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Extraterrestrial Intelligence: An Observational Approach

Existing antennas can set limits on the presence of radio signals from extraterrestrial intelligent life.

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Are we alone? The possibility that other intelligent creatures exist in the universe has challenged man's curiosity and imagination at least since classical times. With the development of modern astronomy in the 20th century, planetary formation, the astronomical basis for the development of earthlike life, has received serious attention. Considerations of the number of stars which may have planets, and of the likely number of life-favoring planets, argue against the uniqueness of the earth and in favor of the development of extraterrestrial intelligence (*1, 2*).

Summary. The microwave region of the electromagnetic spectrum, a plausible regime for signals from extraterrestrial intelligences, is largely unexplored. With new technology, particularly in data processing and low-noise reception, surveys can be conducted over broad regions of frequency and space with existing antennas at flux densities plausible for interstellar signals. An all-sky, broad-band survey lasting perhaps 5 years can be structured so that even negative results would establish significant boundaries on the regime in which such signals may be found. The technology and techniques developed and much of the data acquired would be applicable to radio astronomy and deep-space communications.

Since the development of radio astronomy after World War II, serious observations have been possible. Postulating that extraterrestrial beings will have been motivated to undertake interstellar communications, many authors (*3*) have noted that the radio-frequency spectrum offers a feasible means for those communications. Indeed, it has been realized for more than a decade that a modern radio telescope–radar astronomy system could, in principle, detect a like system many thousands of light years across the galaxy if only the correct frequency, modulation, and spatial direction were known. At least ten organized searches for radio signals of extraterrestrial origin have been carried out, some with the largest existing radio telescopes. No verified detections have resulted from any of these searches.

In 1971 Project Cyclops, a design study of a potentially very large system, was conducted (*4*). A dedicated SETI (search for extraterrestrial intelligence) system was visualized which would begin observations with a minimal number of antennas and grow to attain higher sensitivity as resources became available. The full-sized Cyclops, an array of 1000 to 2500 antennas of 100 meters in diameter (*5*), would be able to detect an omnidirectional gigawatt (10^9 watts) radio beacon as far away as 1000 light years, or leakage signals like those emitted from the earth today out to perhaps 100 light years.

Our interest here is in whether the search for extraterrestrial intelligence can be carried significantly further without the construction of expensive new radio facilities. Past programs have been severely constrained by technology. We argue that new developments in computing systems (some of which were envisaged in the Cyclops study) used in conjunction with existing antennas offer the opportunity, at modest cost, to conduct significant new searches for radio signals from extraterrestrial intelligences over a broad frequency range. A key aspect of such an observational program is enhanced parallel processing of the radio signal—perhaps 10^6 frequency channels simultaneously—combined with state-of-the-art maser receivers of very wide bandwidth and tunability and exceedingly low noise temperature. When used with small existing antennas, these components will allow a comprehensive, all-sky survey to be carried out with low sensitivity over a very broad frequency range. This same technology, when used with larger existing antennas, can materially extend the detection limits for targeted observations of nearby stars as well.

A mixed observing program which combines an all-sky survey and a targeted search is considered by many to be a good strategy to employ at the present time. The sky survey will yield very broad coverage of frequency and spatial location but relatively low sensitivity; the targeted search will yield greater sensitivity but at reduced coverage. With our total lack of empirical evidence, it is not possible to quantitatively evaluate the relative merits of these two strategies. However, since discussions of targeted searches may be found in the literature (*4*) and the all-sky search can be made with smaller and more readily

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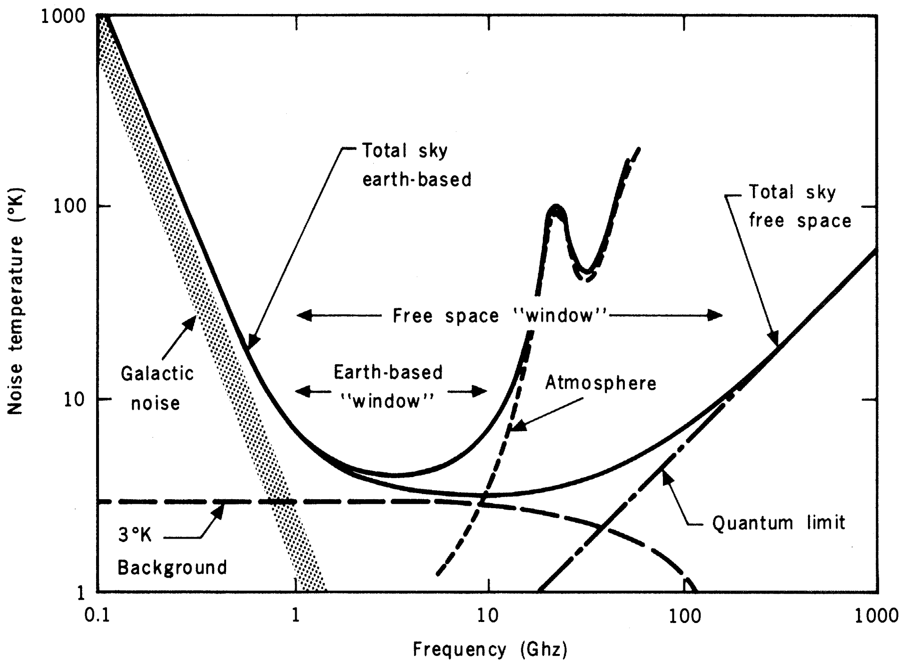

Fig. 1. The microwave windows. The total noise from natural sources has a broad power minimum in the microwave regime, making this spectral region plausible for interstellar signaling. The broad band labeled "galactic noise" indicates an exponential relationship whose magnitude varies with galactic latitude. The atmospheric contribution varies significantly with local meteorological conditions. The curves shown are for clear, dry weather at low antenna elevations (elevation ≈ 20° or 3 air masses). [Adapted from (*4*)]

available telescopes, in the remainder of this article we illustrate primarily the performance that can be achieved now with an all-sky search.

The strength of a broad-frequency, wide-area survey lies in its minimization of the assumptions that must be made about the location of transmitters and extraterrestrial contact strategies. Because of the vastness of the frequency and spatial domains plausible for interstellar signaling, most search efforts to date have relied on assumptions about the frequency of a transmitted signal (such as associations with the 1.42-gigahertz frequency of neutral hydrogen) and have often been limited to nearby stars. Consequently, the negative results obtained so far can only rule out a very limited set of signals from extraterrestrial intelligences, that is, transmissions above a certain intensity in certain narrow frequency ranges mainly from certain nearby stars.

As an example, a broad-frequency, wide-area search could discover a signal intended (*6*) to be detected by "aliens" (us) without a priori assurance of the existence or precise nature of the signal. It seems to us that advanced societies interested in and capable of establishing interstellar beacons may also have acquired enough understanding of the circumstances surrounding and the timing of the emergence of intelligence to dramatically narrow the possible stars to be considered in their search. If so, then directional, beamed transmissions aimed at candidate stars, such as our sun, might exist. Kuiper and Morris (*7*) have presented a case for a fully explored or colonized galaxy from which might originate beamed transmissions in the solar neighborhood. Other scenarios involving bright artificial sources such as interstellar maser signals, astroengineering activities, and galactic synchrotron accelerators have been hypothesized. These would also be tested by such a survey. Because the possibilities seem so numerous and our knowledge of plausible transmission powers is so scanty, a comprehensive search in frequency and spatial direction for fairly strong, easily recognizable radio signals is a logical next step in seeking other intelligent beings.

The Observational Problem

A generalized search within the electromagnetic spectrum can be visualized as one which principally explores the multidimensional space of (i) frequency; (ii) received power flux; (iii) spatial locations; and (iv) modulation. Choices of the range of parameter space to be searched influence from beginning to end the instrumentation and search strategy. The essential argument for an all-sky search is that frequency and spatial coverage is a vital search strategy that has not yet been accomplished. The sensitivities achievable with existing antennas are adequate to detect fairly strong signal levels while systematically searching a broad microwave frequency range over the entire sky. A complementary program of targeted observations can greatly increase the frequency coverage and intensity limits for observing "interesting" objects.

Transmitted frequency. A subject of diverse opinion in SETI strategies is the selection of the frequency regime. On physical grounds, a particularly favorable frequency range for SETI is that between 1 and 100 Ghz. In this region the total noise power generated by the 3K and galactic backgrounds and by quantum noise has a broad minimum which would be nearly the same for observers anywhere in the solar neighborhood or similar regions of the galactic disk.

If noise from the earth's atmosphere is added to these three sources, a minimum remains, but its width is substantially diminished (*8*). (The minimum noise temperature is about 5K between 1 and 10 Ghz.) The frequency regions of these troughs, known, respectively, as the free-space microwave window and the earth-based microwave window (Fig. 1), are the minimum noise regions for the entire electromagnetic spectrum.

The question then arises whether there is some relatively narrow frequency range within this optimum part of the radio spectrum that is especially appropriate for interstellar beacons on a priori grounds. Cocconi and Morrison (*9*) originally argued in 1959 that the hydrogen line frequency, 1.42 Ghz, is a cosmically unique frequency in the radio spectrum which might be used for this purpose. Since that time, however, numerous spectral lines, including strong lines of OH, H_2O, and CO, have been discovered, thereby removing the uniqueness of the neutral hydrogen frequency. The Cyclops report (*4*) noted that because communicating societies will want to transmit and receive without jamming themselves, a band of frequencies rather than a unique frequency is necessary. The band of frequencies between 1 and 2 Ghz was considered optimum because (i) the product of the sky noise times the usable bandwidth is minimal there; (ii) for a telescope of a given diameter larger beam widths are obtained at the longer wavelengths (and hence less severe pointing constraints are imposed); and (iii) collecting area is cheaper at longer wavelengths. The Cyclops report went on to speculate that the 245-Mhz band between the hydrogen line frequency and the 1.665-Ghz hydroxyl line (the lines characteristic of the dissociation products of water) should be a preferred frequency band for water-based intelligent life. While this region of the spectrum is certainly interesting, we believe that the arguments for its exclusive choice are weak. For example, Drake and Helou (*10*) have shown that the optimum frequency for interstellar communications could be nearly 70 Ghz, considering how the motions of inhomogeneous ionized interstellar matter broaden the frequency spectrum of narrow-band radio transmissions. In addition, we note that the frequency choice may be limited primarily by the economics of large, high-frequency, high-gain antennas, or perhaps by the existence of favored choices in the physics of high power generation for the millimeter wavelength region (*11*).

On balance, we believe that the entire earth-based microwave window (and perhaps the free-space microwave window as well) is a plausible regime in which to seek strong beacon transmissions intended for detection by previously unacquainted communicators.

Received power flux. The power flux, φ, impinging on the earth from a distant transmitter in space is given by the simple relationship

$$\varphi = \frac{P_e}{4\pi R^2} \quad \text{watt/m}^2 \tag{1}$$

where R is the distance in meters to the transmitter and P_e is the equivalent isotropically radiated power (EIRP) in watts (transmitted power times antenna gain).

In Fig. 2 the flux that would be received from beamed signals with radiated powers that can be generated now on the earth, or that we can anticipate generating within the next few decades, is plotted as a function of transmitter range. The power flux ratio between the strongest transmitter and the weakest transmitter shown is 10^{10} for these assumptions, testimony to the extent of the unknowns in this exploration. The large range of plausible values further reinforces the wisdom of comprehensively exploring the vast frequency and spatial regimes before major efforts are begun to significantly increase sensitivity over that available today (see below).

Spatial location. Although relatively nearby stars of spectral classes F, G, and K have been considered particularly appropriate for examination, reasonable scenarios asserting adaptability or capability beyond our own suggest a much wider range of target possibilities. Drake and Kardashev (*12*) and von Hoerner (*13*) have discussed the possibility that there might be a population of extremely intense radio transmitters. In addition, transmitter sites are conceivable which are not clearly associated with star locations. These could arise, for example, if artificial modulation of natural radio sources is feasible for technically advanced civilizations. The inadequacy of our own experience indicates the desirability of conducting a comprehensive search of the entire sky.

Modulation. Electromagnetic signals can be varied (coded) in many ways to carry information. However, without information about the code structure, it is not possible to optimize the detection strategy. Recognizing this limitation, we hypothesize a modulation scheme which provides a continuously transmitted strong carrier component of very narrow width compared to natural sources. Because such a signal is easily detectable with a spectrum analyzer, and because the spectrum can be searched systematically, we believe that searching for narrow-band carrier signals is a natural first step in any long-range program. Since other modulation schemes (for instance, pulses) are possible, we believe that these should also be sought as instrumentation becomes available.

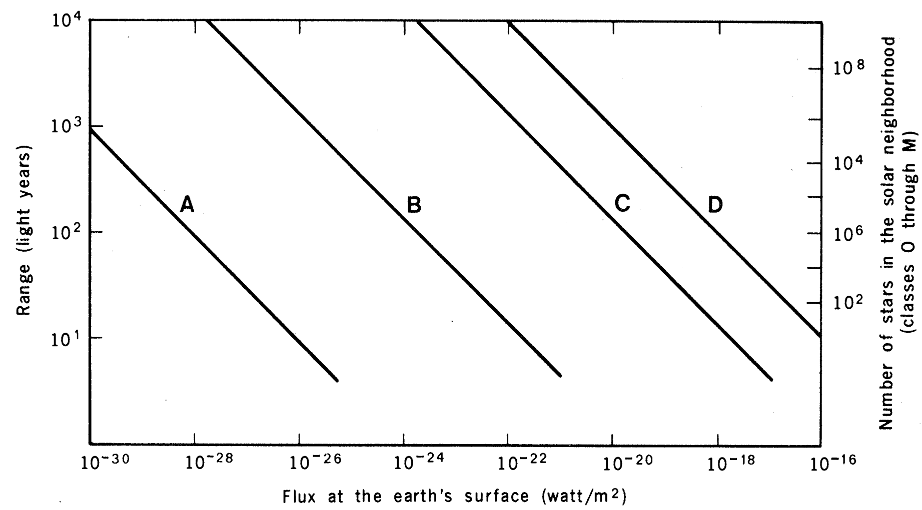

Fig. 2. Flux density capabilities required to detect equivalent isotropically radiated power (EIRP) such as we might generate. Each diagonal line demonstrates the flux density which would irradiate the earth's surface should a transmitter of a specific capability be located at the specified range. (A) Omnidirectional beacon as considered in the Cyclops report (*4*); EIRP = 10^9 watts. (B) Arecibo-scale beamed transmission; EIRP = 2×10^{13} watts. (C) Cyclops-scale beamed transmission; EIRP = 2×10^{17} watts (*22*). (D) Space solar power system beamed transmission by a device such as Glaser *et al.* (*29*) have advocated for microwave power transmission to the earth; EIRP = 10^{19} watts. The number of star targets within a volume encompassed by the range of the left ordinate is given approximately on the right ordinate. About 25 percent of these are "solar-like" (spectral class F, G, and K) stars.

Previous Searches

Table 1 summarizes ten previous searches for radio signals of extraterrestrial origin started before 1976 (*14*) in three countries. These include targeted searches and large-area sky searches for narrow-band signals with highly directive antennas, as well as searches for sporadic emissions with broad-beam antennas. There have been no verified detections.

The first serious search with a radio telescope for intelligent signals of extraterrestrial origin was carried out by Drake (*15*) in 1960, utilizing the 26-m radio telescope of the National Radio Astronomy Observatory (NRAO) at Green Bank, West Virginia. Two nearby stars, Epsilon Eridani and Tau Ceti, both about 12 light years away, were monitored for 4 weeks at a frequency of ~1.42 Ghz, as suggested by Cocconi and Morrison in 1959. Approximately 400 khz of bandwidth was explored with a single-channel receiver of bandwidth 100 hertz. No signals of extraterrestrial origin were discovered. Drake estimated that signals would have been detected if their bandwidth was ~100 hertz and their power flux was 8×10^{-22} watt/m^2.

Eight years after Drake's first search, Troitskii *et al.* (*16*) monitored 11 stars, mostly of spectral type G and less than 62 light years distant, as well as the Andromeda galaxy, M31. A 2-Mhz band around 0.927 Ghz was observed with a 25-channel detector, each channel having a 13-hertz passband. (This frequency was examined because of the characteristics of the available equipment.) An antenna 15 m in diameter located at the Radio-astronomy Station of the Scientific Research Institute of Radiophysics at Ai-

Table 1. Summary of previous SETI efforts. Most star targets examined have been nearby (<100 light years away). An arrow after the year indicates that the search is continuing.

Date	Investigator	Diameter (feet)	Frequency (Ghz)	Total bandwidth examined (Mhz)	Resolution (khz)	Target	Sensitivity (watt/m^2)
1960	F. D. Drake	85	1.42	0.4	0.1	2 stars	10^{-21}
1968	V. S. Troitskii *et al.*	45	0.927	2.2	0.013	12 stars	2×10^{-21}
1970→	V. S. Troitskii	Dipole	1.875			Omnidirectional	
		Dipole	1.0				
		Dipole	0.60				
1972	G. Verschuur	140	1.42	20.0	7.0	10 stars	1.7×10^{-23}
		300	1.42	0.6	0.49	3 stars	5×10^{-24}
1972→	B. Zuckerman and P. Palmer	300	1.42		3.0	602 stars	5×10^{-24}
1972→	S. Bowyer, M. Lampton, J. Welch, D. Langley, J. Tarter, A. Despain	85	Variable	20.0	2.5	Semirandom	10^{-21}
1973→	N. S. Kardashev	Dipole				Omnidirectional	
1973→	F. Dixon and D. M. Cole	175	1.42	0.38	20.0	Area search, $7° < \delta < 48°$*	1.5×10^{-21}
1974→	A. H. Bridle and P. Feldman	150	22.2		30.0	500 stars	
1975→	F. D. Drake and C. Sagan	1000	1.42		1.0	Several galaxies	8×10^{-25}
		1000	1.653		1.0		8×10^{-25}
		1000	2.38		1.0		4×10^{-25}

*δ, Declination.

menkie, Soviet Union, was used. No monochromatic signals from these objects were detected above the noise level, which Troitskii *et al.* estimated to be 2×10^{-21} watt/m^2. This search was basically similar to Drake's search.

Troitskii (*17*) and his colleagues embarked on a rather different observational approach in early 1970. The idea behind this program was to search for sporadic electromagnetic radiation which could be the result of an extraterrestrial engineering activity. The search was carried out at three frequencies in the decimeter band, 1.875, 1.0, and 0.6 Ghz, using dipole antennas and a reflector. The main lobe of the antenna pattern was pointed at the zenith. To distinguish signals of space origin from those of local origin, the observations were simultaneously conducted at two locations separated by 1500 kilometers. Simultaneous events could be timed to an accuracy of < 1 second. Later in 1970, this experiment was expanded to four observation stations (Gorky, Crimea, Murmansk, and the Ussuri region of Siberia). These stations were spaced in latitude over distances of about 1500 km and separated by 8000 km in longitude. In both experiments, it was found that the observed number of coincident events was far higher than estimated on the basis of chance, but these events occurred mainly in daylight. Troitskii interpreted these results to mean that the observed signals did not come from outer space but are probably the result of solar activity. According to Sagan and Drake (*18*), Troitskii and Kardashev are continuing this observation program.

Verschuur (*19*) initiated a ten-star search for narrow-band radio signals in the 1.42-Ghz band in 1972. The stars in this program were chosen on the basis of their proximity and similarity to the sun. Two of the targets were chosen because they may have objects of planetary mass orbiting them. Verschuur used both the 140-foot and 300-foot NRAO radio telescopes for this program. No signals attributed to an extraterrestrial intelligence were observed. Verschuur stated that his limits of detection were 1.7×10^{-23} watt/m^2 with the 140-foot telescope and 5×10^{-24} watt/m^2 with the 300-foot telescope. The corresponding bandwidths are 6.9 khz over a 2.5-Mhz passband and 490 hertz over an 80-khz passband.

B. Zuckerman and P. Palmer [cited in (*18*)], also working with the 300-foot NRAO radio telescope, began an extensive program of searching 602 stars for evidence of narrow-band radiation at 1.42 Ghz. This program, now nearly complete, has not detected any extraterrestrial intelligent signals. The upper-limit sensitivity for this search is estimated to be 5×10^{-24} watt/m^2 in a 3-khz passband.

A new observational approach was initiated at the University of California at Berkeley in 1972 by Bowyer and coworkers (*20*). Their strategy is to carry out the SETI activity as a parasitic experiment on radio telescopes being used for more conventional astronomical research. In this program, the sky locations examined and the frequencies searched are dictated by the primary observing program. There have been several versions of the parasitic instrumentation. The current version has 100 channels and is capable of attaining a resolution of 2.5 khz and a sensitivity of 10^{-21} watt/m^2 sequentially over a 20-Mhz bandwidth. The system is currently installed on the 85-foot Hat Creek radio telescope.

In 1973, Dixon and Cole (*21*) began an all-sky search for narrow-band radiation at 1.415 Ghz, using the Ohio State University 100 by 31 m transit radio telescope. This survey is still in progress and plans are to search over the entire range 1.4 to 1.7 Ghz. The narrowest bandwidth used in this survey is 20 khz. The results are negative to date.

In 1974 the Canadian researchers A. H. Bridle and P. Feldman [cited in (*18*)] initiated a search for artificial extraterrestrial radio signals at the water-line frequency, 22.2 Ghz, using the 150-foot radio telescope at Canada's nationally operated Algonquin Radio Observatory. Approximately 500 solar-type stars have been chosen as candidate targets in this search. The results are not available at this time.

The most recent search described in the literature was undertaken by Sagan and Drake (*18*), who used the 1000-foot radio telescope at Arecibo, Puerto Rico, to examine several galaxies at three frequencies: 1.42, 1.653, and 2.38 Ghz. No positive detections were reported. Estimates of the sensitivities of the search in a 1-khz passband are 8×10^{-25}, 8×10^{-25}, and 4×10^{-25} watt/m^2, respectively.

Summarizing the observations described above, we note that only a minuscule fraction (< 10^{-2} percent) of the microwave window and an almost equally small fraction of the sky have been examined for signals of extraterrestrial intelligent origin. The most sensitive of these searches have achieved flux levels on the order of 10^{-24} watt/m^2. Such a flux level could be produced by a 10^{11}-watt (EIRP) transmitter located at the distances of a nearby star, that is, a transmitter more than two orders of magnitude less powerful than the present capability of the Arecibo radar transmitter.

The sensitivities achieved are thus plausible for the detection of SETI signals, but the extreme paucity of spectral and spatial coverage to date precludes drawing any meaningful conclusions from these negative results.

Table 2. Sample sky search system parameters.

Parameter	Search instrument: Narrow-beam search	Search instrument: Wide-beam search
Antenna diameter (D)	26 m	Varies with frequency
Half-power beamwidth	Varies with f	15° (independent of f)
Sky coverage (fraction of 4π steradians)	0.8	0.8
Aperture efficiency (η)	0.5	0.7
Beamwidth proportionality factor (ϵ)*	0.4	0.7
System noise temperature	15K	15K
Intermediate-frequency bandwidth	300 Mhz	300 Mhz
Number of channels	10^6	10^6
Channel bandwidth (B)	300 hertz	300 hertz
Approximate observing time for 300-Mhz coverage	6 months	2 weeks
Minimum signal per channel (in watt/m^2; 6σ threshold)†	$8.3 \times 10^{-24}(f/1.5)$	$10^{-21}(f/1.5)^2$

*ϵ is defined by the expression $\Omega = \epsilon c^2/(\eta\pi D^2/4)f^2$, where Ω is the beamwidth in steradians and f is frequency in gigahertz. †The minimum detectable narrow-band ($\leq B$) signal depends on the threshold criterion, here six times the standard deviation of the noise, and on the system parameters above; f is frequency in gigahertz.

A Conceptual Observation Program

Existing antennas can make substantial improvements over what has already been done. Moderate-sized existing antennas, dedicated to a SETI program, can provide greatly extended frequency and spatial coverage at sensitivities comparable to those of previous limited-coverage surveys.

As an example, we outline below an idealized observation program (*22*) which could be carried out with two complementary efforts, one with several small horn antennas of 15° HPBW (beam width between half-power points) and the other using one fully steerable 26-m antenna. In the simpler of the two systems, the horn antennas would feed low-noise maser receivers and would be mounted as transit instruments on adjustable declination mounts. For such an idealized system, the rotational motion of the earth would scan the antenna beam along one declination circle in 24 hours. At a beam width of 15°, 75 percent of the sky can be mapped out in an 8-day period if the beam is shifted 15° per day. Allowing for down time and repeat observations, we estimate that the sky (actually 75 percent) could be scanned in 2 weeks and that the entire frequency range from 1 to 25 Ghz could be searched in 3 years if a 300-Mhz instantaneous bandwidth receiver (*23*) is employed. The spectral region from 1 to 25 Ghz covers the earth-based microwave window (Fig. 1) as well as the spectral region containing the 22.2-Ghz line of water vapor.

The sensitivity of a survey carried out in this manner depends on the system parameters and on the length of time a particular element of sky is in the beam. Adopting the instrument parameters for a broad-beam search given in Table 2, we find that a sensitivity of $\sim 10^{-21}$ watt/m^2 is achieved at 0° declination and 1.5 Ghz. Figure 3 shows the variation of sensitivity with frequency for this broad-beam all-sky survey. Slightly improved values are achieved at higher declinations.

The second and supporting effort would be carried out with a fully steerable 26-m antenna, capable of operation throughout the frequency range 1 to 25 Ghz. Such an antenna would have an HPBW of 0.8° at 1 Ghz and 0.03° at 25 Ghz. Because of the small size of the beam at high frequencies, it would be extremely time-consuming to simultaneously achieve broad frequency coverage, large spatial coverage, and high sensitivity. We therefore restrict ourselves to a more limited scenario, surveying 80 percent of the sky at one (300-Mhz wide) frequency setting over a 6-month period. Using the parameters in Table 2 for this system, we find that the sensitivity of the survey would be $\sim 8.3 \times 10^{-24}$ watt/m^2 at 1.5 Ghz and would vary at other frequencies as $8.3 \times 10^{-24} f/1.5$ watt/m^3, where f is frequency in gigahertz. If we assume that this survey is carried out for 5 years, shifting to a new frequency band each 6 months, then ten such surveys can be achieved in a 5-year period. This approach is complementary to the broad-band survey in that particularly interesting frequencies can be given close examination while substantial coverage is obtained at all the program frequencies. Alternatively, the 26-m antenna may be used in a targeted search mode rather than the large-area sky survey mode. As-

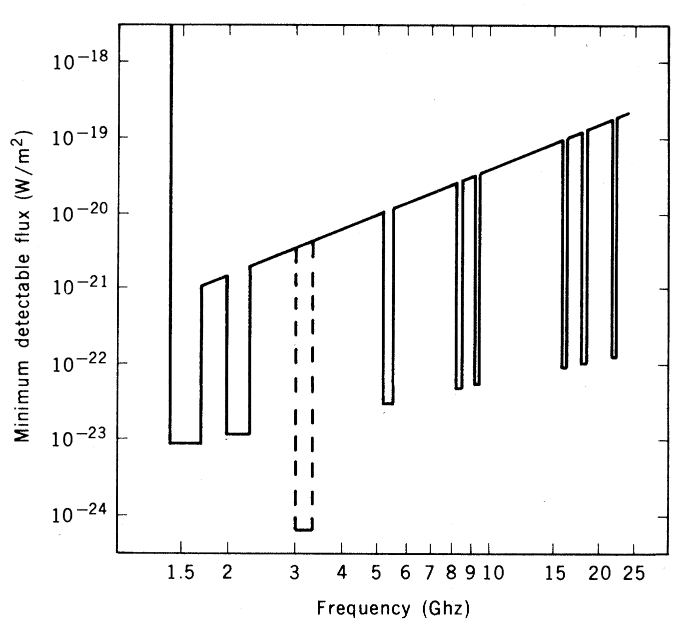

Fig. 3. The example of Table 2 demonstrated graphically. The upward-sloping solid line represents the complete frequency coverage of the broad-beam survey. The notches in the solid line show the improved performance possible over particular frequency bands by the use of a large (26-m) aperture. Both of these cover the entire visible sky. Also shown (dashed line) is a sample frequency of a targeted survey, the sensitivity of which is independent of frequency. Targeted surveys may be useful for particularly interesting local regions at various frequencies.

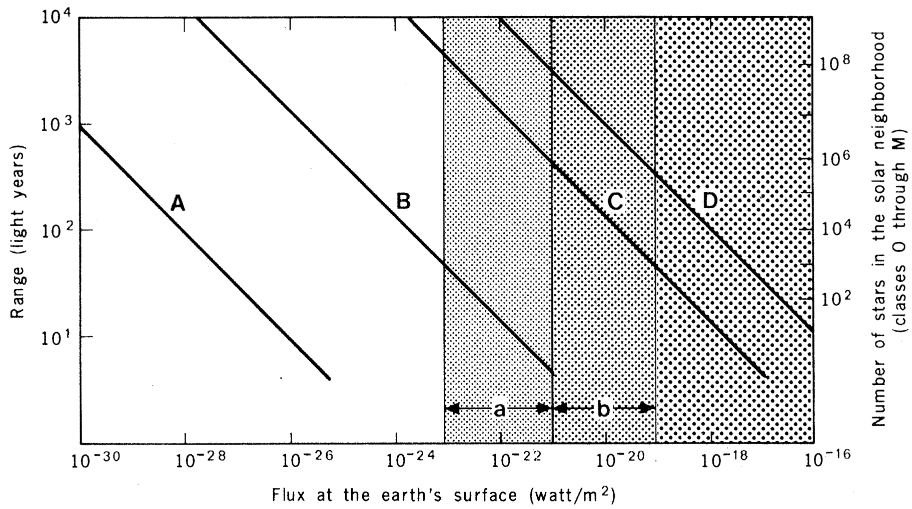

Fig. 4. Relatively modest facilities can perform quite comprehensive SETI surveys in a flux density regime which is significant for signal exploration. The sensitivities anticipated for the approach described here are shown superimposed on the capabilities defined in Fig. 2 for plausible transmitters. The region labeled *a* indicates the regime examined with narrow-beam surveys over about a 3-Ghz total frequency coverage of the entire sky. The region labeled *b* indicates the regime which can be examined with broad-beam antennas over the entire frequency regime 1.4 to 25 Ghz and over the entire sky. The region to the right of *b* is completely covered for all frequencies examined.

suming that 500 stars are observed in a 6-month interval, we find that the sensitivity of the search could be improved to 5×10^{-25} watt/m^2.

Figure 3 shows an example of the sensitivity levels as a function of frequency which could be achieved by the combined broad-beam and 26-m survey. In Fig. 4 we compare the idealized search sensitivities illustrated in this section with the plausible range defined earlier (Fig. 2). We see that relatively modest facilities can perform quite comprehensive SETI examinations in a flux density regime which is significant for signal exploration. Figure 4 shows, for example, that with a detection sensitivity of 10^{-20} watt/m^2 the broad-beam survey could detect Cyclops-scale transmissions (EIRP = 2×10^{17} watts) (*4*, p. 153) if they originate within a radius of 100 light years. Space power station transmitters with an EIRP of 10^{19} watts could be detected out to 1000 light years. The scale on the right ordinate in Fig. 4 gives an estimate of the number of stars of classes O through M that are contained in the corresponding volume. Such an experiment would provide significant SETI data even if no detection were accomplished. At least one plausible scenario—directed transmission of beacons in the microwave window—would be reasonably tested by sampling in frequency and space. In addition, the nature of the background radiation over the whole sky would be investigated in contiguous narrow-bandwidth slices covering the entire regime from 1 to 25 Ghz and more selectively at high sensitivity. Such information would be essential for any detailed design of more ambitious systems for future consideration.

Two new technological factors make the extensive search we have outlined possible: (i) ultralow-noise maser receivers throughout this band, and (ii) new data processors capable of handling very high data rates. The most important development is the capability for spectral analysis of as many as 10^6 data channels examined in real time (*24*). Such an analyzer alone would permit gathering data 10^6 times more rapidly than was possible with Drake's original single-channel receiver. An additional reduction in time by a factor of $\sim 10^2$ can be achieved through the use of the low-noise receivers. If used on the same size telescope as Drake used in 1960, these two improvements alone allow the accumulation of as much data in 1 minute as Drake could have gathered in 190 years of continuous observation.

We argue, therefore, that a modest program of 5 years or so in duration, performing specialized observations with existing antennas to cover a large portion of the microwave window, is a reasonable and entirely warranted observational approach to SETI. The development of megachannel spectrum analyzers and matched data processors is the key enabling step. Presumably, a number of radio observatories can and would wish to participate in such a program (*25*). In addition, small antennas in space operated in the submillimeter region may warrant consideration in the future to extend SETI observations to these presently hidden wavelength regions. The prior development of and ground experience with megachannel processors would enhance the feasibility of such endeavors and facilitate a comprehensive radio astronomical survey as well as SETI (*26*).

Other Benefits

Both the technology applied to the broad-band SETI search described in the previous section and the data collected during the course of the observations could have important secondary benefits for radio astronomy, radio communications, and unrelated endeavors involving very high data rates and real-time preprocessing. Indeed, the program we described has been conceived with this objective in mind to ensure the net value of the enterprise even if SETI yields negative results. The low-noise maser receivers, million-channel spectrum analyzer, and data management system would all represent significant advances in instrumentation.

A receiver capable of operating with a 300-Mhz instantaneous bandwidth over the entire frequency range from 1.4 to 25 Ghz could aid the study of interstellar molecules over that very wide range of frequencies. The broad-band, low-noise preamplifiers requisite for SETI would also facilitate improved wide-band communications with distant space vehicles; increased capability is desirable in that case to improve the accuracy of position determinations needed for navigation, radio science, and celestial mechanics studies with planetary probes.

The spectrum analyzer currently envisioned for the SETI survey would provide $\sim 10^3$ times more channels than are presently in use at any radio astronomical facility. The data management technology developed to handle the flood of primary data involved in a sky survey ($\sim 10^{14}$ bits per day) would be of significant interest to anyone dealing with similarly high data rates, as in radio-frequency monitoring, environmental monitoring by spectroscopy, and similar endeavors.

The SETI observations themselves, particularly those made with beam widths less than 0.5°, would include a substantial amount of data of significance to radio astronomy and astrophysics. For instance, the low-noise, broadband receivers and high spectral resolution of the SETI observations would produce wide-area spectral line surveys comparable in sensitivity to previous surveys, but with greatly improved frequency coverage and higher spectral resolution. Observations of spectral lines of a variety of molecules would improve our knowledge of the distribution of neutral hydrogen in the galaxy and in extragalactic systems, and of the nature of interstellar and circumstellar media. Refined studies of the polarization, distribution, and spectra of radio sources would be possible. For example, the present sky coverage of H_2O sources is necessarily biased. Since H_2O maser lines are quite strong, a broad-beam survey of the type advocated here for SETI is likely to locate many new intense H_2O sources.

Because of the stringent SETI requirements for system sensitivity and bandwidth, the survey would provide new environmental data on man-made radiation and signal degradation of atmospheric origin. This information, and the techniques developed to cope with these problems in connection with SETI, would materially assist the development of models for the performance of deep-space communications links and permit an assessment of the effects of man-made radio signals on future deep-space tracking from the surface of the earth (*27*).

Conclusion

The key issue in detecting evidence of extraterrestrial intelligence is the feasibility of conducting an observational activity. The microwave region of the electromagnetic spectrum, a plausible regime for signals from extraterrestrial intelligences, is largely unexplored. With new technology, particularly in data processing and low-noise reception, surveys can be conducted over broad regions of frequency and space with existing antenna facilities. The flux densities obtainable are reasonable for the detection of interstellar signals, and frequency and spatial coverage can be vastly more comprehensive than ever before.

An all-sky, broad-band survey lasting perhaps 5 years would make significant progress toward achieving evidence of artificial extraterrestrial radio sources (*28*). Further, the idealized program described here is structured so that even negative results would result in the establishment of significant boundaries on the regime in which such signals may be found. Finally, all of the technology and techniques developed would be applicable in important areas of radio astronomy and deep-space communications, as would much of the data acquired.

The question "Are we alone?" will challenge science until positive evidence of extraterrestrial intelligence is encountered by design or serendipity, or until a dominant negative view is built up incrementally from diverse, complementary observational tests. Either outcome will be one of the greatest scientific achievements imaginable, with profound philosophical and theological significance. A comprehensive SETI survey in frequency and space with existing antennas will be a timely and practical scientific response to a basic question about the universe.

References and Notes

1. H. Shapley, *Of Stars and Men* (Beacon, Boston, 1958; Washington Square, New York, 1960).
2. A good review of historical and scientific ideas concerning the likelihood of other intelligent life is given by I. S. Shklovskii and C. Sagan [*Intelligent Life in the Universe* (Holden-Day, San Francisco, 1966)]. A more recent discussion of scientific consideration is contained in the report of NASA's SETI workshops (P. Morrison, J. Billingham, J. Wolfe, Eds., *NASA Spec. Publ. SP419*, in press).
3. For example, see articles by E. Purcell, G. Cocconi and P. Morrison, F. D. Drake, J. A. Webb, R. Bracewell, and P. Morrison, in *Interstellar Communications*, A. G. W. Cameron, Ed. (Benjamin, New York, 1963).
4. For example, see B. M. Oliver and J. Billingham, "Project Cyclops: A design study of a system for detecting extraterrestrial intelligent life," *NASA Contract. Rep. CR114445* (1973).
5. The Cyclops report (*4*, p. 84) estimated the structural cost of a 3-km equivalent array to be \$3 billion to \$9 billion and that of a 5-km equivalent array to be \$10 billion to \$25 billion. In a critique of the Cyclops report prepared by Jet Propulsion Laboratory (JPL) for NASA's Office of Tracking and Data Acquisition, the equipment cost was estimated to be approximately twice that given in the 1971 report, when expressed in 1975 dollars; the operations cost of the array, not specified in the Cyclops report, was estimated to be of the same order as the cost of building the system itself, for a search activity lasting several decades.
6. There are basically two types of extraterrestrial signals that we might detect "accidentally": those due to leakage, and those intercepted from an existing interstellar communications link. As shown in the Cyclops report (*4*, p. 59), the detection of plausible leakage signals would be quite arduous. To detect leakage over a range of only 100 light years would require an aperture with an effective area of several square kilometers, orders of magnitude larger than anything we have. Intercepting an existing communications link is even more unlikely. Von Hoerner (*13*) has shown that the probability of our intercepting a randomly located directive interstellar communications link is very low. Even if we intercepted such a signal, recognizing it would be exceedingly difficult. Societies conducting interstellar communications would undoubtedly seek to obtain the maximum performance from whatever system they employ. It would be to their advantage to spread the signal spectrum over a wide bandwidth. As a result, a small portion of the spectrum would not appear to contain a meaningful signal. Indeed, optimum transmission would be accomplished with signals which, unless we knew the code structure (which cannot be predicted), would appear to be simply a minuscule addition to the natural noise background.
7. T. B. H. Kuiper and M. Morris, *Science* **196**, 616 (1977).
8. Atmospheric absorption is not a significant factor in the region of frequencies known as the microwave window. At these frequencies the major performance degradation caused by the atmosphere is the additive noise, which significantly raises the receiver noise temperature. This is the case because of the exceedingly low noise temperatures which can be achieved with modern maser devices.
9. G. Cocconi and P. Morrison, *Nature (London)* **184**, 844 (1959).
10. F. D. Drake and G. Helou, "The optimum frequencies for interstellar communication as influenced by minimum bandwidth," preprint of a paper presented by F. D. Drake at a JPL workshop on the utilization of existing radio telescopes for SETI, 29 and 30 June 1977.
11. R. E. Edelson, paper presented at the 27th congress of the International Astronautical Federation, Anaheim, California, 10–16 October 1976; *Astronaut. Acta*, in press. Clearly, the power advantages in beamed transmissions are enormous. For example, the great telescope at Arecibo, Puerto Rico, equipped with a transmitting power of only a few hundred kilowatts, could communicate with an equal aperture thousands of light-years away.
12. F. D. Drake and N. S. Kardashev, in *Communication with Extraterrestrial Intelligence*, C. Sagan, Ed. (MIT Press, Cambridge, Mass., 1973), pp. 239–241.
13. S. von Hoerner, *Science* **134**, 1839 (1961).
14. Two more recent SETI observational programs were discussed at the JPL workshop on the utilization of existing radio telescopes for SETI, 29 and 30 June 1977. J. Tarter, J. N. Cuzzi, D. C. Block, and T. A. Clark discussed a targeted search at a wavelength of 18 cm aimed at 201 solar-type stars. A high-speed digital tape recorder was used to achieve a 65,536-channel spectrum analyzer with 5-hertz resolution. M. A. Stull and F. D. Drake discussed a targeted search at 18 cm of 23 sources, including several OH masers and ten main-sequence solar-type stars. The broadband signal was recorded on magnetic tape, rerecorded on photographic film, and then Fourier-transformed with an optical processor. Preliminary results indicate that a 4.2-Mhz bandwidth was obtained with a frequency resolution of 0.5 hertz.
15. F. D. Drake, in *Interstellar Communication*, A. G. W. Cameron, Ed. (Benjamin, New York, 1963), pp. 176–177.
16. V. S. Troitskii, A. M. Starodubstev, L. I. Gershtein, V. L. Rakhlin, *Sov. Astron. AJ* **15** (No. 3), 508 (1971).
17. V. S. Troitskii, in *Communication with Extraterrestrial Intelligence*, C. Sagan, Ed. (MIT Press, Cambridge, Mass., 1973), p. 258.
18. C. Sagan and F. Drake, *Sci. Am.* **232** (No. 5), 80 (1975).
19. G. Verschuur, *Icarus* **19**, 329 (1973).
20. The Berkeley SERENDIP (search for extraterrestrial radio emission from nearby developed intelligent populations) project has been described in a privately circulated letter from the Space Sciences Laboratory, University of California, Berkeley, March 1977. Individuals who have participated in the program are S. Bowyer, W. J. Welch, M. Lampton, J. C. Tarter, J. Freeman, H. Clawson, G. Turner, D. Langley, and A. Despain. S. Bowyer has kindly supplied us with some additional information for this article.
21. R. S. Dixon and D. M. Cole, *Icarus* **30**, 267 (1977).
22. Details of the all-sky survey discussed in this article were developed in collaboration with M. Janssen and T. Kuiper. We thank them for their assistance.
23. Current technology in low-noise maser preamplifiers will support instantaneous bandwidths of about 300 Mhz in the frequencies discussed here, with noise contributions ranging from 2 to 8K. Devices with bandwidths of 250 Mhz are operating in the field, and laboratory versions are now approaching the performance quoted above.
24. Although 10^6-channel processors have not yet been built for these applications, design studies at Ames Research Center and JPL indicate that such analyzers are technologically feasible. The availability of large-scale integrated circuits [see R. Noyce, *Science* **195**, 1102 (1977)] is largely responsible for this breakthrough.
25. Those interested in participating in an experiment of this type are invited to communicate with the authors. Discussions of data processing approaches for such observations would be particularly valuable.
26. If the construction of new, larger antennas (either on the earth or in space) is deemed warranted in the future for SETI, then the developments in data processing and wide-band, low-noise maser amplifiers advocated here will be especially helpful for that endeavor as well. More generally, computing technology has evolved enormously since the original Cyclops study, and further large increases in capability per unit cost seem likely. If the Cyclops observational objectives are addressed again in the next several years, greater reliance on state-of-the-art computing and less on the inherently expensive construction of collectors with areas of 2 to 5 km^2 may prove significantly more cost effective. For example, the original Cyclops study contemplated utilizing only a single, very nar-

row effective beam. In principle, tens or hundreds of narrow beams can be used simultaneously with a suitably designed array, provided adequate real-time computing capability is available. Additional gains in detection can be obtained by increasing the number of frequency channels monitored simultaneously from 10^6 upward. Hence, gaining experience with state-of-the-art data processing systems for SETI, as proposed here in the context of an all-sky search, may be the most promising way to bring the original Cyclops observational objectives within reach.

27. M. F. Easterling (unpublished JPL memorandum) discusses an idea of his and W. K. Victor's to use spectrum analysis capabilities to observe many narrow-band channels simultaneously, obtaining a broadband sensitivity sufficient to monitor the cruise performance of distant spacecraft with small (~3 m) ground antennas. This would make it possible to check the "health" of the vehicles with small, inexpensive facilities, instead of resorting to the very large antennas of the Deep Space Network.
28. R. Sinsheimer (private communication) has stated that SETI activities, even "listen only" activities such as that advocated here, warrant advance consideration by a broader segment of society than the scientists actually interested in pursuing the endeavor. Our publication of the description of the proposed survey along with our views of its value constitutes one kind of practical response to such concerns.
29. P. E. Glaser, O. E. Maynard, J. Mackovciak, Jr., E. L. Ralph, *NASA Contract. Rep. CR2357* (1974).
30. The idea of a wide-frequency, all-sky search for directed transmissions was developed in preliminary form by B.M. while on a Guggenheim Fellowship during 1975 and 1976. The remainder of the effort has been supported by NASA contract NAS7-100.

Recovery of a Deforested Ecosystem

Replacing biomass and nutrients lost in harvesting northern hardwoods may take 60 to 80 years.

G. E. Likens, F. H. Bormann, R. S. Pierce, W. A. Reiners

Cutting of northern hardwood forests sets in motion a variety of ecological effects related to the removal of living vegetation and to the disruption of the forest floor. Stream flow is increased, transpiration is reduced, concentrations of dissolved chemicals in stream water may be increased severalfold, and erosion and transport of particulate matter may be accelerated (*1–4*). Other changes may also occur, such as an increase in soil temperature and moisture, an increase in the rate of decomposition, an increase in nitrification, a decrease in the amount of organic matter in the forest floor, a reduction in canopy absorption and reflection of solar energy, an increase of dissolved substances in soil solution, and a decrease in the *p*H of drainage waters. The sum of all of these factors can have a major destabilizing effect on the landscape. Thus, to efficiently use the renewable timber resource of northern hardwood forests, it is important to know what recovery mechanisms exist and at what rates they occur after a cutting.

About 12 years ago we designed a long-term experiment to test the impact of deforestation on the yield and timing of runoff, snowmelt, and water quality and to determine the rate at which these parameters return to precutting levels. Although this experiment was not designed to simulate a commercial clearcut, it soon became apparent that the results could provide significant insights into environmental questions posed by commercial cuttings in northern hardwood forests. In the autumn of 1965, all of the trees were felled onto a snow surface and left in place on one of the watershed-ecosystems (W-2) of the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire. No roads or skid trails were made in the ecosystem since no wood products were harvested or removed. Thus disturbance of the forest floor was minimized, and postcutting erosion rates could be used to assess the experimental manipulation (deforestation) rather than the effect of mechanical damage on the soil. To separate the effects of nutrient uptake by vegetation from those of increased generation of dissolved nutrients resulting from accelerated decomposition, herbicide was used for the first three growing seasons to keep the watershed bare and to suppress vegetative regrowth. The effects of this experimental deforestation on hydrologic and biogeochemical conditions have been reported (*1–4*). Here we report on the recovery of the ecosystem after the vegetation was allowed to regrow, and attempt to relate these findings to the effects of commercial clearcuttings.

Deforestation had a major impact on both the amount and relative proportions of water, dissolved substances, and particulate matter lost from the ecosystem (Fig. 1). Because of the virtual elimination of transpiration, greatly increased amounts of liquid water drained from the deforested ecosystem during the growing season. Moreover, concentrations of dissolved substances in this drainage water were increased due to (i) accelerated decomposition, nitrification, and mineralization, mostly of organic matter, in the forest floor (*5, 6*); and (ii) the absence of nutrient uptake by vegetation. Coupled with the increased availability of light and with high soil temperatures, these conditions of increased soil moisture and nutrients provided a high potential for rapid regrowth of vegetation. However, vegetation growth was experimentally suppressed by herbicide during the first three growing seasons after deforestation.

Some of the hydrologic and biogeochemical parameters for the ecosystem returned to previous levels within 3 or 4 years (*7*) after the vegetation was allowed to regrow (Fig. 1). However, it is significant that concentrations and net losses of dissolved substances in stream water peaked during the second year of the experimentally prolonged deforestation and had markedly declined before the onset of regrowth (Fig. 1). This pattern suggests that the exhaustion of readily available nutrients and substances for decomposition in the forest floor (probably the more labile, organic nitrogen compounds) limited nutrient loss before any compensatory uptake of nutrients by vegetation occurred (*5*). In fact, the amount of nutrients taken up and stored in living biomass during the first five growing seasons of the recovery period (1969–1974) was not sufficient to account for the continued decline in chemical output in stream water during the period (*6, 8*). In sharp contrast to the rapid loss

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