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A High-Sensitivity Search for Extraterrestrial Intelligence at λ18 cm

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We have conducted a targeted high-sensitivity search for narrow-band signals near λ18 cm using the 91-m radiotelescope of the National Radio Astronomy Observatory. The search included 201 nearby solar-type stars and achieved a frequency resolution of 5.5 Hz over a 1.4-MHz bandwidth. This high spectral resolution was obtained through a non-real-time reduction procedure using a Mark I VLBI recording terminal in conjunction with the CDC 7600 computational facility at the NASA–Ames Research Center. This is the first high-resolution search for narrow-band signals in this wavelength regime. To date it is the most sensitive search per unit observing time of any search strategy which does not postulate a unique magic frequency. Our data show no evidence for narrow-band signals due to extraterrestrial intelligence at a 12-σ upper limit on signal strength of 1.1×10^{-23} W m^{-2}.

INTRODUCTION

Twenty years ago Cocconi and Morrison (1959) published a much cited paper in which they argued for the commencement of a search for extraterrestrial intelligence (SETI) utilizing existing radio-astronomical facilities. During the subsequent two decades many scientists have joined in the debate over the "right" way to conduct a search. At least 15 groups and individuals have felt confident enough of their schemes to devote the effort required to mount an observational search program and then to publish the details of their negative results. These suitably documented observational programs (as well as those never published) have been extremely diverse, ranging from a low-sensitivity array of dipoles scanning the sky, with a broad-input bandwidth and little or no frequency resolution and continuing over a long period of time (Troitskii *et al.*, 1975), to an extremely sensitive search of nearby stars, with a narrow-input bandwidth of 1.0 kHz and an ultrahigh-frequency resolution of 0.015 Hz lasting only 80 hr (Horowitz, 1978). The haystack in which the ETI "needle" might be hidden is so incredibly vast that each of the experimenters has made a guess in order to carve out a small volume of search parameter space (frequency, range, time, direction, modulation, polarization) which may be realistically explored in a finite time with severely limited funding. A more *systematic* approach to SETI at this time requires the construction of extremely large (10^6 to 10^9 channels) multichannel spectrum analyzers (MCSA) to allow simultaneous observation of many adjacent frequency bins,

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in order to provide broad spectral coverage while optimizing the detection probability for narrow-band signals (Black *et al.*, 1977; Edelson, 1977). Hardware versions of these MCSAs do not exist at present (1000 channels is typical of radio observatories), but this paper describes a non-real-time data analysis scheme based on the use of a high-speed tape recorder, which allows an observer to simulate a 65K channel analyzer in a manner which is very telescope efficient.

We have used this technique in a targeted search of nearby solar-type stars over a band of frequencies near λ18 cm, the OH end of the "waterhole" which has been neglected by most previous observers. Our strategy was to maximize the probability for success by maximizing the sensitivity of the search within the temporal and financial constraints common to all terrestrial observers. This emphasis on sensitivity leads directly to the decisions to

(a) limit the area of the sky searched to the directions of the nearby solar-type stars (i.e., main sequence spectral types F, G, and K);

(b) limit somewhat the input bandwidth in order to achieve a high-frequency resolution with a fixed number of channels and still cover a sufficient portion of the microwave window so as not to be restricted to "magic" frequencies.

Although we did succeed in achieving a sensitivity to narrow-band signals of 1.1×10^{-23} W m^{-2} (see footnote 1) over a large enough volume of search phase space to qualify as the beginning of a systematic exploration, we have found no evidence for an ETI signal. We have demonstrated the validity of this technique and accumulated a large amount of data and experience that will aid us in future observational efforts, and in the design of automated signal recognition and extraction hardware to be used in conjunction with the mega-channel spectrum analyzers already designed (Narasimha *et al.*, 1978).

[1] This sensitivity would have been sufficient to detect a transmitter with an effective isotropic radiated power of 7.8×10^{13} W located at the distance of our farthest target star (25 parsec). For comparison the Arecibo Observatory radar transmitter is capable of producing approximately 10^{13} W EIRP.

DETAILS OF THE OBSERVATIONS

Hardware

These observations were made with the 91-m antenna of the National Radio Astronomy Observatory[2] at Greenbank, West Virginia, during 5 days in January 1977, using a linearly polarized feed and dual paramps tunable from 1612 to 1720 MHz that provided a system temperature ~70 K and an aperture efficiency of 0.6. Data were recorded with the Mark I VLBI terminal (Whitney *et al.*, 1976) of the Goddard–Haystack–MIT VLBI group. Figure 1 shows a block diagram of the data acquisition hardware as it was configured for this experiment. The incoming signal was mixed with the first LO at 1500 MHz, high pass filtered, and then mixed with a signal generated by an HP 5105A synthesizer at a frequency of 126 plus or minus the required Doppler shift to correct for the nominal (optically determined) stellar radial velocity. Finally a third LO frequency generated by an HP 5100 programmable synthesizer was used to center the effective bandpass filter at the four preselected frequencies shown schematically in Fig. 2. In addition to the recorded data, the 384-channel NRAO Mark III autocorrelation spectrograph was used on line as a course-resolution (~1 kHz) interference monitor. For a similar reason the total power into the Mark I VLBI terminal and into both of the paramps was also registered on a strip chart recorder. The effective instantaneous bandwidth of the Mark I device is ~330 kHz; shifting the third LO allowed us to increase the spectral coverage of each star by recording the four nearly contiguous fre-

[2] NRAO is operated by AUI under contract with NSF.

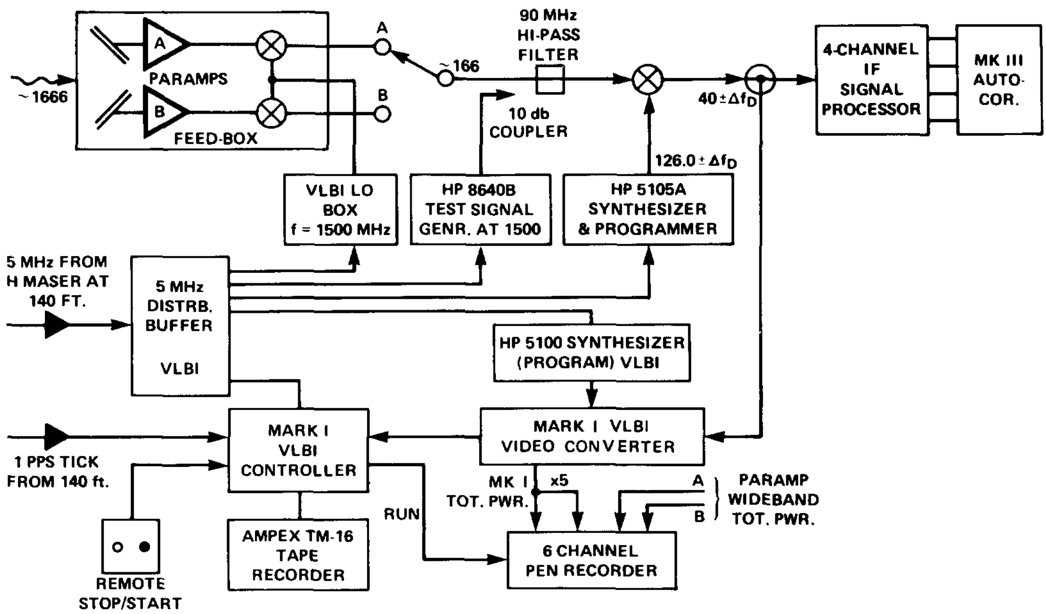

FIG. 1. Block diagram of modified Mark I system. The HP 5105A synthesizer was used to make Doppler corrections for the stellar radial velocities with respect to the local standard of rest, and the HP 5100 synthesizer was used to select four preset center frequencies for observations over four different filter bands.

quency bands shown in Fig. 2. During a single observation of a target star, one magnetic tape was recorded in approximately 4 min (including time required to select manually the center frequencies and write tape end-of-file marks), which suitably matched the limited tracking ability of the 91-m transit telescope. For each star

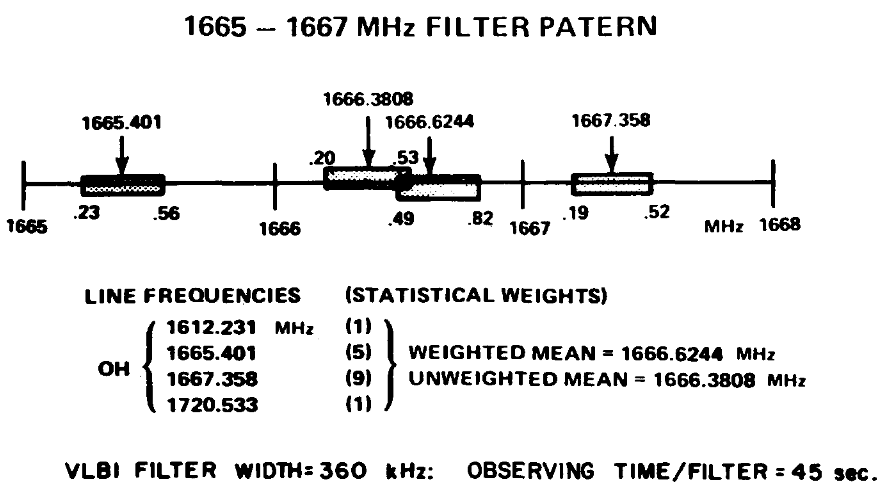

FIG. 2. Frequency coverage near λ18 cm in the rest frame of the target star. The center frequencies of bands 1 and 4 correspond to the two main lines of the OH ground state emission. The two middle bands are centered on the statistically weighted and unweighted means of the four OH frequencies shown.

observed, a reference tape was also recorded with the telescope pointed at the declination of the star, but 6 min preceding in hour angle. In this manner it was possible to observe a little over 1 MHz of the spectrum in the vicinity of the OH main lines for 201 out of a target list of 301 possible stars in a limited observing period.

Sources

The 301 potential targets for this program were selected from the *RGO Catalog of Stars within 25 Parsecs of the Sun* (Woolley *et al.*, 1970). The selection criteria for targets were: spectral class F, G, or K; main sequence luminosity class V (or unknown luminosity class); declination within the range $0° \leq \delta \leq 90°$; and no evidence for multiplicity (as presented by the catalog). This list was subsequently augmented by a few more stars which had been identified as "interesting" by previous SETI observers. The target sources were fairly evenly distributed over the sky and amenable to a short observing program with a transit instrument. Not all of the targets were observed because the hours during which the galactic center was overhead were devoted primarily to a parallel observing program intended to study several OH maser sources at our very high spectral resolution.

Data Reduction

In the Mark I VLBI terminal, the voltage across the "video" IF baseband was clipped 1 bit and sampled. The 1-bit recording scheme, which preserves only the *sign* of the time series of the IF voltage, increases the system noise by a factor of $\pi/2$ (van Vleck and Middlekopf, 1966). The recording rate of 720 kbps allows 138,000 bits to be written on tape in about 192 msec. A short interrecord gap follows (~8 msec) and the cycle is repeated at 200-msec intervals. This formatting defines an "alias-free" integration time of 0.2 sec for our purposes. The corresponding frequency resolution of $\sim 1/T = \Delta f \sim 5$ Hz provided even this preliminary search with a significant improvement in sensitivity over any previous searches having comparable target and frequency coverage. Further reduction of Δf would significantly increase the difficulty of the reduction process by necessitating correction for unknown Doppler drift rates which might be present in extraterrestrial signals.

The maximum frequency drift at 1700 MHz due to the Earth's rotation is ~0.14 Hz sec^{-1} at transit. Thus, for the short integration times we have used (4–40 sec) and $\Delta f \sim 5$Hz, we did not need to correct for the diurnal Doppler drift. It is not unreasonable to assume a higher-frequency stability for the transmitting source. However, we intend to carry out more sophisticated drift corrections in subsequent efforts in order to extend our coherent integration time and obtain the benefits of higher-frequency resolution. In our current mode of analysis, one spectrum of 2^{16} (65,536) channels was obtained from each 200-msec record, producing a 5.5-Hz frequency resolution over a 360-kHz full bandwidth. The useful (3 db) bandwidth is somewhat less, about 330 kHz.

The data were read directly from the VLBI tapes into the CDC 7600 computer at Ames Research Center as 60-bit "words," then each bit was split off as an independent sample by masking. These data were directly Fourier analyzed. The FFT algorithm used was a standard IMSL package (FFT2) modified from a version of the Cooley–Tukey FFT algorithm by Singleton (1967). The size of the basic FFT was limited to 2^{14} or about 16K (complex) by the size of the CDC 7600 high-speed core. A decimation/data handling technique due to Brenner (1969) was used for efficiently creating the full 2^{17}-point transform from the individual 2^{14}-point transform. Resulting power spectra were averaged in bin-reversed order over the desired number of 200-msec records (20 records for the bulk of the data[3]), and a fast bin-reordering algorithm due to Polge *et al.* (1974) was used to output the final result. The entire program was written in Fortran and ran at an average speed of 6 sec of cpu time per 200-msec record for the 2^{16}-point spectrum (averaged and properly ordered).

Amplitude calibration in units of spectral power density was obtained using the observed average system temperature and the van Vleck clipping correction. The algorithm was checked using tape-recorded, monochromatic calibration signals of known power and frequency injected directly into the VLBI system IF channel. Details of the system calibration are given in the next section. Also in the next section we describe the derivation of system sensitivity to narrow-band signals, and the statistical analysis of the data.

RESULTS

System Performance

We have been able to verify our direct FFT approach by successfully detecting three different types of narrow-band signals recorded by Mark I VLBI systems: (1) a weak calibration signal, which was injected into the IF at the 91-m antenna, (2) a strong 10-kHz video phase signal commonly generated during VLBI observations, (3) the CW signal from the X-band transmitter on board the Viking VO-1 Orbiter around Mars. Figures 3a and b refer to this last signal. Figure 3a demonstrates the extreme sensitivity of this observational technique for detecting narrow-band signals; the power contained in the visible peak is only 3.5×10^{-3} (−25 db) of the total power into the receiver input bandwidth (360 kHz). Figure 3b illustrates the additional information which might be extracted from a coherent ETI signal. By observing with sufficient time and frequency resolution, it is possible to determine the Doppler drift rate of a narrow-band signal (−3.2 Hz/sec for VO-1) produced by the relative acceleration of the transmitter (orbital revolution and diurnal rotation) and then perhaps to deduce something about the nature of the transmitter.

In addition to successful detection of these known narrow-band signals, we have also made a statistical evaluation of our system performance. Let y be the observed power in an individual channel (measured in units of the mean power per channel). The spectral probability density due to noise alone when the observed spectrum results from transforming and averaging n independent data records is given by (Oliver and Billingham, 1971)

$$P_n(y) = n(ny)^{n-1}e^{-ny}/(n - 1)!.$$

Therefore in any of our stellar spectra we should expect to find $P_{20}(y) \times 65{,}536$ channels which have a power level y due to the system noise only. An excessive number of channels with $y \gg 1$ would indicate the presence of a signal in addition to the noise. In Fig. 4 we have plotted data from a representative stellar spectrum in the form of a histogram of observed channels vs power; the predicted noise curve has been plotted as a continuous line. Figure 4 is typical of the 908 spectra generated from the 201 stars observed and is consistent with the hypothesis that no narrow-band signal stronger than 1.1×10^{-23} W m^{-2} (see footnote 4) was present at the time of this observation. The excessive number of channels observed for small values of y (<1) results from the gradual decrease in the system sensitivity at higher video frequencies due to the falloff of the effective

[3] Note that this represents only 10% of the data actually acquired for most stars. A factor of ~3 increase in sensitivity could have been achieved by reducing all of the data. But the increased computational effort and costs could not be absorbed. The additional data were used whenever a suspect signal was encountered as described later in the text.

[4] The quoted minimum detectable power level (1.1×10^{-23} W m^{-2}) corresponds to a value of $y = 2.535$ or approximately 12 times the standard deviation in the data. The formal probability of noise alone exceeding the threshold in any single channel of the 65,536-point spectrum formed from an average of 20 independent records is $\leq 2\%$.

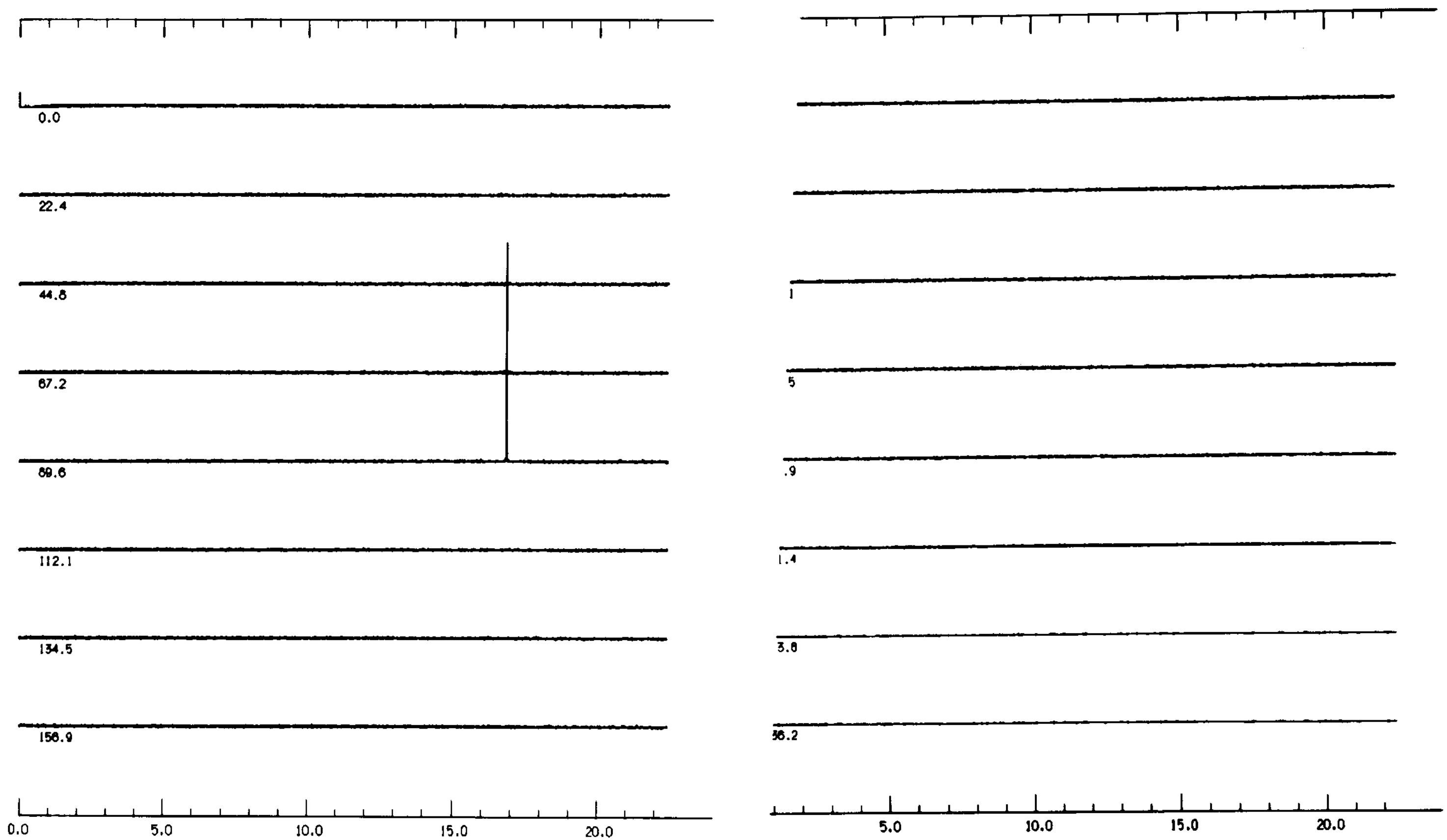

FIG. 3a. Power spectrum from VO-1 at X-band. The frequency range shown is 8408.400–8408.760 MHz. Twenty data records have been transformed to produce this spectrum which has been folded 16 times across the two "pages" of the figure to facilitate display. Frequency increases to the right across each line, the number at the extreme left end of each line is the video frequency (in kHz) and each tick mark on the horizontal axis represents 1 kHz. These data were recorded at the Owens Valley Radio Observatory on calendar day 349, 1977, at UT 1228 as a part of an astrometric determination of the differential position between the Martial orbiter and the quasar OJ287. The experiment was performed by groups at MIT and JPL under the direction of I. I. Shapiro and X. X. Newhall. The data tapes were made available to us by C. Knight of Haystack Observatory.

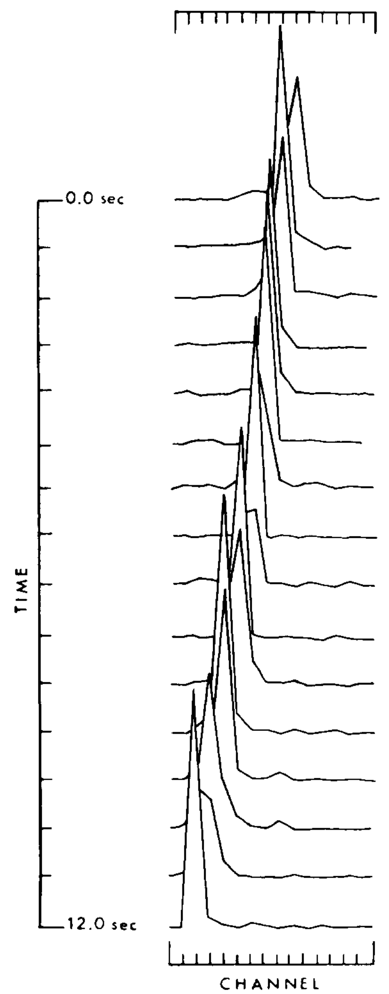

FIG. 3b. Doppler drift in VO-1. Each line of spectrum is the result of transforming a single data record (200 msec) and successive lines are sequential in time, separated by 800 msec. The measured drift rate at the time of observation was −3.2 Hz per second. The individual channel widths are 5.5 Hz.

bandpass (calculation of the mean power per channel has assumed a uniform filter response).

During the data reduction process we encountered 49 sources whose spectra, computed from an average of 20 independent data records, contained individual channels with received power in excess of 1.1×10^{-23} W m^{-2}; these spectra were singled out for additional analysis. In any systematic search of this type, the achievable sensitivity of the experiment is set by the false alarm rate which can be tolerated. Of the 49 events, only 31 persisted upon anaysis of 20 additional records. This agrees with the statistical prediction of 18 "birdies" (expected from noise alone at this power threshold) that would vanish upon analysis of additional data records. Of the remaining 31 events, 11 occur at a frequency of 240 kHz above baseband, independent of the band center frequency or the Doppler corrections for stellar velocities. These particular signals can be ascribed to a hardware problem within the Mark I system itself; this has subsequently been corrected. Of the last 20 "interesting" cases, 19 were found to have signals present at the same frequency and at roughly the same intensity in the reference "off" tape spectra. These signals have therefore been attributed to some form of near field *terrestrial* interference. This leaves only 1 strong signal, for which no "off" tape is available due to hardware failure. It must be emphasized that this

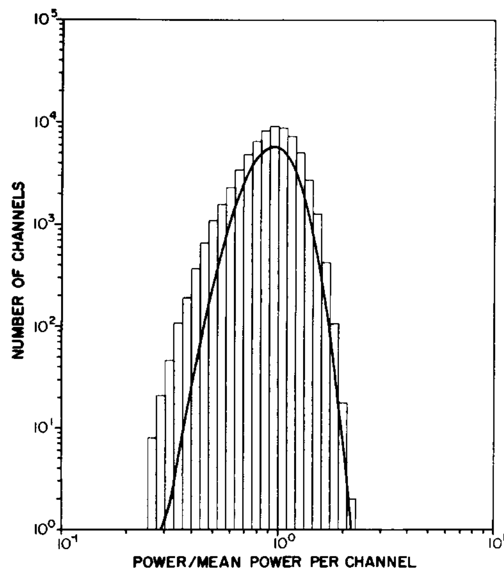

FIG. 4. False alarm statistics. The histogram presents the observed number of channels having power level between $\log y$ and $\log y + 0.04$. The solid curve is the predicted channel numbers from $P_{20}(y)$.

signal does *not* represent a claim for detection of ETI signals, but rather is a potentially interesting signal that is suspected, but not yet demonstrated, to be of terrestrial origin. Because of this uncertainty the target deserves to be included on future SETI observing lists. Source lists for this observing program as well as that of Horowitz (1978) are available from the authors on request.

CONCLUSIONS

Although this search failed to detect any verified ETI signals stronger than 1.1×10^{-23} W m^{-2} coming from the direction of the 201 nearby stars observed at λ18 cm, it was thoroughly validated the novel observing technique employed. Until such time as hardware mega-channel spectrum analyzers are constructed and installed at radio-astronomy facilities to conduct a SETI program in real time, the use of high-speed tape recorders to preserve 1-bit sampled data will provide an extremely attractive method of making systematic SETI observations. The disadvantage of this approach (modest instantaneous bandwidth and large computational overhead on mainframe computational facilities) can be offset by the use of one or more dedicated minicomputers and special purpose hardware processors. The high sensitivity provided by this technique (through high-frequency resolution and targeting of likely candidate stars) produces the overwhelming advantage of minimizing the demands on existing radio-astronomy facilities, which tend to be fully subscribed by standard astronomy programs.

We intend to continue to conduct a systematic targeted SETI program utilizing the methods described in this paper. In addition to the possibility of the detection of an ETI signal during our observations, it is important to continue these high-resolution searches as an aid to the realization of the real-time hardware. The astrophysical and manmade environment in which a SETI system must function has not yet been characterized with sufficient frequency resolution at low flux levels. An acceptable false alarm rate can be achieved only when "known" signals can be removed automatically. We expect to learn a great deal from our continued search efforts, even if they fail in their primary goal.

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