHz or less, none of these were point sources to our beam. No beacon candidates were found in this region.

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APPENDIX

A MINIMUM OBSERVABLE WIDTH FOR THE 21-cm EMISSION LINE OF NEUTRAL HYDROGEN

During the search for extraterrestrial radio beacons that we are conducting at OSURO, it became immediately apparent that any information facilitating a quick separation of potential beacon signals and neutral hydrogen emission would be of interest. With respect to the signal bandwidth criterion that we are using for beacons, it was desirable to calculate a minimum line width for neutral hydrogen (HI) in emission. Knowing this, any signal falling below this minimum immediately comes under suspicion.

My approach is simply to eliminate all of the line broadening effects that I possibly can and to compare what is left with the narrowest possible natural line width. In calculating this natural line width, induced emission caused by the 3 $^{\circ}$K background must be considered along with the spontaneous emission. The emission rate Γ is then

$$\Gamma = Ann' + Bnn' \, I_f$$

where Ann' is the Einstein coefficient ($2.87 \times 10^{-15} sec^{-1}$), and the Bnn' is the Einstein coefficient for induced emission (n is the upper state and n' is the lower state). I_f is given by Planck's law for which the Rayleigh-Jeans approximation may be substituted.

$$I_f = \frac{2f^2kT}{c^2}$$

where c = 2.99773×10^{10} cm sec^{-1} (speed of light)

f = 1.420405×10^{9} sec^{-1} (frequency of the emission)

T = 3 $^{\circ}$K (background radiation)

$$k = 1.38044 \times 10^{-16} \text{ erg } {}^oK^{-1} \text{ (Boltzmann's constant).}$$

Bnn' can be found from the relation

$$Bnn' = \frac{c^2}{2hf^3} Ann'$$

where $h = 6.6252 \times 10^{-27}$ erg sec. (Planck's constant).

The emission rate is then given by

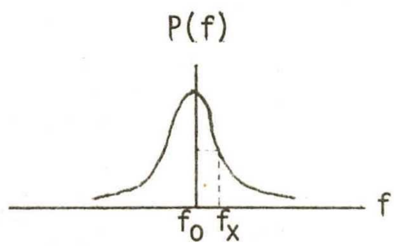
$$\Gamma = Ann' \left(1 + \frac{kT}{hf}\right)$$

$$\Gamma = 1.29 \times 10^{-13} \text{ sec}^{-1}$$

The shape of this unsaturated natural line is Lorentzian. The shape P(f) can be expressed as

$$P(f) = \frac{Q}{4\pi^2 (f - f_0)^2 + (\frac{\Gamma}{2})^2}$$

where Q is a constant and f_0 is the center frequency of the emission line. $P(f_x) = 1/2\ P(f_0)$ as shown in Figure A. Let



Lorentzian profile

Figure A

the line width at half intensity points be $B = 2\ (f_x - f_0)$.
This gives a natural line width of $B = \frac{\Gamma}{2\pi} = 2.03 \times 10^{-13}$ Hz. This is considerably larger than the line width due to spontaneous emission only which is $B = \frac{Ann'}{2\pi} = 4.57 \times 10^{-16}$ Hz. I would like to emphasize

that this background radiation which gives rise to the induced emission component in the natural line width is inescapable.

Likewise, among the broadening mechanisms, collisional broadening, the Stark effect, Doppler broadening due to turbulence, expansion, contraction, and rotation, and other mechanisms can conceivably be avoided. But, Doppler broadening produced by the thermal motion of the emitting atoms that make up the HI source cannot be avoided if the emission is thermal (and not due to a maser-type mechanism), again, due to the 3 ^{o}K background. These emitting atoms have a Maxwellian velocity distribution which is proportional to exp $\left(\frac{-v^2 m}{2kT_k}\right)$ where m is the mass of the atom, v its radial velocity, and T_k its kinetic temperature. The unsaturated line produced by this "cloud" of HI is Gaussian, exp $(-v^2/2\sigma^2)$, where σ is the standard deviation or dispersion. This gives

$$\sigma = \sqrt{\frac{k\,T_k}{m}}$$

Letting the line be at half intensity when $v = v_x$ we note that

$$1/2 = \exp\ -\frac{(v_x - v_o)^2}{2\sigma^2}$$

This gives

$$(v_x - v_o) = \sqrt{2\ \ln 2}\ \sigma$$

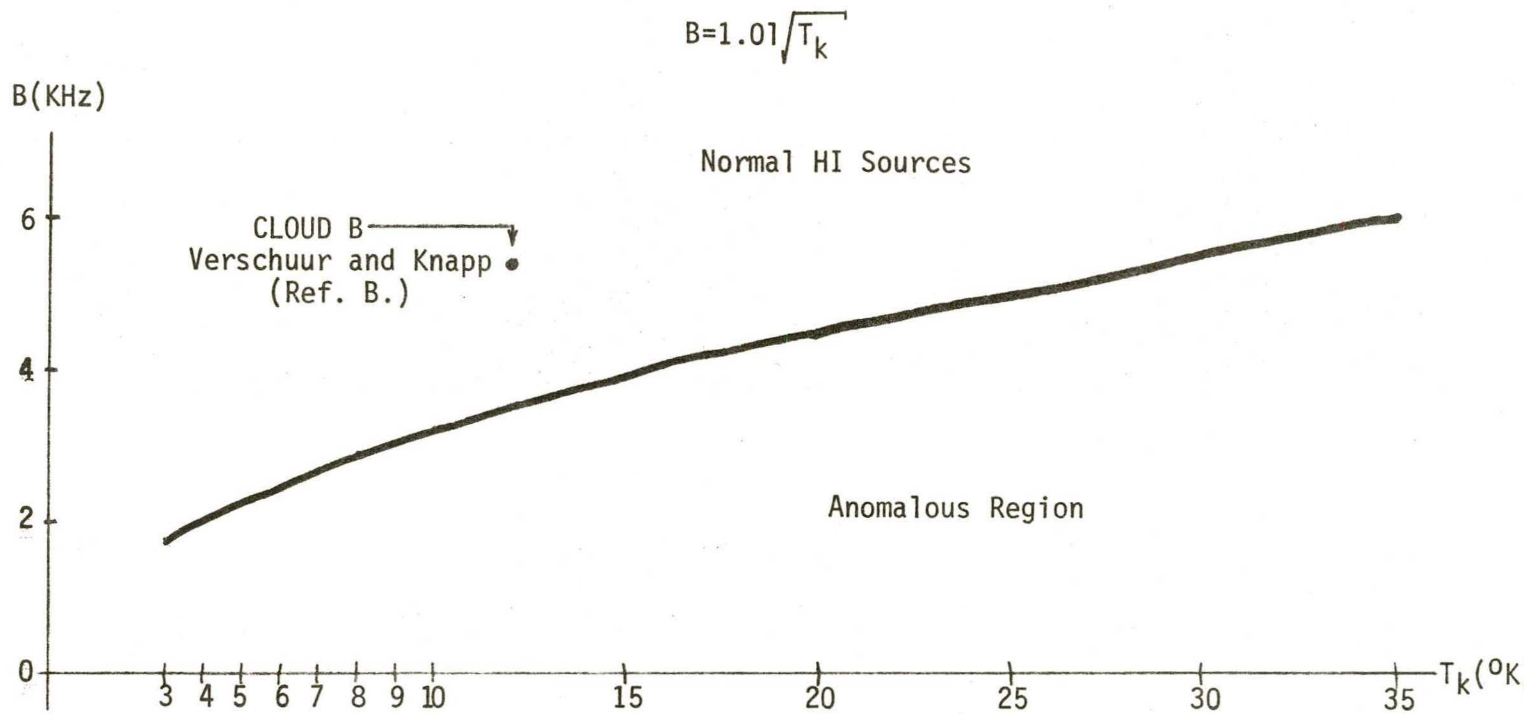
Again letting the line width at half intensity be $B = 2(v_x - v_o)$ we get

$$B = 2\sqrt{2\ \ln 2}\ \sigma$$

$$B = 2.35\ \sigma$$

$$B = 2.35\sqrt{\frac{k\,T_k}{m}}$$

Substituting in for the mass of the hydrogen atom ($m = 1.6733 \times 10^{-24}$g)



A plot of the lower limit of HI line widths.

Figure B

gives

$$B = 2.13 \times 10^4 \sqrt{T_k} \text{ cm/sec}$$

Converting this to frequency (5 KHz = 1.056 km/sec at the hydrogen line) gives

$$B = 1.01 \sqrt{T_k} \text{ KHz}$$

The minimum half intensity line width is when $T_k = 3\ ^{o}K$. The natural line width (even considering induced emission) is still so much smaller than the profile due to doppler broadening that the convolution of the Lorentzian and Gaussian profiles results in an emission line width at half intensity of $B = 1.01 \sqrt{T_k}$ KHz. Thus the minimum observable width for the 21-cm emission line of neutral hydrogen is B = 1.75 KHz.

Figure B is a graph of this lower limit for HI line widths. Any source falling below this line is then an anomaly. The source with the narrowest line width is currently Verschuur and Knapp's "Cloud B" (Reference B) which is marked on the graph.

I began this as a result of a conversation between R. S. Dixon and G. L. Verschuur. I am especially grateful to G. H. Newsom for his very helpful explanation.

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