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Project BETA *by Andrew J. LePage*

Harvard University's Billion Channel Extraterrestrial Assay

Dr. Louis Friedman (at microphone) of The Planetary Society and some of the engineers from Harvard University who designed and built Project BETA. Photo taken October 30, 1995, at the Project BETA Dedication Ceremony.

The Signal

It was a cold winter night and a foot of newly fallen snow softened the contours of the rural New England landscape. The only hint of life seemed to be a solitary Harvard graduate student slowly making his way to the small building near the base of a giant dish antenna. After he warmed himself and his equipment, the giant radiotelescope of the Oak Ridge Observatory in Harvard, Massachusetts whirled to life and the evening's observations began. The antenna skewed towards the Pleiades and the radio spectrum near the line of neutral hydrogen was scanned as had been done many times before.

Without warning, the boredom of another ordinary observing run evaporated when an unexpected signal appeared. The graduate student deftly adjusted the receiver and discovered that this new signal was not only very strong but possessed a bandwidth narrower than his state-of-the-art electronic equipment could measure. "Could it be?" he wondered to himself. This signal had all the attributes one would expect of an artificial signal from the Pleiades. The final test was to move the telescope off the target and see if the mysterious signal would disappear. Unfortunately, this time the signal was still present after the telescope skewed slightly off target. The only reasonable explanation was that the signal was some sort of man-made interference, possibly from a nearby military facility. After the student returned to his routine observations, he could not help but wonder what a signal from an extraterrestrial civilization would actually look like and whether this equipment was up to such a task.

Given the snowy weather in Massachusetts during the winter of 1996, this story could easily be taken to be about Project BETA. In reality, it occurred forty years earlier and our Harvard graduate student was Frank Drake (1, 2). The episode took place while he was using the then new radiotelescope at the Oak Ridge Observatory to map the distribution of neutral hydrogen in the Pleiades. The appearance of this signal prompted Drake to perform calculations to determine what would be needed to detect

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signals from actual ETIs. This intellectual journey ultimately lead Drake to Project Ozma in 1960.

Over the years to come, many other scientists and engineers would join the search using facilities all over the globe. Eventually, another man from Harvard University, Paul Horowitz, would bring the search back to the Oak Ridge Observatory where the seeds of SETI were planted. He would make use of the very same antenna Frank Drake used so long ago and perform the most powerful SETI searches to date.

The Goal

Many SETI programs have made use of a certain portion of the electromagnetic spectrum called the "Waterhole." A favorite spot for microwave SETI practitioners, this band of radio frequencies ranges from about 1.40 to 1.72 GHz. At the high end of this band, the hydroxyl molecule naturally radiates while at the other lies the famous 21 cm neutral atomic hydrogen emission line. This portion of the radio spectrum is called the "Waterhole" because the hydroxyl molecule and hydrogen can combine to form the biologically important molecule water.

The biological implications and poetic imagery of the waterhole concept not withstanding, this frequency band is favored in SETI searches because this is where the background noise in the universe's natural electromagnetic spectrum is at a minimum thus facilitating the detection of weak, distant signals (3). In addition, many believe that near the common hydrogen emission line is a logical part of the radio spectrum for extraterrestrials to place a beacon for others, like us, to find.

Unfortunately, the best way to transmit a beacon that is detectable through the naturally occurring noise is to do so with a narrowband transmission. Because of the frequency broadening effects of free electrons in the thin interstellar medium, the minimum practical bandwidth near the Waterhole is about 0.1 Hz (4). Simple math easily reveals that over a billion possible frequencies or channels exist in this radio band. Searching through so many channels is an enormous task. Project Ozma made use of only a single broadband channel near the atomic hydrogen line (5). Later searches would be performed using narrower bandwidths and more channels, but only a tiny number of the billions of possible frequencies could be searched at any given time with these early systems.

Powerful Multi-Channel Searches Begin

Starting in 1981, Paul Horowitz proposed the construction of a powerful, multichannel SETI system to search through many more channels with almost unprecedented frequency resolution (6). Because of the enormous amounts of data that such a system would produce, a computer would have to be programmed to search through the raw spectral data so that only the most promising signals would be brought to the attention of the human operators.

The following year, Horowitz started building his first system, dubbed Sentinel. He made use of the latest computer and electronic technology to produce a small, portable system to sift through a still remarkable 131,000 radio channels (7). Because of its portability, it could in principle be carried by hand anywhere on the globe and hooked up to any sensitive radio telescope. Ultimately, it ended up performing its search using the same radio telescope Frank Drake used a quarter of a century earlier.

With funding from the Planetary Society and numerous private donations, Horowitz and his team used the experience gained with Sentinel to build an even more powerful system called META (Million channel Extra-Terrestrial Assay). Starting in 1985, META made use of an array of powerful computer processors to sift through eight million radio channels that covered 400 kHz of bandwidth (8).

While this system could scan more frequencies and bandwidth than any other built to date, it still could survey only about 0.1% of the Waterhole at any given time. As a result, "magic" frequencies still had to be chosen, such as near the 21 cm neutral atomic hydrogen line or its second harmonic line. The relatively narrow bandwidth also required that a variety of Doppler shift corrections be made depending on the choice of preferred frames of reference. The frames of reference considered in META included a heliocentric frame to detect signals intentionally beamed towards our solar system as well as the galactic barycentric frame of reference and in relation to the cosmic microwave background (8). These latter two frames of reference could be used to detect beacons transmitted across our galaxy or our local group of galaxies.

What was needed was a system that could search 100% of the Waterhole with good frequency resolution. Such a wide bandwidth would eliminate the need to choose a specific magic frequency and reduce the heavy reliance on Doppler corrections to a preferred frame of reference. Based on experience with META and taking advantage of the great leaps in computer technology, Paul Horowitz and his team determined that such a goal was possible within a modest budget.

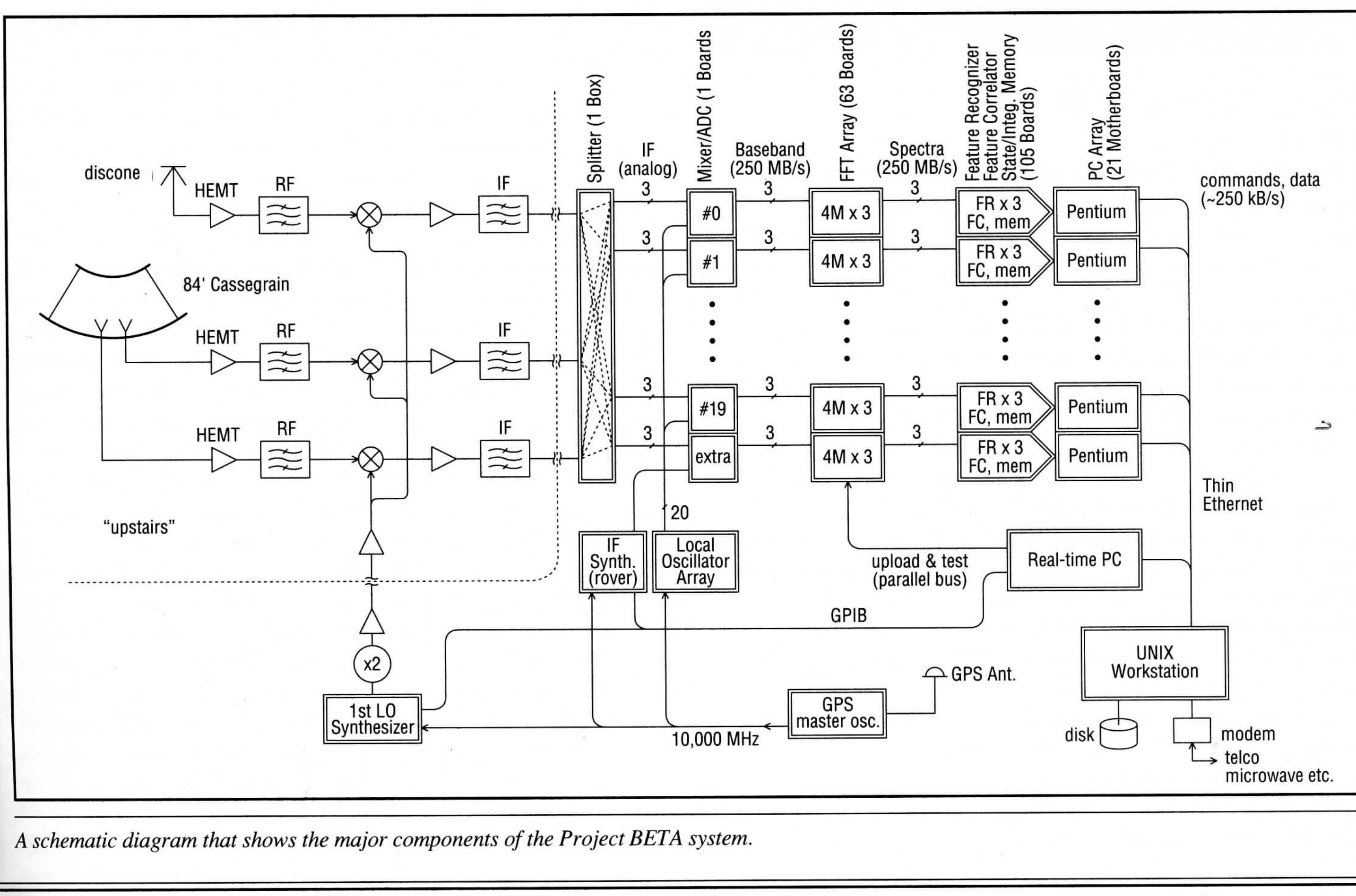
In 1991, with financial support from the Planetary Society, the Bosack/Kruger Charitable Foundation and NASA, Project BETA (Billion channel Extra-Terrestrial Assay) was born. While NASA funding ceased in 1992 when all federal expenditures on SETI were cut, contributions of equipment and components were forthcoming from Advanced MicroDevices, Fluke, Hewlett-Packard, and Intel Corporations as well as from Ohio State's SETI pioneer, John Krause (6).

To keep expenses within budget, some electronic components used in BETA were salvaged from a host of used electronics shops and flea markets all around the Boston, Massachusetts area. Additional components were donated by various corporations including three gigabytes of RAM donated by Micron Technology estimated to be worth about $100,000. A band of dedicated students fabricated, assembled and tested all the custom-made boards used in the system. Finally on a sunny fall day in October of 1995, all the hard work and planning came to fruition when an antique copper knife switch was thrown and Project BETA officially began operation.

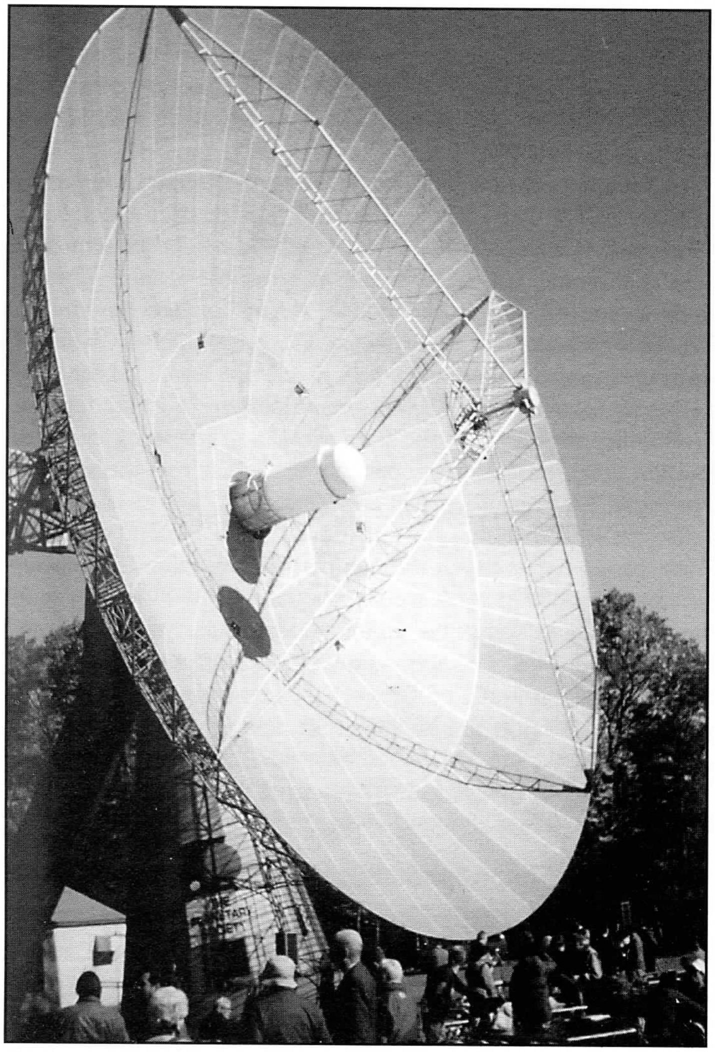
Project BETA is the most advanced SETI system yet built. With the ability to search through 640 million radio frequencies received by three antenna feeds, it is the first SETI system with the capability to search the entire Waterhole in one fell swoop. Because of its huge computing power, this system also possesses an enormous amount of flexibility, allowing the sky to be searched in a multitude of different modes which add to the chances of detecting any extraterrestrial signals that may exist. What follows below is a description of this system that only begins to give a hint of the power of BETA.

A Triple-Antenna Approach

Project BETA performs its survey with the same radiotelescope used earlier by Projects Sentinel and META. Located at the



A schematic diagram that shows the major components of the Project BETA system.



Project BETA dedication ceremony.

Harvard-Smithsonian Oak Ridge Observatory in Harvard, Massachusetts, this fully steerable 26 meter (84 foot) Cassegrain antenna has been in use since the mid-fifties for a variety of radio astronomy projects. This dish is equipped with dual feedhorns housed in a radio-transparent fiberglass cylinder at the telescope's Cassegrain focus. Each feedhorn has a half degree beamwidth. One looks one degree to the east of the antenna's boresight and the other one degree to the west. A third omnidirectional discone antenna observes the horizon in all directions.

Installed specifically for Project BETA, this new discone antenna is needed to monitor any terrestrial interference that may be present. Interference detected by META, with its relatively small bandwidth, would quickly pass out of band due to Doppler chirping, thus only temporarily taxing its computer system. BETA's much larger bandwidth means that interference is continually present. To avoid overloading the signal processing hardware further downstream, a means of independently monitoring man-made radio interference is crucial.

While the equatorial-mounted main dish can follow targets in the sky in a sidereal tracking mode, initially Project BETA will use it for what is called a meridian survey. In this survey, the antenna is pointed at a certain elevation angle due south. The Earth's rotation then allows the antenna to scan a half degree wide strip across the entire celestial sphere over the course of a sidereal day without having to move.

The following day the elevation angle is changed by the telescope's one half degree beamwidth and it begins to scan the adjacent strip of the sky over the course of another day. This system can survey about three quarters of the sky visible from Oak Ridge (ranging from -30 degrees to +60 degrees declination) in as little as six months. The actual time to complete a survey will be longer because of unavoidable system downtime, weather, and time spent on re-observing interesting strips of sky.

While performing its meridian survey, the system is looking for a constant, narrowband carrier signal that displays a certain pattern of visibility to the antennas and their feedhorns. This visibility pattern acts as a type of sidereal detection filter. First, a potential SETI signal would appear in the east horn. If the signal is constant, it should take about two minutes for the source to transit the feedhorn's beam as the Earth rotates. Then the signal is expected to become detectable by the west horn again for about two minutes. If, at the same time, the omnidirectional antenna watching for terrestrial interference does not detect this signal, it would be concluded that an extraterrestrial signal candidate had been detected. Once fully operational, the telescope would then automatically move ahead of the signal's position in the sky by several beamwidths and watch for a repeat performance. If the same pattern is detected again, an e-mail message would be automatically sent to the Harvard University campus by the system's main computer workstation.

This capability to immediately reobserve a promising signal is a major improvement over Project META. During its years of operation, META detected 37 promising ETI signal candidates (referred to as "extra-statistical events") (8, 9) but was unable to repeat its observations until the following day. None of the candidate signals were detected again even after extended targeted searches. Project BETA will ultimately have the capability to reobserve a signal within minutes of its detection and continue observations for as long as the signal is present or until it nears too close to the horizon. If the signal is especially interesting, the BETA allows for a scan of the same strip of sky the following day just as META. However, because of BETA's much larger bandwidth, it will be more likely to re-acquire the signal if it is still present but Doppler shifted elsewhere in the radio spectrum. The sidereal detection filter comes into play if the east-horn-then-west-horn pattern is not observed. If some other pattern of the visibility of a narrow band signal is observed, it cannot be a distant extraterrestrial signal. If the terrestrial discone antenna ever detects a signal seen by the main dish's feedhorns, it must surely be man-made radio interference. In this way, the discone antenna itself acts as a powerful filter with the ability to veto a detection, thus lessening the burden of the processing equipment further downstream.

The two feedhorns and the discone antenna each employ their own HEMT low-noise amplifiers connected to agile heterodyne front-end down-converters that step down the frequency of the signals received. This system uses a dedicated computer controlled Local Oscillator whose signal is derived from a 10 MHz GPS master oscillator. The Local Oscillator's frequency is altered to correct the output signal for the Doppler shifts resulting from the Earth's motions. In this way, the system stays precisely tuned to the Waterhole frequency band in a heliocentric frame of reference.

The three receivers feed an array of 21 quadrature mixer/digitizers that use a 10 MHz GPS phase-locked Local Oscillator array to synchronize their operation. This arrangement allows the received signal to be converted into a stream of digital numbers corresponding to the strength of the signal at each data point. These digital signals are then fed into a 250 million-channel Fourier spectrum analyzer at a rate of 250 megabytes per second.

The Fourier Spectrum Analyzer

The array of 21 quadrature mixer/digitizers feeds a dedicated array of 63 Fourier spectrum analyzer boards. The spectrum analyzer breaks down the incoming signal into its individual frequency components using an algorithm called the Fast Fourier Transform (FFT). Named after Jean Baptiste Joseph Fourier, the early 19th century French mathematician who developed the concept, the FFT shows that any function—such as a radio signal—can be described as a linear combination of cosine waves of various amplitudes, frequencies and phases. The FFT is a mathematical method for quickly processing any digital signal to determine the strength and phase of the individual discrete frequency components of which it is composed. A program can be written to perform the FFT or, to increase the processing speed, a computer circuit can be custom made to perform this transform on an incoming digital signal.

Nature makes use of the Fourier transform in its construction of the human ear. Consider the sound produced by an orchestra or band. The notes produced by each of the musical instruments combine to form a complex pattern of sound waves. The ear takes this pattern of air pressure variations and breaks the signal into its individual frequency components in the inner ear. Each of these frequency components is basically a musical note. This information is then turned into nerve impulses, sent to the brain where it perceives the pitch and loudness of the incoming sound waves and interprets it as music. Just as the human ear takes a complex pattern of sound waves and converts them into a spectrum of musical notes, the 63 FFT boards in BETA take the received radio signals and break them down into a spectrum of radio frequency channels.

As is the case with so many of BETA's components, no commercially available FFT boards were capable of performing the task, so they were custom designed and built by the Project BETA team. Each board in the FFT array is an innovative three-chip design that performs a four megapoint complex FFT every two seconds. The algorithm that led to this design evolved from the elegant design developed by the Berkeley SETI group for SERENDIP.

Each board was designed and assembled from scratch including all the card cages, power supplies and all interconnecting cabling. While many of the boards' components were obtained second hand, some of the more important and difficult to find devices were donated by various corporations. The large amounts of RAM needed for the boards was generously donated by Micron Technology while the Mach CPLDs that control the FFT array's operation were donated by Advanced MicroDevices.

A total of 70 boards (the primary 63-board array and seven spares) were assembled and soldered by a veritable army of steady-handed students. Despite the complexity of the boards, with a grand total of a quarter of a million solder joints, about 90% of them worked properly the first time the system was powered up for testing.

The spectrometer array operation is completely synchronous using a 40 MHz differential ECL clock distribution generated from the 10 MHz GPS-derived master oscillator mentioned earlier. This synchronization signal is distributed to each FFT board ensuring that they all work together in lock step. The FFT board controller routinely performs a pairwise board validation using test ports fitted to each board. The test signal used is produced by a pseudorandom test vector generator implemented on the Mach 210 CPLD. By comparing the test results from two different boards processing the same test signal, the FFT boards' functionality can be verified. If the results from the two FFT boards are equal, both boards are functioning properly.

Each of the radio channels of the FFT boards' spectrum is only 0.5 Hertz wide, much narrower than the television channels that are commonly used today. Despite this, BETA's channel width is still ten times coarser than the 0.05 Hertz channel width used in Project META (8). The high frequency resolution of META was traded for speed so that a much wider range of frequencies could be scanned more quickly. Since the 250 million channels of the FFT array are evenly divided among the three antenna feeds, the system has an instantaneous bandwidth of about 40 MHz.

In order to meet the goal of scanning the entire 320 MHz wide Waterhole, the system has to make eight 40 MHz steps in frequency to scan the entire band. To do this, the system samples the incoming signal for two seconds and processes it on the fly. After data from one 40 MHz wide band is gathered, the adjacent frequency band is observed followed by the next and so on. Over the course of 16 seconds, the entire Waterhole radio spectrum is scanned and the process then repeats. The system is also capable of maintaining a fixed frequency so that a particular band of frequencies can be continuously observed.

Since it takes about two minutes for a radio source to transit the beamwidth of each feedhorn, any discrete radio source would be observed up to eight times, thus allowing the system to make multiple observations of a potential ETI signal. If this technique used in Project BETA were applied to a system with the same frequency resolution found in META, it would take almost a half an hour to scan the entire Waterhole, thus increasing the complexity and time needed to perform an all sky survey.

A Look At The Feature Recognizer

The output of the 63 FFT boards is fed at 250 megabytes per second to the most crucial of all the system's components: The Feature Extractor. As was the case with the spectrum analyzer, no off-the-shelf hardware existed that was capable of processing data on the fly at this rate. As a result, a custom Feature Extraction system was designed and constructed to process the enormous amounts of data produced by the FFT board array.

The hardware configuration of this portion of the system consists of 21 copies of three Feature Recognizers, one Feature Correlator, and a donated Micron Technology Inc. RAM memory board which acts as a State Machine, all interfacing with a Pentium ISA bus donated by Intel. Each set of boards receives data from three FFT boards covering a common 2 MHz portion of the radio spectrum from the three antenna feeds. Twenty of these board sets cover the 40 MHZ instantaneous system bandwidth. An extra 21st set acts as a redundant "rover" set that can perform independent operations such as monitoring one of the other board sets to detect errors. Each of these 21 sets of boards is housed in its own mini-tower case with an integral power supply. These mini-towers are set on metal shelves in a building adjacent to the main antenna.

In operation the four million point output spectrum from each FFT board is passed to one of three Feature Recognizers mounted in a PC mini-tower. A moving 4,000 point baseline average is set by summing the squares of the magnitudes of the complex Fourier spectrum. The data point in the center of this boxcar average, as well as the baseline, then proceeds to the next processing step. Here the power sum is barrel shifted and the square root is taken to convert the data value back to a magnitude. This square root function is preprogrammed as a one function variable that uses precalculated values encoded on ROM. This eliminates the need to calculate a square root and greatly increases the processing speed.

Next the data value is multiplied by four different threshold values. These multiplication tables are also precalculated based on the desired threshold values and stored on ROM. The threshold values, as well as the amount of the barrel shift, can be set on the fly by the PC. Every element of the magnitude spectrum is then compared to all four baseline-threshold products. The largest threshold represents a signal well above the noise baseline. The lower thresholds are used to track signals of lesser strength without necessarily forwarding them to the PC. One of the Feature Recognizers in each mini-tower contains extra RAM. The extra memory allows this particular Feature Recognizer to operate in an integration mode where the power spectra are summed and stored. Since it takes several seconds for the entire spectrum to be read through the slow PC bus via the Feature Correlator, the PC can request that only a small section of the spectrum or "slot" be quickly read. If the antenna is operating in a sidereal mode where it can track an interesting target for several minutes, the PC can request that the entire spectrum be downloaded during the course of an integration.

This spectrum can also be recirculated through the Feature Recognizer board's signal recognition circuitry and processed just like an ordinary spectrum as described above. This system provides substantial flexibility because each Feature Recognizer can be independently programmed by the PC allowing the signals from different antenna feeds to be processed in different modes simultaneously. While this mode of operation would not allow the use of the sidereal detection filter algorithm, it could allow interesting signals detected by the east horn to be reobserved in an integration mode by the Feature Recognizer in the corresponding west horn.

Feature Correlator

The Feature Recognizer results from each of the three antenna feeds are then passed to the Feature Correlator. The Feature Correlator forwards data from preselected slots or other interesting frequencies to the PC. The PC can automatically forward the baseline and signal magnitudes from all three antenna feeds occurring in certain frequency slots. If certain frequencies are not interesting due to the frequent presence of terrestrial interference, they can be notched and never passed to the PC. This notching prevents loss of potentially interesting signals due to the time needed for the system to transfer and process useless radio interference.

The system will also watch for potentially promising signals that are not currently slotted or notched and forward those new data to the PC. This determination is made by a programmable State Machine that keeps track of the data in time and frequency space. The State Machine is RAM that contains a program which can be altered by the PC. Reprogramming of the State Machine takes place in two seconds and can be performed while the rest of the system is operating. During this down time for reprogramming, the State Machine will be unavailable and this set of boards (consisting of the three Feature Recognizers and one Feature Correlator) will be unable to process new input signals for its assigned 2 MHz band for one data cycle. The inconvenience of this two-second downtime is avoidable if the reprogramming takes place while one of its Feature Recognizers is otherwise occupied in an integration mode. The programs used to control the State Machines are written in an intuitive language in an easy to understand format that was specifically developed for this project.

The State Machine receives a 14-bit number from each Feature Recognizer for each frequency bin during a processing cycle. The first seven bits convey how many thresholds are exceeded by the signal from the three antenna feeds. Since each Feature Recognizer can be in one of five states (with between zero and four thresholds exceeded), these seven bits (with 128 possible values) must convey 125 possible states to the State Machine. The State Machine also receives five bits describing the time based state which is stored in the Feature Recognizer's RAM for the next time a particular frequency is visited. This allows the system to keep track of what is going on in a particular frequency bin from one scan to the next. An additional two bits represent the frequency based state and is sent to State Machine itself from the previous frequency bin. This quantity allows the system to keep track of signals in adjacent bins. This will be especially useful for recognizing slightly broadened transmissions or those whose frequencies fall between the discrete frequency bins of the system.

Based on these 14 bits of information, the State Machine generates an 8-bit number for each frequency bin. The first 5 bits is time based state information to be stored. This quantity is retrieved and used for comparison the next time a particular frequency bin is scanned in a full 16-second data acquisition cycle. The next 2 bits contain frequency based state information to be forwarded to process the next frequency bin. The last bit specifies whether the data for this particular frequency bin should be forwarded to the PC via the low bandpass PC bus. Since the State Machine processes the state information for all three antenna feeds in a particular 2 MHz frequency band, it can perform tests to reject signals resulting from terrestrial interference.

A Pentium-based Design

The entire system is easily configurable from the PC. The Feature Correlators can be directed to consider certain areas of the spectrum as more or less interesting than others. In cases where there is persistent interference from any source (e.g. terrestrial interference), those frequency channels can be "notched" out and always ignored. Since the operation of the other boards resident in the mini-tower does not use all of the PC's processing power, it can be programmed to perform higher level processing of data passed by the Feature Correlator. This arrangement is quite flexible and allows new detection algorithms to be programmed with only a moderate amount of effort.

Each of the 21 Feature Correlators communicates with a dedicated Pentium-based PC motherboard with 16 MB of RAM housed in the same mini-tower. The 21 Pentium PCs do not have

Some of the Pentiums used by project BETA

any drives, monitors, or keyboards of their own due to the complexity and expense of maintaining so many extraneous pieces of hardware. Instead these PCs communicate over a thin-wire Ethernet with a UNIX workstation on-site that serves as a 1.44 MB floppy disk. To increase the flexibility of this array of computers, individual Pentiums can be booted from a different "virtual" disk, allowing them to run different computer programs specific to an individual task. This feature is especially useful for programming the redundant "rover" PC.

The UNIX workstation utilities have been modified to ease accessing and manipulating the PCs' MS-DOS format disks and their virtual images. This capability allows the programmer to easily copy programs from one PC to the network-accessible virtual disks where they can then be tested and run. As a result, the back end computers appear identical to a computer with a disk to the software. This setup greatly eases software development.

The computer arrays are programmed in C++. A DOS extender is used to provide a "flat" memory model that is not subject to the usual memory segment and 640 kilobyte memory limitations found in a normal DOS operating environment. The C++ programs are linked using hand crafted assembly language subroutines. This results in a fast, clean interface between the high level C++ code and the Pentium motherboard hardware and greatly improves the processing speed of this custom configuration.

Also connected to this LAN is a special "real-time" PC. It is used to calculate planetary ephemerides for a variety of purposes. It uses these ephemerides, for example, to derive Doppler corrections with a long term accuracy of 5 meters per second. The computer then uses this information to control the frequency of the Local Oscillator's frequency generator. The ephemerides information also lets the system know when to notch out frequencies due to solar interference.

The real-time PC acts as a central clock by sending synchronization packets across the LAN to keep the system operating in step. Display software shows useful real-time quantities such as the current UTC and sidereal times, antenna pointing, and the current frequency band under observation. These quantities, along with synchronization packets, are also forwarded to the workstation.

Upon receipt of Ethernet packets from the real-time PC, the workstation interrogates each Pentium in the backend array. The PCs then report data relating to new hits received and slots that have been completed. The workstation is also capable of requesting premature slot downloads and frequency notching. The workstation dynamically monitors the quantity of data received whereupon it can modify the threshold values for each PC separately. This allows the system to maintain optimum network and CPU loading.

Depending on its ultimate processing demands, the workstation is also potentially available to perform more higher level processing of interesting signals. The entire BETA system is capable of producing a full compact disk load of raw data every couple of seconds. Since storing this amount of data is impractical, additional processing by the PCs and/or the workstation will be needed so that only the most interesting data are archived in the relatively limited hard disk space. Commands and data to be processed or archived pass through the LAN at a rate of about 250 kilobytes per second.

Another UNIX-based workstation located on the Harvard University campus can communicate with the system at Oak Ridge over the net. This allows Project BETA team members to check on the system's status, download archived data, and upload new instructions without having to make the hourlong drive to the observatory. The system can also be run remotely from this station, allowing the user to manually control the equipment. Using a variety of graphical displays, the user can also monitor the radio spectra from all three antenna feeds as they are taken. These sorts of capabilities will be most useful during the early phases of operation as the system is debugged and optimized.

The whole Project BETA computer system operates at an astounding 40,000 MIPS (40 billion operations per second) and contains 3.2 gigabytes of RAM serving a total of 200 processors. While BETA's individual components and computers may be commonplace, taken together the system qualifies as one of the world's most powerful, albeit highly specialized, data processing computers.

Moving Towards the Survey

While the system was up and running at the time of this writing, Project BETA has not yet begun regular autonomous observations of the sky. Because of its complexity and the enormous amount of data that must be processed, it will take time to fine-tune the equipment and software so that the system will operate at maximum efficiency with only infrequent human intervention. One issue that must be addressed is radio interference. While Harvard, Massachusetts is far from any city, television transmitters in the nearby Boston and Worcester areas constantly bathe the Oak Ridge site with noise. Portions of the Waterhole are protected from direct broadcasts by international treaty, but there exists a large amount of radio interference from the sideband leakage of nearby transmitters. A small 100-watt UHF transmitter with an isotopic antenna gain located just 100 kilometers away, for example, can meet statutory spurious emission limits and still leak noise into the Waterhole that results in a signal thousands of times higher than the ambient background noise (8). Considering the number of transmitters that are more powerful than this and closer than 100 kilometers, such interference is always present.

Another source of noise is the ever more common cellular telephones and other small, high frequency transmitters nearby. In addition to contending with mobile transmitters, there is a cell site

Project BETA componentry.

just down the road from the Oak Ridge Observatory that serves the local area. Assurances have been given, however, that this transmitter will be moved if it proves too much of a nuisance.

The man-made interference is not restricted to the ground, either. Sideband leakage from Russia's constellation of GLONASS Earth orbiting satellites (the equivalent of the American Global Positioning System or GPS) is quite common due to the more relaxed design standards of its transmitters. Other satellites also contribute their fair share to the ever growing level of man-made radio interference from the heavens.

Experience will be needed to determine which radio frequencies are most commonly polluted by interference and which should be "notched" so that the system's Feature Recognizers will ignore it. Intermittent noise from various man-made sources that occurs at unnotched frequencies should be rejected with the current algorithms because they do not display the visibility pattern expected from an ETI and would also exhibit a distinctive Doppler chirp signature.

Another area in need of fine-tuning is the values of the four thresholds. The values of these thresholds will be important in that the system will track only interesting signals and not waste time processing worthless noise or interference. While there have been many studies and simulations performed to determine the levels of naturally occurring background noise, real data and experience gathered by actual operation of the system is required to assign the appropriate thresholds.

The detection algorithms are also in need of fine-tuning. Presently the system is set to look for narrowband carrier wave transmissions with a constant intensity. Observations will be required to see how the algorithms will react to scintillation as well as other naturally occurring effects that can modulate the incoming signal. Research and observation are required to determine how to detect other types of signals, such as those that may be modulated with a period of seconds or minutes. Studies will also be required to develop an algorithm to detect and recognize signals that might be drifting through frequency space over the course of several observations.

The detection algorithms will have to be robust enough to contend with other real-world problems. For example, the main radio telescope's structure flexes when the wind blows. Under even moderate wind conditions this flexure can result in the telescope's aim drifting by about a beamwidth. (Members of the Project BETA team have quipped that this is probably the reason why the telescope was available for their work.) Currently there is no way for the Feature Correlators to take this into account since it takes data serially in time and assumes that all apparent target motion is the result of the Earth's rotation. Some sort of position sensor may need to be fitted to the dish to measure its true position. With modifications, it may be possible for the Feature Correlator, working with the higher level processing capabilities of the PCs, to correct for the wind induced aiming errors or at least ignore the data that is adversely affected.

With all the operational modes available to various components, tests will be performed to determine which combination or combinations yield the best results in various types of searches. Even when the initial survey is completed, surveys using other modes or even targeted searches of specific stars could be carried out to broaden the range of possible types of transmissions that could be detected. It is even possible that totally new search strategies not yet conceived could be programmed and undertaken because of the immense flexibility of Project BETA's hardware.

Because of its power and flexible design, Project BETA represents the pinnacle of what SETI can accomplish using today's technology. This highly innovative, custom-built system promises to return a wealth of data for years to come provided that the generous funding from the Planetary Society, as well as from other private sources, is maintained.

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