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MICROWAVE SEARCHES IN THE U.S.A. AND CANADA

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Search strategies for ETI may run the gamut from passive, in which they do all the work, to active, in which we do all the work. Searches for electromagnetic radiation occupy a middle ground - success requires a cooperative effort. Indeed the Cyclops[1] design was based in part on the idea of cost-sharing between the transmitting and receiving societies.

To date, there have been fewer than 20 radio searches for signals from ETI. All have, apparently, produced negative results unless someone is hiding something in their bottom drawer. We will discuss six of the most sensitive searches that have been carried out in the United States of America and in Canada.

All six of the searches listed in Table 1 assume that interstellar communication will involve a signal of very narrow bandwidth. If the transmitting society has only a certain amount of microwave power available to transmit, then the signal-to-noise ratio at the receiving end can be made highest when this power is concentrated into the narrowest possible range of frequencies. In addition, very narrow signals can easily be distinguished from ordinary thermal emission from interstellar molecules and atoms. Signposts for signals from ETI are, therefore, either rapid variability (timescales of seconds to days) or a bandwidth significantly narrower than either a thermal bandwidth corresponding to temperatures $\sim$ 10 K, or a line narrowed unsaturated maser.

Patrick Palmer and Ben Zuckerman (hereafter PZ) were the first to take advantage of the very considerable advances in instrumentation in spectral line radio astronomy in the 1960's. They pointed the 91-meter transit telescope of the U.S. National Radio Astronomy Observatory toward stars within 25 parsecs (80 light years) of the Sun. These stars were taken mostly from Gliese's catalog[2] plus a few from the RGO catalog[3]. The motivation for a targeted search of nearby stars (four of the six programs in Table 1) is as follows. Given existing telescopes and receivers, we are not yet capable of detecting omni

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TABLE 1

RADIO SEARCH PROGRAMS

DATE	OBSERVER	OBSERVATORY	WAVELENGTH	TARGET	SENSITIVITY
1972 - 76	PALMER ZUCKERMAN	NRAO 91 m	21 cm	∿ 670 NEARBY STARS	10^{-23} (W/SQ M)
1973 - PRESENT	DIXON COLE	OHIO STATE 53 m	21 cm	ALL SKY	FEW × 10^{-21}
1974 - LIMBO	BRIDLE FELDMAN	ALGONQUIN 46 m	1.3 cm	∿ 70 NEARBY STARS	FEW × 10^{-22}
1975 - 76	DRAKE SAGAN	ARECIBO 305 m	21 cm 18 cm 12.5 cm	SEVERAL NEARBY GALAXIES	10^{-24}
1977	TARTER AND FRIENDS	NRAO 91 m	18 cm	200 NEARBY STARS	FEW × 10^{-24}
1978	HOROWITZ	ARECIBO 305 m	21 cm	185 NEARBY STARS	FEW × 10^{-27}

directional broadcasts from Kardashev Type I civilizations across interstellar distances (a Type I civilization is one that is not much in advance of our own). Therefore, if we are to detect Type I civilizations, we must look for powerful beamed transmissions. Such beacons are not likely to be pointed at Earth except by our nearby neighbors.

Targeted searches that examine only a few hundred nearby stars are not particularly significant in the best-guess Drake/Sagan[4] scenario - $\lesssim 10^6$ civilizations in the Milky Way - since $\gtrsim 10^5$ stars should be searched to find one civilization. But if the Milky Way has been physically "colonized" by means of interstellar rocket travel, then many (most) of the nearby star systems should harbor technical civilizations and the negative results to date may already be of some significance[5].

PZ limited their search to F, G, K, and M type main sequence stars based on classical arguments: such stars may provide a habitable zone which is stable for a sufficiently long time to allow life to originate and to evolve into a technological civilization. In the absence of interstellar colonization, these limits on spectral type may be much too broad if the continuously habitable zone is as narrow as estimated by Hart[6]. But, if the galaxy has already been colonized, then essentially all main sequence stars, and possibly red giants as well, should be examined.

Various binary star systems were included in the PZ program. If the star-star separation is less than about one-third or greater than about three times the radius of the habitable zone, then planets in this zone will have stable orbits for billions of years[7]. Of course, it is conceivable that planets do not form in multiple star systems.

In their search for narrowband signals, PZ used the NRAO 384 channel autocorrelation receiver. One hundred and ninety-two channels covered 10 MHz total bandwidth and the other 192 channels covered 625 kHz. The latter 192 yielded a spectral resolution of 4 kHz per channel, just narrow enough to discriminate against emission by interstellar hydrogen atoms. The spectrometer was centered at the λ 21-cm rest wavelength of the hyperfine (spin-flip) transition of hydrogen in the rest frame of each observed star. Stars were observed on the order of 4 minutes per day for approximately 7 successive days. About 10 stars that showed "glitches" - time variable signals - were reobserved, usually after a delay of about one year. In only one such case was a second glitch observed. In no case was the glitch duty cycle large enough to justify much optimism that an ETI signal had been observed since the main protection against terrestrial interference is the "protected" nature of the 21-cm band. The detailed results of the PZ program have yet to be published.

Search programs of this type will miss leakage signals such as the TV carrier signals for Mork and Mindy and even the stronger military radars by many orders of magnitude if they are transmitting at the same power levels as we now do[8]. However, a narrowband signal from a 40-megawatt transmitter on a 300-ft. antenna could have been detected by PZ as far away as the most distant stars they observed.

Some of the stars examined in the four targeted stellar search programs in Table 1 are sufficiently close that there would have been time for an alien civilization at the star to have detected our leakage radiation and to have beamed an "answer" back to us that could have arrived by 1972 (or later). Two rather solar-like stars, τ Ceti and ε Eridani, are only ∿ 10 light years from the Earth and, therefore, satisfy this constraint. These were the two stars examined at length by Frank Drake in project Ozma in 1960 and recently by PZ and others more briefly, but with much greater sensitivity.

A search project that is fairly similar to the PZ program is being carried out at the Canadian National Radio Observatory in Algonquin Park by Alan Bridle and Paul Feldman (BF). The primary difference is that BF observe at the water line wavelength 1.3 cm (22.2 GHz). Consideration of non-instrumental sources of noise - e.g., atmospheric, galactic, 3 degree cosmic background - suggest that in an optimized ground-based search program wavelengths between 10 and 20 cm will be quietest (e.g., Fig. 5-2 in Reference 1). According to this figure, 1.3 cm is inferior to 21-cm mainly because of absorption of the 1.3 cm waves in the Earth's atmosphere. However, at the present time, many receivers and telescopes are far from optimum; the largest contribution to the system noise temperature is instrumental and Fig. 5.2 is not especially relevant. Thus, the relatively poor sensitivity of the BF program is due more to an inferior receiver and a small telescope than to the effects of the Earth's atmosphere.

BF covered a total bandwidth of 10 MHz with 30 kHz resolution. They have, so far, examined 70 stars within ∿ 45 light years of the Earth during a total of ∿ 140 hours of observations. Results are not yet published. The BF program is presently in cold storage but will be resumed if and when a better 1.3 cm receiver becomes available at Algonquin Park.

The program carried out by Paul Horowitz has been completed and results are published[9] (but not a list of target stars). Because he used a very large telescope and ultrahigh spectral resolution, Horowitz was very sensitive to very narrow signals but he covered only a limited phase space.

Horowitz search a total bandwidth of only 1 kHz but with 0.015 Hz resolution! (65,536 equally spaced frequency bins). This resolution was dictated by two considerations: the short term stability of the Arecibo rubidium reference oscillator and the ultimate limit to narrowband interstellar radio propagation - line broadening by multiple scatterings from fluctuations in the ionized component of the local interstellar medium. Because he was able to cover only 1 kHz of bandwidth, Horowitz adopted a search strategy which assumed that the transmitting society has accurately measured the radial velocity of our Sun and/or the velocity of the center of mass (barycenter) of the solar system - the two differ by at most ± 60 Hz at 21-cm wavelength. Therefore, They transmit at a frequency such that their signal arrives in our solar system at the hydrogen-line rest frequency of either the solar or barycentric system. It is interesting to note that within the next few decades the best radial velocity measurements of solar type stars we are likely to make are at the 10 m/s level. The accuracy will be limited most probably by bulk motions in the stellar atmospheres. Ten m/s corresponds to ∿ 50 Hz at 21-cm wavelength.

Because of the spin and orbital motions of the Earth, it was necessary to update the local oscillator thousands of times during the few hundred seconds that characterized Horowitz's observations of a given star. (See Figure 1 in reference 9 for a block diagram.) Data were recorded on a 9-track magnetic tape, fast Fourier transformed off line, and displayed in a 256 x 256 raster.

Horowitz examined F, G, and K main sequence stars (from the RGO catalog), but excluded all known binaries. Total telscope time involved was 80 hours. A megawatt transmitter on an Arecibo-like antenna could have been detected out to distances of 1000 parsecs, if the bandwidth of the signal was < 0.015 Hz. Horowitz showed that one can construct a 65,000 channel radiometer with very narrow resolution over a limited frequency range with only moderate computational effort and present the results in such a way that they can be studied easily by people. In addition, when one observes with very narrow bandwidths, terrestrial interference becomes a negligible problem. Horowitz had no false alarms.

Another recent novel search technique, due to Jill Tarter et al.[10], also achieved excellent frequency resolution and many channels. One-bit sampled data were recorded on a high speed Very Long Baseline Interferometer tape recorder (recording rate = 720 kb/s). The data tapes recorded at NRAO were read and analyzed in post-real time, and yielded a total spectral coverage of ∿ 1.2 MHz with 5.5 Hz resolution - the equivalent of a ∿ 200,000 channel spectrum analyzer. (A block diagram is given in Figure 1 of reference 10.)

During a single observation of a target star, one magnetic tape was recorded in approximately 4 minutes which is well matched to the limited tracking capability of the NRAO 91- m transit telescope. Integration times were sufficiently short that the maximum frequency drift at 1666 MHz (18 cm wavelength) due to Earth rotation was comparable to the 5.5 Hz resolution. Therefore, Doppler drift corrections to update the LO system were not required. Δf can be reduced below 5.5 Hz in this type of experiment, but then the data reduction becomes more difficult.

Tarter et al. observed at the upper (OH) end of the "water hole"[1]. Like Horowitz, they examined (apparently) single F, G, and K main-sequence stars from the RGO catalog.

This program is continuing and promises to yield the best frequency resolution until mega-channel spectrometers are built. Its disadvantages, modest instantaneous bandwidth and large computational overhead, can be partially overcome by the use of dedicated mini-computers and special purpose hardware processors.

All four of the searches discussed above concentrated on nearby stars. An "all-sky" survey is also feasible even though it takes a lot longer to complete. Most of the time only distant stars or galaxies are in the telescope beam and such distant civilizations are unlikely to be directly beaming at our solar system (unless perhaps one of their probes happened to be here!). Therefore, when compared with the targeted search mode, a given power received at the Earth in the all-sky mode would, in general, imply a very much larger power source at the transmitting end.

An all-sky survey is currently underway at the Ohio State University Radio Observatory[11,12]. About half the sky has been searched during an essentially continuous effort begun in December 1973. The spectral coverage (500 kHz total bandwidth at 10 kHz resolution) and sensitivity are only modest but the virtue of this program is its longevity and the opportunity to frequently recheck any interesting directions in the sky. The most interesting signal detected during the first six years of searching is described in reference 12.

It has been argued[13] that the absence of extraterrestrials on the Earth already dooms to failure any search for galactic civilizations. However, if the nearest technical civilization has emerged in a nearby galaxy rather in the Milky Way, then They may not yet have had sufficient time to travel here. A search of nearby galaxies could reveal only Kardashev Type II or Type III civilizations that are capable of generating enormously more powerful radio beacons than our own Type I civilization (see Appendix B in reference 1). A brief search ($\sim$ 100 hours of telescope time) of 5 nearby galaxies was carried out by Frank Drake and Carl Sagan at the Arecibo Observatory. Leo I, Leo II and M49 were each covered by observations at 9 positions. Many positions were observed in M31 and M33. Each galaxy was observed at 3 separate wavelengths (21 cm, 18 cm, and 12.5 cm). In all cases, 3 MHz of bandwidth was covered with 1 kHz resolution using the 1008 channel correlator at the observatory. For observations of M33 at the H (21-cm) and OH (18-cm) wavelengths, the spectrometer was centered at the radial velocity of the known hydrogen emission at each position that was observed. Observations of the other galaxies were centered at the systemic velocity where known or else all possible systemic velocities for the local group were used.

The hope was to find one super-civilization in the $\sim 10^8$ stars included in the Arecibo beam during each observation. The results of the Drake/Sagan program have not been published.

What of future searches at comparable levels of sensitivity? The Ohio State Survey and the Tarter search are continuing and the

Bridle/Feldman program may emerge from cold storage if a new 1-cm system is installed on the ARO 46-m telescope. In addition, SETI may parsitize the radio astronomical community in two ways. One is to hop aboard radio observations being carried out for other purposes[14], by constructing automated SETI backend systems. The other takes advantage of the sad fact that, after ∿ 20 years, many radio telescopes are considered obsolete for radio astronomy and are consequently undersubscribed. Such telescopes could be dedicated in part or entirely to SETI.

What of future searches at much improved levels of sensitivity? Technology now exists to produce both the mega-channel spectrum analyzers and the sophisticated signal detectors required to analyze the output of these spectrum analyzers in real time. These backend devices and state-of-the-art low noise feeds and receivers could be employed at existing radio telescopes in order to systematically observe the nearest solar type stars and make a complete sky survey over a much broader range of frequencies at much greater sensitivity than has been possible to date. All of the searches listed in Table 1 (and all other searches of which we are aware) have made use of equipment originally designed and constructed for radioastronomical observations. SETI searches with such equipment are never optimum as one is looking for something which conspicuously does not match the type of emission the hardware was designed to detect. Non-optimum, but it is cheap! The question is whether funds should be invested to build SETI-specific hardware in order to increase sensitivity and make more efficient use of observing time on existing telescopes.

Answers to this question will depend upon each individual's assessment of the size of N and, as we have seen at this meeting, there is no concensus with regard to that number. In addition, the answer must depend on the significance of the negative results of the searches conducted to date and the expected increase in significance of the results from any expanded search. Here it may be possible to achieve more agreement than in the matter of N.

Any search for manifestations of technology from extraterrestrial intelligence must explore an eight-dimensional parameter space which Frank Drake has called "The Cosmic Haystack". The eight parameters are: 3-spatial, 1-temporal, 1-frequency, 2-polarizations and 1-transmitted power. Figure 1 is an attempt to compress these 8 dimensions into 3 and depict just how large the haystack might be. To do this, it is necessary to assume that 2 orthogonal polarizations are being received simultaneously, that the duty cycle of the signal is high and therefore the probability of detection is independent of time and finally that any modulation present is intended to make the detection problem easier and does not make the signal more noise-like. Two of the three spatial directions can be represented on one axis as the number of targets 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, but even this may be an underestimate. The

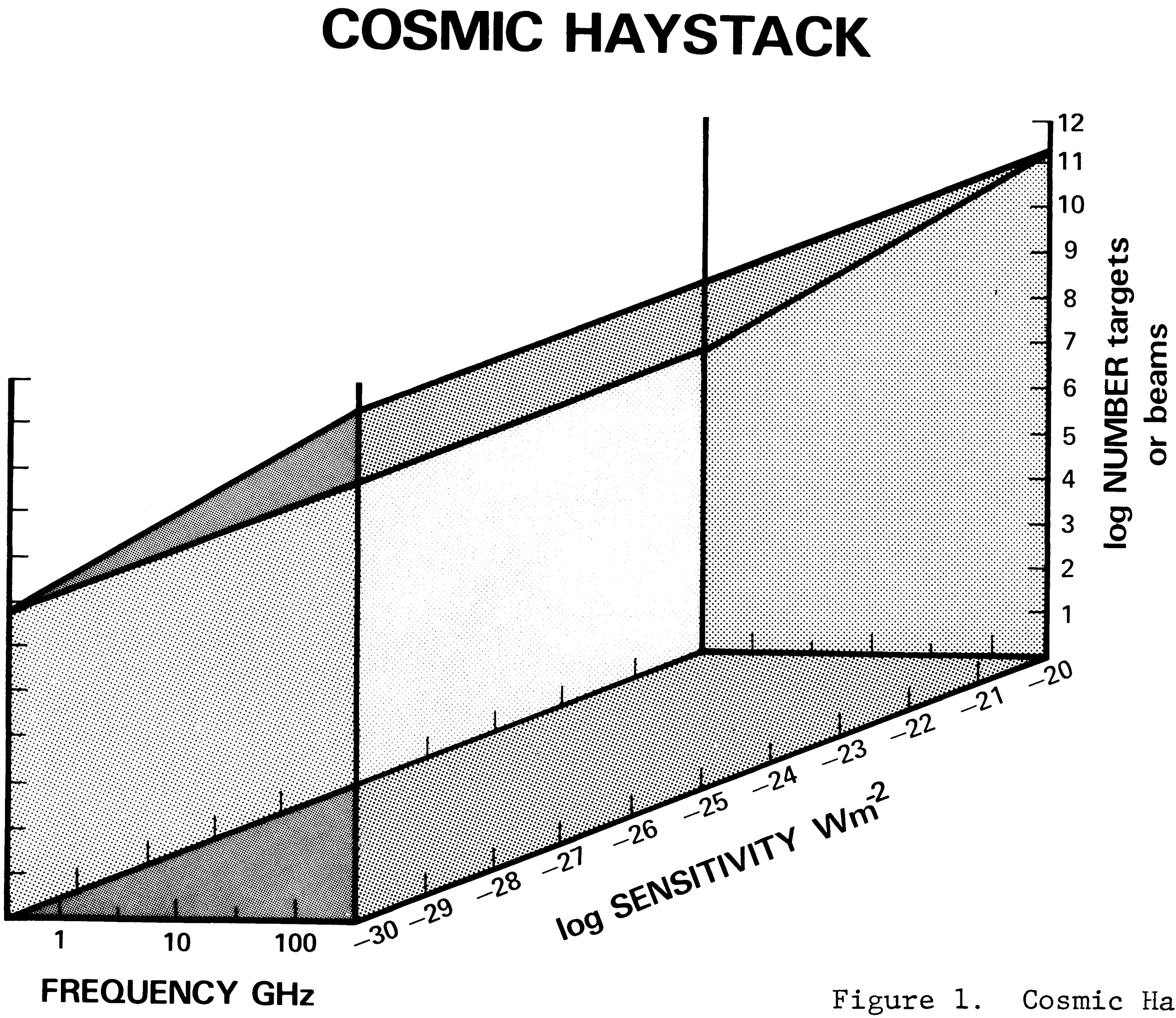

Figure 1. Cosmic Haystack

remaining axis of Figure 1 combines both the third spatial dimension and the unknown transmitter power; this axis is the sensitivity of the search measured in Wm^{-2} received within the narrowest channel of whatever detector is being used. The boundaries on this last parameter are the most arbitrary. The low sensitivity end has been set at 10^{-20} Wm^{-2}, which corresponds to 1 Jansky over 1 MHz of bandwidth and is roughly the level at which previous radioastronomical surveys of the sky should have detected a signal if such existed at the frequencies of these surveys. The high sensitivity limit is what would be required to detect the planetary radar transmitter at Arecibo Observatory, if it were located on the far side of the Galaxy. This is roughly the sensitivity of Cyclops array[1]. The sloping ceiling to this Cosmic Haystack has been drawn as the number of directions on the sky (increases as frequency squared) that our largest telescope (Arecibo) would need to be pointed in to conduct an all-sky survey (assuming of course that such a telescope could see the whole sky, Arecibo can't).

If each unit on each axis is given equal weight, then there are some 3×10^{28} cells (of size 1 Hz x 1 Arecibo Beam x 10^{-30} Wm^{-2}) which may have to be examined in order to complete a systematic search of our own Galaxy! Clearly not all of these cells are of equal importance. The observations listed in Table 1 represent attempts to concentrate on certain more "likely" cells within the constraints imposed by available astronomical instrumentation. How much of the haystack has been searched in this manner? Figure 2 is a summary of the programs in Table 1. It should be immediately obvious that only a small fraction ($\sim 10^{-17}$) of the haystack volume has been explored thus far. In spite of the fact that considerable effort has been expended by the observers involved in each of the searches, the significance of their negative results may not be very great.

Simultaneous sensitivity, bandwidth coverage and frequency resolution over the entire haystack volume requires a major effort including construction of dedicated collecting area[1]. However, moderate coverage of all these parameters (representing a factor of 10^7 improvement over Figure 2) could be achieved in the next decade with existing antennas and the SETI-specific instrumentation mentioned above. Figure 3 shows the volume of parameter space that might be covered by this approach. Studies of cost effective ways of achieving this coverage are being conducted at NASA-Ames Research Center and the Jet Propulsion Laboratory. While this approach may prove too grandiose for SETI skeptics, it is important to remember that a systematic search for evidence of extraterrestrial technology has not yet been conducted and is ultimately required to answer the questions: "Where Are They?", "Are We Alone?". Although some of the observational programs of Table 1 are continuing, it is probable that their main contribution will be to provide operational experience in how to conduct a systematic search.

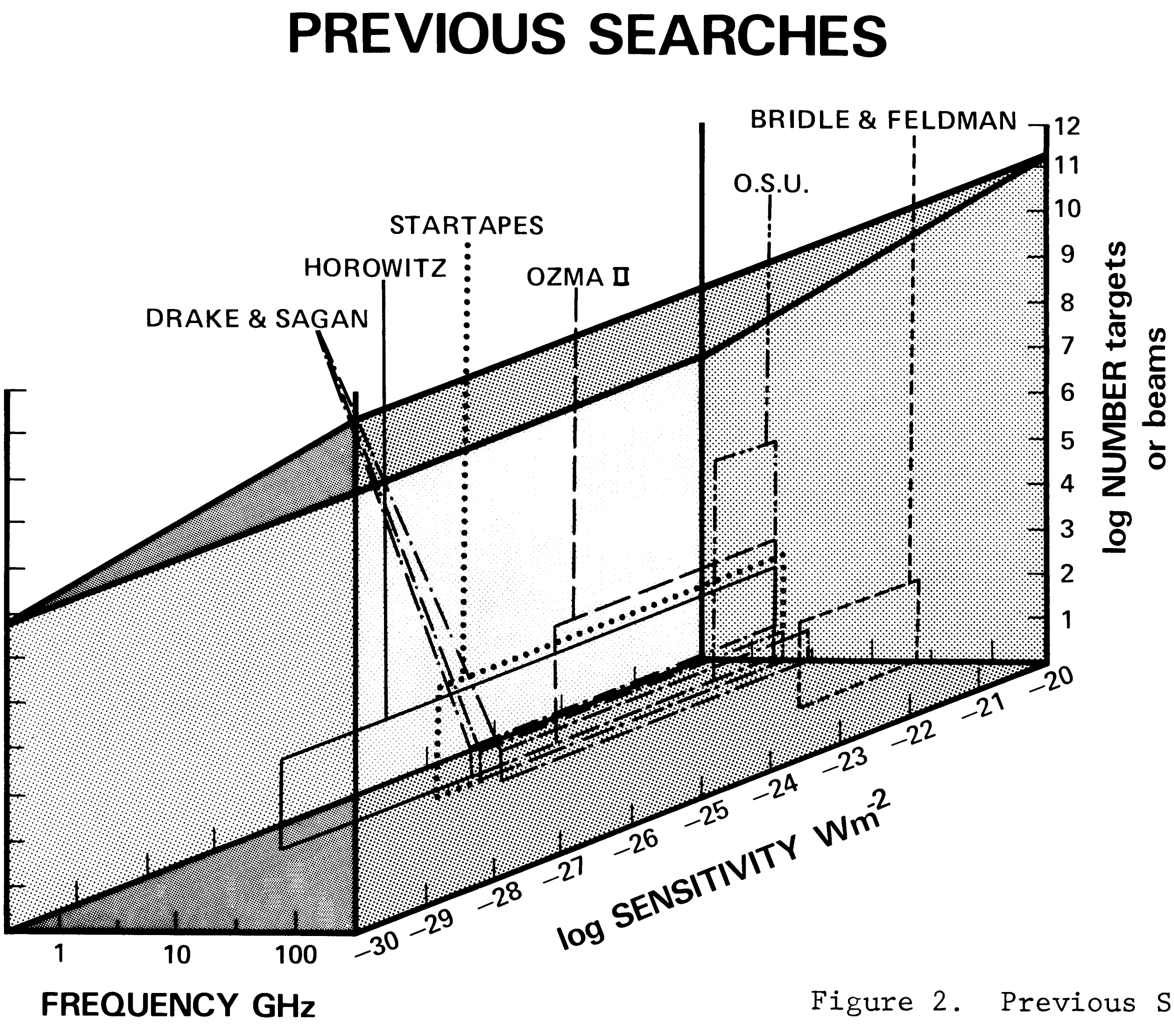

Figure 2. Previous Searches

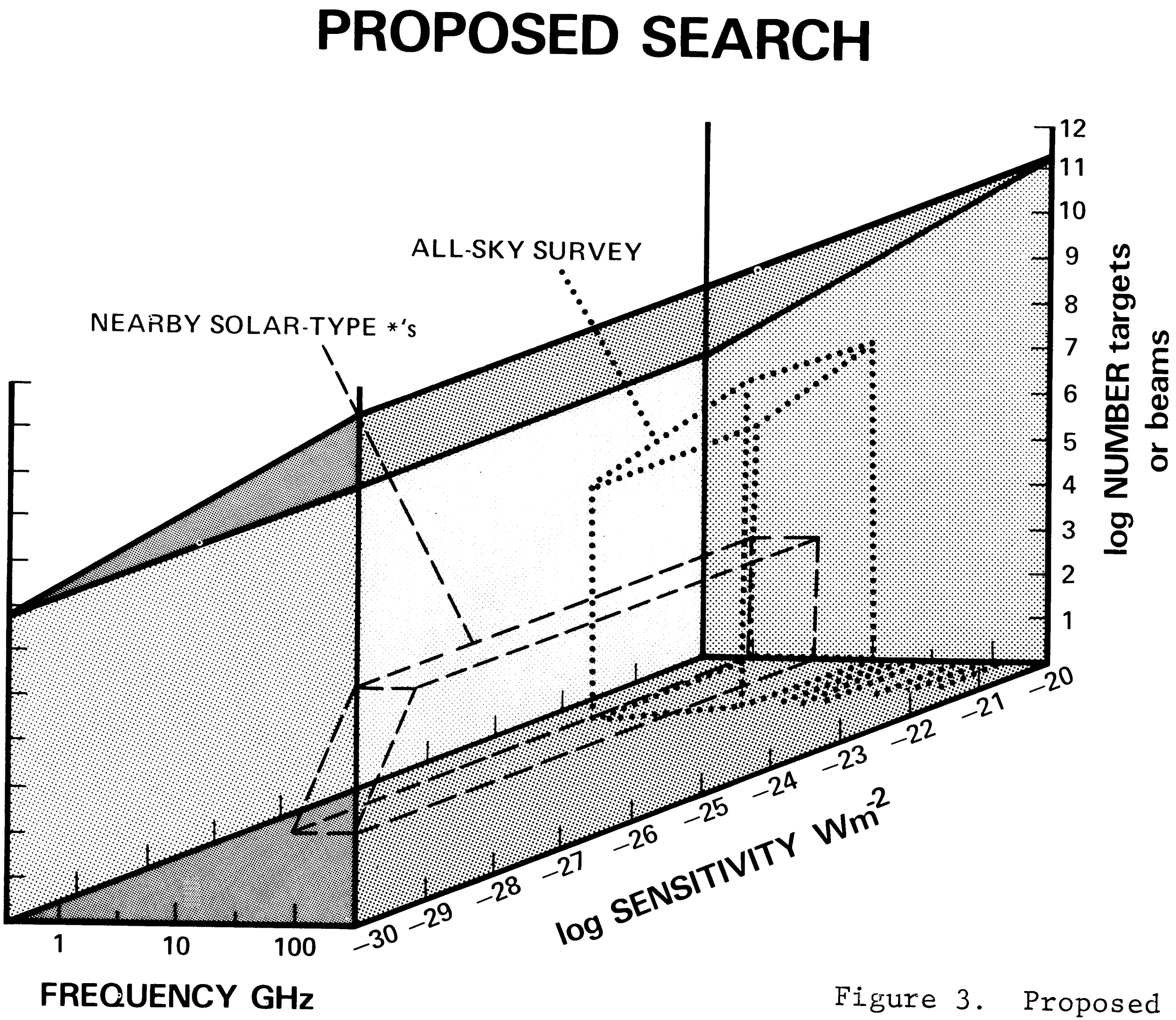

Figure 3. Proposed Search

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