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The Berkeley Parasitic SETI Program

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Parasitic programs for the Search for Extraterrestrial Intelligence (SETI), carried out concurrently with conventional radio astronomical observing programs, can be an attractive and cost-effective means of exploring the large multidimensional search space intrinsic to this effort. We describe a microprocessor-based automated SETI acquisition system which searches for and records spectra of narrowband signals in the IF band of an observatory receiver. Data taken with this system over 35 days at the Hat Creek Radio Observatory at 1612 MHz are discussed. Out of approximately 10^5 spectra processed during this period, 4000 were identified by the system as containing narrowband signals and were recorded. Subsequent analysis indicates that over 3900 of these are due to local RF contamination. The remainder are undergoing further investigation.

INTRODUCTION

Conditions favorable to the development of life may be widespread in The Galaxy. Therefore there may exist a considerable number of extraterrestrial life forms, some of which may be "intelligent" and have developed civilizations capable of interstellar communication. It has been argued (e.g., Oliver and Billingham, 1971; Morrison *et al.*, 1977) that a civilization wishing to advertise its existence for purposes of initiating communication would employ an electromagnetic beacon. Operation on a single radio frequency would make most efficient use of available transmitting power and produce an obviously artificial signal in the midst of the astrophysical spectra line environment.

Since 1960, about 20 small-scale Searches for Extraterrestrial Intelligence (SETI) have been carried out. A summary of the search parameters of 15 SETI efforts is given by Murray *et al.* (1978). Subsequent searches have been reported by Horowitz (1978) and Tarter *et al.* (1980). No evidence of beacon signals has yet been found. However, the combination of all the SETI efforts to date, having had limited capacity for frequency and spatial coverage, has scarcely begun to cover the large multidimensional search space.

In this paper we describe instrumentation and software constructed to allow a parasitic search strategy to be implemented. We feel that this parasitic approach offers an attractive and cost-effective means of searching for strong ETI signals.

THE BERKELEY SETI ACQUISITION SYSTEM

We are conducting a SETI program requiring neither dedicated antennas nor dedicated time on existing antennas. The program employs a SETI-specific unsupervised automated acquisition system which searches for narrowband signals in the IF band of a radio telescope during its utilization for more conventional astronomical pursuits. Spectra of signals meeting predetermined criteria are stored on magnetic tape for more detailed analysis at a later time. Observing frequencies and directions are selected by primary (non-SETI) programs at the observatory. The lack of control over observing frequencies and directions may not be a serious disadvantage, since transmitting societies could conceivably lie in any direction and generate signals in any part of the RF spectrum

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received by the telescope. In fact, some of the frequencies most often observed by radio astronomers have been felt to be logical choices for a transmitting society's beacons, and hence good choices for SETI. It has even been suggested (Makovetskii 1980) that transmitting societies will choose to increase their effective gain and probability of accidental detection by limiting transmissions to a small number of directions directly toward or away from "interesting" astronomical objects.

The advantages of this method of data acquisition include very low operating cost per unit observing time, negligible impact on observing schedules, and eventually large amounts of data collected. Since any discovery made in this way would be fortuitous for the primary user of the radio observatory, the observing program has been named Project SERENDIP.[2]

Observing parameters such as the antenna pointing coordinates, RF observing frequencies, and observatory local oscillator frequencies are under the control of the primary user. These data and the identification of astrophysical sources within the beam may be obtained directly by interfaces to the telescope drive system and frequency synthesizers or to the observatory computer, or by reference to the primary observer's logs or data files.

The SERENDIP acquisition system was designed to ignore most naturally occurring sources (the focus of the primary observer) and to preserve only those data samples most likely to contain signals of intelligent origin. The SERENDIP system does this by searching specifically for narrowband signals exceeding some preset threshold power. To achieve the greatest system sensitivity, consistent with resources available for post-processing of the resultant data, the power threshold is set to produce an alarm rate of about 4000 events per month of collection. Post-acquisition processing of this volume of data can be completed in under four hours.

[2] Also an acronym: Search for Extraterrestrial Radio Emission from Nearby Developed Intelligent Populations.

The SERENDIP system consists of a real-time microprocessor-controlled spectrum analyzer with algorithms for performing simple statistics and digitally recording selected spectra. Its major components, shown in Fig. 1, are a microprocessor with 4K 12-bit memory, a remote-programmable frequency synthesizer, a mixer-AGC-baseband system, a 100-channel autocorrelator, 12-bit A/D converter, a teletype, an oscilloscope, and a 7-track incremental magnetic recorder. A battery backup power system for volatile memory and full automatic restart capability has been provided as protection against power interruptions.

In operation, sequential 100-kHz segments of the radiotelescope receiver's IF band are downconverted and folded over to a baseband of 0 to 50 kHz by the frequency synthesizer, mixer-AGC circuit, and lowpass filter. The baseband is then presented to the autocorrelator, a 100-channel hybrid digital–analog unit with selectable sample rate and computation period. A sample rate of 100 kHz, a maximum lag time of 1 msec, and an integration time constant of 20 sec are employed for the SERENDIP program. The 100 analog pedestal voltages can be read out of the autocorrelator sequentially upon command from the microprocessor. A dual-gain amplifier, switched by the microprocessor, has been provided in order to separately scale the zero-lag element, which represents average power over the sampled bandwith. This enables the A/D converter to sample both zero and nonzero time lag voltages with high resolution. An unusually strong coherent signal may saturate the A/D converter, destroying information as to its spectral form, but the system will still detect it. After sampling, a cosine Discrete Fourier Transform (DFT) is computed by the on-line software. The computation takes about 30 sec.

Meanwhile, the synthesizer frequency is incremented by 100 kHz and the autocorrelator processes the next segment of the IF

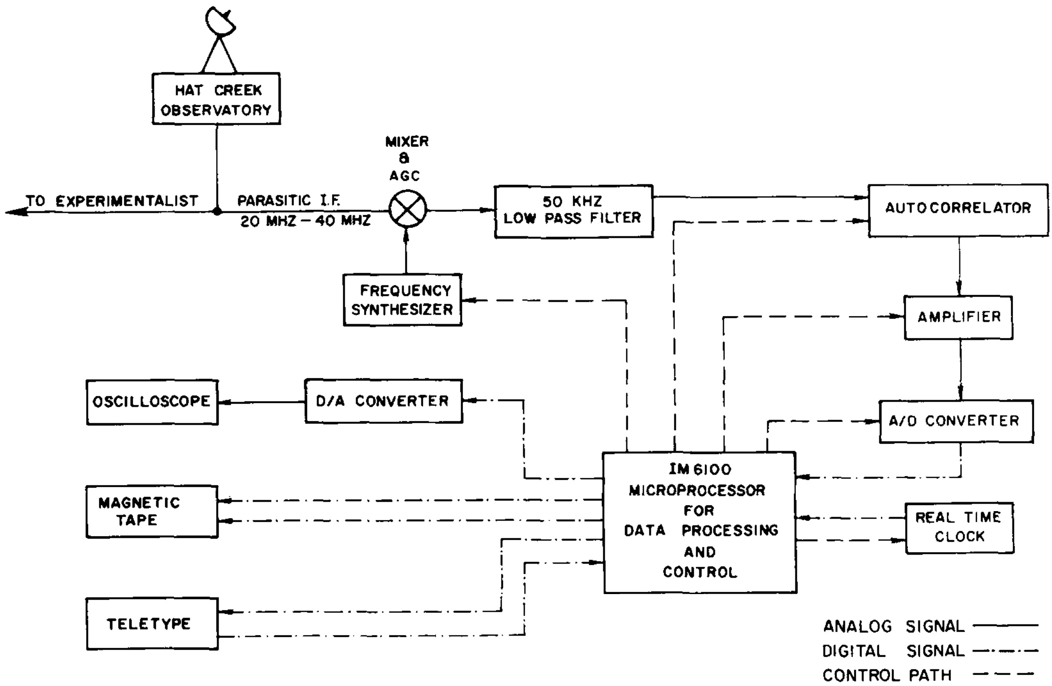

FIG. 1. Block diagram of SERENDIP real-time data acquisition system. Under control of the IM6100 microprocessor, 100-kHz segments of the observatory receiver's 20- to 40-MHz IF band are mixed and folded to a baseband of 0 to 50 kHz. The 100-point power spectra are computed by means of an autocorrelator and software DFT. Spectra having power in individual channels exceeding a preset threshold are recorded on 7-track digital magnetic tape. Oscilloscope and teletype allow real-time data display and experimenter interaction.

band. The resulting power spectrum is examined by the program for the presence of a spectral peak greater than some selected number, n, of standard deviations above the mean noise power. If any are found, the autocorrelation function, power spectrum, time according to a real-time clock, synthesizer frequency, and other SERENDIP system parameters are written on digital tape for further, off-line analysis. In addition to the signal analysis functions described above, the microprocessor controls all peripheral devices and allows interrogation of system status and modification of system parameters without interrupting the ongoing data analysis.

The SERENDIP system was installed on the 85-ft. radiotelescope of the University of California's Hat Creek Radio Observatory (HCRO) located about 270 miles north of the Berkeley, California campus; it operated without human supervision except for monthly tape changes. Figure 2 shows the system in place at HCRO.

The operating parameters are summarized in Table I. These result in a spectral resolution of 500 Hz with a twofold ambiguity due to the folding of the IF signal. The adopted parameters represent a number of compromises resulting in the scanning of the 20-MHz IF bandwidth of the HCRO receiver once every 100 min, a time period over which the telescope typically tracks an individual direction on the sky. Unity SNR is achieved by a narrowband flux density of

$$\begin{aligned}\phi &= \frac{kT}{A_{\text{eff}}}\sqrt{\frac{b}{t}} \cdot 2 \cdot 2 \cdot \sqrt{2}\ \text{W/m}^2\\ &= 1.15 \times 10^{-22}\ \text{W/m}^2,\end{aligned}$$

where T is the system temperature (55°K), A_{eff} is the effective aperture (264 m^2), b is

TABLE I

SERENDIP/HCRO OPERATING CHARACTERISTICS

Antenna size	85-ft. diameter; 264 m^2 eff. aperture
System temperature	55°K[a]
Search frequencies (determined by ongoing radio astronomy research)	917–937 1410–1430 1602–1675 1853–1873 MHz ~5 GHz
Number of channels	100
Frequency resolution	2 × 500 Hz
Frequency coverage	20 MHz centered on observing frequency
Integration time	30 sec (time constant = 20 sec)
Sensitivity (SNR = 1)	1.15×10^{-22} W/m^2[b]

[a] 65°K at 6 cm.
[b] 1.4×10^{-22} W/m^2 at 6 cm.

the bandwidth per channel or resolution (1000 Hz), and t is integration time constant (20 sec). The two factors of 2 and the factor of $\sqrt{2}$ account for polarization loss, for frequency switching employed in spectroscopic observations at HCRO, and for an accumulated-baseline subtraction algorithm in the SERENDIP software, respectively. (In fact, since frequency switching is done at a rate much faster than the 20-sec integration time constant, we actually sample two 100-kHz-frequency bands separated by 10 MHz at any instant.)

The detection threshold, n, is set to produce approximately 4000 records (the capacity of one 1200-ft spool of tape) per month. For Gaussian-distributed noise alone, the appropriate value would be n = 3.3. Currently, a larger value of n = 4.5 (corresponding to a sensitivity of 5.2×10^{-22} W/m^2) is being used to limit detection of persistent local interfering signals and achieve the desired tape filling rate.

In Fig. 3 we depict the autocorrelation function of a data sample in which the SERENDIP system found a narrowband signal. Only the 99 function values for positive time lags are shown; the zero-lag coefficient was suppressed. Although the presence of a cosine form is unmistakable, its amplitude (~0.001) is quite small. The cosine transform of this function as computed by the SERENDIP system is plotted in Fig. 4 in units of standard deviations from the mean of all channels in the spectrum. The spectral peak which triggered the preset threshold has an amplitude of about $7\frac{1}{2}\sigma$ and occupies a single 500-Hz channel.

POST-ACQUISITION DATA ANALYSIS

Software for off-line analysis of data preserved on tape is implemented on a PDP 11/40 computer at UCB's Department of Astronomy and Radio Astronomy Laboratory. Routine processing catalogs record number, date and time, peak frequency and power, and, when available, right ascension, hour angle, declination, azimuth, and elevation associated with each recorded spectrum. Plots and tabular listings of selected autocorrelation functions and power spectra may be generated, and the local parameters sensed by the SERENDIP system can be related to the global parameters of the observation and displayed as in Figs. 3 and 4. Off-line FFTs of the tape-recorded autocorrelation functions are also available for system debugging and validation purposes.

Since most signals meeting the detection criteria of SERENDIP occupy fewer than three sequential channels (as in Fig. 4), signal identification is not necessarily aided by subjecting each spectrum to detailed visual examination. Any signal source which is other than a statistical fluctuation is likely to be detected more than once. Therefore a fruitful approach is to search for systematic behavior in the gross characteristics in the detected signals over time. For example, in Figs. 5a and b we show the position in the IF band of each recorded spectrum vs time. Each dot signifies that a record was written containing a detected narrowband signal at the indicated intermediate frequency. The resolution of the display (time in hours and frequency in 100 kHz) is sufficient to reveal many significant signal characteristics. In the present example, most of the detections

FIG. 2. The SERENDIP data acquisition system is self-contained in one equipment rack except for the teleprinter shown at right. From top to bottom: 7-track incremental recorder; oscilloscope; the SERENDIP cabinet containing front-end electronics, A/D and D/A converters, microprocessor, memory, real-time clock, and power supplies; paper tape reader for program loading; remote-programmable frequency synthesizer; 100-channel autocorrelator.

fall into a small number of categories. These will be discussed below.

In another presentation, telescope pointing directions associated with recorded spectra are plotted in right ascension and declination, as in the example of Fig. 6. Polar plots in azimuth and elevation are useful for recognizing certain local RFI sources.

SAMPLE RESULTS

We present here the results of SERENDIP operation at HCRO during a 35-day system trial period beginning in March 1980. At the beginning of the run Dr. B. Baud of UCB's Department of Astronomy was engaged in observations of OH masers

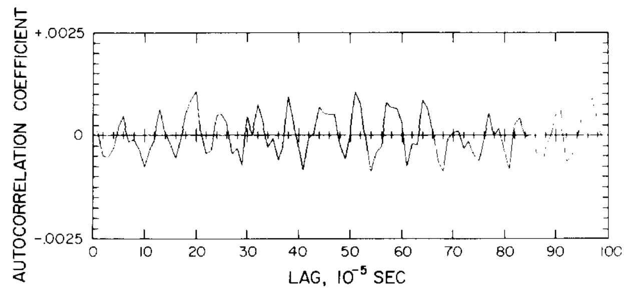

FIG. 3. Autocorrelation function of a data sample containing a narrowband signal. This function was computed by the autocorrelator and was used by the microprocessor to compute a power spectrum.

in the atmospheres of 60 red giant stars. Each star was examined (integrated) for 1 hr, and the entire sequence was repeated many times until the program's termination. A cooled field effect transistor amplifier and a single circularly polarized receiver were in use, producing a system temperature of 55°K. The maser line rest frequency of 1612 MHz was converted to an intermediate frequency of 29.5 MHz, which was filtered and centered within a 1-MHz bandwidth for use by the observer. The full 20-MHz IF bandwidth was available for analysis by the SERENDIP sys-

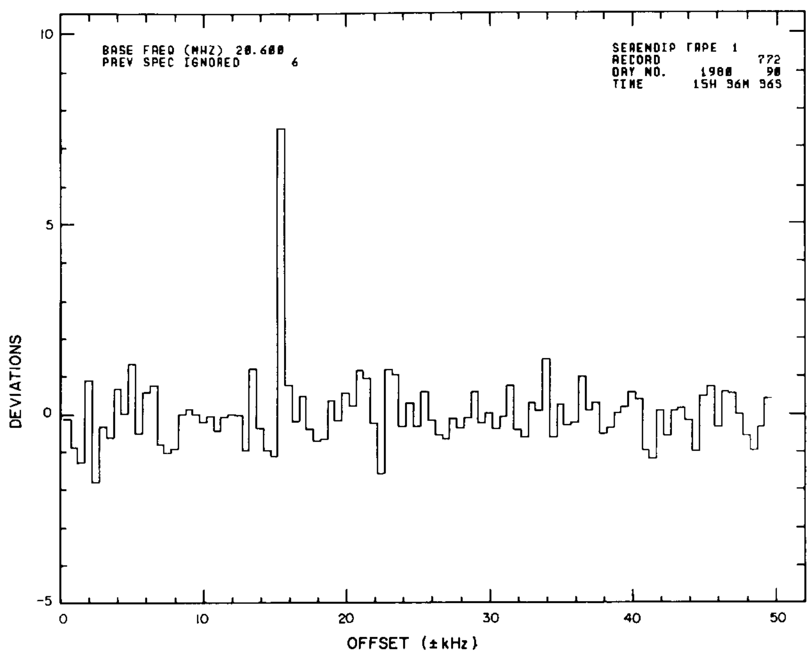

FIG. 4. The power spectrum produced by the on-line Fourier transform of the autocorrelation function in Fig. 3. The labels at the top of the figure identify the global observational circumstances and are appended when the graphic displays are generated during routine post-processing. A narrow spectral peak is seen with power of 7σ, which is well above the detection threshold of 4.5σ. Although this is the type of spectrum hypothesized for signals of ETI origin, it is also the type produced by many man-made sources. More information than is contained in individual data samples is needed for signal identification.

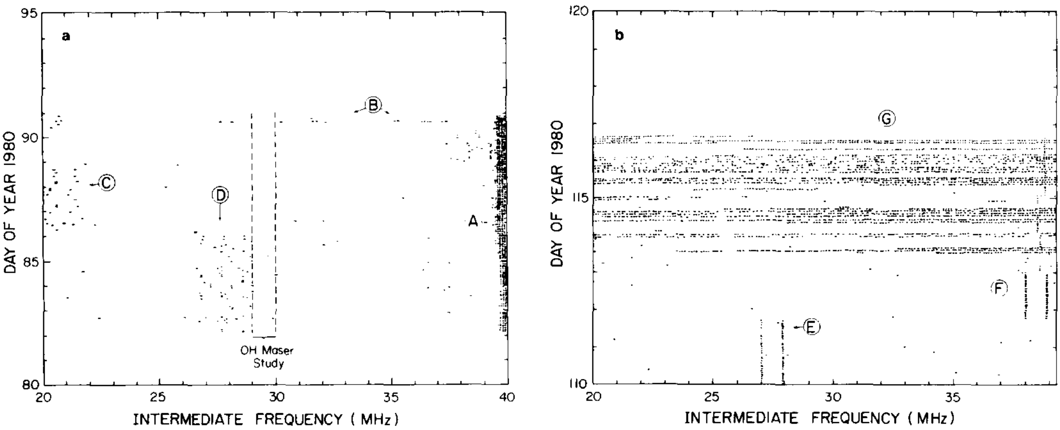

FIG. 5a. IF band frequencies of detections for 1980 Day Nos. 82–90. Frequency limits of the OH maser study are shown. Several sets of detections with distinctive characteristics appear in this display, and have been arbitrarily labeled for discussion in the text. Set A was found to be caused by a 40-MHz oscillator in the HCRO receiver. Set B was associated with the shutting down of the receiver's front end due to problems with its refrigeration system. Detections in Sets C and D tend to come in pairs and triplets separated by 920 kHz, probably associated with frequency switching in use at the time. Frequency shifts *between* the pairs and triplets correspond to velocity corrections being applied to the receiver frequency by the observer's program. These signals are suspected of being caused by one of the HCRO synthesizers.

FIG. 5b. Sets E and F undoubtedly have the same sources as C and D in Fig. 5a. Because of problems with the HCRO receiver's refrigeration system during this period, the OH maser program was not operating. Nevertheless, detection events of this type persisted, even after the front end was finally turned off on Day 113. The link between this condition and sets B (Fig. 5a) and G is explained in the text.

tem. The antenna's half-power beamwidth at this frequency is 31 arcmin.

Red giants are not expected to be congenial locations for life. However, the stars were concentrated near the plane of the galaxy so, except in the case of a few stars at high galactic latitudes, the resulting SETI survey included many disk stars of all types within the telescope beam. In Fig. 6 we show the positions of the objects under study.

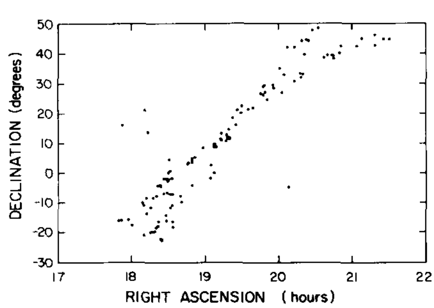

FIG. 6. Sky coordinates of observations prior to stowing the antenna on Day 97. Pointing directions were determined by the OH maser observing program. Most of the objects studied lay in the direction of the galactic plane. Half-power beamwidth was ~0.51°.

During this period, over 10^5 spectra were computed and examined by the SERENDIP microprocessor. Of these, approximately 4000 were found to contain spectral peaks exceeding the background by at least 4.5σ, and were recorded on digital tape. Later, the acquisition times and spectral characteristics were catalogued and examined for the presence of systematic behavior which would help to identify the nature of the sources.

Excerpts from the frequency—time displays are given in Figs. 5a and b. In these presentations there appear to be several distinct sets of data samples, each presumably associated with a particular signal source and each a potential ETI signal and candidate for reobservation unless proven otherwise. These have been given arbitrary labels for convenience in discussion.

The group of signals marked set A was found to be caused by a 40-MHz local oscillator in the HCRO receiver. The oscillator placement in the signal path was several stages below the SERENDIP tap but some leakage occurred nevertheless. After Day 91, we identified the extraneous nature of this source and we reduced the upper limit of the IF scanning to 39.3 MHz in order to eliminate detections of this signal.

Signal sets B and G, though separated in time, result from a single condition: shutting down of the HCRO receiver's front end due to problems developing in its refrigeration system. In this state, the SERENDIP system receives only the low-power, wideband noise generated in the HCRO mixer and IF stages. Its autocorrelation function is vanishingly small and the computed power spectrum is dominated by numerical noise which has enough power in the first bin above dc to exceed the detection threshold. Due to the persistent difficulties with the refrigeration system, observations of the OH masers were discontinued by the astronomical observer on Day 97 (not shown). However, the HCRO receiver and the SERENDIP acquisition system continued to operate with the antenna in the stow position until Day 116.

Signal sets C, D, E, and F are all characterized by pairs and triplets of detections at 920-kHz intervals. The individual peaks contain about 13σ, or 1.5×10^{-21} W/m^2 referred to the antenna, distributed over two or three consecutive channels. There is evidence that the signal being detected is derived from one of the HCRO frequency synthesizers, but the mechanism of its generation is not clear. The shifts in frequencies are associated with rapid frequency switching employed in spectrosocpy and, for sets C and D, slow velocity corrections being applied to a synthesizer frequency setting by the primary observing program. Most of the signals of this type occurred outside the 1-MHz portion of the IF band being examined in the OH maser study. However, some of them fell within the observer's "reference" spectra (spectra recorded at a shifted or offset frequency, which do not contain any known astronomical sources, and which are to be subtracted from the "signal" spectra), and hence appeared in his computed spectra as large anomalous negative peaks. Because the signal pairs persisted over many positions in the sky, and because these detections continued to occur after total failure of the refrigeration system on Day 113, an ETI origin can be ruled out.

These data are illustrative of the types of signals which occur in an active observatory environment and which must be recognized during post-acquisition analysis and factored into a continuing observational protocol.

There are approximately 60 data samples from the 35-day period not clearly associated with the previously described groups. Some of them can be seen in Figs. 5a and b. Further analysis of these detections will include efforts to find and then explain nonrandom distributions of their features, as was done for the groups described above. Ultimately a residue of detections may remain. Some of these are expected to be due to statistical fluctuations of the Gaussian noise. However, with $n = 4.5$, only three such are predicted to occur in 1 month. Therefore, it is appropriate to include the residual unexplained detections in a master list of targets and frequencies to be scheduled for reexamination.

CLOSING REMARKS

The parasitic SETI system described here has been implemented and is currently operating. In an initial run of 35 days, 4000 narrowband spectra exceeding a preset threshold were recorded. By examining the distribution of these spectra in frequency—time space at least 98% of these detections were found to result from one or another of three locally generated signal sources. Two of the three have been identified as instrumental and can be eliminated in future data collection. The third has been tentatively identified as instrumental.

The behavior of the remaining 2% of signals is not well organized in terms of the simple parameters used up to now. Additional heuristic programs will be implemented to investigate them for evidence of man-made or instrumental origin. Once the identifiable instrumental contamination has been eliminated and the detection threshold has been lowered, all detection events may resemble the present 2% residue. Detection events due to statistical fluctuations will become more prevalent; as thresholds approach 3.3σ, they will dominate the data set. The search for nonrandom behavior will have to extend to many more features than we have used up to now. Cluster analysis may be useful for isolating multiple detections of discrete signal sources in parasitic SETI data, the number of entities to be identified being thereby reduced to a few clusters having systematically determined characteristics, plus a residue of individual detections. Unidentified clusters and signals would then be made the subject of followup studies. Cumulative sky-maps portraying the detection limits and directions searched will serve as status reports for this continuing parasitic program.

ACKNOWLEDGMENTS

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