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RECENT SETI OBSERVATIONS AT ARECIBO

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Abstract—During 1980 and 1981, the 305-m radio telescope at the Arecibo Observatory in Puerto Rico was used to conduct a high resolution search for narrowband signals from the direction of 210 nearby solar type stars and 5 OH masers. For each star at least 4 MHz of bandwidth surrounding the 21-cm HI line and/or the 18-cm OH lines was studied with a spectral resolution of 5.5 Hz in both right and left circular polarization. The formal limit of sensitivity achieved during the course of this search varied depending upon the particular receivers available. In all cases the search could have detected a narrowband transmitter of power comparable to the Arecibo planetary radar, had any such been transmitting on the frequencies searched during the time of observation out to the distance of the farthest target star. As in previous searches, the number of "false alarms" encountered was far greater than predicted on the basis of Gaussian noise statistics. A small number of stars have exhibited signals which cannot immediately be explained in terms of astrophysical or man-made sources and deserve reobservation. This is typical of the results of previous non-real-time searches and does not yet constitute the detection of an ETI.

1. INTRODUCTION

This paper presents preliminary results from a series of observations which constitute one particular search for extraterrestrial intelligence (SETI). During the period from November 1980 through November 1981, we searched in the direction of over 200 nearby solar type stars seeking narrowband radio emission at frequencies surrounding 1.4 and 1.7 GHz. The observations were made with the 305-m Arecibo Observatory† radio telescope using special-purpose data acquisition hardware and software developed by the observatory staff for our SETI observing program (P426). After a lengthy period of checkout for the new hardware and software, the actual observations were conducted on two runs of three days each, separated by almost exactly 1 yr. A total of 78 hr of telescope time was allocated to these observations. In the sections that follow, we briefly describe how the data were collected, recorded, analyzed and archived, as well as a synopsis of our results and the lessons we have learned and their implications for future systematic high resolution targeted searches.

2. DATA ACQUISITION

In previous observations conducted at the 91-m telescope at NRAO in 1977[1] *et al.* we demonstrated that a rapidly sampled 1-bit representation of the voltage incident on a radio telescope (as a function of time) may be tape-recorded and subsequently Fourier transformed on a large mainframe computer in order to produce a very high frequency resolution power spectrum. With this approach, the bandwidth of the observation is limited by the sampling rate and the bin width (resolution) achieved is set by the maximum length of time over which data are sampled continuously. In 1977 we utilized a Mark I VLBI (very long baseline interferometry) recorder with a sample rate of 720 KHz and a maximum sample time of 192 msec. The hardware thus limited us to an instantaneous bandwidth of 360 kHz (filter characteristics degraded this to 330 kHz effective bandwidth) and a bin width of 5.5 Hz. Even though one is forced to accept an overall increase in the system noise by a factor of $\pi/2$ as a result of 1-bit sampling, our previous search demonstrated that it is possible to conduct a reasonably sensitive SETI over a non-trivial range of frequencies and from a large number of directions (stellar targets) in a manner which is very economical of telescope time. We were encouraged to attempt a larger search expanded in targets, frequency coverage and sensitivity, and one that would also be able to observe in two orthogonal polarizations simultaneously!

Since sensitivity to narrowband signals is improved as the square of the telescope diameter, but only as the square root of the amount of telescope time, we proposed to use the world's largest radio telescope (305-m) at Arecibo, Puerto Rico for a time (100 hr), which is typical of that granted more conventional observational programs. This facility did indeed possess a vintage Mark I tape recorder, but our desire to observe in two polarizations simultaneously and the recorder's state of disrepair dictated that we propose that the observatory

†Arecibo Observatory is operated by the National Astronomy and Ionosphere Center under contract to the National Science Foundation.

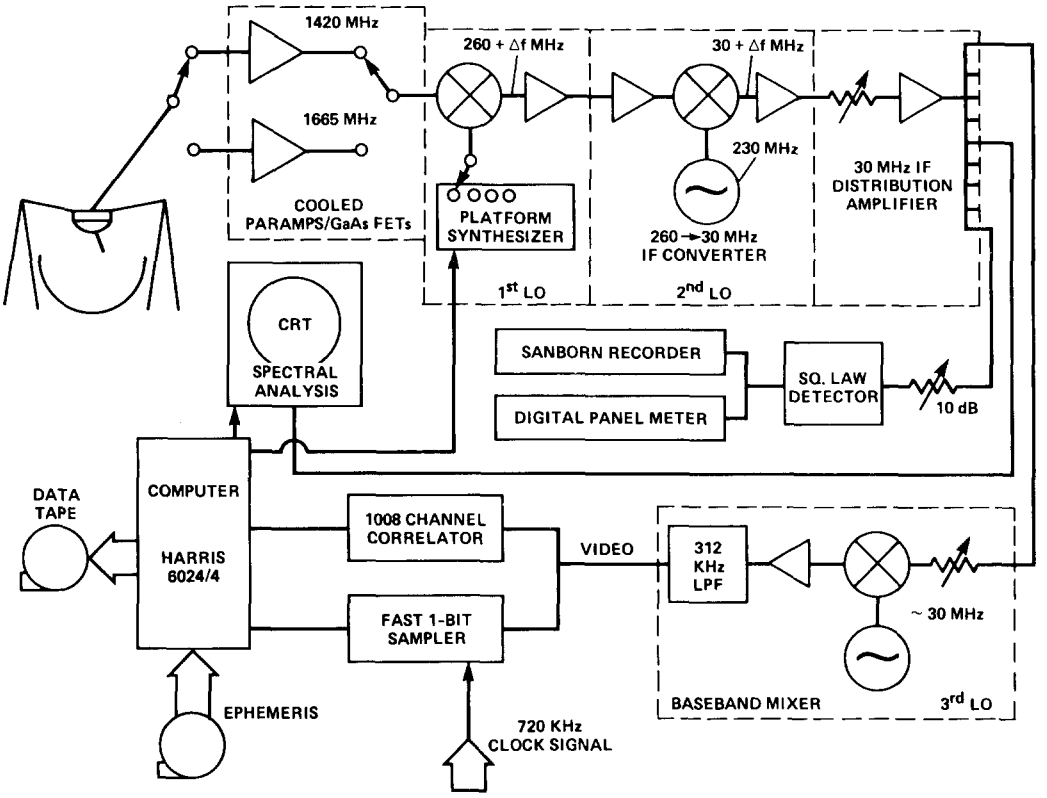

Fig. 1. Data acquisition system at Arecibo Observatory, as configured for SETI observations.

construct a fast 1-bit sampler for SETI and other users. This instrument, consisting of parallel clippers, two 12-bit shift registers, a clock and double buffers, was designed and built by Miguel Feyjoo of the Arecibo Electronics Department. It was designed to run at a maximum rate of 10 MHz under control of the data acquisition computer and to allow the 1-bit sampled data to be buffered and reformatted on-the-fly before being written to magnetic tape. Because we had already created a large volume of software to process VLBI format data, we chose to use the rapid 1-bit sampler at a leisurely 720 kHz rate and continue the sampling for only 0.2 sec before interrupting and transferring data from the buffers to tape. Software that would allow interaction of this hardware with the observatory's standard data acquisition and tracking programs was prepared for the SETI observations by Dr. Robert Duquet of the Computation Department at Arecibo. Data sampling, reformatting and writing to tape is initiated and synchronized by the data taking computer which also acquires and tracks the desired stellar source and steps the local oscillators to provide the total requested frequency coverage. Two trial observing runs were required to eliminate strong 60 kHz signals produced by the sampler clock pulses and to remove the majority of the software bugs.

Figure 1 is a block diagram of the data acquisition system at Arecibo, including the 1-bit sampler. Our observations made use of a 40-ft dual circular polarization line feed (which illuminates about 700 ft) and a sequence of continuously improved receivers at 18 cm and 21 cm. System temperatures (near zenith) during the various runs ranged from 130 K with the original 18 cm cooled paramp to 40 K with the newest cooled GaAs FET 21 cm amplifier. For the majority of the stars observed, the system temperatures were 40–60 K at 21 cm, and 70–80 K at 18 cm. As indicated in Fig. 1, the receiver is a standard super-heterodyne configuration using three LO's to convert RF frequencies to video and to insert Doppler compensations. For SETI, this intrinsically means three separate frequencies at which spurious interfering signals from satellites, transmitters and local digital equipment can be mixed in! In an attempt to provide a crude indication of strong RFI sources, we also ran the observatory's 1008 channel autocorrelator in parallel with the 1-bit sampler, with 504 channels being devoted to each polarization. For the narrowband "birdy" signals in which we are most interested, this approach proved useless. However existing software for the correlator did provide us with a mechanism for transferring the essential parameters of each observation into an informational header written to tape.

Figure 2 is an attempt to illustrate the frequency coverage achieved during these observations. The numbers on Fig. 2 refer to the frequencies in MHz (at rest with respect to the Sun) associated with the various band centers and edges drawn. We used the 312 kHz low pass filters at the observatory to define an instantaneous video

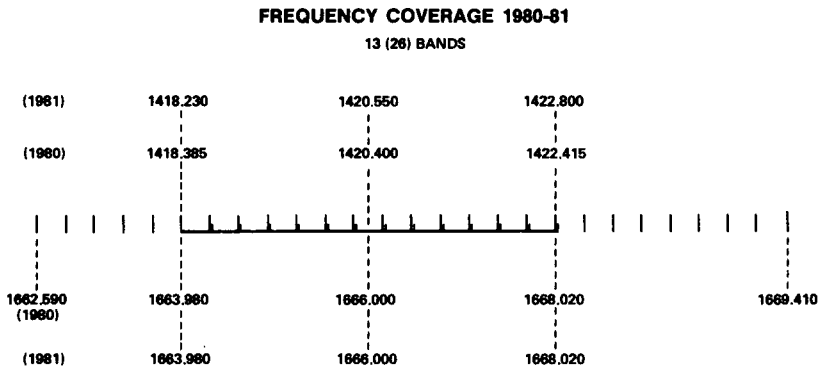

Fig. 2. Frequency coverage for SETI observations at Arecibo Observatory. 13 bands of 312 kHz width were used for 21 cm observations in both 1980 and 1981, but with slightly different band center frequencies. 26 bands were used for 18 cm observations in 1980 and 13 bands in 1981. In all cases, adjacent band centers were separated by 310 kHz.

frequency band commensurate with the 720 kHz rate of the 1-bit sampler. (The slight oversampling prevented aliased-in noise from above the upper edge of the filter.) The controlling software shifted the 3rd LO by 310 kHz 13 (or 26) times, such that a continuous band of frequencies stretching over 4 MHz (8 MHz) was observed sequentially with slightly overlapped filters.

During our first observing run in 1980, we altered the software to record 26 contiguous bands near 18 cm in an attempt to achieve a more favorable ratio between the time data were actually being recorded and the time required to slew the telescope to the next available stellar target. This in turn caused us to observe within frequency bands normally occupied by meteorological aids and led to increased problems with interference. In subsequent runs we made use of the observatory's pointing simulation program to optimize the order in which the list of target stars was observed, and we returned to the 13 band/4 MHz frequency configuration.

For each star observed (at either 18 or 21 cm) a complete set of observations recorded onto 1/2 of a 2400-ft, 9-track 1600 bpi magnetic tape consisted of 13 files (26 files) of data on 13 frequency bands, observed while tracking the targeted star, followed by 13 more files of data on the identical frequencies observed while tracking an "off" source piece of sky at precisely the same declination, but 5 arc min later in right ascension (about $1\frac{1}{2}$ HPBW's). In this way reference data were recorded with the antenna in approximately the same pointing position as when tracking the star. Each frequency file contains 15 sequential records of 1-bit sampled data from each of two polarizations (each record contains in excess of 140,000 bits), as well as the accumulated 1008 point spectra for that frequency band observed with the autocorrelator during the 3 sec required to acquire the 15 records of 1-bit sampled data. At any frequency band, data from the "off" source position are recorded about 120 seconds after the data from the star.

In addition to the OH masers W49, W51, +10011, U ORI and ON1, which we observed at high resolution at 18 cm, we had proposed to observe the 243 solar type stars (F, G, K luminosity Class V), which lie within 25 psec of the Sun and are visible from Arecibo[2], over 4 MHz of frequency surrounding both the 21 and 18 cm lines. We have in fact succeeded in observing 210 of these stars at one or both of these frequencies and the data have been reduced. The majority of the stars not observed were those near the extreme declination limits of the telescope. The time required to slew the antenna to these targets was prohibitive and would have required missing many other targets at more modest declinations.

3. DATA ANALYSIS

The data tapes were treated in the same manner as described in[1]. However, since the total frequency range per star (number of frequency bands to be transformed) was a factor of 6.5 greater than our previous observations, it was necessary to construct more efficient and highly optimized data analysis software in order to save time and money. This was accomplished by one of us (Larry Lesyna) with considerable success. A package of highly efficient subroutines for the computation of FFT's of arbitrary power-of-two lengths had been created for a CDC 7600 computer by John Middleditch of Los Alamos Scientific Laboratory (see e.g.[3]). These routines were modified to operate on the Ames 7600. The bulk of the routines were written in the COMPASS assembly language, hence they are not generally transportable to another machine. From our experience, they may be transportable to another machine in the CDC Cyber series, however. The routines are best used when the number of transform points is so large that LCM (large core memory) is necessary for storing input data to be transformed, or FFT overhead is significant. Execution speed for this new software is about a factor of two better than IMSL routines; a transform of $2^{17} = 131{,}072$ real elements can be completed in under a second of CPU time. For each frequency band 5 time sequential FFT's were averaged to produce a single 65,536 channel power spectrum.

In addition to the optimized FFT routine, we also modified our previous data reduction scheme by introducing an 8-point estimation of the mean power per channel expected across the band. As before, we ignored

all signals occurring at ≤1 kHz above baseband (it was not unusual to see all odd harmonics of the 60 cycle line current up to the 17th!). We adopted the philosophy that all narrow band signals having a formal probability ≥98% of being due to something other than noise would be subjected to more analysis. For each such "birdy", the next 5 records of data at that frequency were analyzed and if the signal persisted, the remaining 5 "on" records and the data from "off" source as well as the data from the correlator were analyzed.

This procedure minimizes the computational overhead while maximizing the potential for identifying statistical anomalies. However, it must be noted that overall a factor of $(3)^{1/2}$ is lost in sensitivity by not analyzing all available data "on" each source (but the computational cost savings is a factor of 3).

In total, the initial analysis of the 210 stars required the computation of 10,426 averaged 65,536 point spectra (5 FFT's per spectra). At the 98% level, we would have predicted 209 "birdies" to be re-examined in detail. Instead we found 291, of which only six sources at 18 cm and eight sources at 21 cm remain as potential candidate sources for reobservation and further study of IF, RF and video frequency patterns in an attempt to identify the nature of the signals.

4. RESULTS AND CONCLUSIONS

Several of the "birdies" (9 in all) found near 1.4 GHz can be explained by the existence of HI clouds along many lines of sight through the galaxy. This type of "birdy" is usually broadband compared to the observational bin width. The correlator data sometimes proved successful in detecting such signals. Some of the excess OH frequency "birdies" are associated with the extreme 13 (out of 26) bands, at frequencies above and below the protected radio astronomy band established by the WARC (World Administrative Radio Council). This latter type of signal has often proved the most interesting and most difficult to assign directly to the category of man-made-interference. The detected signals are likely to be narrowband and highly variable (modulated?) in time. This type of signal is intrinsically the most interesting to study because it is one good example of what we might expect from an ETI, but here the correlator fails to provide any assistance. As configured, the correlator is not sensitive enough to detect (in 3 sec or less) the presence of the very narrowband signals, even though they are clearly discernible in the 1-bit sampled data. This should not be surprising because one loses a factor of $(600/5.5)^{1/2}$ in sensitivity relative to the 1-bit sampler results due to the poorer frequency resolution. This factor is not compensated by the gain in sensitivity of $(3)^{1/2}$ due to the larger integration time for the correlator. Over all the correlator is about six times less sensitive to narrowband signals than is the 1-bit sampler, and is therefore not very helpful in the most tantalizing cases.

Of the 14 potential ETI signals alluded to above, two remain on our list because magnetic tape problems eliminated the "off" source spectra needed for comparison. Five of the birdies at 21 cm will probably turn out to be HI clouds along the line of sight, because several other sources observed before and after and in the same region of the sky all appear to contain broadband emission from atomic hydrogen. It is possible that the 5 arc min offset in RA would have conspired to move the smallest clouds out of the "off" source beam.

One of the H "birdies" is distinctly narrowband (being detected in only two adjacent channels) and has no signal detected in the "off" source—exactly the type of signal we are seeking. However this same source was observed with the same instrumentation at the same frequencies two days earlier, and these prior observations show no signal at all "on" or "off". The source remains on our list for reobservation.

What have we accomplished, what have we learned? For those people who favor the idea of mechanically rotating space structures beaming a "pulse-like" signal with repetition cycles of minutes, it may not seem that we have accomplished much in our search which looks at each star/frequency band for only three seconds. However, because we have used the large Arecibo telescope, we have in fact conducted a sensitive search for continuously present narrowband ETI signals over a large number of the frequencies.

We have definitely learned that magnetic tape is not the ideal medium for acquiring and storing data in any large-scale observing program. The eventual goal should be hardware multi-channel analyzers producing *many* channels simultaneously on-line and fast special purpose hardware processors analyzing all this spectral data *in real time*. However, it is going to be very difficult to teach a machine to correctly recognize the maze of signal types waiting in the spectrum to masquerade as ETI's. Figures 3 and 4 should make this clearer.

Figure 3 represents 65,636 spectral channels averaged from 5 data records in a single polarization for one 312 kHz frequency band. The frequency axis has been folded back and forth across 2 "pages" and the numbers at the beginning of each line represent the frequency in kHz above baseband of the first channel in the line. The spectra from the other polarization channel looks nearly identical. Clearly there is a strong single channel signal present near 15 kHz above base-band. The "off" source spectra shows nothing at this frequency, in either polarization, so this source might properly be considered a candidate ETI signal. However, a signal does exist in the "off" source in both polarizations at a frequency of 627 Hz above the detected signal in the "on" source. Although the observatory's astronomical tracking program can introduce a shift of 2 or 3 channels between "on" and "off" source due to Doppler corrections, 627 Hz cannot be explained in this manner. What should a real-time hardware signal detector be instructed to do? The resolution of the problem is shown in Fig. 4. Here we have plotted four columns of spectra corresponding to "on" and "off" in each of two polarizations. Each small horizontal plot represents 256 points surrounding the frequency of the original birdy. Each horizontal line represents a single sequential spectrum (not averaged) recorded at 0.2 sec intervals. In this presentation there is an obvious similarity between the nature of the "on" and

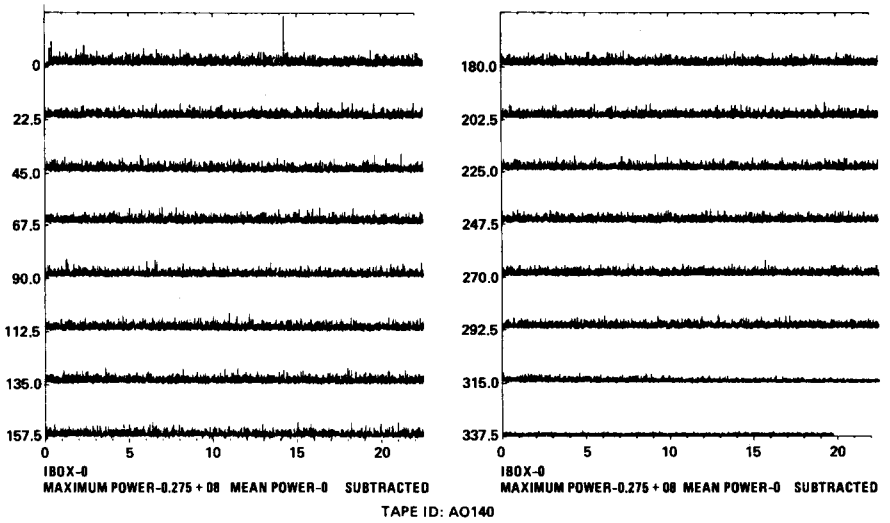

Fig. 3. Averaged power spectrum resulting from 5 sequential time samples for a single polarization. The 65, 536 channels of spectral data covering 360 kHz have been folded back and forth across 16 lines. Numbers at the start of each line represent the frequency of the first channel in the line, expressed in kHz above baseband.

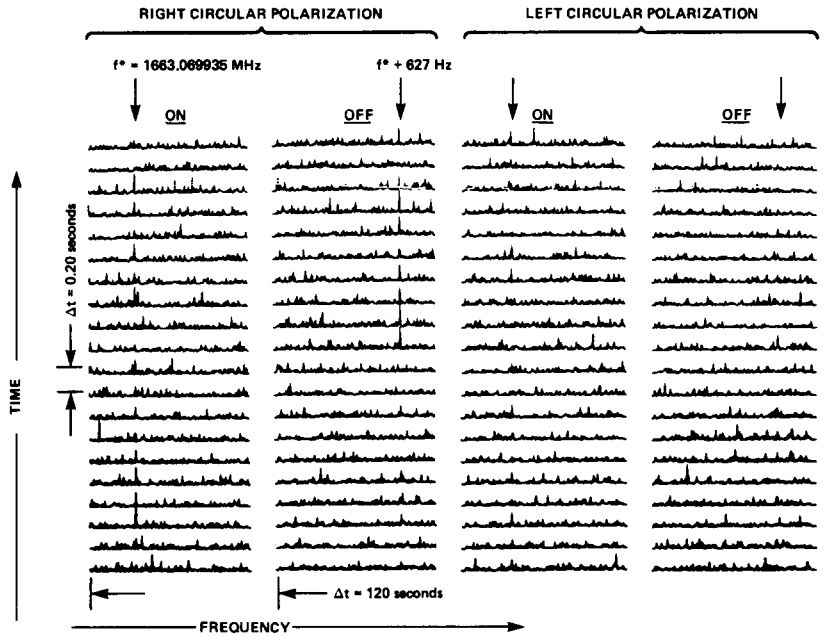

Fig. 4. 256 channels of spectral data surrounding the narrowband feature in Fig. 3. Individual time samples have been arranged vertically. Data from both polarizations "on" and "off" source are displayed. The time between successive samples is 0.2 sec. "Off" source data are recorded approx. 120 sec after "on" source data.

"off" sources. With the help of a computer CW detection algorithm or a critical eye, it is possible to discern a second, weaker signal present in both "on" and "off" spectra at a frequency difference of about 570 Hz from the previously detected signals. During the 120 sec between the recording of "on" and "off" data at this frequency band, the relative intensities of these two CW signals reversed. This pair of frequencies can be shown to overlap "on" and "off" with an additional shift of 49.5 Hz, which might be explained by a combination of allowable signal drift rate (less than 1.7 Hz/sec) and Doppler tracking adjustments during the 120 sec interval between "on" and "off".

It will be difficult to construct on-line pattern recog-

nition hardware capable of dealing with complex signals such as the one in Fig. 4. This lesson and the short list of interesting targets for reobservation constitute the major conclusions of this study.

Acknowledgements—This type of research requires accurate and tedious attention to detail in order to compute and archive the large number of requisite FFT's and to "sleuth" out all the signals found. In this endeavor we have benefited greatly from the efforts of Alison Tucher, William New, Raymond Cole and Cassandra Seeger. This may be the last tape-recorded project we undertake because a large multi-channel spectrum analyzer will soon be operational, but we couldn't have begun to contemplate this task in the absence of their help and the financial support provided by Dr. John Billingham of NASA-Ames Research Center (via Cooperative Agreement UCB #23301). We also wish to thank the staff at the Arecibo Observatory for fully supporting our atypical mode of data acquisition and the management of the Very Large Array for allowing Dr. Duquet to continue his participation in this project after he joined the staff of that facility.

REFERENCES

1. J. Tarter, J. Cuzzi, D. Black and T. Clark, A high sensitivity search for extraterrestrial intelligence. *Icarus* **42**, 132–144 (1980).
2. R. Woolley, E. A. Epps, M. J. Penston and S. B. Pocock. Catalogue of stars within twenty-five parsecs of the sun. *Roy. Observ. Ann* **5**, Herstmonceux (1970).
3. J. Middleditch and F. Cordova, The colors of the pulsations and flickering of SY cancri during outburst. *Appl. J.* **255**, 585–595 (1982).