The NASA SETI Sky Survey: Recent Developments

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NASA's Search for Extraterrestrial Intelligence (SETI) project utilizes two complementary search strategies: a Sky Survey and a Targeted Search. The SETI team at the Jet Propulsion Laboratory (JPL) in Pasadena, California, has primary responsibility to develop and carry out the Sky Survey part. This article describes progress that has been made developing the major elements of the survey including a 2-million channel wideband spectrum analyzer system that is being designed and constructed by JPL for the Deep Space Network (DSN). The new system will be a multiuser instrument; it will serve as a prototype for the SETI Sky Survey processor. This prototype system will be used to test the signal detection and observational strategies on DSN antennas in the near future.

I. Introduction

NASA's Search for Extraterrestrial Intelligence (SETI) microwave observing project is preparing to carry out two complementary search strategies: a Sky Survey and a Targeted Search. The NASA Ames Research Center has primary responsibility for developing and carrying out the Targeted Search. Similarly, the Jet Propulsion Laboratory (JPL) has primary responsibility to develop and carry out the Sky Survey. The two approaches are complementary in that the Targeted Search stresses sensitivity to detect either pulsed or continuous signals, and the Sky Survey gives up sensitivity in order to survey the 99 percent of the sky that is not covered by the Targeted Search.

The objective of the Sky Survey is to search the entire sky over the primary frequency range from 1.0 to 10.0 GHz for evidence of narrowband signals of extraterrestrial origin. Frequency resolutions as narrow as 20 Hz will be used.

Table 1 is a summary of the objectives of the survey. A significant technical challenge is to design an observational system that will meet maximum sensitivity requirements, use existing radio telescopes, and allow completion of the survey in a "reasonable" time span of 5 to 7 years. The basic strategy for conducting the survey is introduced in [1]. This article describes progress that has been made and gives a high-level description of the hardware and software of a prototype signal processing system that is currently under construction.

II. Antenna Scan Strategy

Several scan strategies were considered for the Sky Survey and parametric studies were conducted to help in the selection process. These studies clearly showed that the antenna beam must be actively scanned across the sky at a high rate if the survey is to be completed in the allotted time. The NASA SETI plan calls for the Sky Survey to use the 34-m DSN antennas. Because these antennas will not be dedicated to SETI, the scan strategy is quantized so that blocks of time as small as 6 hours can be scheduled and efficiently used.

To accommodate the strategy, the celestial sphere is divided into 900 sky frames that are 60 deg wide by one deg high. The shape and size of the sky frame were selected to maximize the time spent scanning along the width of the sky frame and to minimize the time lost turning around at the edges. At the lower frequencies, where the antenna beamwidths are larger, it will be possible to observe a stack of several sky frames at one time; the resultant observed area of sky might be 10 deg high, for example. Careful scheduling will permit each sky frame to be observed when the width is nearly parallel with the horizon so that the antenna elevation angle will be nearly constant during each scan line. This is done to improve the uniformity of the system sensitivity within the sky frame.

A scan pattern has been selected which can be described as the "racetrack." The scan direction is oriented along a contour of nearly constant elevation and the order of progression of successive scans is chosen to minimize elevation change as time progresses. Thus, the sky frame is observed from top to bottom as it rises in the east; the same sky frame is observed bottom to top as it sets in the west. A schematic diagram of the oval ("racetrack") pattern is shown in Fig. 1.

Details of this scan pattern have been derived so as to utilize the time efficiently, to maintain maximum system sensitivity with uniformity across the sky frame, and to facilitate the signal detection process. Finally, certain features of this pattern can be used to discriminate against some classes of radio frequency interference (RFI). This concept is explained in the following section.

III. Receivers and Signal Processing

The SETI Sky Survey requires an end-to-end system that includes large antennas equipped with microwave feeds, polarizers, amplifiers, and receivers that will span the entire frequency band from 1.0 to 10.0 GHz. Preliminary designs for these subsystems are being studied. However, the most challenging components of the system are the spectrum-analyzer and signal-detection subsystems. Much of the challenge of the signal processor involves the impact of RFI, which is expected to be problematic, but which is poorly characterized at this time. The final design of the Sky Survey processor system will benefit if a prototype system is tested in an observational environment that includes RFI. For this reason the SETI Team at JPL decided to build and test a prototype system.

SETI is collaborating with the DSN Advanced Systems Program to design and construct an engineering development model (EDM) of a wideband spectrum analyzer system to serve as a prototype for the SETI Sky Survey processor. A functional block diagram of the EDM system is shown in Fig 2.

The principal features of the EDM system are as follows:

(1) The Wide Band Spectrum Analyzer (WBSA) is a 2^{21} channel FFT (Fast Fourier Transform) spectrum analyzer which covers an instantaneous bandpass of 40 MHz. The WBSA will operate on the 40-MHz signal at selectable resolutions of 20 Hz, 40 Hz, 80 Hz, 160 Hz, and 320 Hz. Clock-down modes will be available to increase each of these resolutions by factors of 8 or 64. Arbitrary time-domain windowing functions can be implemented in the hardware. Two independent accumulators are available so the system can function in the Dicke-switched mode commonly used for radio astronomy. Two 20-MHz wide channels of opposite polarization can also be implemented.

(2) The Background Estimation Convolution and Threshold (BECAT) assembly is a hardware module that applies the "along scan" detection algorithm described below. It uses convolution and order statistics to determine the detected power baseline in segments

across the passband and to apply a signal threshold that reduces the data rate by a factor of 10^3 or 10^4.

(3) The EDM software system manager is a network-based C language environment based on the ANSI C standard. It provides observatory control, data acquisition, and analysis and it designed to be portable to any system running Berkeley UNIX.

The WBSA has been fully designed and is presently under construction. It operates at 4.5 GOPS (Giga operations per second) and uses 20-MHz IEEE standard arithmetic units. The system contains 76 Mb of dynamic random access memory (DRAM). It is contained in a single electronics equipment rack and is controlled by a separate Masscomp 5600 computer. Specifications for the BECAT module are approaching completion; design work will begin in the near future.

The EDM system hardware consists of 37 large-size (40 x 40 cm) circuit boards capable of holding 600 16-pin dual-in-line-packages (DIPs). Twenty boards are unique designs and 17 are copies. To date, 5 boards have been completely designed, fabricated and tested; 8 other boards are currently in process. A completed fixed-point Fast Fourier Transform (FFT) board is shown in Fig. 3.

The EDM software system has been designed and a framework program is currently operating at JPL. The first of three successive software "builds" is scheduled for completion by the end of 1989. The functionality of the system is increased as each "build" is completed.

IV. Sky Survey Signal Processing

The instantaneous bandpass of the EDM is 40 MHz. Because the system gain profile will not be perfectly flat over the passband, the first step in the background estimation is to normalize the spectral data across the band. This is done by multiplying with an inverse gain matrix that is regularly updated during the calibrations performed as the antenna is turning from one scan to the next.

The resulting normalized spectrum is then divided into subspectra whose bandwidths are optimized for "spectral flatness." Each subspectrum is then examined to determine a pair of order statistics. The r_1th smallest order statistic is used to determine the mean noise temperature of the subspectrum and the r_2th smallest is a test of the validity of the assumed probability distribution function. The algorithm leads to an excellent estimate of the noise power in each subspectrum. The estimate is also robust against strong RFI because it avoids using outliers of the probability distribution function.

For the next stages of the EDM detection process, it is convenient to describe the steps as they are applied to a single frequency bin. These steps are schematically shown in Fig. 4. As the antenna beam scans across the sky at a rapid rate, the WBSA produces a complete 2^{21} point spectrum every 50 msec. For each frequency bin in the spectrum, the WBSA hardware accumulates several spectra and passes the accumulated data on to the BECAT module (Step 2). The number of accumulated spectra and the antenna scan rate are chosen so that five independent accumulations are acquired during the time that the beam has moved one half-power beam width (HPBW) on the sky. In Step 3, the accumulated data samples for each frequency bin are convolved with a 5-point filter that matches the shape of the point-source response function (output power versus time) for the scanning antenna beam. The output is compared to the mean noise power (described above) and signals that exceed a preselected threshold are compared with RFI frequency "maps" resident in the system. Those which do not match frequency patterns of previously detected RFI are stored on disk and passed on to the signal detection software (Step 4).

Next, one considers the inter-scan tests applied in the EDM software. The algorithm is based on the underlying assumption that putative extraterrestrial signals will be originating so far from earth that they will be spatially fixed on the sky; that is, they will match the sidereal motion of the stars. Therefore, a signal with sufficient strength will appear on two or more adjacent scan lines, and the lines will appear at the same place along the scan line because the sky frames are produced after the scan line data are compensated for sidereal motion. This feature makes interstellar signals distinguishable from RFI and random noise, which will generally not move with sidereal rate and direction. A schematic description of this process is shown in Fig. 5.

Another useful discriminator against RFI is the ratio test, which also utilizes the features of adjacent scan lines as well as knowledge of the beam shape in the direction orthogonal to the scan line. For this test we identify a candidate signal, then look for a companion signal on the adjacent scan lines. If the candidate signal is strong, the companion signal(s) should appear with the proper ratio unless the signal is RFI or has disappeared in the time interval between scans. The effectiveness of the ratio test diminishes as candidate signals become weak relative to the system noise.

The BECAT module is designed to provide up to 8192 reports during each spectrum accumulation. This corresponds to a data rate of 800 Kbytes per sec, which can be compared with the 84,000 Kbytes per second data stream from the WBSA accumulator. Each report consists of four numbers, as follows:

(1) The first frequency of a contiguous run of bins that exceeds threshold

(2) The number of bins in the contiguous run

(3) The integrated (convolved) power contained within the run

(4) The maximum (unconvolved) power in a single bin of the run

The first three quantities characterize the signal that appeared above threshold. The fourth quantity is used to determine if the detection was due to a signal that was present throughout the five accumulations that match the convolutional filter, or if a single accumulation contained a burst with sufficient intensity to exceed threshold even after being diluted by the four other accumulations. Events which fail this test cannot be summarily dismissed as RFI, however, because they could be caused by a pulsed signal. These events will be identified for follow-up observations.

V. Duration of the Sky Survey

The time required to complete the Sky Survey depends upon several factors that affect the scan rate and the number of scans that must be made. Some of these parameters have already been selected: the survey will span the frequency range from 1 to 10 GHz, and it will be carried out with 34-m parabolic antennas. Preliminary designs of microwave receiving systems indicate that the instantaneous bandwidth for the 6 lowest frequency bands will be 160 MHz, and the bandwidth for the remaining 25 higher frequency bands will be 320 MHz.

The spacing of the adjacent scan tracks in the sky frame affects the spatial uniformity of the survey sensitivity. The nominal spacing is 1/2 HPBW. As the HPBW decreases with frequency, the number of scan lines for each sky frame will increase linearly with frequency.

The one remaining free parameter is the angular scan rate of the antenna. The tradeoff is between sensitivity and survey duration; slow scan rates improve the sensitivity and extend the time required to complete the survey. The JPL studies show that a reasonable compromise is to scan at 0.2 deg per sec and to schedule about 30 sec to complete the turnaround between scans. With these rates, one can compute the time required to scan the sky for each of the 31 frequency bands that span the 1-10 GHz range. The result is shown in Fig. 6. Note that the scan time increases almost a factor of 10 from the lowest to highest frequency surveys.

The right-hand ordinate in Fig. 6 displays the cumulative scan time as successively higher frequency surveys are included in the ensemble. For our scan rate of 0.2 deg per sec, the complete survey will require 725 days, or about 2 years of continuous round-the-clock observations. Of course, this means that the real survey will take 3 or 4 times as long when one considers that the antenna may only be scheduled one-third of the time for the survey and that even scheduled time must be allocated for maintenance, weather, and follow-up observations of "interesting" signals. Thus the observing schedule must be adhered to in order to complete the survey in the allotted time. The alternative would likely be to reduce the frequency range of the survey.

VI. Conclusions

The EDM system is scheduled to undergo validation tests at Goldstone in 1990. These include the following:

(1) Testing and refinement of the signal detection algorithms

(2) Testing of alternative scan strategies and observatory control functions

(3) Testing of RFI rejection techniques

Results from these tests need to be fed back into the design of the full-scale Sky Survey processor, which will be built in the early 1990s.

Reference

[1] S. Gulkis and E. T. Olsen, "The Search for Extraterrestrial Intelligence," in *Proceedings of the NRAO Workshop Number 11*, K. I. Kellerman and G. A. Seielstad, eds., pp. 161–162, 1986.

Table 1. Objectives of the NASA SETI sky survey

Parameters	Objectives
Spatial coverage	Entire celestial sphere
Frequency range	1.0 to 10.0 GHz inclusive and higher spot bands
Duration	$\approx$ 6 years
Frequency resolution	$\approx$ 30 Hz
Instantaneous bandpass	$\approx$ 300 MHz
Sensitivity	$\leq 10^{-23}\sqrt{f(\mathrm{GHz})}\ \mathrm{Wm}^{-2}$
Polarization	Simultaneous dual circular
Signals	Primarily CW with natural radio astronomy fallout

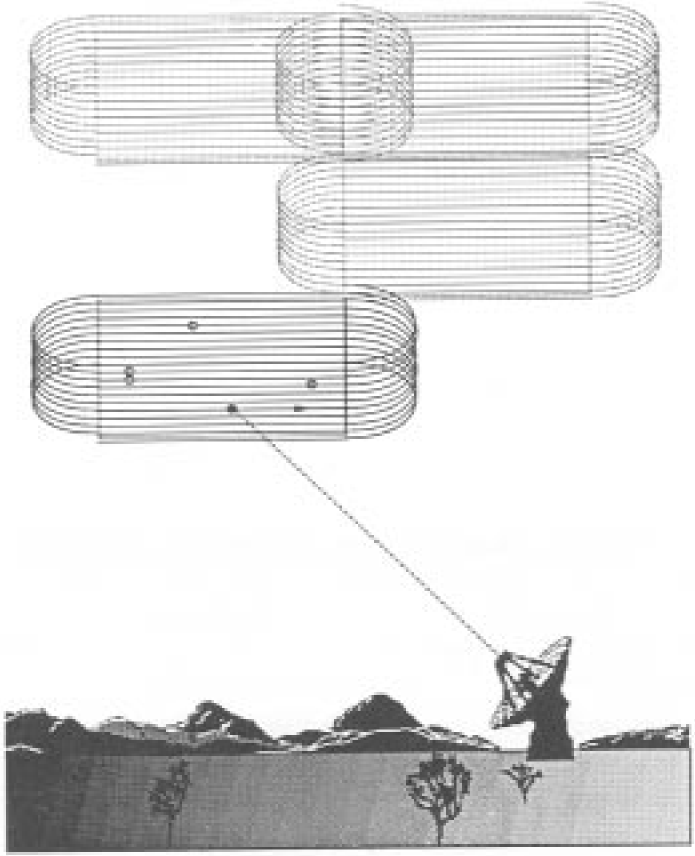

Fig. 1. Sky survey oval scan pattern.

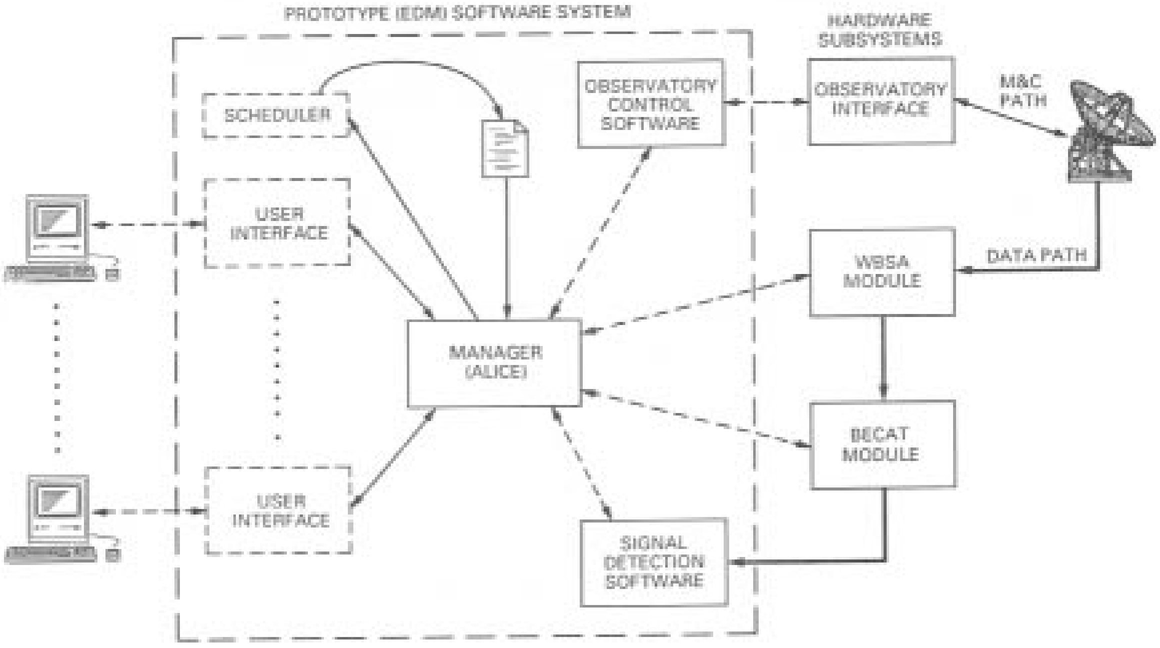

Fig. 2. Prototype system functional diagram.

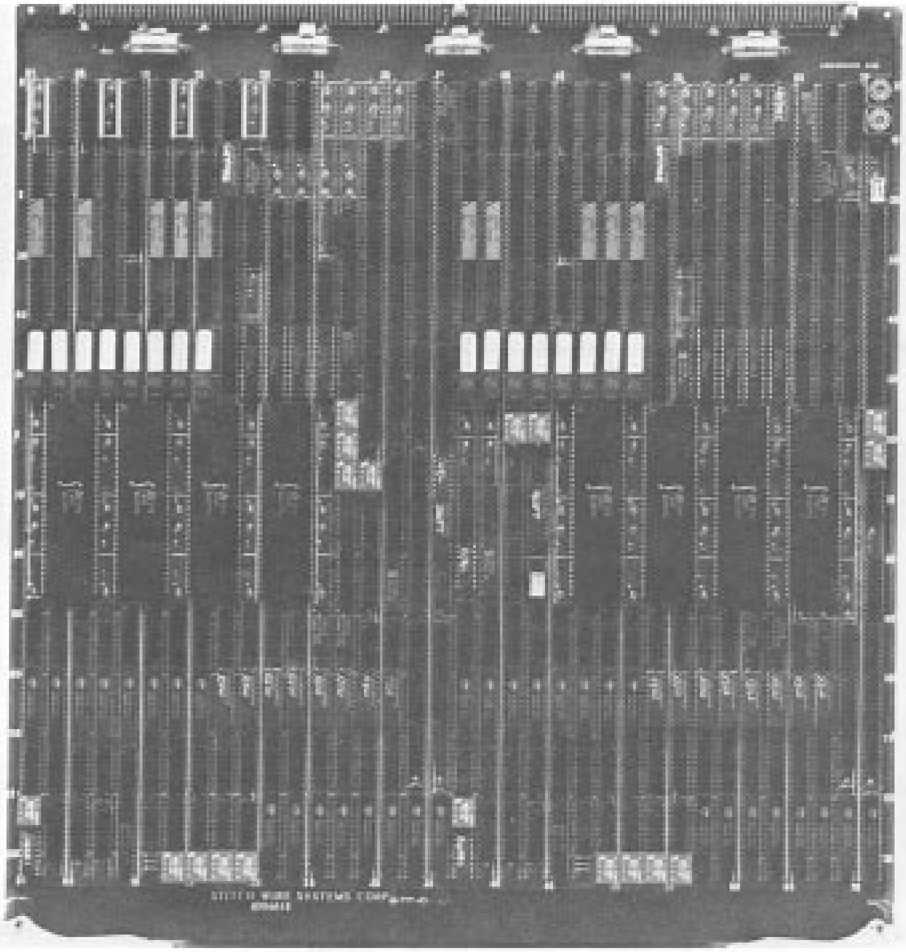

Fig. 3. Engineering Development Model (EDM) of survey processor: a fixed-point FFT board.

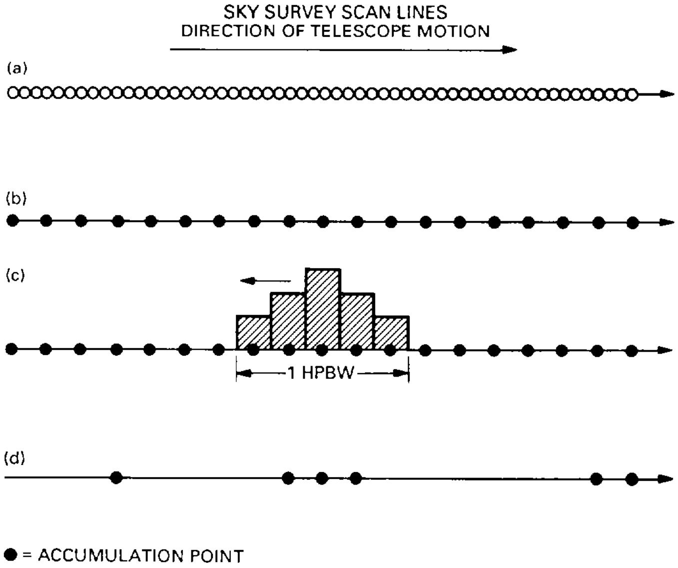

Fig. 4. Signal processing in prototype hardware: (a) high-speed sampling; (b) several spectra are co-added (accumulated) by the WBSA; (c) a 5-point convolutional filter is applied by the BECAT; (d) data above BECAT threshold are passed to the signal-detection software.

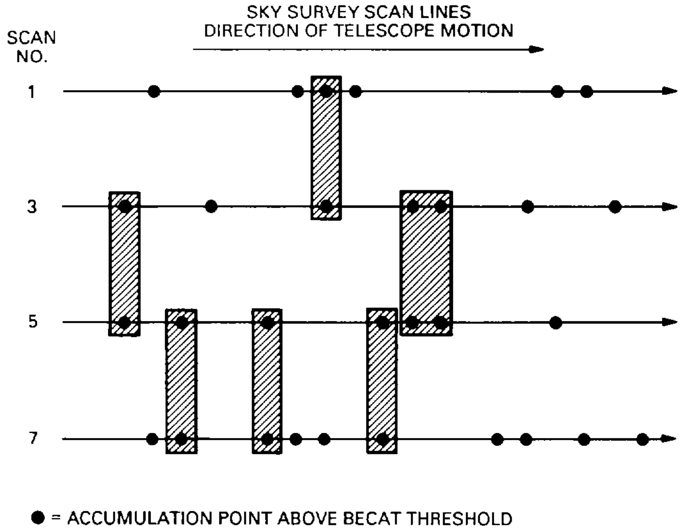

Fig. 5. Signal processing in prototype hardware. The detection software compares candidate points aligned on adjacent spans.

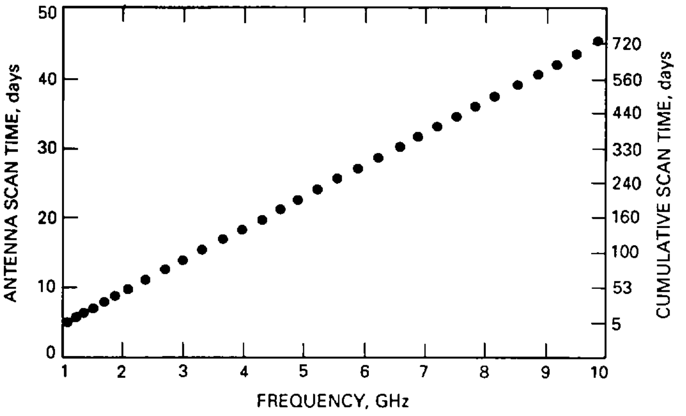

Fig. 6. Time required to scan the sky in 31 adjacent frequency bands.