USING A PATTERN MATCH TECHNIQUE AND MOVABLE FEED TO DETECT NARROW-BAND CELESTIAL RADIO SOURCES AT THE OHIO STATE UNIVERSITY RADIO OBSERVATORY

A Thesis

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by

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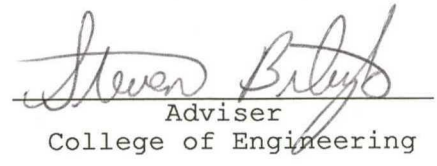

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CHAPTER I

INTRODUCTION

The Ohio State University Radio Observatory (OSURO) is well known to have the longest running dedicated microwave observing SETI (Search for Extraterrestrial Intelligence) program in the world. Pioneered by Robert S. Dixon in 1973, and continuing under his supervision to this day, the Ohio SETI program has witnessed several unusual SETI-type phenomena [1]. In recent years, the OSURO has been upgraded to observe the entire "water hole" (1.4 - 1.7 GHz) and to perform real-time data analysis to allow immediate followup on SETI-type strikes. This thesis is a description of the system which I implemented at the OSURO to do just that. It is intended that this thesis be a manual for future operators, maintainers, and upgraders of the system.

The system which I implemented at the OSURO, called LOBES (Low Budget ETI Search), is an attempt to follow the "SETI Zoom Techniques" laid down by Dixon and Van Horne in [18]. They suggest that the immediate followup of possible ETI signal strikes is advantageous over delayed followup because of the sporadic nature of ETI signals. If the detection rate is low, taking time out to more closely examine a particular phenomenon means that another interesting phenomenon will probably not be missed.

Certain aspects of the LOBES strategy differ from Dixon and Van Horne's "SETI Zoom Techniques". An RFI database was not used

in this project; an attempt was made to reject RFI using a switched feed horn system and a pattern match algorithm. The rate at which the LOBES system scans the water hole is different from the 10 seconds suggested by Dixon and Van Horne. The sampling rate slows in LOBES as the declination of the OSURO gets farther from the celestial equator. This allows the receiver integration time to increase without distorting the received signals.

A search similar to LOBES was conducted by Cole and Dixon in 1974 at the OSURO [8]. Eight narrow-band channels centered on the hydrogen emission line were analyzed for point source narrow-band radiators. A switched feed receiver was used, much in the same configuration as the current system. The 8 strip chart traces were analyzed visually for the switched antenna pattern. In 1975, a fifty channel receiver was used to scan the hydrogen emission line [27]. An IBM computer was used to analyze the data in real time, flagging interesting signals. Several search algorithms simultaneously checked for pulsed or continuous wave signals which conformed to the OSURO's antenna pattern. No immediate followup was possible with these searches, since the OSURO was not steerable in right ascension (RA). In the LOBES system, a computer looks at the data for an antenna pattern much as a human would, and moves the feed horns to continuously re-detect a signal once it is found.

In the following chapters, a summary of microwave SETI strategies and data analysis techniques is given. A description of the OSURO receiving equipment and computer system used is then presented, followed by the theory of the LOBES techniques. The procedures used and results found are then discussed. Finally, a

list of recommendations for future work is suggested.

My intent was not to do a sky survey; it was to make this phase of the Ohio SETI program operational. For that reason, a liquid cooled receiver front end was not used for this project and the antenna declination was not systematically changed.

Even with the Low Noise Amplifiers (LNAs) at ambient temperature, the system managed to detect broadband celestial radio sources and terrestrial satellites.

CHAPTER II

SETI SIGNAL SEARCH STRATEGIES

SETI has been a pursuit of dozens of research teams for the past 30 years. Extensive concentration has been centered on detecting signals in the microwave region. In particular, the 1-10 GHz microwave band is widely agreed to be a likely place to find ultra-narrowband beacons or pulses [2,3,4]. Thanks to modern computer technology, receiving equipment can now be made to receive millions of channels, each a fraction of a Hertz in bandwidth. However, there is a tradeoff in data processing: the more channels there are to analyze, the longer it takes to follow up on possible strikes. With SETI, it is important to reobserve interesting phenomena as quickly as possible.

There are, of course, other SETI strategies which do not involve microwave techniques. Astronomers have looked in the infrared band for hotter than normal, non-visible light emitting objects, which could be the byproduct of large astroengineering projects [5,6]. Also notable is the search for optical-frequency beacons. These search techniques will not be discussed here.

2.1 Data Gathering Techniques

A large number of factors figure into gathering data for analysis of SETI signals. Antenna aperture, receiver sensitivity, and

observing time are three major ones. Large telescopes dedicated to SETI with state of the art receiving equipment are rare.

Once observing times have been obtained, two types of data gathering techniques have been widely used: the all sky survey and the targeted search [4,7]. For those simply looking for microwave beacons anywhere in the sky, a sky survey is preferred. Others know where they want to search, such as neighboring stars, nearby galaxies, or particular star types. The targeted search is used by these researchers. Knowing from where the signal is expected allows a researcher to increase the sensitivity and bandwidth of the search. Since most radio telescopes can track a point in space for many hours, the object of interest can be analyzed for a long time. After a certain amount of time, or if no signal is detected, the telescope may be pointed to another candidate.

Although targeted searches look at the most likely candidates for ETI signals, they still cover a very small percentage of the sky. ETI signals could conceivably be coming from any part of the sky. Dixon [7] has stated that at a range of 1000 light years, there are at least 4 G-type stars in the OSURO beam, when it is pointed to any part of the sky. There also might be supercivilizations which have constructed beacons which outshine closer, weaker beacons. For these reasons, sky surveys are presently a less sensitive, but necessary facet of SETI.

Thanks to advances in microchip design and manufacture, many modern microwave receivers have been designed with the ability to receive millions of channels a fraction of a Hertz in bandwidth. Modern computer technology has greatly increased computing speed, allowing Fourier analysis techniques and interferometry to join

heterodyning as ways to gather narrow-band microwave data.

2.1.1 Heterodyned Input

When the Ohio SETI program went on the air in 1973, 8 heterodyning receivers were used to search for SETI beacons [8]. Later, fifty 10 kHz bandwidth heterodyning receivers were employed. These searches looked for beacons close to the hydrogen emission line (1420 MHz). The receivers were swept in a way that would remove any doppler shift caused by the earth's motion relative to the galactic center of rest.

A problem with square-law receivers is that the phase of the signal is destroyed when the signal passes through the square-law detector. If the signal is transmitted using phase modulation, all of the signal information, except the carrier frequency, is lost [7].

2.1.2 Fourier Decomposition

Modern high speed computer architectures have made possible the simultaneous reception of millions of narrow-band channels. Since Fourier methods use the sampled waveform, phase information remains intact. This allows the detection of more types of signals than square-law techniques.

Current Fourier analysis systems include NASA's MCSA, UC Berkeley's SERENDIP, and Harvard's META. Most of these have the capability of resolving channels down to one Hertz or less.

The MCSA (Multichannel Spectrum Analyzer) developed by NASA resolves an 8-256 MHz band into 1024, 32, or 1 Hz bandwidth

channels [9]. Each of the two MCSAs receive a right circular and left circular polarized version of the input to the antenna. Computer programs are written to identify CW beacons and pulses. Unlike other projects, however, the NASA MCSAs do not receive a swept IF to remove doppler shifts. Instead, computer algorithms shift consecutive spectra relative to each other to discover linearly changing frequencies [10].

The SERENDIP (Search for Extraterrestrial Radio Emission from Nearby Developed Intelligent Populations) II SETI project is a system designed to look for ETI signals on the same telescope where non-SETI work is being conducted [11,12,13]. This unusual technique provides the advantage of a random search pattern, since ETI signals can come from anywhere in the celestial sphere. A disadvantage, however, is that following up on an ETI signal strike is difficult, since moving the antenna would probably interfere with the non SETI researcher's work. The SERENDIP II system has a total bandwidth of 1.2 MHz, with a channel width of 1 Hz. Since the observed frequency band is determined by a non-SETI researcher, the "magic frequencies" in the water hole are not always observable. This random frequency selection, like the random antenna beam direction, adds the advantage of uncertainty in detecting the unknown signal; since the frequency of the ETI signal is unknown, it is conceivable that the signal could be at any frequency.

The META system is an expansion of Project Sentinel, spearheaded by Paul Horowitz at Harvard University [14,15]. The META and Sentinel systems resolve bandwidths down to a fraction of a Hertz. A swept local oscillator compensates for a variety of selected centers of rest. Both targeted and sky survey searches

have been conducted using these ultranarrowband approaches. Sentinel's total bandwidth is too narrow to observe signals with an acceptable doppler shift. Sixty thousand 0.015 Hz bandwidth channels are all that Sentinel can observe, resulting in one kHz total bandwidth, so the frequency sweeping has to be precise. META covers 400 kHz with 0.05 Hz bandwidth channels. Thanks to the swept local oscillator and the narrow bandwidths of the channels, nearly all terrestrial interference has been rejected by these systems.

2.1.3 Interferometry

Modern computing powers have made it possible to combine the outputs of several radio telescopes to increase collecting area and spatial resolution. One such system is the VLA (Very Large Array). The VLA uses 27 telescopes, each 25 meters in diameter, as an interferometer.

The VLA has been conducting celestial radio observations since 1980. The array geometry allows very precise location finding capabilities and increased aperture. The increased aperture comes from the many antennas used. The increased resolution comes from interferometric analysis of the data. The resolution possible with such an array is much better than any single antenna receiving alone [16]. Normal high resolution observations of the VLA, however, are not as effective for SETI signal searching. This is because the VLA must observe the same point in the sky for hours to gather data, and then rejects, or filters out, any anomalous data. This data would be that corresponding to ultranarrowband radio signals.

Dr. Jill Tarter has proposed a parasitic SETI observing program called PIPELINE, which would operate at the VLA as radio astronomers conduct the sky-mapping program currently in operation [17]. This SETI system would use the output of the astronomers' spectrometers - not its own dedicated spectrometer as in the SERENDIP II system. It is unlikely that the bandwidths astronomers use will be less than a few kHz, therefore the sensitivity of this search would be low compared to a dedicated facility.

An innovative synthetic aperture system is under development at the Ohio State University. The Argus project, or "radio camera", would use an array of helical antennas which would be capable of determining the direction and frequency of all point source celestial objects simultaneously. The Argus project conceived at OSU would be the most complete sky survey of all time. Data from hundreds of stationary helices set up in a 2-dimensional array would be sampled and analyzed. Since the entire sky visible from the Argus latitude can be analyzed all at once, it is possible that an ETI signal - and other interesting astronomical phenomenon - may be found immediately after Argus begins operation [18]. A prototype radio camera was built and successfully operated at the Ohio State University [19]. It detected radio signals emanating from the horizon, and could gather data for all 360 degrees simultaneously. There are limitations in this approach, a major one is that each helix requires a receiver. The amount of data to be processed by Argus would be enormous, so central, high-speed processing of data probably would be used.

2.2 Data Analysis Techniques

A major bottleneck in most SETI systems is the data analysis process. In most cases it is important to quickly weed out RFI (Radio Frequency Interference) and to determine whether a "strike" has occurred. A most desirable condition is the on-line processing of data. Since ETI signals can be presumed to be transitory in nature, the detected signal may not be present soon after detection. On-line processing of data considerably shortens the delay in followup. However, when millions of channels are to be analyzed, the computing needs of the data analysis can become astronomical.

The following sections are a brief review of some SETI data analysis techniques used in past and present systems.

2.2.1 Strip Chart Record

Before computers were easy to use in data analysis, strip chart recorders plotted the output of receivers. Cole [8] visually looked for a reproduction of the OSURO antenna pattern in strip chart records taken of 8 narrow-band channels centered on the hydrogen emission line. Since he was conducting a sky survey using the switched feed horns of the OSURO, a constantly radiating narrow-band celestial point source would create the unique switched antenna pattern in one channel as it drifted through the switched beams. This data analysis technique is cumbersome because of the time needed to decipher the record kept on hundreds of yards of paper. The technique becomes increasingly difficult as more channels are analyzed. Cole's processing was not done on-line.

Several hours were needed to analyze the day's record. Some time delay could be tolerated, however, because at that time (1973) the OSURO was only a meridian transit instrument. Immediate followup would mean only as soon as the next day.

2.2.2 Frequency Sweeping

Much discussion has revolved around how or if ETI's would adjust their beacons in order to make their frequencies appear constant to the receiving civilization. The conclusions drawn are that we also must adjust our receiving frequency, since ETI's do not know the particulars of the receiver's velocity or location. Any velocity difference between the transmitter and receiver will cause a constant frequency signal to drift in frequency. A signal of this sort is said to "chirp" or "sweep". A receiving civilization can increase their receiver's integration time by sweeping their receiver in such a way as to remove the sweep caused by doppler shift. This receiver sweep allows the signal to be received in one channel for a longer time than if the signal had "swept through" in a shorter period of time. The problem is knowing in what way to sweep.

Some have postulated that a transmitting civilization would analyze the light from the target solar system's sun to determine that sun's velocity relative to the transmitter. The beacon's frequency would then be adjusted such that it appears constant to an observer with the same velocity as the target sun. If the receiver is in motion with respect to the target sun, the receiving civilization must sweep its receivers to remove orbital effects. This would only work for "targeted transmissions". Others believe

that beacons and receivers should be swept such that the transmitted and received frequencies are at rest with respect to the galactic center of rest or the 2.7 degree K background radiation. These strategies necessitate constant calculations of antenna beam direction and the motion of the transmitter/receiver with respect to the chosen reference frame in order to sweep properly.

A more recent frequency sweeping technique is used by NASA in their MCSA project. No sweeping of the receiver is involved. Instead, consecutive channel samplings (called spectra) are saved in computer memory. If the input signal were drifting in a linear way, the spectra may be skewed such that the drifting signal is added up (integrated) and is detected. This technique has an advantage over other frequency sweeping techniques in that fewer assumptions are made of the signal's sweep rate [10]. It is disadvantageous, however, if the signal sweeps through the channel in a time shorter than the channel's integration time. In this case, the signal might not be detectable. The NASA engineers thus decided to ignore the signals which sweep faster than one channel width per integration interval.

As receivers have become more narrow-band, frequency sweeping has become much more of a problem. NASA's MCSA data analysis technique is an interesting way around the frequency sweep problem, however it is computationally intensive.

The need to sweep seems inherent because doppler shifts constantly affect the frequency spectrum of the signal. A detection methodology which can intrinsically bypass the need to sweep seems desirable. Such a method has been proposed by Dixon and Klein. They suggest that incoming signals can be decomposed not with a Fourier Transform (FT), but with a Karhunen-Loeve Transform (KLT)

[24]. The FT transforms a (band limited) time-varying signal into the space spanned by all frequencies - the frequency spectrum. The KLT uses the data itself to describe the best orthonormal space for the data. If the data is not sinusoidal, such as a sinusoid varying in frequency over time, it would be smeared or distorted by the FT, and would thus be less likely detected. The KLT, however, would determine that something important had been detected and would reference RFI files to determine if the signal were interference or not. Since there are DFT chips which can perform Fourier Transforms, it is conceivable that there might someday be a DKLT chip.

CHAPTER III

INSTRUMENTATION

The OSURO is well known for its sky survey and SETI work. The receiving equipment used for this project was installed in 1983. A movable feed system was implemented by me as part of my part-time employment at the OSURO. Information on the receiving equipment and PDP computer system was documented by Bolinger [20]. Information on the rest of the instrumentation used in the LOBES project has been documented in an OSURO internal report [21]. Figure 3.1 shows the basic layout of the instrumentation used.

3.1 Antenna

The OSURO is a 53 m Kraus-type radio telescope, located in Delaware, Ohio. The antenna consists of a fixed parabolic reflector, a tiltable flat reflector, and a 3.82-acre aluminum ground plane between the reflectors. Plate I is an aerial view of the OSURO.

The antenna half power beam width (HPBW) is 40 minutes of arc in declination and 8 minutes of arc in RA at 1415 MHz. The spacing between the dual feed horns create two beams pointed at the same declination, separated by 37 minutes of arc in RA.

The feed horns are on the ground plane, 128 m from the base of the parabola. Their location provides shielding of RFI

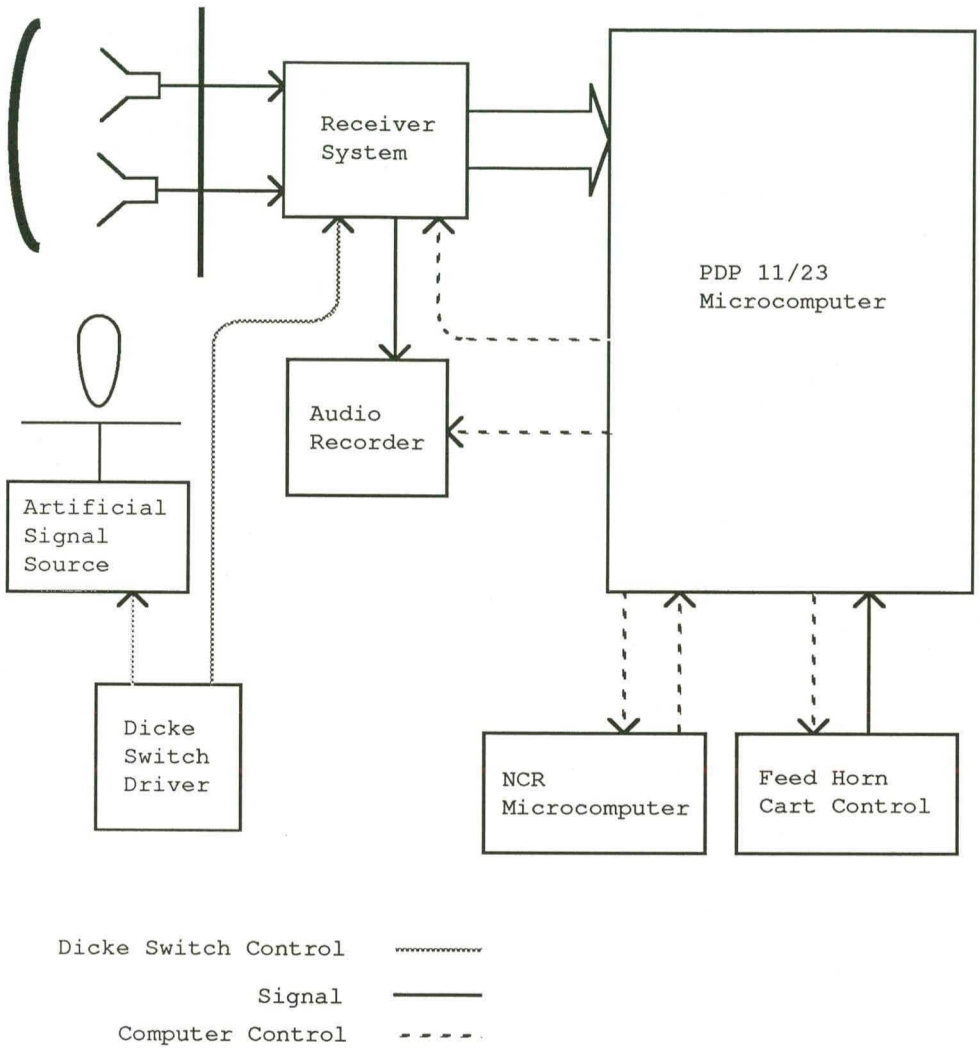
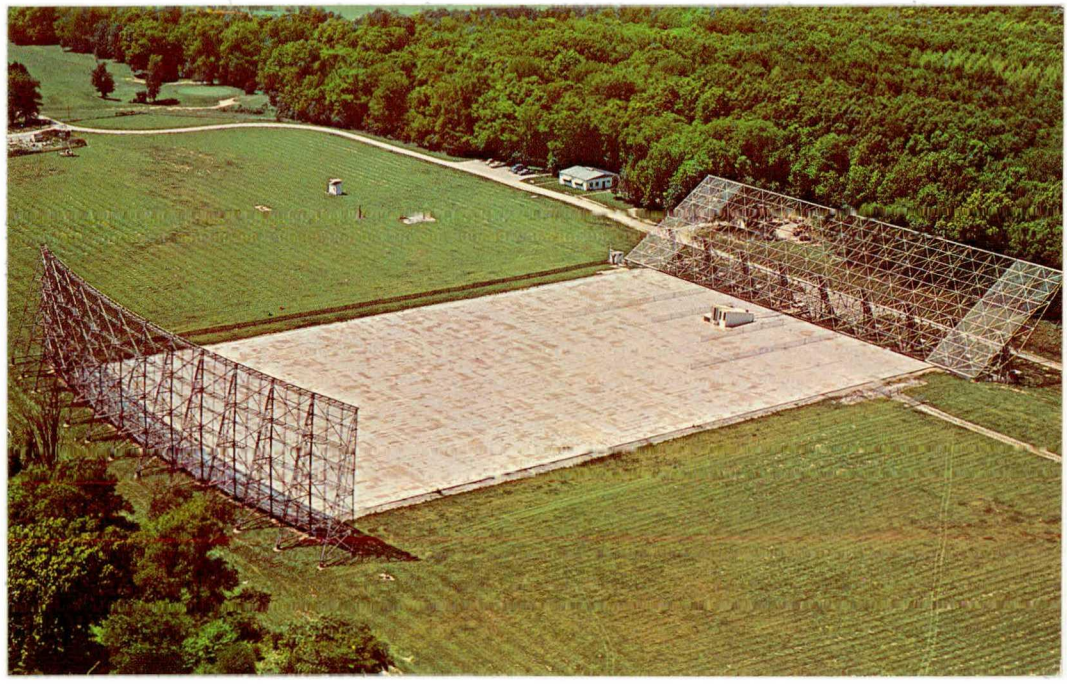


Figure 3.1 A block diagram of the instrumentation used.

PLATE I The OSURO antenna. The parabolic reflector is 110 by 21 m and the flat reflector is 104 by 31 m.



from the north and south by the reflectors and from below by the ground plane. They receive vertically polarized radiation in the 1.4 - 1.7 GHz range observed.

3.2 The Receiver System

The receiver system is similar to the Switched or Dicke receiver as described by Tiuri and Raisanen in Kraus' Radio Astronomy [3]. However, whereas a Dicke receiver constantly compares antenna temperature to a reference noise source, the OSURO receiver compares two antenna temperatures generated by the dual feed horns. The switching rate is 79 Hz. As described by Dixon and Van Horne [18], the water hole is analyzed by the OSURO's receiver system.

A bank of fifty 100 kHz bandwidth and twelve 10 kHz bandwidth superheterodyne receivers provide RF detection. The receivers square-law detect in parallel a 30 MHz IF signal. The first local oscillator is generated by a Hewlett Packard 5105A Frequency Synthesizer, whose frequency is computer programmable. The bank of fifty receivers is "hopped" at 5 MHz intervals, covering the water hole in 60 hops, producing a 3000 channel spectrum of the water hole. The output of the receivers go to multipliers, also called phase-sensitive detectors, which detect imbalances of received power in phase with the Dicke switch. The output of the phase-sensitive detectors go to A/D inputs of a PDP-11/23 computer. The PDP A/D converts the DC component of the output of the phase-sensitive detectors and transfers the data to an NCR microcomputer for analysis. A block diagram of the receiver system is shown in Figure 3.2. Detailed information on the receiving equipment at the OSURO can be found in [20].

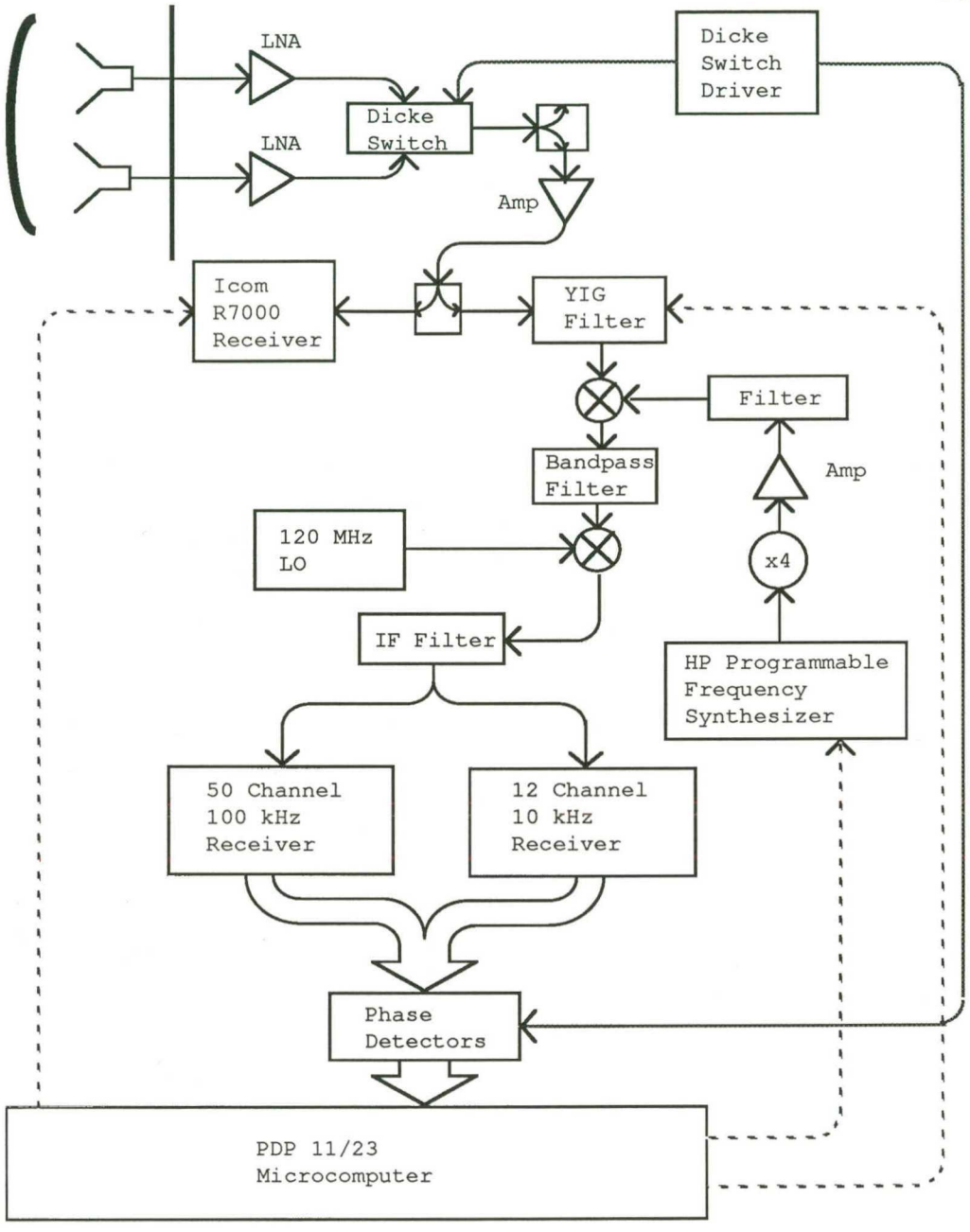


Figure 3.2 Block diagram of the receiver system.

A negative voltage from a phase-sensitive detector implies greater power in the west (leading) horn than in the east (trailing) horn for that channel, and a positive output implies more power in the east than the west. It must be stressed that the difference between the horns is being measured, and not the absolute power in either horn. This effect is useful in detecting celestial radio point sources, since such sources will not be in both beams simultaneously. Conversely, terrestrial interference may likely blanket both feed horns equally. If this is the case, the phase-sensitive detectors output zero volts DC, since there is no difference in the power received by the horns. Thus, the dual feed horns can "see through" the interference, and can still register a celestial source in spite of RFI. Celestial radiators with a large angular width are corrupted by the switched feed horns, and are not easily detectable, because the antenna patterns created by both beams will interfere with each other.

An ICOM-R7000 communications receiver is used to demodulate detected signal down to the audio range. It is tuned via a serial line from the PDP. Its audio output is recorded by a conventional audio cassette recorder. Also recorded is the WWV time signal for a time stamp.

3.3 The Feed Horn Cart

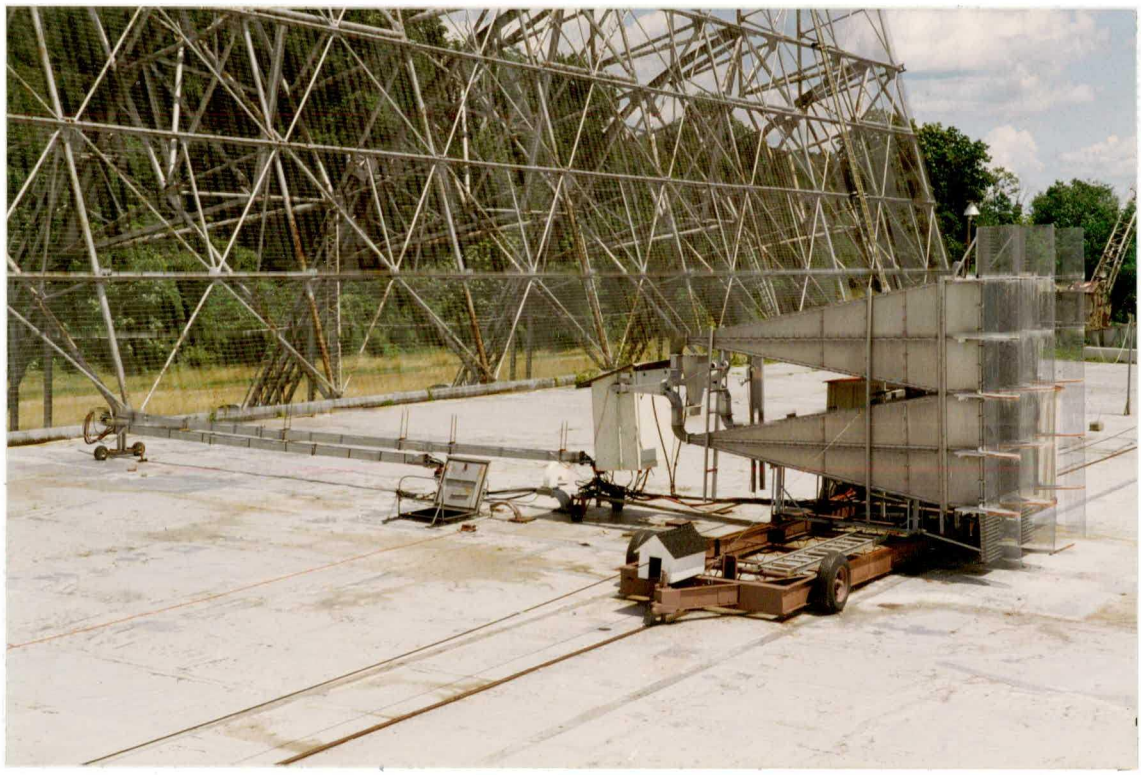
The feed horns are mounted on a cart which moves horizontally in the focal plane. Cables carrying the RF from the preamps to the receiving equipment travel through a device called the "scissors" to prevent tangling. Since celestial source radio images move laterally in the declinations the OSURO can observe, the lack of

vertical positioning does not cause a problem. The cart is capable of moving at the slow speeds necessary to track a celestial object -- 0.8 cm/sec -- with great accuracy, and at faster speeds for repositioning. The PDP-11/23 controls and monitors the position and speed of the horn cart. A nichrome wire running the entire length of the travel of the cart -- called the 'slidewire' -- and a wiper mounted on the cart provide the sensing of the cart's absolute position. Limit switches mounted on the underside of the cart sense when the cart has reached its limit of travel. Plate II is a picture of the feed horn cart. The scissors are closed, on the right. The specifics of feed horn cart control and maintenance are given in [21].

3.4 The Artificial Signal Source

An artificial signal source was used to simulate a narrow-band source moving through the feed horns. It transmits a carrier at a frequency of roughly 1422.5 MHz, with a narrow (< 5 kHz) bandwidth. Its antenna is connected with a pin diode, so it can be switched on and off quickly. The antenna transmits close to the ground plane, between the feed horns and the flat reflector. Its signal blankets both feed horns. A controller was built which would turn the output of the source on and off in or out of phase with the Dicke switch, so it would appear to the phase-sensitive detectors that a source was focused on one or the other feed horn. The source signal generator and controller are located in the focus room, where controlled temperature and humidity keep the output of the generator reliable.

PLATE II The feed horn cart from the west.



3.5 The Computers

Two computers form the backbone and brain of the LOBES system. The main computer is a PDP 11/23, installed at the OSURO in 1983. It provides all the data input and controls the horn cart and receiving equipment. The PDP's RSX11M operating system is multitasking, and there are always tasks running in the background while LOBES is in operation which have nothing to do with LOBES. Since the PDP already performs many functions, it was decided that the signal detection algorithms should be run on another computer: the NCR.

The NCR microcomputer is an IBM PC-XT clone. It communicates with the PDP via a serial line. Pattern match results and other data are written to a floppy disk in the NCR. When signal followup occurs, the NCR's printer makes a hard copy of the event. Every 3000 channel spectrum sample, real-time strike information is output to the screen. There is a large computational burden on the NCR, which has an 8087 math coprocessor.

3.6 The Computer Programs

The two computers -- the PDP-11/23 and the NCR -- need to communicate smoothly and quickly in order to immediately followup on a hit. More precisely, the programs running on the two computers -- PDP-LOBES and NCR-LOBES -- must be able to swiftly execute their instructions, even though they need to transfer instructions and data over a serial link. Both serial port interrupts are disabled for this process; the ports are polled and the operating systems are bypassed.

Handshaking is used for the fastest transfer of data. The PDP-LOBES program (written in FORTRAN) is always the first to send out its "hand": a prompt comes from PDP-LOBES which tells NCR-LOBES (written in C) that the PDP is ready to accept a menu choice. The PDP-LOBES program is all menu driven. The program itself was written as though the NCR were a person dictating commands by making menu choices through a terminal. The NCR controls the PDP because the NCR has more memory, an IBM compatible operating system and disk protocol, can display graphics, and does not have to collect the data or run other tasks.

A quick transfer of data is necessary because each of the 3000 channels must be processed by the pattern match algorithm. Since there are two computers available, parallel processing can be exploited. The PDP can collect and compress new data while the NCR processes the just-transferred data. The PDP has normal system tasks running in the background, which do take up some overhead, but the NCR is usually the bottleneck in the system. Because the (nearly) real time processing on the NCR is relatively demanding, the transfer of new data must be swift. A one-sided sending of data from the PDP to the NCR seems the most optimal, but the interrupt routine on the NCR demands too much overhead for the transfer to allow a 9600 baud rate. Therefore, it became necessary for NCR-LOBES to transfer a confirmation byte back to the PDP, which could be considered an "echo", which PDP-LOBES waits for before transferring another byte of data.

The time used to collect one spectrum is different from the nominal 10 seconds suggested by Dixon. The time was lengthened to 21.4 seconds per spectrum at the celestial equator and increases by a factor of $1/\cos(\delta)$, where δ is the antenna declination, as δ

is changed. This allows a fixed number of samples, seven, between maxima in the switched feed horn pattern. Thus, the programs go through a $21.4/\cos(\delta)$ second cycle of data collection, data transfer, pattern match, and a closeup look at the largest hit. When a major hit occurs, the ICOM receiver is tuned to the center of the 10 kHz channel which caused the strike, the audio recorder is turned on, and the hit is monitored. While the audio recorder is recording, the ICOM receiver mode cycles through AM, FM, and SSB, dwelling in each mode for $5/\cos(\delta)$ seconds. Data from the 12-10 kHz phase-sensitive detectors is sent from the PDP to the NCR every 5 seconds, and is printed out on the NCR's printer. No checking of previous hits is done to determine if the source was a hit 24 sidereal hours before, which would indicate a continuous true celestial source.

A flow diagram of the entire process is shown in Figure 3.3. After moving the horn cart and monitoring the hit, the pattern match variables must be re-initialized, because the old data is useless; the horn cart is retraced back to center focus, and a different part of the sky will be observed than at the time immediately before tracking. If any communication problems occur between the NCR and the PDP, then the NCR re-initializes its variables and attempts to recover proper communications.

Listings of the FORTRAN and C algorithms can be found at the OSURO [21].

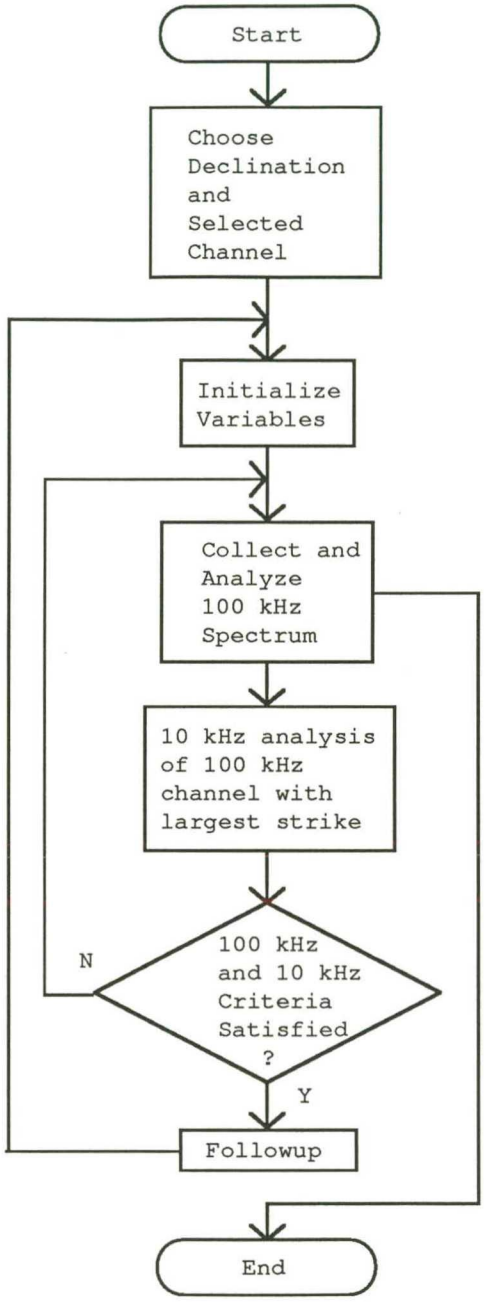


Figure 3.3 A flow diagram of the computer programs.

Chapter IV

THE LOBES SEARCH STRATEGY

4.1 The Initial Detection

As described by Dixon and Van Horne [18], the water hole is analyzed by the OSURO's receiver system. A bank of 50-100 kHz receivers "hop" at 5 MHz intervals, covering the 300 MHz water hole in 60 hops, producing a 3000 channel spectrum.

The time allotted to gathering a 3000 channel spectrum at 0 degrees declination is 21.4 seconds. This results in 7 spectra sampled in the 150 second delay between the switched feed antenna pattern peaks. The sampling time per spectrum at non-zero declinations is $21.4/\cos(\delta)$ seconds, which maintains 7 samplings for an antenna pattern, regardless of the declination. This lengthening in the sample time increases the integration time of the receivers, and it allows the antenna pattern match algorithm to operate independently of antenna declination.

4.1.1 The Switched Feed Horn Pattern

Many radio telescopes use one feed horn, whose input is constantly being received. The power of radio sources is measured by the

increase of antenna temperature. The OSURO uses two feed horns whose outputs are switched, as described in the Receiver System section of Chapter 3. The antenna beams point at the same declination and are separated in right ascension. As a source passes through the beams, an imbalance of horn power is output by the phase-sensitive detectors. The shape of the antenna pattern is shown in [8,18] and Figure 4.1.

The spacing in time between the peaks of the switched feed pattern caused by a celestial radio source varies depending on the observed declination. The spacing between the peaks is 37.5 minutes of arc, which translates to 150 seconds of RA, at 0 degrees declination. The time between peaks at different declinations has been approximated as $150/\cos(\delta)$ seconds. This approximation is adequate for the +63 to -34 degree declination range observable at the OSURO. In August, 1990, I conducted a test to accurately estimate the velocity of a celestial radio image (OI-284.3) in the focal plane of the OSURO [22]. The results confirmed the 30 second (RA) HPBW at 0 degrees declination, as described by Dixon in [18]. Like the peak spacing of the switched antenna pattern, the HPBW time also gets longer with declinations closer to the celestial poles. However, the switched beams will not overlap. One can visualize the switched feed pattern stretching in time when the declination is moved toward the poles, until it takes twice as long at +-60 degrees declination.

Diffuse radio sources (those with a large angular extent) can be in both beams simultaneously. For this reason, the switched feed system is not efficient in observing them. Fortunately, an ETI signal is assumed to be a point source, since it will supposedly be produced by a distant, compact source. It is in fact the

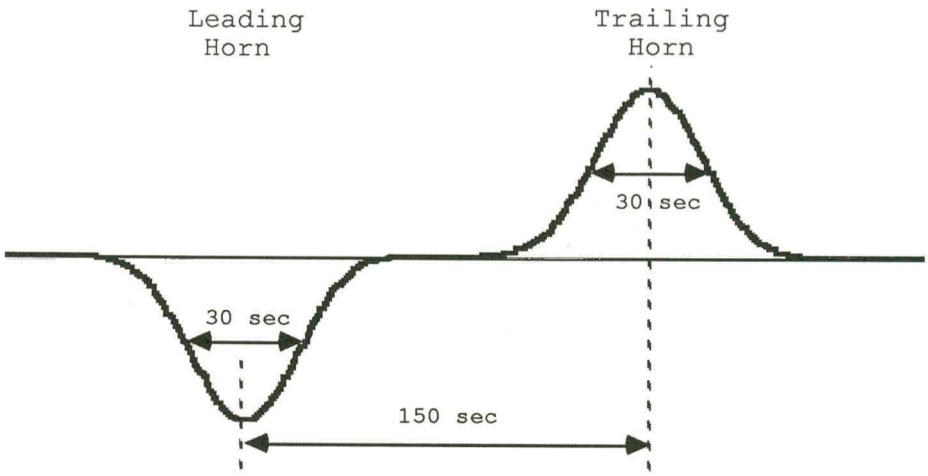


Figure 4.1 The switched feed antenna pattern produced by a drift scan of a point source at 0 degrees antenna declination.

design of the switched feed system to ignore power impinging on both feed horns simultaneously. This removes local RFI and diffuse sources; it allows a point source to "shine through".

4.1.2 Sampling and Normalizing the Data

The 100 kHz receiver must change its center frequency 60 times to collect data for an entire spectrum. It must delay for a finite time during each hop to allow the receiver system to settle. During this delay the data for the previous 50 channels can be processed. The data is first transferred to the NCR via handshaking in software. Then the NCR normalizes the data, updates the channel average and standard deviation, and passes the normalized data to the pattern matching algorithm. The equations for normalization and statistics are as follows:

```
normdata = raw data - average                          (4.1)
average = average*(1-1/smave) + normdata/smave         (4.2)
stdev = stdev*(1-1/smstd) + 2*abs(normdata)/smstd      (4.3)
```

where

```
normdata = normalized data for a channel
average = average for a channel
stdev = standard deviation for a channel
smave = 30, filter time constant for average
smstd = 160, filter time constant for standard deviation
```

The initial values of the averages and standard deviations are valued stored from the last time the LOBES process terminated. Thus, starting transients are minimized. The average calculation

is an IIR lowpass filter. The standard deviation calculation is like an IIR filter, however it is nonlinear because of the abs() function used.

A special provision is taken to keep a strong signal from causing a channel's standard deviation to get large too quickly. A new standard deviation is calculated only if

abs(normdata) < 2*stdev

If this were not implemented, the signal might be ignored because it was too small a multiple of the channel's standard deviation. Also, if a few strong spikes of RFI occur, the channel's standard deviation would take a long time to recover to its proper value. The choice of 2*stdev is relatively arbitrary. Computer simulations of this calculation modification show that it has little effect on the standard deviation, except when a signal is present.

The only filtering of the initial raw data occurs when the data value for a channel equals zero. If a channel saturates the A/D input, the PDP assigns the input a value of value -32,767 (Hex FFFF). This data value cannot be transmitted to the NCR with the compressed data scheme used, so this values is assigned a value of 0. To overcome the potentially devastating effect these 0 values may have on the average and standard deviation, they are filtered out: ignored. Essentially, the zero value alerts the NCR that the channel was saturated, and the NCR sets the zero-valued raw data equal to the raw data for the same channel in the previous spectrum. Since the A/D's on the PDP output the range 0 to 4095 (12 bits), 0 is a valid data value and should be considered in all calculations. This exception seems valid, however, because a true

raw data value of 0 is so close to producing an A/D error it might as well be classified one. If an input saturates the A/D in the positive sense (as though a value greater than 4095 were needed), then the input is also assigned a value of 0. It is an option to ignore the channel if it saturates, for there is obviously a very strong signal on it. The filtering allows strong signals to be detected and not rejected.

4.1.3 Matching the Data to the Pattern

The pattern matching algorithm matches the data in each 100 kHz channel to the antenna pattern created by the switched feed horns. The algorithm registers a strike when the signal is still in the trailing beam, thus allowing immediate followup.

The algorithm uses the normalized data described previously to update the average and standard deviations of the channels. Negative normalized data implies that a source is in the leading feed horn. Positive normalized data implies that a source is in the trailing beam. Near zero normalized data implies that equal power is in both beams. Essentially, the pattern match algorithm looks for a negative normalized data value followed by a positive value, delayed by the number of spectra samples between the peaks in the switched feed antenna pattern.

The pattern match sequence starts when the current normalized data value for a channel is greater than the previous normalized value. Plus, the previous value must have been less than -1 times the standard deviation of that channel, and the current value must be less than -0.5 times the previous value, a positive number. This corresponds to the detection of the falling edge of a

signal's power in the leading beam. The counter for that channel is incremented from 0 to 1. The previous value is stored as the peak value of the source in the leading beam. It is called the point of ascension, or "POA". After the next spectrum is sampled, the new value is compared to the stored POA value. If it is greater than the POA value, and less than -0.5 times POA, then the counter increments to 2. Otherwise, the counter resets to 0, and a new POA data is looked for. This process of checking new data and incrementing the counter continues until the counter reaches 6 or 7. At this point, 6 or 7 spectra have been sampled: the time it takes for a signal to move from one antenna beam peak to the other. If the new data value is less than -3.33 times POA and greater than -0.3 times POA (both positive values), then a strike has occurred. The strike value for a channel is calculated thus:

strike = (new normalized data - POA data)/(2*stdev)

Figure 4.2 shows the criteria in a graphical way. Since the sampling time changes with the declination, Figure 4.2 will not change with declination; there will always be 7 spectra sampled between peaks in the switched feed antenna pattern.

Since the peaks are a known 7 spectra for each declination, why then try to detect a strike after only 6 spectra are sampled? Because of the uncertainty in the triggering position caused by the location of the signal in the leading feed horn and because the spectra take 2/3 of the beam's HPBW to collect. It is an advantage to detect a source early - after 6 samples - while the source is within the trailing beam's HPBW, than after 7 samples, when the source may quickly pass out of the beam and be

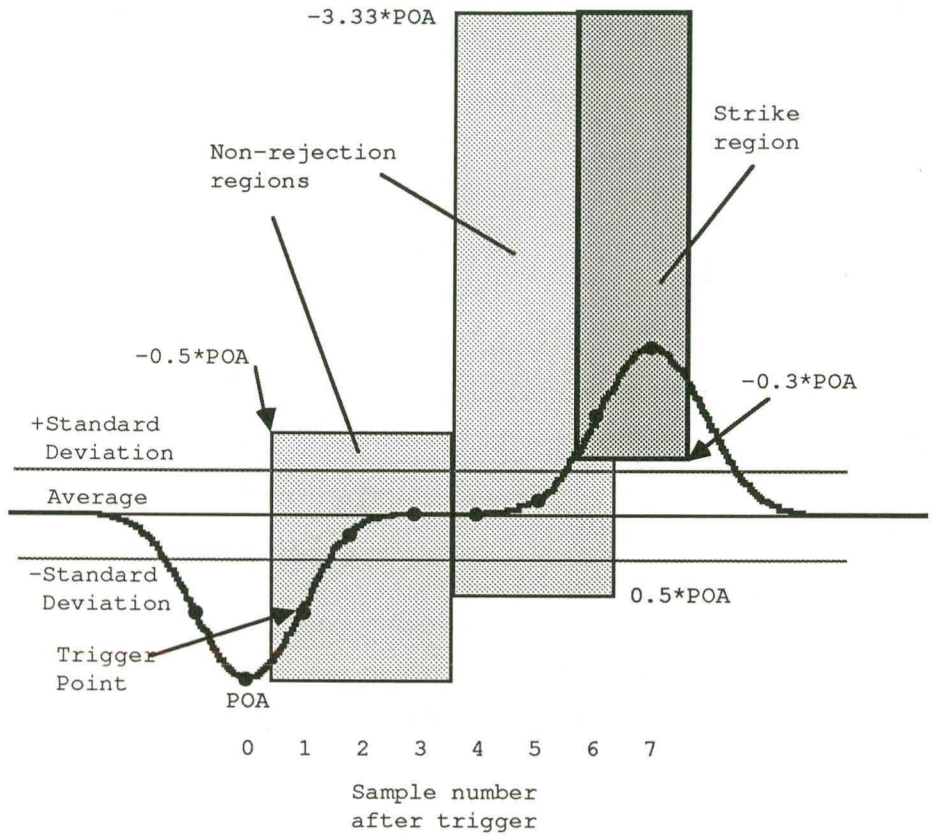


Figure 4.2 The 100 kHz channel pattern match criterion.

undetectable by the 10 kHz receivers. There is also uncertainty in the source's location in either beam caused by the system noise.

Once a strike has occurred, it is compared to the largest strike calculated for that spectrum. If the current strike value is greater, then the current strike becomes the largest strike and the current channel number replaces the previously larger strike channel number. In any case, a variable containing the number of strikes for that spectrum is incremented and the strike value is added to an accumulator. These are some of the data stored on disk for later analysis.

This process produces strikes on several channels per spectrum collected, every $21.4/\cos(\delta)$ seconds. An immediate followup of the largest strike is deemed necessary only after further investigation verifies a narrow-band strike. Inherent in this process is the fact that a channel cannot produce two consecutive strikes. There must be a delay of at least 6 or 7 spectra samplings after a channel registers a strike before another strike can occur, because its counter is reset to 0 and must count up to 6 or 7 again.

4.2 Narrow-band Detection

After all the 100 kHz channels have been processed, the channel with the greatest strike value is analyzed with the 10 kHz receivers. The 10 kHz receivers are centered over the 100 kHz channel of interest, as described in [18]. If the 100 kHz channel strike has a sufficiently high value and if the 10 kHz criterion is satisfied, then the 100 kHz data collection stops and the 10

kHz channels are constantly analyzed. Otherwise, 100 kHz data collection continues as normal. Even though the maximum 100 kHz strike value may be below the preprogrammed minimum value, the 10 kHz data collection is performed to keep spectrum collection evenly spaced.

4.2.1 Frequency Lookaside

The average values for the 100 kHz channels is calculated as described above. The average values for the 10 kHz receivers, however, are not known for arbitrary parts of the water hole. For this reason, a technique which I call "frequency lookaside" is used to estimate the average values of the 10 kHz channels in the vicinity of the 100 kHz channel of interest. The principle is simple: the 10 kHz receivers are tuned to a frequency near but not overlapping the frequency of interest, where they are allowed to settle. The data from the 10 kHz phase-sensitive detectors are collected, then the 10 kHz receivers are tuned to the frequency band of interest: the center frequency of the 100 kHz strike. The receiver system is allowed to settle once again, then the data are collected again from the 10 kHz phase-sensitive detectors. The first data set is considered to be the "averages" of the 10 kHz channels. Thus, to determine whether a signal is present in the second set of data the first set is subtracted from it. This should produce a set of data whose average is close to zero. If a signal of the kind LOBES is trying to detect is present, only one difference will be large and positive. The rest of the difference values must be no greater than or less than zero by by a fraction of the maximum difference. Plus, the maximum channel value must

be greater than all other channels using the data collected when the 100 kHz channel of interest was analyzed. These criteria are laid out graphically in Figures 4.3 and 4.4.

This technique has several drawbacks. First, the frequency band chosen to be the "average" is not checked for RFI, and could thus distort an otherwise legitimate strike. Second, the integration time of the 10 kHz phase-sensitive detectors must be cut in half in order to accomplish twice as many "looks". The first problem may not be so much of a problem; if there is RFI in the vicinity of the frequency of interest, then there is a chance that some RFI may corrupt that frequency band. The RFI may even have been the cause of the strike. The second problem must be accepted as a necessary expense to estimate the 10 kHz channel averages.

Frequency lookaside is used in all 10 kHz channel analyses. The "average" reading is taken 200 kHz (2-100 kHz channels) higher in frequency than the band of interest. The settling (integration) time of the 10 kHz system is 1.0 second, hence the total time to collect the 10 kHz data is 2.0 seconds. This value remains constant with different declinations.

If both the 100 kHz and 10 kHz detection criteria are satisfied, the collection of 100 kHz data is suspended and the 10 kHz channels are used to analyze the data. From this point, the return to normal 100 kHz data collection requires that all pertinent pattern match variables for the 100 kHz channels be reset, since there will have been a period of time when no spectra were collected: the previous data will not have any contextual relationship with the new spectra collected, considering the sequential nature of the pattern match algorithm.

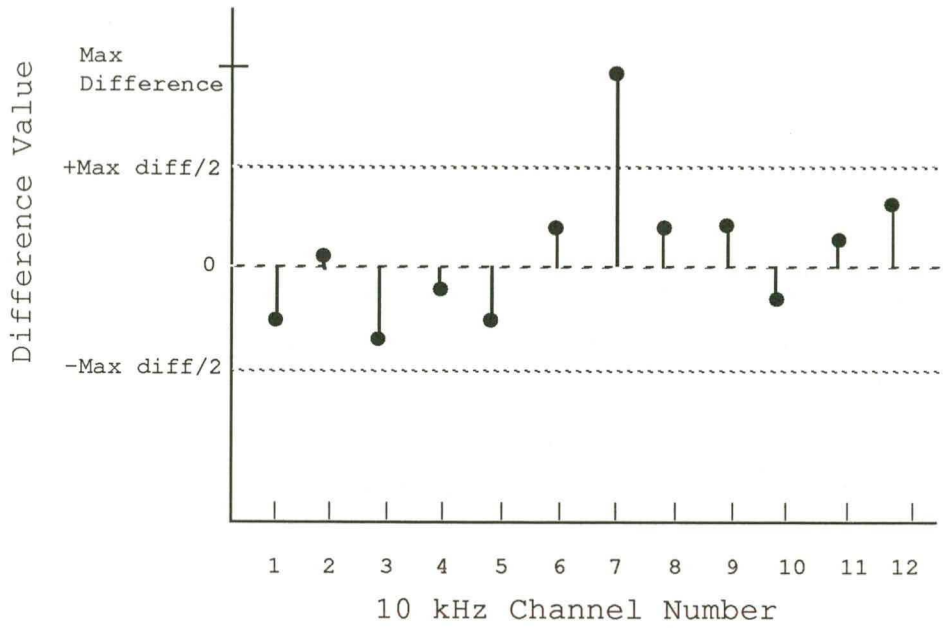


Figure 4.3 10 kHz frequency lookaside criterion.

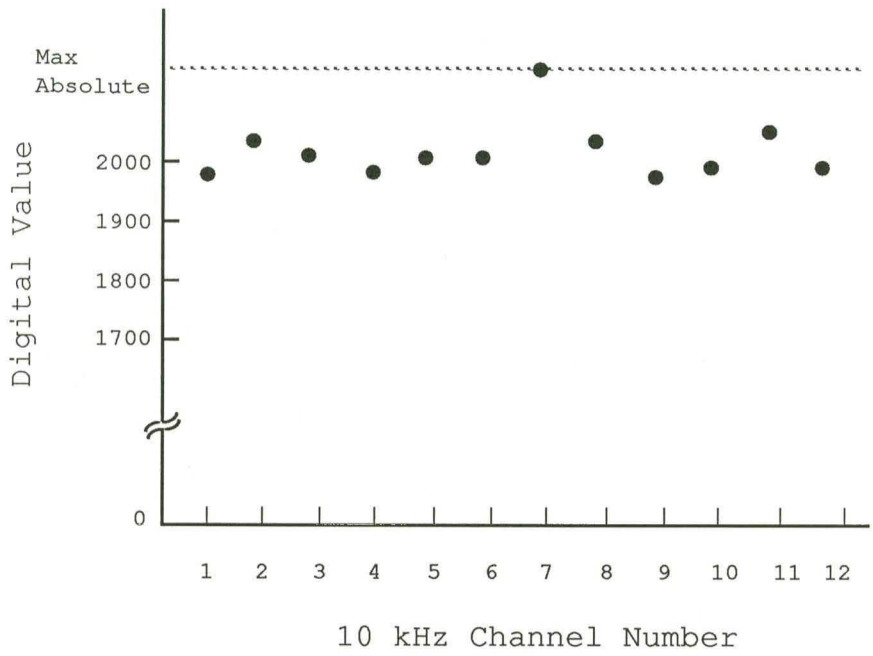


Figure 4.4 10 kHz criterion on
100 kHz channel of interest.

4.2.2 Stationary Monitoring

Assuming that the LOBES system has committed itself to monitoring a strike, the first thing it must do is wait for the signal to disappear. If the signal is detected over a long period of time by the 10 kHz receivers then it probably is not a signal of interest. A true celestial point source will move through the trailing beam for a maximum of 1 minute (at 0 degrees declination). The practical time is shorter, considering the 30 second (RA) HPBW, and the fact that the strike may have registered after the trailing beam maximum had been passed.

For this thesis, the time between 10 kHz analyses during this phase is $5/\cos(\delta)$ seconds. This allows changes in declination without affecting this detection criterion. If the signal is detected 12 times, it is considered RFI and the 100 kHz data collection resumes. If the source is not detected two times in a row, the next stage of followup, moving the feed horns, occurs.

During this initial monitoring of the source, any narrow-band source detected on a 10 kHz channel which was not the initial strike channel (one of the remaining 11 channels) is considered to be RFI. It is assumed that during this short time after detection the frequency shift caused by doppler sweep will be small compared to 10 kHz. Thus, if the signal changes in frequency by even one channel it is considered RFI and is ignored. Normal 100 kHz data collection then continues, after all channel strike histories are cleared.

The audio recorder is turned on at the beginning of this phase of source monitoring. It is turned off when normal 100 kHz data collection resumes. Each time the 10 kHz receivers are used

(5/cos(δ) seconds), the ICOM-R7000 receiver mode is rotated to AM, FM, or SSB (CW). This allows the signal to be demodulated in as many modes as possible. This differs from the 3 seconds suggested in [18].

4.3 Following Up

The technique for tracking a source as described in [18] differs from the technique used in the LOBES system. Dixon suggests that the feed horns begin tracking the source when it reaches the peak response in the trailing feed horn. Plus, he describes the feed horns tracking the source for 1-2 hours at the sidereal rate, recording the signal as demodulated by the ICOM receiver. It seems that this technique is most effective in recording signals which are sporadic, or perhaps pulsed, since the entire tracking time is used for each strike.

4.3.1 Moving the Feed Horns

The technique I used to track is more applicable for CW signals and signals pulsed at least once per beamwidth. Once the signal has gone away, the feed horns are moved to place the trailing beam just ahead of the source and then are stopped. The 10 kHz receivers then are analyzed once every 5 seconds to attempt to re-detect the signal. If the signal were a constant frequency carrier, the response recorded by the 10 kHz channel detecting the signal will look just like the trailing beam's antenna pattern, since it will drift through the trailing beam. After the time it takes for a source to drift through the trailing beam, about 60/cos(δ)

seconds, the feed horns are again moved to place the trailing beam ahead of the source - if the source was detected at least once in the beamwidth wait. Else, the feed horns retrace back to center focus, where normal 100 kHz data collection resumes. This allows less time to be wasted tracking a source which has disappeared, or in tracking RFI mistaken for a signal.

4.3.2 Repeat of Narrow-band Detection

I used several different criteria to determine whether the signal was present during the trailing beam scan. In all of them, the source needed to be detected only once during the offset scan in order for the feed horns to be moved in anticipation of the source again. This allows for the detection of pulsed, or low-duty signals. It is difficult to lay down too stringent a criterion, since the nature of the signal is unknown. However, some attempts to allow for doppler sweep, and to reject RFI, were made.

After the initial narrow-band detection, the channel number of the detected signal (1-12) is stored and is used as a criterion for subsequent detections.

Technically, a detection on channels 1 or 12 should not be allowed, since these channels fall outside of the passband of the 100 kHz channel of interest. However, to allow for errors in tuning, and considering the non-uniformity of the pass bands of the receivers, 10 kHz channels 1 and 12 can register legitimate strikes.

Several methods I used to re-detect a signal are shown in Table 4.1. The narrow-band sampling and determining of the strongest channel is the same as shown in Figures 4.3 and 4.4.

Table 4.1: Methods used to re-detect a signal

Causes for acceptance	Causes for rejection
Detection on same channel	No detections
Detection on same channel or adjacent channels	Detection on a channel not the same as the initial one or its adjacent channels

Note that the system is not sensitive only to CW signals drifting in frequency at constant rates when adjacent channels are checked, as others have attempted to detect [10].

When the signal is detected in an adjacent channel, no re-tuning of the ICOM receiver occurs. The audio recorder records from the moment of narrow-band detection until the feed horns begin the retrace back to center.

4.4 Stored Data

After every 100 kHz spectrum sample, a data record is saved to floppy disk. The data consists of some of the outputs of the pattern match algorithm, and other data for system diagnosis and timekeeping. When a strike occurs, the narrow-band data collected when tuned to the 100 kHz channel of interest is stored. Some character strings are also stored. These provide explanations of what the LOBES system was doing during source tracking, and provide error logging.

CHAPTER V

PROCEDURE AND RESULTS

5.1 Procedure

An experiment was made running the LOBES system from September 5, 1991 until March 15, 1992. The antenna declination was -13 degrees the entire observing time. During that time the LOBES system required routine maintenance every few days to replace data storage floppies, audio cassettes, and printer paper. The system detected narrow-band satellite broadcasts, the narrow-band test signal, and also detected broadband sources. The automatic followup of narrow-band detections revealed no sources which reliably reproduced the trailing feed horn beam pattern, indicating that no true celestial narrow-band sources were re-detected.

5.2 Results of the LOBES Project

The LOBES system detected the artificial source and natural microwave sources reliably and consistently. Most remarkable was its ability to detect the ridge of strong emission along the galactic plane. The sun also showed up as a broadband source during most of the observation period. The artificial signal source was detected nearly every time it was used, and matched the

narrow-band detection criterion so well that the LOBES system consistently followed up on it. A satellite or group of satellites consistently produced false alarms twice a day, and the LOBES system usually followed up on them. No attempt was made here to reject such RFI using a separate, omnidirectional antenna, as described by Dixon [18], but should be done in future work.

5.2.1 Simulated Source Detection.

The artificial signal source worked well in testing the LOBES system. The system followed up on the source virtually every time it was used. The signal source provides a very stable frequency output, so the 100 kHz channel where the source will appear is known beforehand, or can be found using a procedure described in [21]. Knowing this channel allows the operator to select it for disk storage. Not only was the channel data stored, but also its strike value, if it registered a strike. This in no way affected how the channel was processed. Figure 5.1 shows the raw data stored during a source simulation and the output of the pattern match for that channel. Also shown is the average and standard deviation of the selected channel as recorded at the time of detection. The drop in the data after the peak of the source in the trailing horn indicates that a detection and followup had occurred: no spectra were collected during that time. When the data resumes, the cart has retraced, and normal spectra sampling has resumed.

Figure 5.2 shows the printout of the followup of a different simulated source detection. The asterisks to the right of the 12-10 kHz channel values indicate that a signal was detected on the

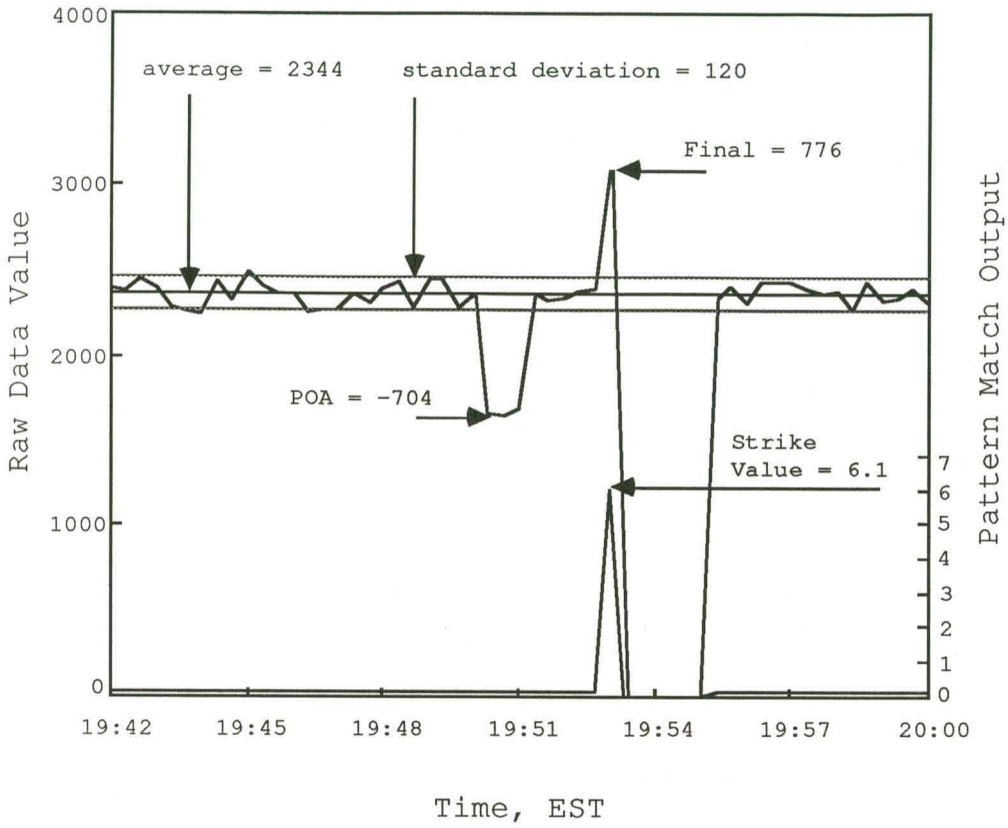


Figure 5.1 Detection of the simulated source.

```
HIT, ch:  249, nb: 4, freq: 1422.430 at: 16:52:23 on 11-25-1991.
 poa: -240, pod:  190, stdev:  60.2, ave:   2310

1826 1961 2029 3540 1950 2020 1861 1891 2077 1691 1726 2035  0  *
1917 1626 1833 3522 1928 2059 1969 1956 1978 1692 1897 1903  11 *
1935 1791 2139 3470 1915 1801 2018 1939 1912 1969 2023 1978  16 *
1957 1991 2028 3506 2160 1935 1843 1972 1923 1706 1896 1921  21 *
1933 1544 1799 1954 1959 1962 2094 1878 1936 1749 1823 1763  27
1799 1692 1902 1858 1882 1985 1736 2085 1966 1806 2043 2008  32

The cart is now at: 1880, time: 16:52:58.    Moving the cart.

1983 1927 2075 1934 1911 2048 1935 2038 1913 1855 1828 1867  50
1814 1854 2129 1893 1736 1784 1873 1861 1872 1861 1916 1870  55
1887 2104 2096 1942 2011 1818 1883 1891 1892 1806 2151 2041  60
1984 1789 2034 3229 1819 1991 1815 1999 1892 1614 1861 1948  65 *
1790 1879 1938 3078 1896 1932 1970 2191 2071 1913 2067 1916  70 *
1954 1723 2188 3157 1921 2078 1977 2004 2206 1891 2029 1943  75 *
1941 1908 2180 3066 1780 2052 1740 1703 1896 1732 1711 1938  80 *
2016 1867 2050 3154 1903 1669 1740 1831 1922 1624 1937 1857  85 *
1864 1989 2005 3038 2232 1941 1814 1549 1870 1587 2169 1876  90 *
1928 2265 2274 1884 1947 1992 1816 1965 1935 1860 1884 2030  95
1900 1763 2223 1918 1840 1977 1749 2027 1766 1789 1904 2082  100
1826 1756 1910 1890 2243 1791 1798 1814 1956 1731 1709 2162  105

The cart is now at: 1945, time: 16:54:07.    Moving the cart.

1651 1946 2087 2042 1806 1909 1915 1624 1974 1759 1842 2048  119
1929 1781 2145 1944 1926 2240 2018 2102 1986 1677 2070 1722  124
1663 1693 2061 1900 1829 1964 1810 2024 2004 1954 1879 1792  130
1849 1847 2077 2118 1865 1878 1924 1978 1906 1772 1840 1779  140
1773 2105 1927 1913 2018 1848 1930 1871 1895 1925 1858 1878  145
1923 2046 2069 2038 2222 2126 2236 1860 1913 1375 1871 1696  150
2041 1868 2128 2045 2153 1961 1850 2052 2048 1764 1965 1625  155
1729 1858 2141 1844 1927 2077 1969 1850 1954 2037 1938 2007  160
1850 1929 1979 1928 1890 1856 1783 2031 2003 1619 1721 1834  165
1709 1587 2098 2125 2128 1837 1950 1887 1977 1900 1987 1863  170
1912 2048 2178 2030 2066 1912 2254 1899 1862 1627 1847 1776  175

Retracing the cart from: 2016, time: 16:55:17. Recorder off.
The cart is done retracing.
```

Figure 5.2 Followup of the simulated source detection.

original channel. Note in Figure 5.2 that the value of the detected channel was nearly 3500 all the time. This indicates that that channel was saturated. As stated elsewhere [21], the positive saturated output of the 10 kHz phase-sensitive detectors does not equal or exceed +5 volts, and hence does not cause an A/D overload. Recall from Chapter 4 that an output from a phase-sensitive detector greater than the average indicates a signal in the trailing feed horn. The 100 kHz channel was not saturated, however, as Figure 5.1 shows, thereby providing a realistic simulation of a (relatively) weak signal passing through the beams.

Over the course of several months, the signal source drifted upward slowly in frequency. This provided the fortunate ability to randomly test any of the 12-10 kHz channels. Each channel appeared to receive equally well, and the detection algorithm detected the signal no matter in which channel it fell. A few rare times the signal showed up equally in two adjacent channels, causing no followup. A testament to the fine tuning of the system is the fact that the source was never detected on 10 kHz channels 1 or 12. As discussed in Chapter 4, 10 kHz channels 1 and 12 fall outside the passband of the 100 kHz channel of interest. Channels 1 and 12 are accepted as valid detection channels to compensate for variances in receiver tuning and channel bandwidths. It seems that these uncertainties were compensated for fairly well, at least in the signal's 1422 MHz region.

5.2.2 Satellite Detections

Experimentation with the signal source showed that constant frequency sources do not cause detections on 10 kHz channels 1 or 12.

One type of detection, however, would often show up on channels 1 or 12. A satellite or group of satellites broadcasting with narrow-band, drifting carriers were the causes of these detections, which occurred regularly around 0700 and 1900 EST. There was no indication of sidereal periodicity in their character, however, so they have been ruled out as fixed celestial sources.

Figure 5.3 shows the LOBES followup of such a strike. Figure 5.4 shows the 100 kHz data for this strike as used by the pattern match algorithm. This was a strike of 11.9 standard deviations for 100 kHz channel 2893, whose center frequency is 1686.850 MHz. All strikes caused by these satellites fell within the 1670 to 1690 MHz range. The strike values for these satellites were the largest registered during the observation period, thus indicating that these sources were powerful.

The strike in Figures 5.3 and 5.4 was detected on 10 kHz channel 1 because the signal was slowly changing in frequency as it was received by 100 kHz channel 2893. When the pattern match algorithm registered channel 2893 as a strike, the signal was nearly out of the channel's passband. When the narrow-band data for channel 2893 was analyzed, the signal had in fact passed out of channel 2893's band, but 10 kHz channel 1 still caused the detection. The followup in Figure 5.3 did not last long because the signal frequency continued to drift out of the frequency band of interest.

It is unknown whether the source monitored in Figure 5.3 made an antenna pattern - as detected by the pattern match algorithm - because it passed through the main antenna beams at the expected sidereal rate. The zero values in the narrow-band data in Figure 5.3 indicate that the leading feed horn at times detected the

```
HIT, ch: 2893, nb: 1, freq: 1686.800 at: 18:25:23 on 12-01-1991.
 poa: -463, pod:  215, stdev:  28.6, ave:   2338

3546 2466 2097 1948 1893 1999 2128 1852 1990 1920 2025 1971 0  *
3524 3545 2058 2055 2026 1998 1957 2089 1945 1847 2030 1911 10
 137  457 1868 1980 2066 2018 1988 1905 1962 1990 2048 1935 15

The cart is now at: 1877, time: 18:25:41.    Moving the cart.

1992 2049 2179 3422 3555 2253 2010 1993 2014 1900 1995 2006 32
2003 2252 2310 3520 3511 2951 2187 2070 1987 1850 1999 1991 37
1956 1907 2020 1995 1715 1754 2024 2041 1971 1803 1912 1985 42
1442 1934 1973 2052 1932 2001 2134 1981 1948 1943 2008 2069 48
1734 1895 2039 2000 1888 1934 2094 1925 1957 1841 2043 2070 53
2914 2061 2083 1927 1974 2014 1970 2040 2038 2030 2010 2034 58 *
3542 2139 2057 1998 1909 2092 2079 1896 1955 1817 2003 1951 63 *
2617 1990 1915 1965 2050 1977 1975 1984 1999 1836 1984 1964 68 *
2083 1972 2055 1960 2016 2044 1945 2020 2005 1881 1985 2108 73
2097 1937 1915 1982 2006 1980 2047 1886 1901 1841 1991 1995 78
1725 1780 2026 1983 1934 1953 2005 2073 2002 1828 2094 2076 83
2025 1955 2026 1946 1986 1997 1961 1958 2011 1793 2000 1940 88

The cart is now at: 1943, time: 18:26:50.    Moving the cart.

1854 1422 1256 2036 1960 1977 2030 2124 1934 1909 2015 2050 101
1980 1925 2090 2021 2030 2016 1943 2019 1939 2007 2050 1978 106
1977 1943 2054 2038 2019 2084 2004 1955 2000 1942 1953 1999 111
1944 2025 2049 1976 2055 2003 2142 1953 1961 1815 1967 2054 116
1961 1810 2068 2062 2020 1997 2123 2040 1986 1880 1981 1996 121
2001 1960 1957 2023 2063 2076 2000 2097 1977 1895 2006 2069 126
2008 1945 2017 2037 1915 1987 1934 1956 1895 1922 1994 1964 131
1898 1844 1969 1916 1980 2076 2112 1924 1984 1805 1992 1938 137
1982 1903 1932 2027 1982 2074 1922 2035 2038 1948 2087 2042 142
1971 2023 1894 2012 2054 1993 1983 2072 1944 1958 1985 2004 147
 580    0 1999 1984 1897 1855 2029 1952 2004 1928 2001 2035 152
 824    0 1878 1927 2012 2055 2069 1993 1976 1796 1900 1941 157

Retracing the cart from: 2013, time: 18:28:00. Recorder off.
The cart is done retracing.
```

Figure 5.3 Followup of a satellite detection.

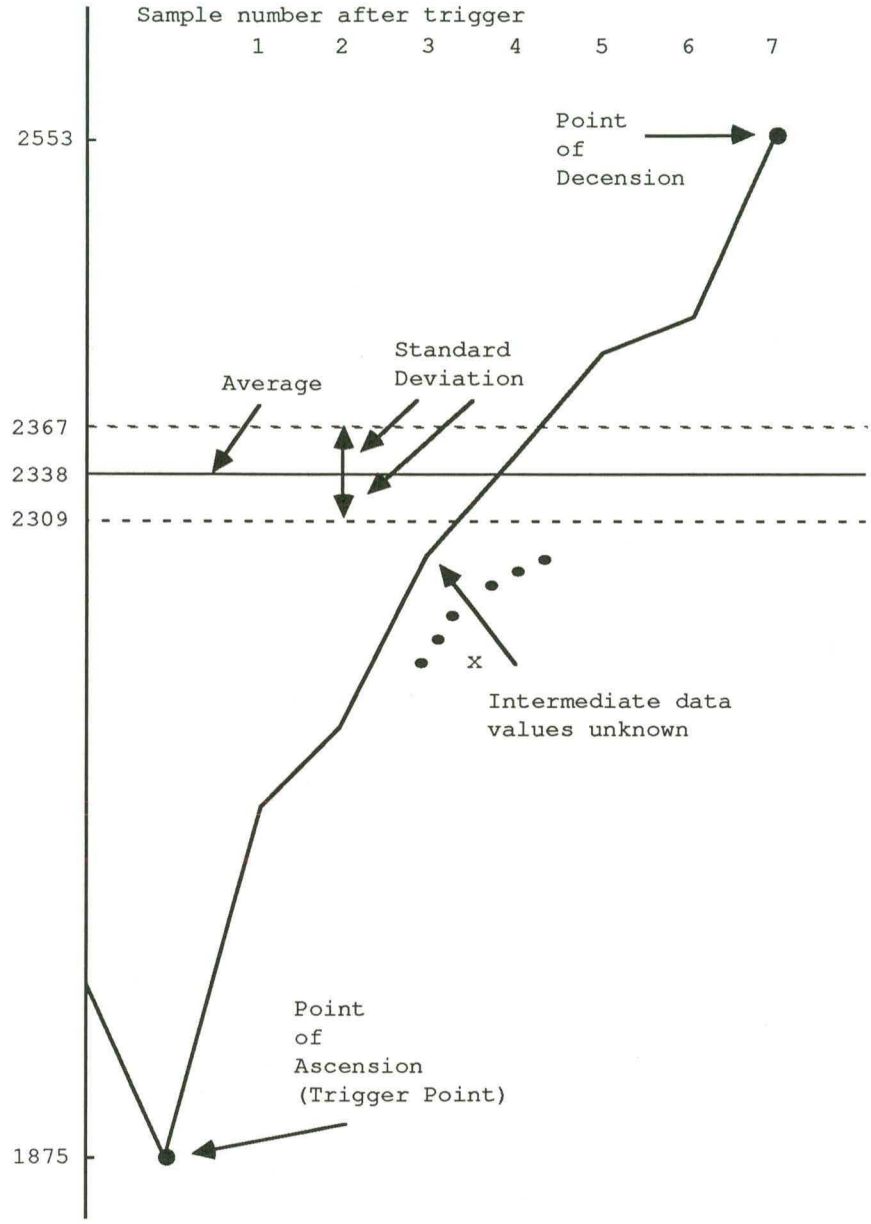


Figure 5.4 The point of ascension and final value for a satellite pattern match detection.

signal more strongly than the trailing horn.

These satellite detections may occur because large signal impulses appear in a single 100 kHz channel, producing a pattern match strike where a narrow-band frequency is present. The satellite probably does not pass through the antenna beams, but more likely blankets both feed horns in a random way. When the narrow-band channels are analyzed, the satellite signal may or may not be stronger in the trailing feed horn. If it is stronger in the leading feed horn, no 10 kHz channel detection occurs. If it is stronger in the trailing feed horn, a detection will occur if a strong power is seen on only one of the 12 10 kHz channels.

5.2.3 Success of Followup

Since a constantly radiating narrow-band (< 5 kHz) celestial source at near-constant frequency would be re-detected during followup, and since a re-detection must occur in order for the feed horns to move, the number of moves the horn cart makes during followup is the ultimate criterion of detection. Unfortunately, no followups with a large number of cart moves occurred at the -13 degree declination observed. Therefore, it is safe to assume that the LOBES system detected no such source.

The only consistent times more than one followup move was made were when the satellites described above were detected. Typically, only one followup would occur; the signal would not be re-detected.

5.2.4 Broadband Strikes

After analyzing several days' worth of the stored data, I realized that there were two events occurring per day which caused more than 100 pattern matches (strikes) in a single spectrum. In fact there were up to 4 spectra in a row where more than 100 strikes occurred. One was occurring with solar periodicity, and the other with sidereal periodicity. They were the sun and the galactic plane. Since the observed declination was -13 degrees and the observations took place from September, 1991 to March, 1992 from 40 degrees north latitude, the sun was near the antenna beams every day. Also, at -13 degrees, the antenna beams pass close to the center of the galaxy, where the galactic ridge is a strong, broadband stripe, as observed by Kraus [23]. Even though these sources are broadband and diffuse, they provided the important confirmation, in addition to the signal simulation, that the pattern match algorithm works well.

Analysis of the selected channel and its strike information confirms that the pattern match algorithm detects the sun. Figure 5.5 shows the selected channel (center frequency of 1422.350 MHz) and its pattern match output for a sun transit on October 25, 1991. Note its similarity to Figure 5.1, the simulated signal strike. Figure 5.6 is the total number of strikes per spectrum for the same sun transit shown in Figure 5.5. Note how the plot of total hits confirms that the selected channel "struck" at the same time as many other channels. The drop to zero in Figure 5.6 after the broadband detection confirms that a large number of channels struck, resetting their match algorithm counters to zero, producing fewer than normal strikes. In fact, during this

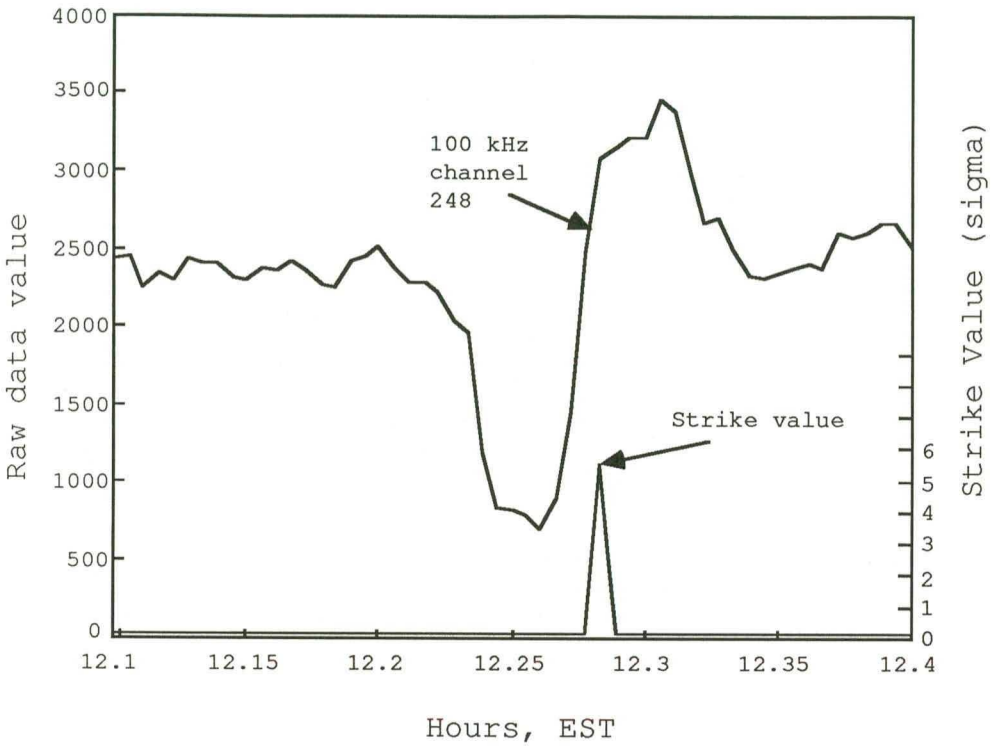


Figure 5.5 Selected 100 kHz channel (1422.350 MHz) during a sun transit. Data taken on October 25, 1991.

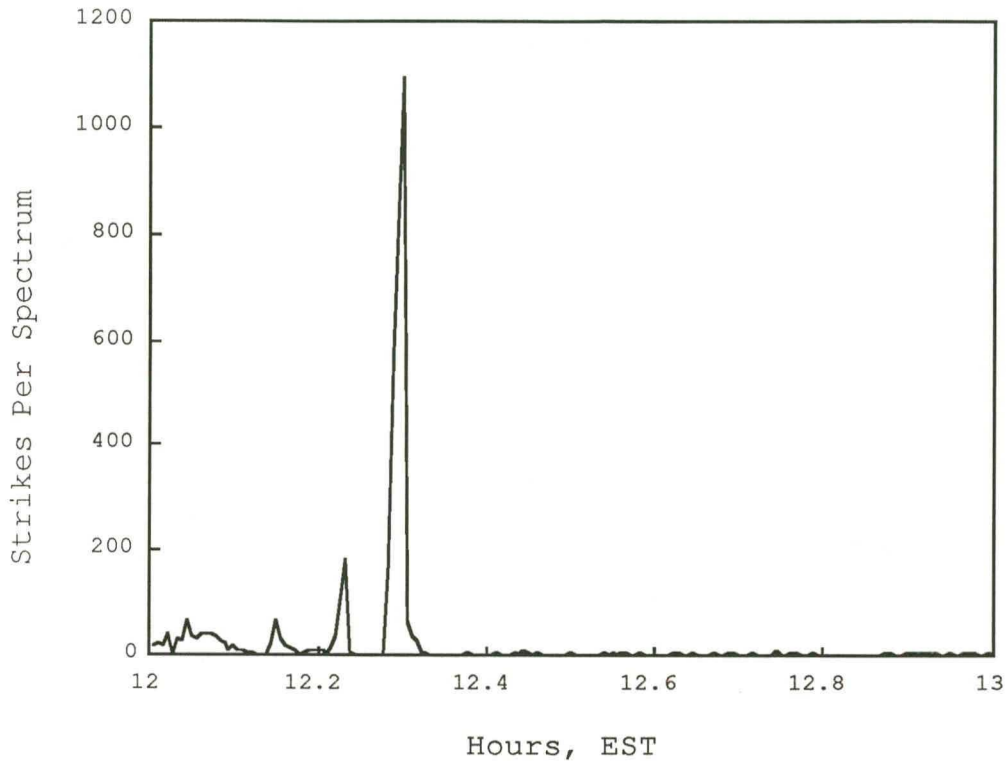


Figure 5.6 Total strikes per spectrum for a sun transit, October 27, 1991.

particular sun transit, 2100 channels registered a strike, out of 3000 possible.

The sun passed directly through the antenna beams on October 28, 1991. The sum of total hits per sun transit versus sun declination is shown in Figure 5.7.

The most satisfying detection which occurred was the transit of the galactic plane close to the galactic center. At -13 degrees declination that part of the galactic plane is located at 18 hours 20 minutes RA (epoch 1950). Every 24 sidereal hours, 300-400 100 kHz channels registered the galactic plane's transit. This provided a convenient celestial "broadband beacon" to confirm that the pattern match algorithm was working. Figure 5.8 shows the total strike values for the galactic plane transit. It is obvious from repeated observations that the galactic plane falls on the same RA consistently, as it should for a constant antenna declination.

It is interesting to note that the average strike value during the sun transits were large, as shown in Figure 5.7, whereas the galactic plane transit produced an average strike value of around 1.5 standard deviations. The normal non-broadband average strike value is 1.0.

There is no need for the horn cart to move upon broadband detection, unless a narrow-band signal is detected with the proper criterion. Since the sun is unlikely to have such a strong narrow-band frequency, it is understandable that no narrow-band strikes should occur during the sun transit. As some have suggested, the galactic plane may be the most likely place for ETI detections. So far, though, no narrow-band detections have occurred during the galactic plane transit.

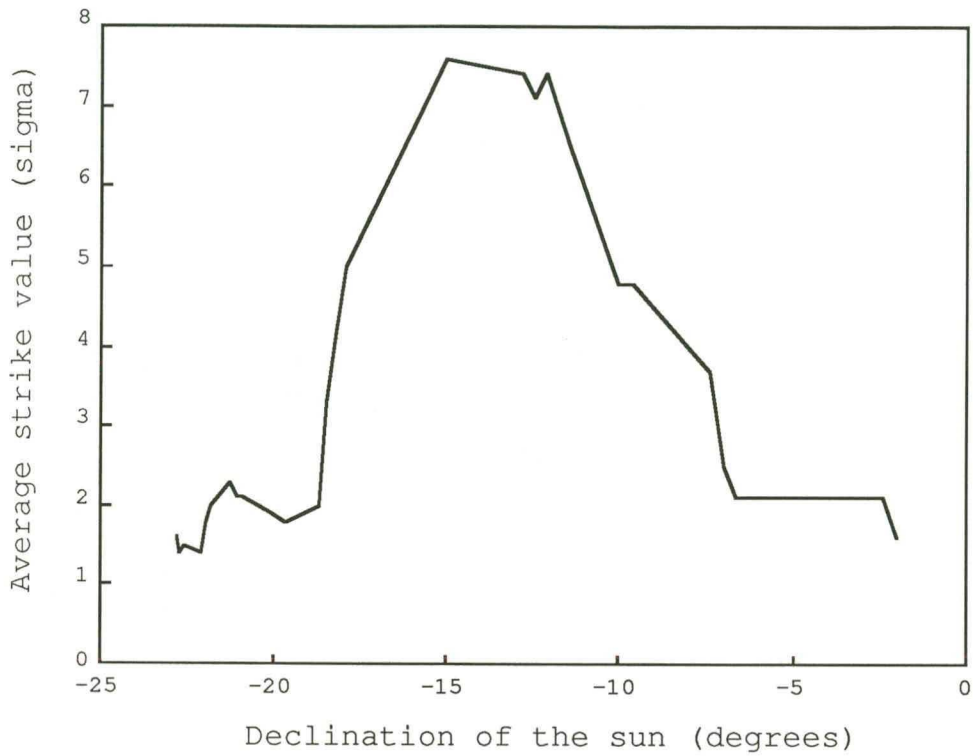


Figure 5.7 Average strike value versus declination for sun transits.

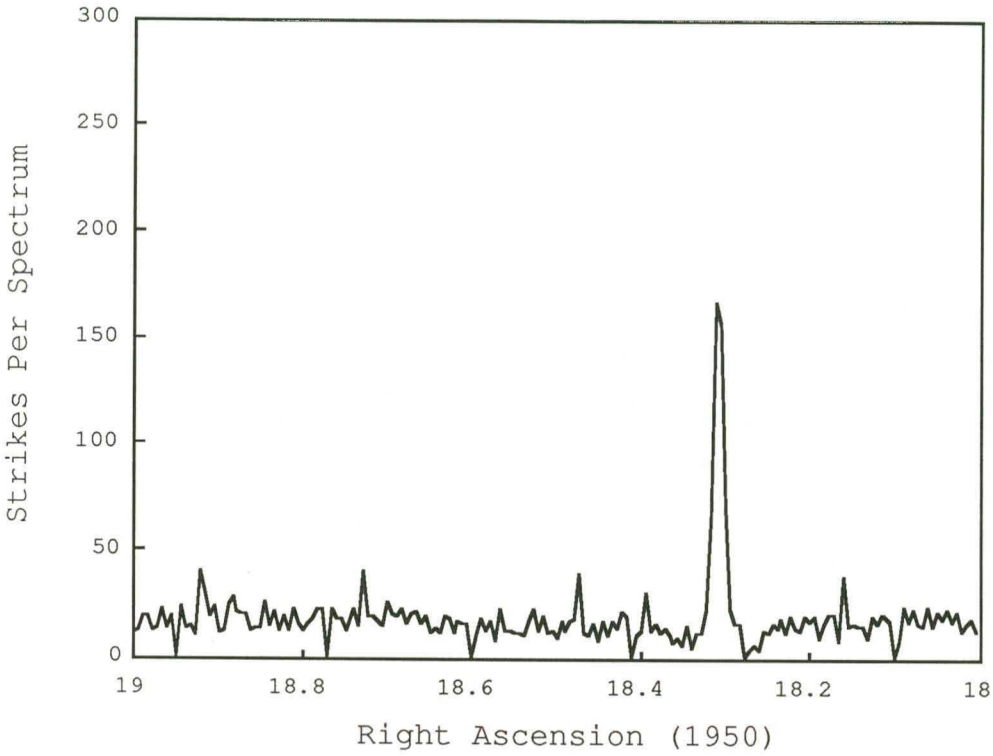


Figure 5.8 Total strikes per spectrum for the galactic plane transit, October 25, 1991.

The weak detection of the galactic plane shows that the sensitivity of the receiver is low. Even though broadband celestial sources exist at -13 degrees declination, none produced a total number of strikes per spectrum greater than the norm, which would have signaled their detection, as did the sun and galactic plane.

CHAPTER VI

Conclusions and Recommendations

6.1 Conclusions

The LOBES system detected and followed up on several narrow-band signals in a sky survey of -13 degrees declination over the period September 15, 1991 to March 15, 1992. Most of the sources were determined to be man-made satellites and local radio interference, not true celestial sources. Detection of the test signal and broadband sources confirmed that the pattern match and the narrow-band detection algorithms worked well. Frequent tests of the LOBES system confirmed that the receiving system worked well and that the feed horns moved accurately during source followup.

6.2 Recommendations for Future Work

The intent for this project was not to conduct a survey. It was, rather, to utilize the knowledge of the switched feed antenna pattern at the OSURO to detect celestial signals. This being satisfied, the next logical step is to conduct a systematic sky survey. My recommendations for future work outline some of the steps which must be taken to upgrade the LOBES system and the OSURO to smoothly conduct a sky survey of the water hole. Following those

suggestions, I propose two methods for detecting radio sources in an area larger than one beam width, which are analogous to current remote sensing techniques.

6.2.1 Current System Upgrade

All observations in this study were conducted with the LNA's at ambient temperature. Cooling the LNA's with liquid nitrogen would improve the signal to noise (S/N) ratio, thus providing greater sensitivity to weak sources.

Currently the system temperature and antenna effective aperture are only estimated. Studies should be undertaken to measure these factors in order to compare the sensitivity and coverage this system as compared to other SETI systems.

At present there is no RFI rejection besides using the pattern match algorithm and the switched feed system. The OSURO is equipped with a discone antenna mounted near the feed horns. It had been used to detect RFI in a past study [25], but currently is not in operation. This discone system needs to be integrated into the LOBES system to reject and analyze RFI.

The artificial signal should be used automatically to test pattern match algorithm and to run diagnostics on the 100 kHz and 10 kHz receivers. At this time the artificial signal is operated manually. For receiver diagnostics the LOBES system must be shut down. If the LOBES system instead ran tests automatically, regular performance assessments could be acquired easily without taking the system down.

For this study, the data stored by LOBES was studied to analyze the long term, steady-state performance of the system. Both

the pattern match algorithm and receiver system performances can be assessed using the stored data. Even with custom C and MATLAB programs to display the data, the analysis of the stored data proved cumbersome. A future project could be developed which could automatically analyze the data, looking for radio sources, cataloging RFI, and determining system noise temperature. The radio sources could be cross-referenced to known sources, providing confirmation of antenna direction, and perhaps providing new information about those sources.

6.2.2 Alternative Methods

Conventional large radio telescope receivers use a single feed horn, producing a single narrow beam of reception. As the effective aperture of the antenna gets larger, the beam gets narrower and the S/N ratio gets larger. One perceives the distribution of radio sources by placing powers received by congruent beam positions next to each other. This method of creating a radio "picture" of the sky takes quite a long time. It takes even longer for the largest radio telescopes because of their very narrow beams. Thus, the instruments most capable of observing weak radio sources can only map them very slowly. One way to increase the sky coverage of these large radio telescopes is to place a grid of stationary feed horns in the focal plane, thereby creating several beams and many times more coverage. Another way is to continuously scan one feed horn over an area of the focal plane, in a method much like an electron gun scanning across a CRT. The feed horn might also be able to track a source in order to analyze it with a longer integration time.

A grid of stationary feed horns in the focal plane could allow one to display the output of each in real time as a raster on a CRT. The beams of the feed horns could overlap, thus increasing spatial resolution. Different frequencies could be displayed as different colors, thus helping to identify radio objects. Neural network algorithms (or hardware) could be trained to recognize different classes of objects, such as broadband and narrow band sources, point and diffuse sources, RFI and celestial sources. If a particular source were interesting, all the receiving and processing power could be concentrated on the output of the particular feed horn where the source is centered. This would be similar to the biological function of centering the fovea of the retina on an object of interest which was seen in the periphery.

There are several problems with the feed horn grid approach. First is aperture blockage. In order for the grid to resolve a relatively large angular extent of the sky, the grid may block a large percentage of the aperture, thus reducing the overall sensitivity of the system and distorting the beam shape. The second problem is that in order to maximize the integration time of the entire system, each feed horn would need its own receiver system. A grid of, say, 20 by 20 feed horns would require 400 receivers and would cover an area of approximately six degrees by six degrees at a large radio observatory at 1415 MHz. A third problem is that the center of the focal plane receives the most power, whereas a radio image becomes weaker and distorted the farther it gets from center focus. The outer feed horns may be designed to compensate for some of these distorting effects.

The second approach I am recommending is using one feed horn to scan the focal plane, producing a two-dimensional picture of the radio sky. The feed horn could be mounted on a drafting board-type of mechanism, which could provide lateral and vertical motion, in the case of the OSURO's focal plane. The feed horn could be swept along a line of constant declination, moved a fraction of a beamwidth in declination, and swept back at constant declination. When the maximum declination is reached after several sweeps, the feed horn could be retraced back to the starting declination, where the scanning would resume. As in the feed horn grid approach described earlier, the display could be in colors representative of the objects' radio spectra, and neural networks could be trained to identify objects on-line. If more information on an object were desired, the feed horn would track it to increase the integration time. This is again similar to centering the fovea on an interesting object in the periphery.

There are several problems with this approach also. First is the integration time. In order to filter out as much receiver noise as possible, the receiver integration should be long -- as long as ten seconds for the OSURO. With this approach there would then be a tradeoff between integration time and sky coverage. A problem related to integration time is the number of times the feed horn would observe an object while that object is in the focal plane. Several successive pictures could be overlaid to increase sensitivity. A transient event, such as a SETI signal, would be missed or discarded as RFI if not enough pictures were taken of the signal. A second problem with this approach is the need for a large mechanical structure. In order to resolve a picture one hour in RA and five degrees in declination at the OSURO,

one would need a structure at least 100 feet long by 70 feet high. This structure would provide little aperture blockage, since it is mostly open space, however with exposure to the elements, this structure could become difficult to maintain and repair.

Both of the above approaches can be seen as analogs to the remote sensing devices used by the SPOT and LANDSAT land observation satellites [26]. The SPOT detectors are a linear array which resolve in parallel a swath of the ground below. Each of these detectors can resolve three frequency bands in the visible and near infrared ranges. The SPOT detector system is analogous to the feed horn grid approach. The LANDSAT sensing device is a single detector which receives its input from a mirror. This mirror sweeps a lateral image of the land across the detector, allowing it to "see" only one spot on the ground at a time. By placing the scan lines next to each other, one builds up an image of a swath of the ground. This is analogous to the single, sweeping feed horn approach. There are many image processing techniques currently in use to manipulate remotely sensed data which could be applied to radioastronomical data. If the radio data were released in a suitable format, such as GIF, many more researchers would be able to study it. Plus, if reliable, repeatable coverage were possible, transient events in the radio sky may be discovered.

It would be no easy feat to outfit a radio telescope with either of the above two approaches. However, with radio telescopes soon to be built in space, such factors as effective aperture and sensitivity may be easy to overcome. First, because of the weightlessness of space, a radio telescope could be built extremely large and to an extremely precise shape, increasing its

effective aperture. Second, because of the insulating property of vacuum, a helium-cooled front end would need infrequent service and would provide excellent S/N ratio. Thus, the aperture blockage caused by a grid of feed horns could be minimized, and a single scanning feed horn could resolve smaller angular features at higher sensitivity.

LIST OF REFERENCES

[1] R. S. Dixon, "The Ohio SETI Program, The First Decade," *Proc. I.A.U.*, Symp. No. 112, Reidel, 1985.

[2] G. Cocconi and P. Morrison, "Searching for Interstellar Communication," *Nature*, Vol. 184, p. 844, 1959.

[3] J. D. Kraus, *Radio Astronomy*, 2nd Ed., Cygnus-Quasar, 1986.

[4] B. Oliver and J. Billingham eds., "Project Cyclops," NASA Rept. CR114445, 1971.

[5] V. I. Slysh, "A Search in the Infrared to Microwave for Astroengineering Activity," *Proc. I.A.U.*, Symp. No. 112, Reidel, 1985.

[6] N. S. Kardashev, "Strategy for the Search for Extraterrestrial Intelligence," *Acta Astronautica*, Vol. 6, pp 33-46, 1979.

[7] R. S. Dixon, "A Search Strategy for Finding Extraterrestrial Beacons," *Icarus*, Vol. 20, pp. 187-199, 1973.

[8] D. M. Cole, "A Search for Extraterrestrial Radio Beacons at the Hydrogen Line," Master's Thesis, The Ohio State University, 1976.

[9] A. M. Peterson, K. S. Chen and I. R. Linscott, "The Multichannel Spectrum Analyzer," *Proc. I.A.U.*, Symp. No. 112, 1985.

[10] D. K. Cullers, I. R. Linscott and B. M. Oliver, "Signal Processing in SETI," *Communications of the A.C.M.*, pp. 1151-1163, Vol. 28, 1985.

[11] S. Bowyer, G. M. Zetlin, J. Tarter, M. Lampton and W. J. Welch, "SERENDIP," *Icarus*, Vol. 53, pp. 147-155, 1983.

[12] C. Donnely, S. Bowyer, H. Herrick, D. Werthimer, M. Lampton and T. Hiatt, "The SERENDIP II SETI Project: Observations and RFI Analysis," Space Astrophysics Group, Publ. No. 428, 1990.

[13] S. Bowyer, "The UC Berkeley Program," *First Contact*, B. Bova and B. Preiss eds., pp. 215-220, NAL, 1990.

[14] P. Horowitz and W. R. Alschuler, "The Harvard SETI Search," *First Contact*, B. Bova and B. Preiss eds., pp. 206-214, NAL, 1990.

[15] P. Horowitz, B. S. Matthews, J. Forster, I. Linscott, C. C. Teague, K. Chen and Peter Backus, "Ultranarrowband Searches for Extraterrestrial Intelligence With Dedicated Signal-Processing Hardware," *Icarus*, Vol. 67, pp. 525-539, 1986.

[16] P. J. Napier, A. R. Thompson and R. D. Eckers, "The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope," *Proc. IEEE*, Vol. 71, No. 11, pp. 1295-1320, 1983.

[17] J. Tarter, "Using the Very Large Array and Other Radio Telescopes to Perform a Parasitic Search for Extraterrestrial Intelligence," I.A.F. Report No. 84-245, 1984.

[18] R. S. Dixon and T. F. Van Horne, "SETI Zoom Techniques," OSURO Preprint 89-1, 1989.

[19] J. L. Bolinger, "A Simultaneous Multi-Beam Phased Array Using Digital Processing Techniques," Master's Thesis, The Ohio State University, 1988.

[20] J. L. Bolinger, "The RED Book: OSURO PDP and Receiver Systems," OSURO document, 1988.

[21] R. K. Childers, "The LOBES supplement: Operation and Upkeep of the LOBES SETI system," OSURO document, 1991.

[22] R. K. Childers, "An Extended Observation of OI-284.3 Using the OSURO Tracking System," OSURO document, 1990.

[23] J. D. Kraus, "The Center of Our Galaxy," *Sky and Telescope*, Vol. 65, p. 30, 1983.

[24] R. S. Dixon and C. A. Klein, "On the Detection of Unknown Signals," a paper presented at the USA-USSR Joint Conference on SETI, Aug. 8, 1991, Santa Cruz, CA. Proceedings in press.

[25] S. Ahmed, OSURO document, 1989.

[26] J. B. Campbell, *Introduction to Remote Sensing*, Guilford Press, 1987.

[27] R. Dixon, "The Ohio State University Program," *First Contact*, B. Bova and B. Preiss eds., pp. 199-205, NAL, 1990.