1981NASCP2156..391W

SETI — The Search for Extraterrestrial Intelligence: Plans and Rationale

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A moderate but wide ranging exploratory program is described which would use existing radio telescopes and advanced electronic systems with the objective of trying to detect the presence of just one signal generated by another intelligent species.

As presently envisaged, the SETI effort involves a 10-year program which will search a well-defined volume of a multidimensional search space for microwave signals of extraterrestrial intelligent origin, using existing antennas and special purpose data acquisition and analysis systems having very high throughput. The entire sky will be surveyed in two polarizations between 1.2 and 10 GHz with resolution binwidths down to 32 Hz. More than 700 nearby solar type stars and other selected interesting directions will also be searched in two polarizations between 1.2 and 3 GHz with resolution binwidths down to 1 Hz. Particular emphasis will be placed on those solar type stars that are within approximately 20 light years of Earth. An analysis system will detect the presence of a wide range of pulses, carriers, and complex or drifting signals. The sky survey will be about 300 times more sensitive and will cover 20,000 times more frequency space than previous surveys. The targeted search will extend the type of signals being sought, the number of targets by a factor of 4, and the range of frequencies covered by a factor of 3×10^6.

INTRODUCTION

The only practical way we know now to test the idea that life exists beyond our Solar System depends on an intelligent fraction of that life providing an electromagnetic signature we can recognize. The physical laws of the Universe, a relatively mature microwave technology, recent digital solid-state achievements, and a minimum number of ad hoc assumptions have permitted the development of a promising set of exploratory strategies for detecting a range of possible electromagnetic signals of extraterrestrial intelligent (ETI) origin. As a result, Ames Research Center (ARC) and the Jet Propulsion Laboratory (JPL) are proposing a moderate research and development exploratory program using existing radio telescopes and advanced electronic systems with the objective of trying to *detect* the presence of just one signal generated by another intelligent species, if such exists.

In the scientific community, the notion that intelligent life might exist elsewhere is a widely held hypothesis with decades of increasing confidence in its essential validity in the presence of increasing controversy. It follows directly from two other hypotheses: given a suitable and sufficiently enduring environment, life is a normal, natural consequence of the long-term application of the basic physical and chemical processes of our Universe; and, as all human experience seems to attest, once a physical process has been found to occur, it can be found occurring elsewhere. But the notion is still an extrapolation based entirely on indirect and mostly Earthbound evidence gathered from many disciplines by a single example of life, intelligent by self-definition and ignorant of any prohibitory physical law. To some skeptics, Martin Rees once retorted, "Absence of evidence is not evidence of absence!" (Oliver and Billingham, 1973). But, of course, neither is it evidence of presence. Despite the many elaborate and largely anthropocentric discussions to date, there is no foreseeable way to test such an interesting hypothesis other than to suitably explore the outer Universe.

BACKGROUND

Much of the extensive history of the Life in the Universe concept is covered under "Additional Reading" at the end of this paper. The essence of the scientific arguments developed in these papers and in many others is as follows. Modern astrophysical and astronomical theory predicts that planets are the rule rather than the exception and are likely to number in the hundreds of billions in our Galaxy alone. Given a suitable location and environment for any single planet, current theories of chemical evolution and the origin of life predict that life will begin. Once life has been established and given a period of billions of years of comparative stability on the planetary surface, it is argued, life will sometimes evolve intelligence. In some cases, the next step may be the emergence of a technological civilization. While we believe ourselves to be an example that this complex path was followed at least once, there is no broad agreement as to how many other technological civilizations might currently exist in our Galaxy. A joint discussion of this topic during the 1979 General Assembly of the International Astronomical Union in Montreal, Canada, showed the optimists and pessimists to be separated by at least six orders of magnitude in their estimates. On that occasion, as he had done 20 years earlier in his pioneering paper, Morrison urged that a search be conducted to experimentally determine (or at least bound) the number of other technological civilizations, as it cannot be calculated from first principles.

In parallel with the scientific arguments for the existence of ETI, there has been a rapid growth in the techniques and technology used in radioastronomy. In recent years, there has been an increasing acceptance of the hypothesis that the most effective way now to detect the existence of other civilizations is to listen for their signals in the microwave region of the spectrum. Indeed, there have been numerous separate searches over the past 20 years. In all cases, these pioneering SETI observations have been pursued with small budgets and with comparatively primitive data processing equipment. It seems clear that reasonable chances of detecting an ETI signal can come about only from more thorough observational procedures using more sensitive and sophisticated data processing systems.

A series of SETI science workshops, chaired by Philip Morrison (Massachusetts Institute of Technology) and supported by the NASA Office of Space Science, was conducted as part of a two-year feasibility study. The results of the science workshops were published as NASA SP-419, "The Search for Extraterrestrial Intelligence" (Morrison et al., 1977). The conclusions of the workshops were:

1. It is both timely and feasible to begin a serious search for extraterrestrial intelligence.
2. A significant SETI program with substantial potential secondary benefits can be undertaken with only modest resources.
3. Large systems of great capability can be built if needed.
4. SETI is intrinsically an international endeavor in which the United States can take a lead.

The proposed SETI effort is an integrated program incorporating the proposals generated by the science workshops under conclusion 2. The plan recognizes the timeliness of conclusion 1, not only in terms of available technology, but in terms of the very serious problem of man-made interference at radio frequencies. For a SETI program to require only modest resources, it must be ground-based yet still have access to those portions of the frequency spectrum where the search for potentially weak signals is to be accomplished. The most recent allocations of the microwave spectrum to numerous users worldwide serve to emphasize the need to proceed with a SETI exploration as soon as possible.

In accord with conclusion 2 above, a significant SETI program can be carried out without new radiotelescopes by equipping existing telescopes with instrumentation of enormous capability, unavailable to previous searchers. Recent electronic developments offer the opportunity to conduct more efficient searches with higher sensitivity and with broad sky and frequency coverage. Key aspects are the ability to process simultaneously more than 10^7 frequency channels, ultra-low noise cryogenic receivers having wide bandwidth and tunability, and sophisticated on-line and off-line signal processing and identification systems.

Starting with Project Ozma in 1959, there have been some 22 separate radio searches for ETI signals, many of them still continuing. Though they represent an impressive effort, they have covered only a very small fraction of the parameter space in which an ETI signal might be expected. The program described here should provide at least a 10-million-fold increase in search space coverage, compared to the sum of all previous searches.

In summary, the underlying rationale for SETI is based on the confluence of major developments in science and technology over the last two decades, leading to both increased interest and increased capability. Controversy over the probability of success can only be resolved by conducting the search.

GOAL AND OBJECTIVES

SETI has as its goal the detection of evidence of the existence of extraterrestrial intelligence. To approach this goal, a series of specific objectives, covering a 10-year period, has been established:

1. Develop a sound scientific and technological search strategy, considering the laws of physics as currently understood, the present state of technology, and the opinions and expertise of the engineering and scientific community.
2. Systematically test for the presence or absence of a wide variety of radio signals.
3. Explore and evaluate other approaches where a theoretical basis suggests a promising search regime.

4. During the search, gather the crucial environmental and engineering data required to better understand the natural and man-made constraints on the observations and simultaneously acquire scientifically interesting astronomical data.

5. Maximize the utility of technology developed for SETI to other objectives such as deep space communication and information management.

SEARCH STRATEGY

A comprehensive search should examine the basic dimensions of signal space: source location, transmission frequency and power, signal modulation, and polarization. But, clearly, it is not possible to search for all kinds of signals at all frequencies from all directions to the lowest flux level, even though weak signals may be more likely than strong signals. There must be a tradeoff between sensitivity and signal character, and between spatial and frequency coverage and the constraints imposed by limits of time and resources.

The very first choice made in the proposed strategy is to limit the search to the electromagnetic spectrum. The use of communication carriers other than electromagnetic waves for signaling over interstellar distances is either prohibited by the nature of the interstellar medium (absorption, scattering, or magnetic bending) or involve exotic particles whose detection is not possible with present-day technology.

Astrophysical sources produce large quantities of electromagnetic radiation throughout the spectrum, forming a background noise that impedes detection of any weak signal of extraterrestrial intelligent origin. Therefore, it makes sense to search first for signals wherever this cosmic pollution is least. This leads directly to the second strategic choice: to limit the search in frequency space to the relatively quiet microwave region of the spectrum. State-of-the-art technology, cost, and time constraints further restrict the portion of the microwave region which may be explored effectively.

The strong general preference for a microwave search, as the most promising near-term strategy, first appeared in the science workshop report "SETI" (Morrison et al., 1977). There have been continuing discussions of this position, much of it pertaining to the advisability of conducting a search in the far infrared region of the spectrum; but it remains the conclusion of the discussants that, for now, a search of the microwave region is the preferred strategy.

It is useful to attempt to estimate the volume of the search space which may need to be explored to detect a microwave ETI signal. A comparison can then be made between the portion of this total volume which has been searched to date by individual researchers and the fraction of the total volume to be covered by the program being considered here.

Figure 1 is an attempt to give a three-dimensional graphic representation of a multidimensional search space that has been named the "cosmic haystack." To accomplish this dimensional compression, it is assumed that the search is conducted in two orthogonal polarizations and that the signal is present for a significant portion of any randomly chosen observing time, and that any modulation present does not give the signal such extreme complexity as to render it noiselike to the detector. Two of the three spatial dimensions can be represented on one axis as either the number of directions examined or the number of telescope beams needed to tessellate the sky. The frequency axis covers the entire microwave region of the spectrum from 300 MHz to 300 GHz. The remaining axis combines both the third spatial dimension and the unknown equivalent isotropic radiated power (EIRP) of the transmitter; this axis is the sensitivity of the search (measured in $\mathrm{Wm^{-2}}$) received within the narrowest channel of whatever detector is being used. The boundaries of this last parameter are the most arbitrary. The low sensitivity end has been set at 10^{-20} $\mathrm{Wm^{-2}}$, which corresponds to 1 jansky (10^{-26} $\mathrm{Wm^{-2}\ Hz^{-1}}$) over 1 MHz of bandwidth and is roughly the level at which previous radio astronomical surveys of the sky might have detected a signal if such existed at the frequencies of these surveys. The high sensitivity limit is what would be required to detect an Arecibo planetary radar transmission (EIRP = 10^{13} W) if the transmitter were located 30 kpc away on the far side of the Galaxy. The ceiling to the cosmic haystack slopes because it has been drawn as the number of directions on the sky in which a 213-m telescope (equivalent to Arecibo) would need to be pointed to conduct an all-sky survey; this number increases as the square of the observing frequency.

Figure 2 shows the portions of parameter space explored by SETI observations reported during the past 20 years. The total volume encompassed by these searches is about 10^{-18} of the volume of the cosmic haystack in figure 1.

The strategy proposed here is simply to detect as wide a range of types of ETI signal as possible while expanding the boundaries of the parameter space searched. It is also a systematic exploration of the microwave regime which will determine physical limitations on SETI strategies resulting from background radiation, and will necessarily develop methods to deal with man-made radio frequency interference (RFI). The proposed strategy surveys the entire celestial sphere over a broad range of the spectrum at limited sensitivity and examines specific directions at higher sensitivity but over a smaller portion of the spectrum. The observation in specific directions is intended to permit detection of weaker signals originating from the neighborhood of nearby stars selected *a priori* to present especially promising pos-

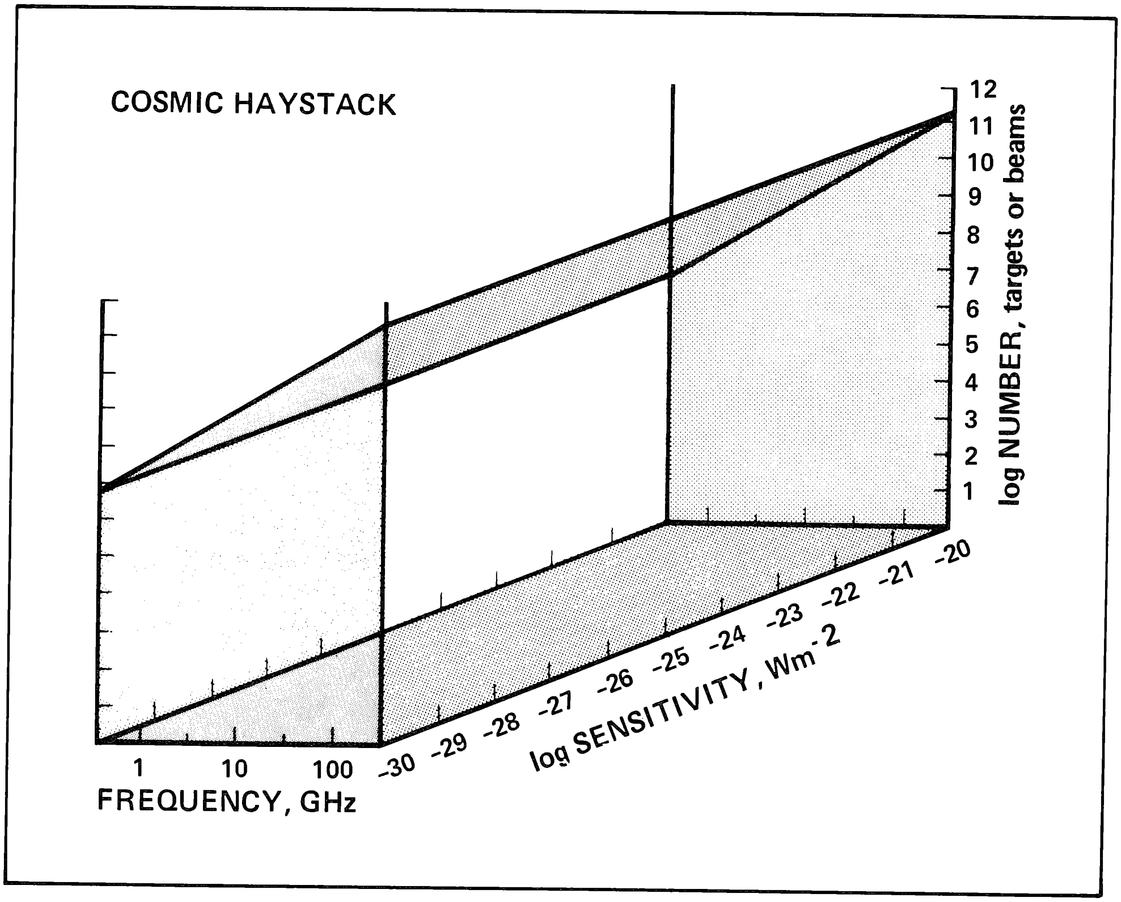

Figure 1. *Cosmic haystack – a three-dimensional graphic representation of multidimensional search space. To accomplish this dimensional compression, it is assumed that the search is conducted in two orthogonal polarizations and that the signal is present for a significant portion of any randomly chosen observing time, and that any modulation present does not give the signal such extreme complexity as to render it noiselike to the detector. Two of the three spatial dimensions can be represented on one axis as either the number of directions examined or the number of telescope beams needed to tessellate the sky. The frequency axis covers the entire microwave region of the spectrum from 300 MHz to 300 GHz. The remaining axis combines both the third spatial dimension and the unknown equivalent isotropic radiated power (EIRP) of the transmitter; this axis is the sensitivity of the search measured (in Wm^{-2}) received within the narrowest channel of whatever detector is being used.*

sibilities or of stronger signals from particularly interesting aggregates of stars at greater distances. This mixed strategy ensures that all possible life sites are surveyed to a significantly low flux level.

It is assumed that ETI transmissions will be strongly polarized, and that circular polarization is very probable in the case of an intentional interstellar transmission because its polarization remains unaltered during propagation through the interstellar medium. We further recognize that signals may be relatively narrow-band ones, pulsed or continuously present. Signals of this

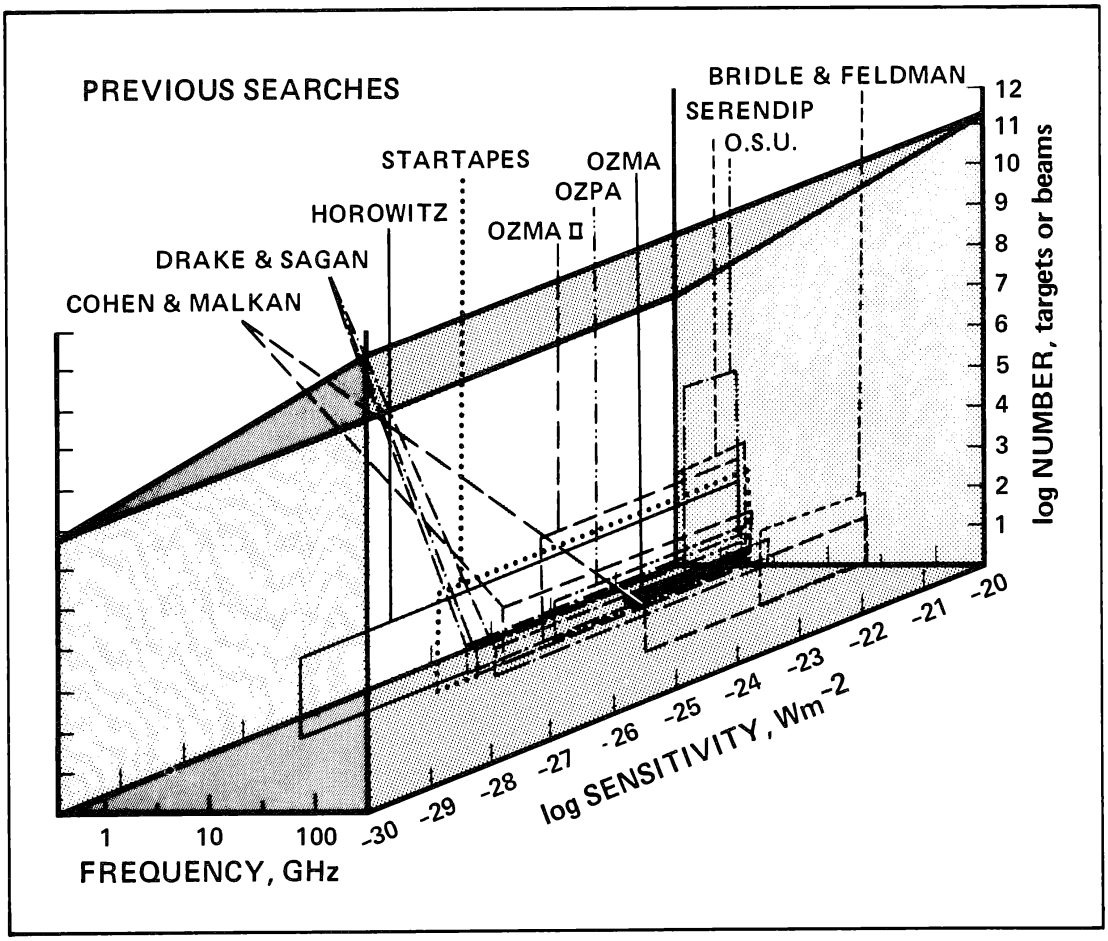

Figure 2. *Cosmic haystack plus those portions of parameter space which have been covered by previous searches.*

nature are much easier to distinguish from natural astrophysical sources and noise than are complex broadband ones. They are also more economical for the transmitting society and, for a given EIRP, can be detected at a much greater range. Thus the search will be carried out in two circular polarizations (although the receiver will be adjustable to permit matching any polarization), using dual solid-state multichannel spectrum analyzers (MCSAs) capable of resolving the broad instantaneous bandpass into many narrowband channels on a real-time basis.

Three general classes of signals can be envisaged:

I. Signals that are compressed in frequency; an obvious example is a CW signal or carrier (drifting or nondrifting).

II. Signals that are compressed in the time domain; the simplest example being a regularly pulsed signal (drifting or nondrifting).

III. Signals so complex as to exhibit little or no fine structure over the temporal and spectral windows of the detector; many kinds of intercepted transmissions may belong in this class.

The characteristics of the proposed SETI systems should allow detection of the exemplary signals of classes I and II to a power level of order one and ten times the mean noise power per channel, respectively. For the third class of signals, or other examples of the first two classes, the sensitivity achieved will depend on the data analysis schemes implemented and therefore is indefinite at present. In the limit of broadband, featureless signals, detection reduces to a total power mode with the sensitivity set by the long-term gain stability of the receiving system.

To assure that sensitivity is not seriously degraded through a mismatch between the resolution of the MCSA and the spectral or temporal structure of a possible ETI signal, in one mode of observing, on-line power thresholding and accumulation will be carried out over a frequency resolution range of 4096:0.25 Hz in steps of factors of 2. Complex signal outputs are planned at resolutions of 1, 32, and 1024 Hz. For pulsed signals, successive additions of power spectra from two or four adjacent channels or two or four sequential time samples provide spectra having sensitivities nearly equivalent to matched filter detectors at all intermediate steps in the frequency resolution hierarchy.

OBSERVATIONAL PLAN

The large number of unknown factors inherent in SETI has led to the adoption of a strategy that examines the entire sky while also concentrating on certain selected targets, in order that a significant portion of search parameter space be covered. This requires the use of both northern and southern latitude telescopes. The specific goal and objectives of the target and sky survey searches have been identified and now must be translated into a realistic and achievable observing plan.

The observational plan assumes the use only of existing radio telescopes; modifying or upgrading of facilities is possible, but not constructing new telescopes. Therefore, telescope availability is a key factor that directly impacts the objectives of the microwave observing program and the resources required to achieve them.

A. Targeted Mode

The primary candidates for particular observational attention will be the solar type stars (spectral types F, G, and K, luminosity class V) which have been identified within 25 parsecs of the Sun. The frequency range to be covered will be $1.2 \leqslant \nu \leqslant 3.0$ GHz, and as many spot bands between 3 and 25 GHz as time and resources permit.

This range of continuous frequency coverage roughly corresponds to a 1-dB decrement in the free space spectral utility function relative to its maximum value near the "waterhole" (1.4 to 1.7 GHz). The free space spectral utility function (fig. 3) is just an inversion of the more familiar temperature bandwidth index (see fig. 3, p. 71, in Morrison et al., 1977) which represents the effective noise in a receiver whose channel widths are optimized for any constant Doppler drift rate.

For a continuously present signal, sensitivity depends mainly on which telescope is used since the integration time required to reach a given sensitivity depends on the fourth power of the effective diameter of the aperture. Only 243 solar type stars are visible to the 213-m-diameter* facility at

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*213 m diameter is that portion of the 305-m-diameter reflector which can be illuminated with a line feed having a 1-dB bandwidth of 30 MHz.

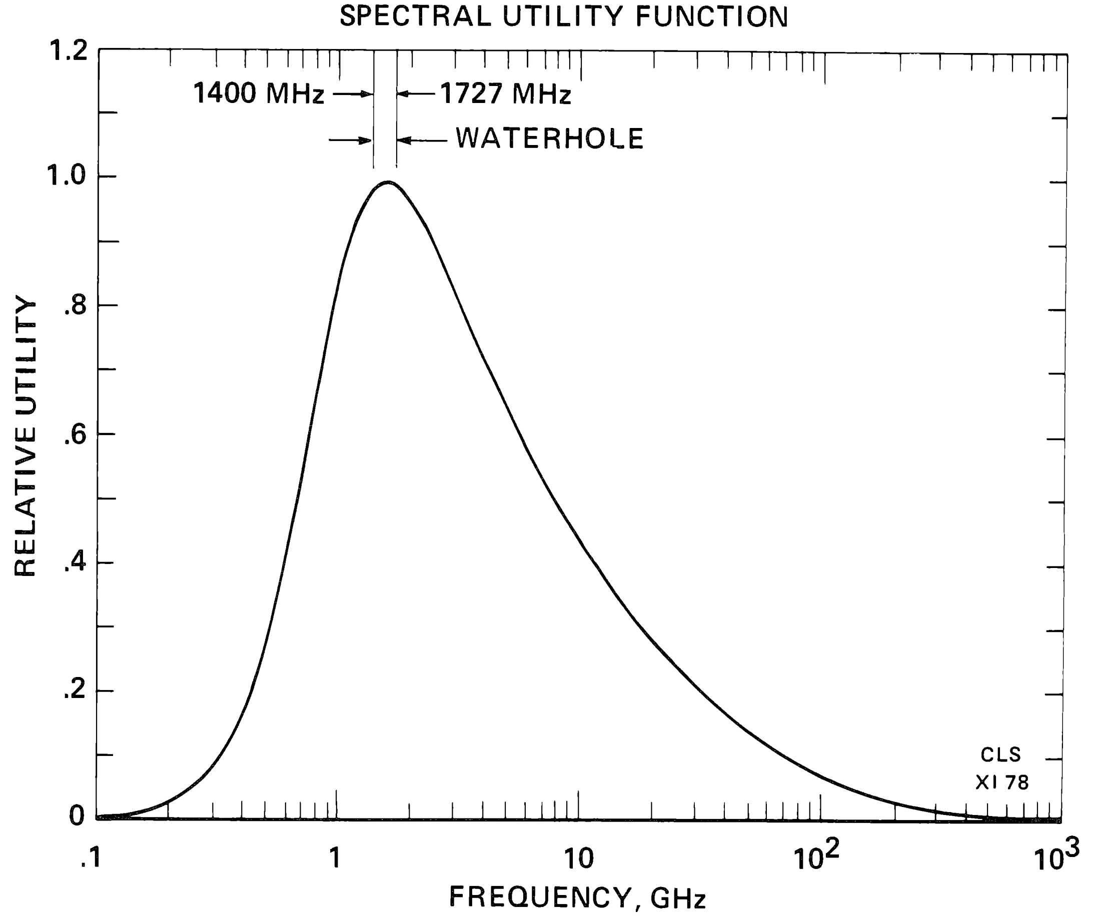

Figure 3. *Spectral utility function; an inversion of the more familiar temperature-bandwidth index which represents the effective noise in a receiver whose channel widths are optimized for any constant Doppler drift rate. The minimum in the temperature-bandwidth index represents the frequency of maximum utility for interstellar communication with ultranarrow-band signals.*

Arecibo; the remaining candidate stars will have to be observed using antennas at least a factor of 2 smaller in diameter. The resulting increase in integration time required to achieve the Arecibo sensitivity, a factor of approximately 20, cannot be contemplated for a program extending over a reasonable period of time. Instead, at all other sites, stars will be observed for approximately the same integration duration per frequency band as at Arecibo. That integration time is determined by the type of signal being sought and by our best estimate of the time likely to be available for SETI.

The observing program allows for additional or alternate options, besides the systematic search of nearby identifiable solar type stars. If telescope time or the number of SETI systems constructed permit, it is desirable to dwell for a longer time on a larger subset of the candidate stars than currently planned, in an attempt to pick up weaker signals or those having a lower effective duty cycle which might be more characteristic of leakage radiation or rotating beacons. Aggregates of stars may also be selected as targets even though they are more distant. These aggregates may contain a distribution of transmitted signal powers, many or most of them too faint to detect; however, the most luminous transmitter at the tail of the unknown distribution may, in fact, be observable. As one example, a small number of directions near the galactic plane, towards the galactic center, contains the vast majority of all stars in our Galaxy.

B. Sky Survey Mode

This microwave search mode will include 100% of the celestial sphere. The frequency range to be covered will be $1.2 \leqslant \nu \leqslant 10$ GHz and as many spot bands between 10 and 25 GHz as time permits. This range of continuous frequency coverage spans the flat minimum of the terrestrial microwave window, and represents the highest frequency to which a sky survey can be made at reasonable sensitivities, in reasonable times. As in the targeted mode, the lower frequency limit is determined by engineering costs for feed construction.

To gain a better understanding of the constraints on time and sensitivity for this sky survey, it is necessary to consider a specific mode of observation. It is proposed that the telescope primary beam be swept across the celestial sphere at a constant rate. This is not the only choice possible, but is, in fact, a good compromise between search sensitivity and duration.

The reason for the choice of constant scan rate is the tradeoff of sensitivity against time required. A constant angular tracking rate ensures that sensitivity varies slowly with frequency ($\sim\nu^{1/2}$), while the time required to cover the frequency range required is not overwhelming ($\sim\nu^2$). If the rate were chosen so that the sensitivity would not vary with frequency, the time required to complete the entire survey would vary as ν^3. On the other hand, maintaining a constant beamwidth at all frequencies would require a time to complete the survey that varies as ν, but it would result in a sensitivity that varies as ν^2. The constant tracking rate approach is an attractive intermediate case and one which is operationally tractable.

C. Search Space Coverage

It is clear that, all other things being equal, sensitivity to narrow-band signals is increased as the individual channel width decreases. The sensitivity remains constant beyond the resolution at which the ETI signal is broader than the channel. The true physical limit to the narrowness of a signal is not to be found in the hardware of the transmitting society or the receiving one; it is due to the dispersive medium through which the signal must pass. For distances $\geqslant$1000 light years, the interstellar medium will probably degrade any transmitted signal to a bandwidth of $\geqslant 10^{-3}$ Hz. This bandwidth limit may be small compared to uncertainties in providing compensation for stellar relative motion. Finally, modulation of the signal will further widen the received spectrum. We conclude that 0.1 Hz represents the minimum resolution applicable.

It is also clear that the search duration decreases as the product of number of channels and channel width, Nb, increases. A design choice (based on funding and state-of-the-art technology) has been made to limit the number of channels to N = 7,864,230. The maximum instantaneous resolution, b, will be 32 Hz for the sky survey and 1 Hz for observing targets. Thus the instantaneous bandpass of the sky survey receiver will be 252 MHz and that of the targeted survey receiver will be 7.9 MHz. Figure 4 is an attempt to display the volume of the cosmic haystack which could be searched, employing the foregoing observing strategy. This volume of search space represents an improvement of a factor of $\sim 10^7$ over the coverage shown in figure 2.

Figure 5 shows the range of sensitivities that may be realized during the observing program in both the sky survey and the targeted observations. For comparison, sloping lines representing a range of transmitter EIRP have been included so that the sensitivity required to detect classes of transmitters having the indicated EIRPs can be deduced as a function of distance to the transmitter. The numerical limits of sky survey and target sensitivity are estimated, based on reasonable values for available collecting area, system noise temperatures, integration time, and acceptable false alarm rates which are considered to be achievable in the observing program.

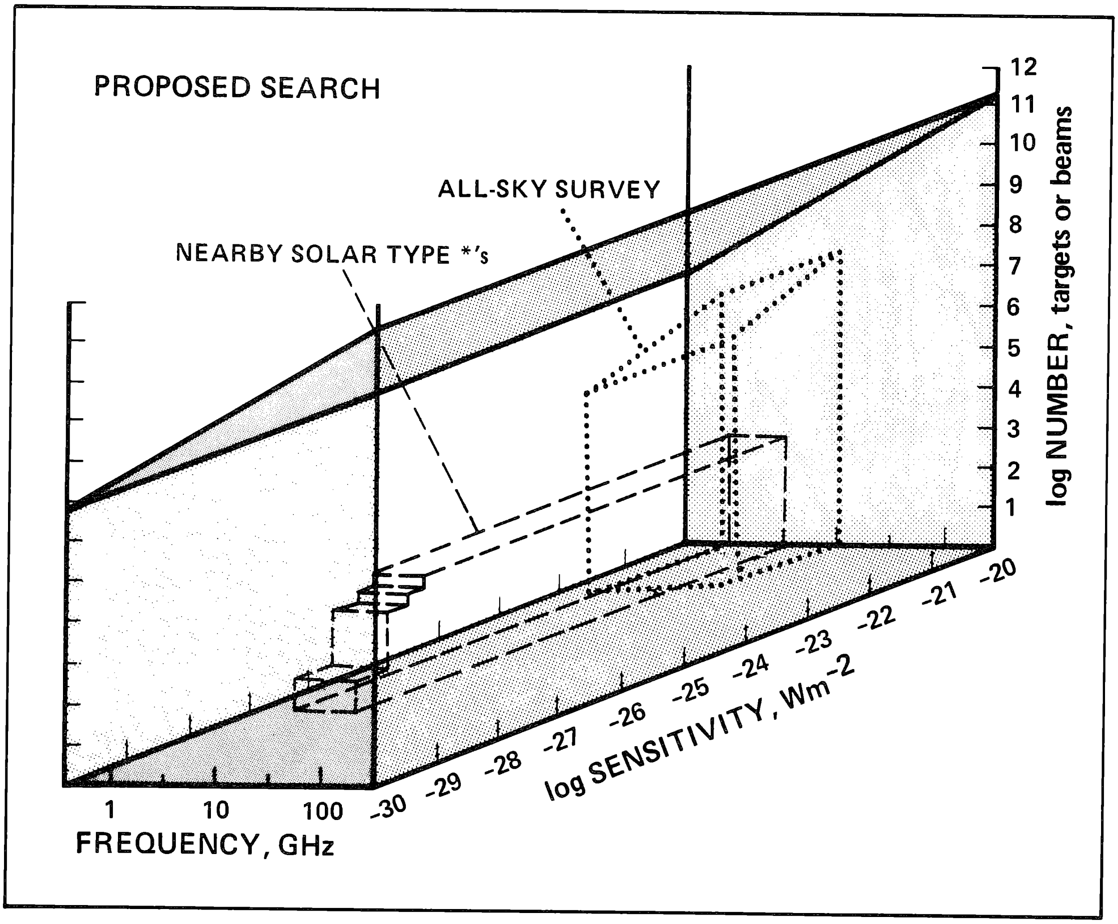

Figure 4. *Cosmic haystack plus the volume of search space which will be covered by the proposed search strategy.*

Neither of the search modes will be capable of detecting leakage radiation at power levels comparable to our own TV transmitters. However, the planetary radar transmitter at Arecibo could be detected at a distance of 400 light years with the *minimum* sensitivity of the targeted search or out to about 18 light years at the lowest frequency of the sky survey.

INSTRUMENTATION

This section describes the approach and current concepts used in developing the SETI instrument system. Figure 6 is a functional block diagram of the receiving system. There are three major elements. First, a wide-band dual polarization feed and low-noise amplifier system. Second, a digital spectrum analyzer constructed with modules that can be configured as appropriate for the capabilities of the site being used and for the specific search strategy

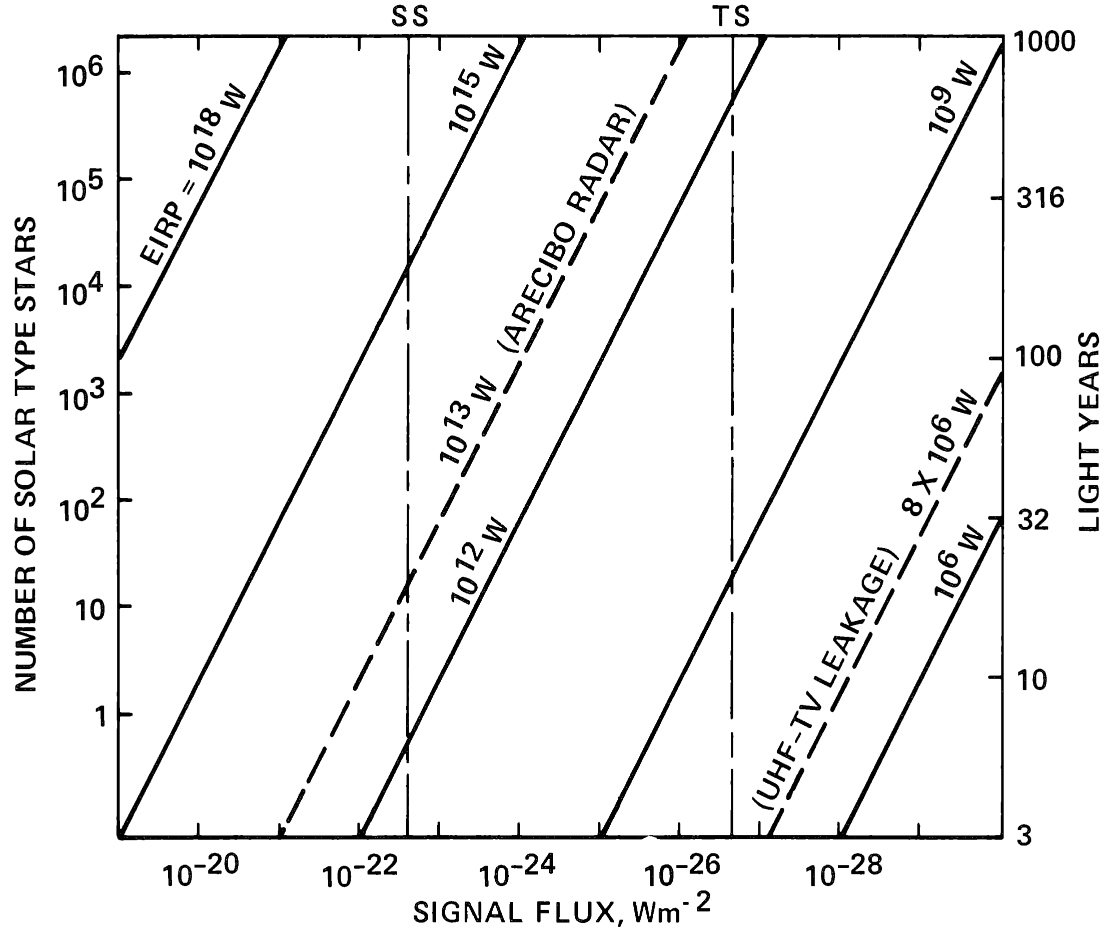

Figure 5. *Maximum sensitivities that may be realized during the observing program in both the sky survey (SS) and targeted observations (TS). For comparison, sloping lines representing a range of transmitter EIRP have been included so that the sensitivity required to detect classes of transmitters having the indicated EIRPs can be deduced as a function of distance to the transmitter.*

being undertaken. Third, a signal processing and control element to examine a reduced data set (preselected by the high-speed computational capabilities of the spectrum analyzer) to determine which information should be kept for further study and/or archiving, and to control the real-time actions required to collect data on interesting signals detected.

It is important to note that we are describing technological aspects of the SETI program while we are simultaneously engaged in a very active design phase. Therefore, although no fundamental philosophical change in the nature of the instrumentation is expected, the precise manner in which the functional requirements are met is still under consideration. With this caveat, table 1 gives the functional requirements on the instrument system as dictated by the search strategy.

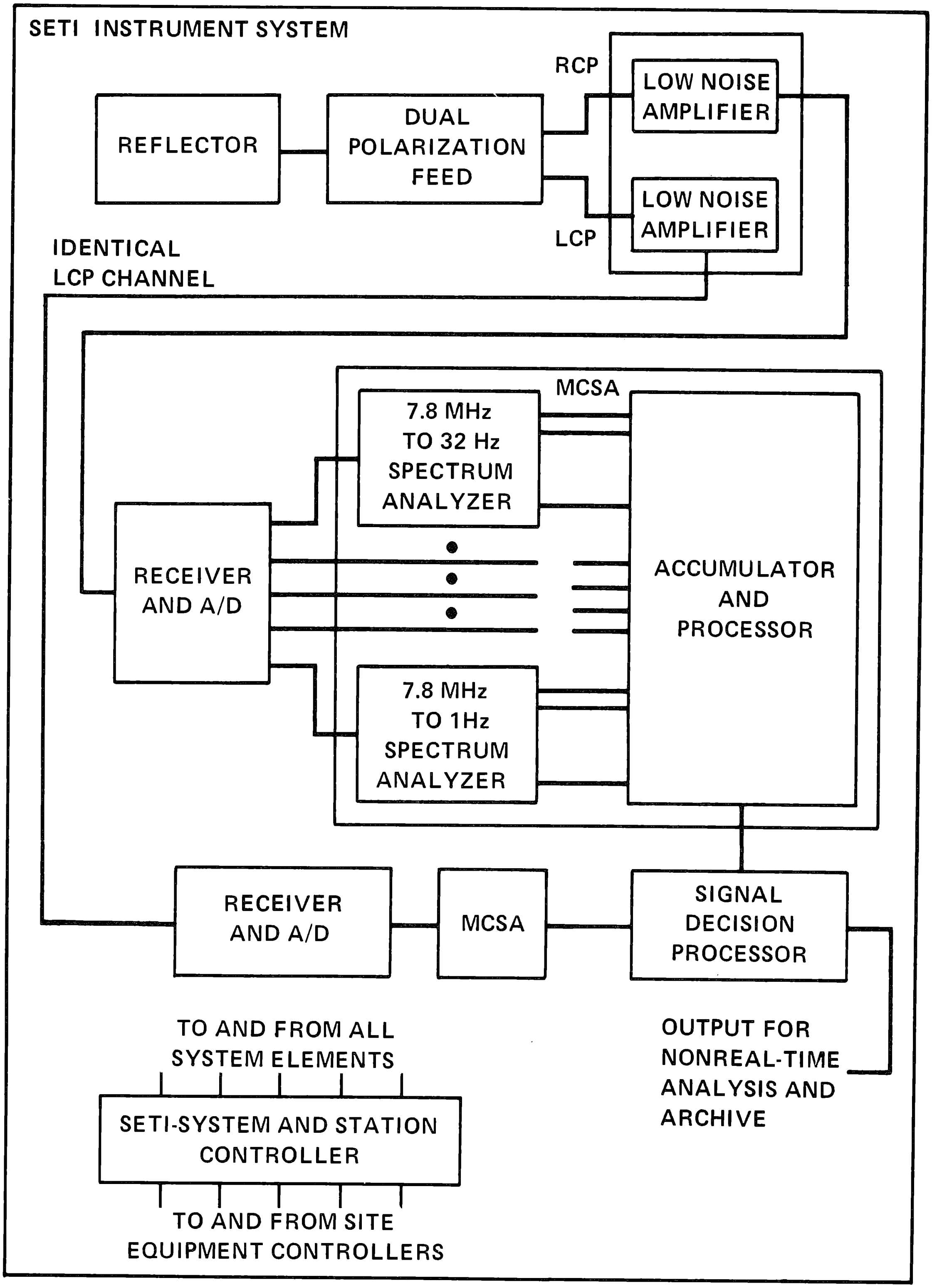

Figure 6. *Functional block diagram of SETI system.*

TABLE 1.– OVERVIEW OF INSTRUMENT SYSTEM FUNCTIONAL REQUIREMENTS

Specification	Requirement
RF tuning range	1.2 to 25 GHz, in 9 or 10 bands
Instantaneous RF bandpass	300 MHz or to antenna capability
Polarization	Simultaneous RCP and LCP, adjustable to match any signal polarizations
Gain stability	$\Delta G/G \sim 10^{-3}$
Gain calibration	Noise adding diode to measure gain and gain stability as function of frequency across passband(s)
Frequency stability	$\Delta\nu/\nu \leqslant 10^{-13}$ over 10^3 sec; all local oscillators (LOs) locked to single-frequency standard
Equivalent system input noise temperature	State of the art consistent with resources
Computer control of	Antenna aspect and motion; LOs, gains, polarizations, integration times, passbands and resolutions, signal analysis and memory functions, peripheral equipment, data flow, etc.
MCSA bins per polarization	*Narrow band,* 7.9 MHz; 7,864,320 1-Hz bins; 245,760 32-Hz bins; 7680 1024-Hz bins; pseudo bins of 0.25, 0.5, 2, 4, 8, 16, 64, 128, 256, 512, 2048, 4096 Hz *Broadband,* 252 MHz; 7,864,320 32-Hz bins; 245,760 1024-Hz bins; 4096 61-kHz bins
Available digital MCSA output signals	Power and unprocessed complex voltages at 7.9 MHz, 61.4 kHz, 1024 Hz, 32 Hz, 1 Hz
Signal processor; instant replay; auxiliary tests	To be determined

A. Low-Noise Amplifiers and Feeds

The low noise amplifier system envisioned for the SETI system is based on an existing design which JPL constructed for the National Radio Astronomy Observatory. It is a tunable cryogenic microwave maser operating in the range 19 to 25 GHz with an instantaneous bandwidth of better than 300 MHz. (A newer design with a center frequency of 32 GHz may prove to be the ultimate choice.) By preceding this device with a cryogenically cooled, parametric upconverter, the large instantaneous bandwidth of the maser can be moved quite far down in frequency while still maintaining a very low-noise temperature. Systems such as this have now been operated in the laboratory at an input RF frequency of about 2.3 GHz and with an equivalent noise temperature of 4 K. To obtain the full frequency range required for SETI requires eight or nine upconverters.

The baseline plan envisions the implementation of two upconverter-maser devices in a single cryostat. Each device is used for the amplification of one sense of polarization from a dual polarized feed. The maser system is a technically optimum choice because of its exceedingly low-noise temperature. However, current technology in cooled FET (field effect transistor) amplifiers, especially at the lower frequencies, may provide a less costly alternative without too great a sacrifice in performance. Hence a study will be undertaken to evaluate the tradeoffs between these two approaches.

The antenna feed structure depends on the reflector system it illuminates. The use of corrugated feed horns with large paraboloidal reflectors will permit the full bandwidth capability of the masers to be used. In clear dry weather, a zenith system noise temperature of about 15 K can be expected at 1.2 GHz and about 35 K at 10 GHz. With other than the paraboloidal reflectors, special feed designs will be required. For example, the 1000-ft Arecibo spherical reflector currently requires the use of a line feed, with an instantaneous bandwidth of about 30 MHz and a tuning range of only 80-100 MHz, regardless of center frequency.

B. Multichannel Spectrum Analyzers (MCSAs)

Four basic spectral analysis techniques have been examined for their suitability in SETI: classical RLC comb filter technology, surface acoustic wave technology, optical power spectrum technology, and digital techniques. The studies to date show that the digital approach is far superior in terms of capability, flexibility, reliability, and cost.

The search strategy requires two different configurations of the basic MCSA modules. The all-sky, wide-frequency range survey needs MCSAs with large instantaneous bandwidths. The targeted search needs MCSAs with higher frequency resolution and a wider range of time resolution. After studies of various competing digital techniques, it has been found both technically and economically desirable to construct both types of MCSAs with a high degree of commonality down to the board level.

The basic MCSA architecture is as follows. A real instantaneous intermediate frequency (IF) bandwidth of 7.9 MHz is down-converted to two 3.95-MHz base bands by a quadrature mixer (fig. 7). After low-pass filtering, the two signals are digitized at a 25% oversampled rate of 9.83 MHz. The two outputs, I and Q, are then processed together by two stages of finite impulse response (FIR) filters, which produce 7680 parallel channels, each 1024 Hz wide.

The use of digital filters, rather than, say, a single pipeline FFT approach, has a number of important advantages. At insignificant added cost, linear phase, low ripple passbands can be formed with channel to channel crossovers at the 0.1-dB down points and 60 or more dB attenuation

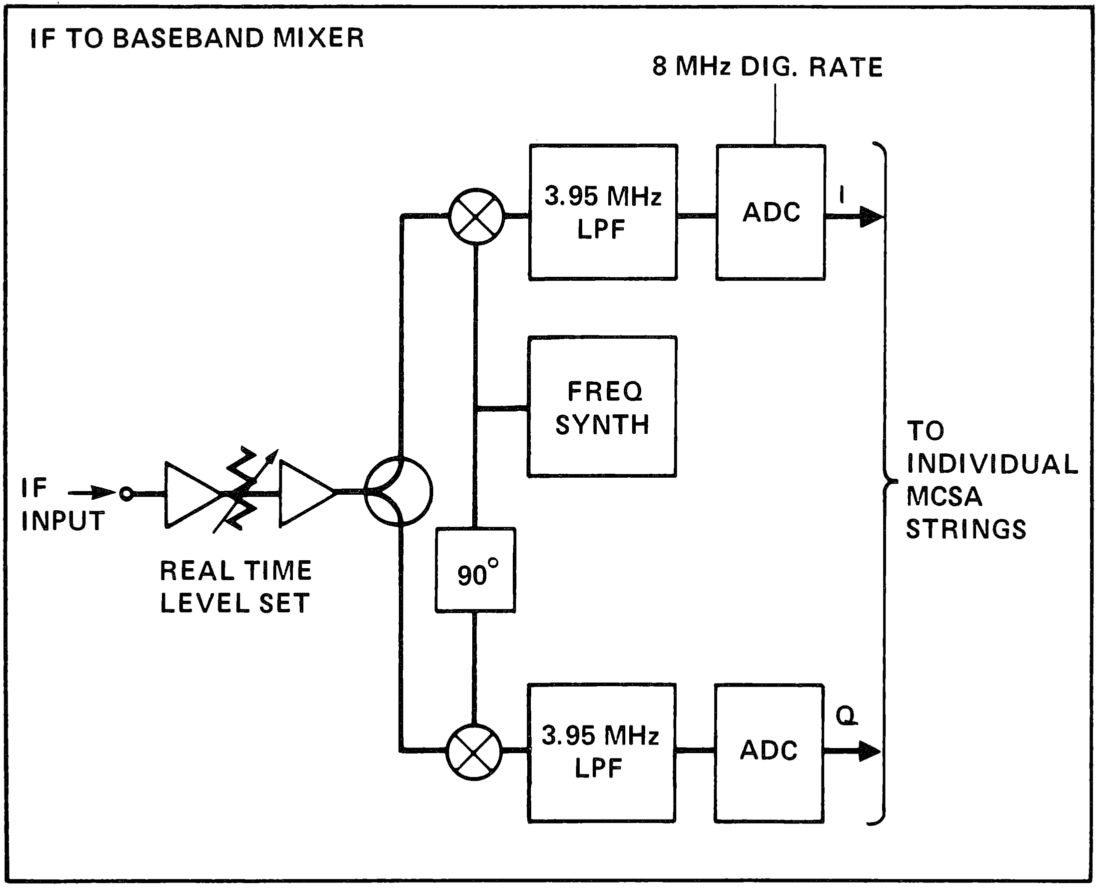

Figure 7. *Block diagram of the intermediate frequency (IF) to baseband mixer. A real instantaneous IF bandwidth of 7.9 MHz is converted to two 3.95-MHz bands by a quadrature mixer. After low-pass filtering, they are each digitized at a slightly oversampled rate of 9.83 MHz, producing two outputs, I and Q.*

by the middle of the adjacent channels (and in all other channels). This provides a desirable freedom from aliasing effects when observing in the presence of even quite strong interference in one or more channels. At the crossover frequencies, there is no loss of sensitivity. The fact that a signal can appear in two passbands is not a significant problem. The rapid development of parallel channels enhances system reliability. The 128-channel filter can be built on one quickly replaceable plug-in board, and the bulk of the components are downstream. The parallel strings, though working on separate data, are controlled in parallel. Furthermore, a wide range of additional spectrum manipulation can be carried out on line by software changes alone, without altering the wiring and parts of the preceding stages as is so often necessary with pipeline FFT systems. Note, however, that the final decision on the MCSA architecture (BPF/DFT or pipeline FFT) will not be made until extensive comparison testing of breadboard hardware has been completed.

Figure 8 is a block diagram of one of 32 parallel spectrum analyzers, which together make up the 7.9×10^6 channel broadband MCSA for the all-sky wide-band survey. The total instantaneous bandwidth is 252 MHz, and the frequency resolution is 32 Hz. The transition from the 1024-Hz level to the 32-Hz level is carried out by microprocessor-controlled DFT algorithms. The microprocessors are controlled by software and plug-in firmware, so that, for example, dedrifting or dedispersion transforms can be implemented if desired. Further details can be found in Peterson et al. (1980).

Power spectra and unprocessed complex voltages are available at the outputs of each stage of the MCSA. Accumulation before or after thresholding can be accomplished within the MCSA at each stage in the resolution string. If the analysis of a suspected signal requires it, higher resolution over a more limited bandwidth can be obtained in either of two ways: by clocking down the MCSA or by adding one or more of the 1024-Hz to 1-Hz DFT boards used in the narrow-band MCSA (discussed below).

Figure 9 shows the configuration of the narrow-band MCSA which consists of one or two strings of the broadband MCSA plus some additions. In parallel with the 32-Hz DFT boards are 1024-Hz to 1-Hz DFT boards to provide 7.9×10^6 1-Hz output bins. Power spectra and unprocessed complex voltages are available at three resolution levels. Accumulation before or after thresholding can be accomplished at each resolution bandwidth. Most important, though, is the construction of a series of real and pseudo resolution bandwidths in powers of two which are thresholded for pulses.

The strings of different resolutions are formed in the following way. At each of the real resolution levels, 1, 32, and 1024 Hz, two and four adjacent frequency bins are added together to give pseudo binwidths of twice and four times the basic binwidth; and two and four successive individual bin outputs are added together to give 1/2 and 1/4 the resolution of the basic

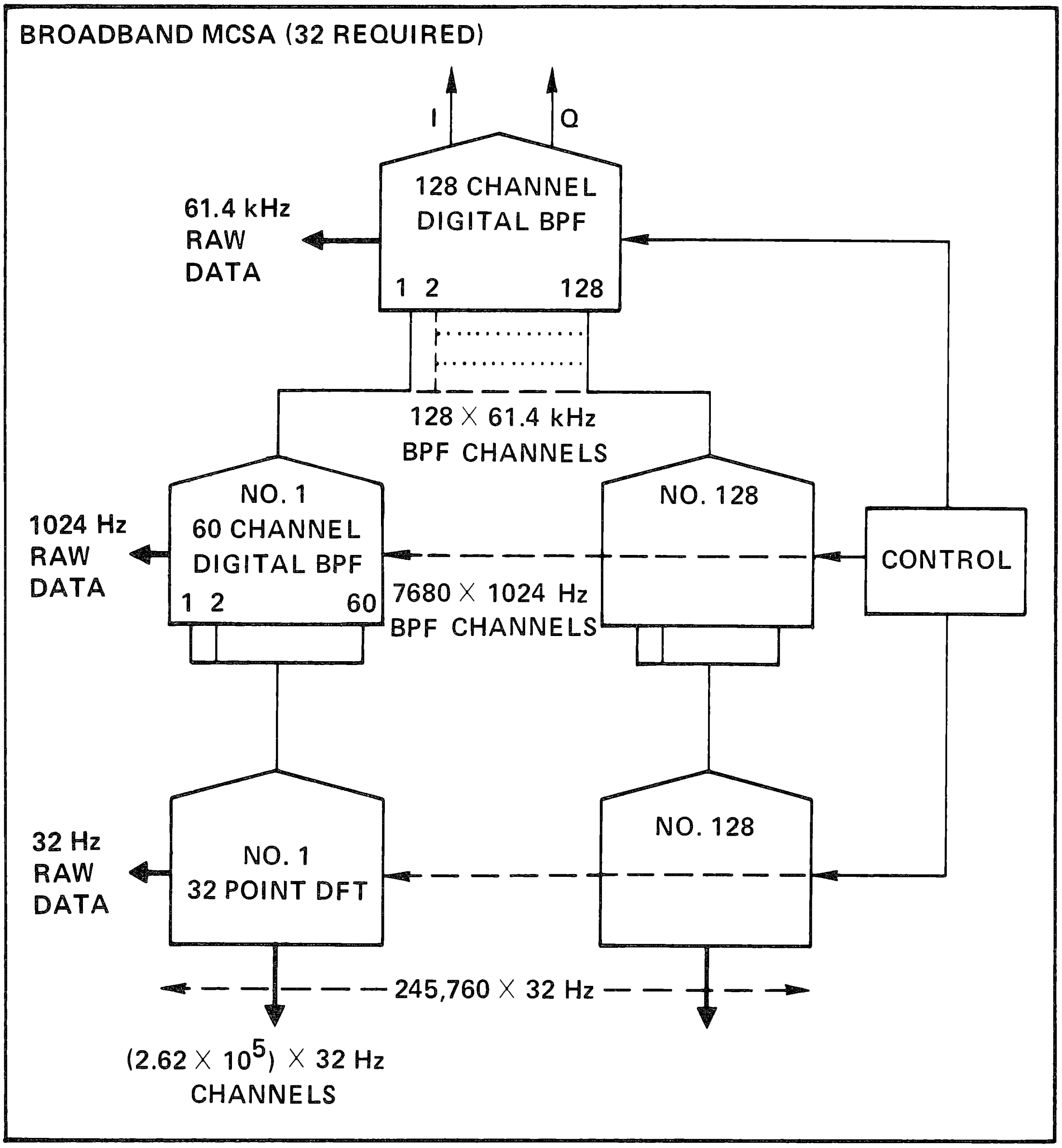

Figure 8. *Block diagram of one of 32 parallel spectrum analyzers which together make up the 7.9×10^6 channel MCSA for the all-sky wide-band survey.*

binwidth. This pseudo binwidth construction process introduces, at most, a 3/4-dB signal loss, compared to direct DFT computation. As a result, one may search for a wide range of relatively narrow-band energetic pulses with durations increasing in powers of two from 0.25 msec to 4 sec. Longer pulses are handled at a later stage in the data manipulation, as is the storage and analysis of pulses from all the different spectral bands.

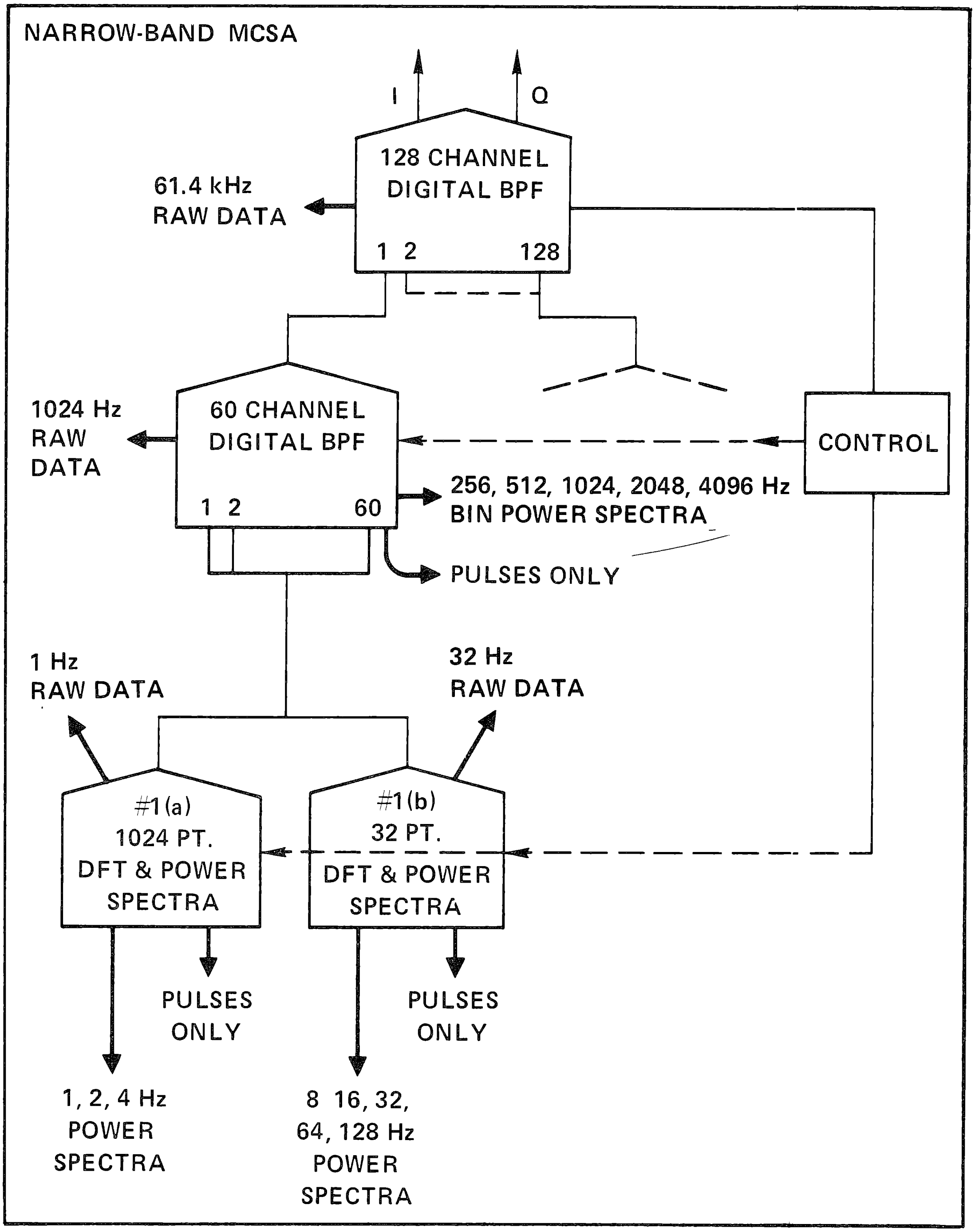

Figure 9. *Narrow-band MCSA consists of one or two strings of the broadband MCSA plus some additions. In parallel with the 32-Hz DFT boards are 1024-Hz to 1-Hz DFT boards to provide 7.9X10^6 1-Hz output bins. Power spectra and unprocessed complex voltage are available at three resolution levels.*

C. Signal Processor

The design of the signal processor is just beginning, as is the complete definition of the auxiliary signal identification tests, on line and off line. But a few remarks are useful at this time. For the case of the sky survey, spectral data from the broadband MCSA can appear with frequency resolutions from 32 to 1024 Hz, in powers of two, by suitably programming the microprocessor DFT operations in the third resolution stage of the MCSA. Successive spectra will be accumulated and read out four or five times per full half-power beamwidth scanned on the sky. Maximum sensitivity is preserved if adjacent scans are saved and reduced together. There is the option to threshold the accumulated spectra on line or at some later time, or both. Still to be determined is just how much of what data is to be archived. Early experience testing prototype units under real observing conditions will be important in this determination.

Thresholding on line will be employed to determine if any signals are present. If there are any, a series of automatic tests will be performed to identify their nature and origin.

For the targeted search, 10 to 32 complete 1-Hz spectra from the narrow-band MCSA will be saved and searched for drifting continuous signals in one or more channels, and for pulses of duration longer than 4 sec which show some kind of coherence in the time-frequency-polarization domain — for example, three or more pulses equally spaced in time, or pulses alternating in frequency and/or in polarization. This process will be repeated for successive groups of 10 to 32 spectra and, at the end of observing in a particular direction, the accumulated threshold surviving residues from the successive spectral batches will be analyzed for signals.

Pulses appearing in the 0.25- to 4096-Hz resolution spectra will have been thresholded at a level that produces, for example, an *average* of 10^3 to 10^4 false alarms per spectrum. These will be saved for a period of time and scanned for regularities. This procedure permits thresholding at appreciably lower S/N, thus increasing system sensitivity to pulsed signals. As with the broadband system, the appearance of a possible signal will initiate auxiliary tests. How much of the 1-Hz spectral data is to be preserved for off-line study, distribution, or archiving is yet to be determined.

Studies are planned to see if there is a practical way to optimize sensitivity to an even wider range of signal types, using the frequency-time-polarization data in the 32-spectrum matrix. In addition, there will be studies to see if there is a practical way to employ predetection integration. In principle, for classes of signals containing enduring, coherent frequency components (e.g., carriers or subcarriers), sensitivity increases in proportion to time with predetection integration; sensitivity only increases with the square root of time for post-detection integration.

An "instant replay" facility will be provided so that the relevant raw (complex) data can be preserved for off-line analysis when the real-time system is unable to analyze the nature and origin of a signal satisfactorily. One attractive hardware solution to this task is the Mark III recorder being developed by NASA-Goddard and the Haystack Observatory for VLBI Astronomy and Geodesy.

The signal processor will store data on tape in two batches for the permanent archives – one for data relevant to SETI, the other for data deemed to be of long-lasting significance, based on prior consultation with the scientific community at large. The bulk of the incoming data is noise of negligible interest and will not be saved.

SIGNAL IDENTIFICATION

The data rates expected, on the order of a gigabit per second at every real frequency resolution, require that most of the data be examined automatically on line and immediately discarded if no interesting patterns are detected. Only that very small fraction deemed significant in that it contains a possible ETI signal or important astronomical data would be recorded for posterity and off-line analysis.

The simplest class of signal is a continually present, nondrifting narrowband pattern that appears in one or more channels. The signal processor is required to integrate power spectrum samples over a period of time and to test at the end of that period whether one or more channels display a sufficient excess power level over the mean noise power level so that one may confidently conclude that a signal has been received. The signal processor requires an accumulator vector array that will not overflow in the integration time, and a software/hardware package that carries out the statistical analysis.

A more difficult class of signal is a pattern that is pulsed, may be drifting, and may appear in one or more channels. A threshold test is made during each sample of the power spectrum, with the level set so that the false alarm rate is about 10^{-4}. Thus, each sample yields about 10^3 or more data points, which must be stored to permit time-frequency-polarization series analyses. Data so stored over the duration of the observation in one direction must be analyzed before the succeeding observational set is ready for analysis. The analysis must search over frequency and polarization space for drifts and discrete, systematic shifts, and in the time dimension for periodicity. One is looking for pulse repetition periods from about twice the reciprocal binwidth up to about 1/4 the observing time in a single direction.

A class of signal still more difficult to detect is a continuously present, slowly drifting pattern. No threshold test is applied to such a signal until it is dedrifted. The entire power spectrum is stored sample by sample. Data so stored over some appreciable time must then be analyzed in the time required to take the sample set. Dedrifting is memory-intensive. Ideally, one would like to save perhaps 1000 spectra at 1-Hz resolution, dedrifting in increments of 1 mHz/sec. An attractive compromise would appear to be as follows: decrease memory by a factor of about 32 to 1, save and analyze spectrum samples in groups of 32, and preserve only the residues from the 32 sample sets.

Once a potentially interesting signal pattern is flagged by normal observing procedures, a hierarchy of signal identification protocols will be brought on line; for examples, see the partially ordered listing in table 2. To

TABLE 2.– CANDIDATE SIGNAL IDENTIFICATION TESTS

Apparently Continuous Signals:

1. Signal in RF, IF, BASE, or IMAGE BANDS?
2. Does signal correlate with output from "omni" RFI receiver?
3. Consult catalog of RFI and natural signals in disk memory.
4. Check harmonic radiation possibilities.
5. Are other signals being received simultaneously?
6. Optimize resolution bandwidth and polarization.
7. Any frequency/phase/polarization/time structure?
8. Can local oscillator be phase-locked to signal?
9. Any recognizable modulation scheme?
10. An observable frequency drift rate? Terrestrial? Other?
11. How does signal change with antenna pointing?
12. Source direction apparently fixed on celestial sphere?
13. Signal receivable at another site? Any parallax?
14. Does signal show a frequency-drift pattern cyclic in time?
15. Further tests for proper motion and parallax: Are interferometric observations possible? VLBI? Reobserve at many later times.
16. Off-line study of frequency assignments.
17. Off-line analysis of signal, using recorded raw data. Search for coherent structure in signal. Search for a suitable "matched filter" for signal.

Intermittent or Pulsed Signals:

18. Look for coherent patterns in and among these parameters: Frequency, phase, polarization, and time; in the short term and in longer terms.
19. Same tests as for apparently continuous signals.

conserve scarce telescope time, a major effort will be devoted to designing automated procedures to quickly identify the usual types of RFI. For instance, tests for items 1 through 5 in the table will be designed to be carried out in seconds or less, if there is enough signal, and should be able to identify a large percentage of the RFI commonly experienced at radio observatories.

CONCLUSIONS

The total effort envisaged for this program will require about 10 years—5 years for the SETI instrumentation development followed by 5 years for observations. To accomplish this, several narrow-band SETI systems would need to be replicated so that simultaneous northern and southern hemisphere targeted observations could be performed during the period in which the sky survey was being conducted with the wide-band SETI system. The present program calls for the use of the NASA Deep Space Network antennas and facilities as well as non-NASA observatories as SETI observing sites. Although the procedural details for vitally needed SETI involvement by non-NASA observatories and by the general scientific community have not yet been determined, it is anticipated that this will be accomplished through scientific proposals to NASA. In addition, alternative approaches are expected to be forthcoming and will be encouraged.

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ADDITIONAL READING

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