SECTION VI

TECHNOLOGICAL PROGRESS IN RADIO SEARCHES

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VI. TECHNOLOGICAL PROGRESS IN RADIO SEARCHES

INTRODUCTION

The search for radio signals from extraterrestrial intelligence is a complex, multi-dimensional problem that only now we are beginning to address fully. The component dimensions of the search space include: Location of sources; Transmission frequency; Signal strength; Bandwidth; Polarization; Modulation; On-off periods. The probability of success clearly depends on the extent to which these different dimensions will be explored. This in turn depends critically on the time available for SETI on large radiotelescopes and on the time period allotted for a comprehensive search program, both of which have their time limitations.

In the early stages of the search, pressured by limited resources and a still rather primitive technology, the generally accepted practice was to minimize the ranges of these parameters by assuming that the extraterrestrial civilization would be assisting us in our searches by transmitting at a known frequency such as the 1,420 MHz line of atomic hydrogen. Indeed many searches based on this premise were conducted in the past 25 years and some are still going on. The lack, however, of any positive results from this strategy, together with the rapid technological progress in computers and electronics has prompted NASA to develop a comprehensive search program that minimizes the restrictions placed on a SETI search. The NASA search program will explore a wide frequency range and will search for signals with a variety of modulations (continuous wave or pulsed signals, polarized or not, with or without a Doppler drift, etc.).

It is generally believed that radio signals will be narrowband to conserve energy. Therefore in order to improve our signal to noise ratio (SNR) we need receivers with bandwidths that are as narrow as possible. But since we do not know the exact frequency of the signal, in order to search a wide frequency band in a reasonable time period, we need a high resolution radio frequency spectroscope, i.e., a device that would be able to resolve a relatively wide band of frequencies into a very large number of narrowband channels. This is the function of a Multi-Channel Spectrum Analyzer (MCSA). There are several such instruments now available with as any as 65,000 channels, but NASA has contracted a group at Stanford University headed by Allen Peterson to construct an 8.25 million MCSA, where M would now stand for Mega.

This instrument will consist of 112 units, each with 73,728 channels, for a total of 8,257,536 channels. The first of these units was completed early in 1985 and underwent a successful demonstration in March of 1985 tracking with the 64m Goldstone antenna of the Deep Space

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Network the signals of Pioneer 12 which is now in orbit around Venus. The entire MCSA is scheduled to be completed by 1988, but probably more realistically by 1990, and will be able to analyze an 8 MHz bandwidth into 8.25 million channels, or bins as they are often called, 1 Hz wide. It will also be able to analyze the same 8 MHz bandwidth into channels 32, 1024 and 73,728 Hz wide, in all cases examining simultaneously both left and right hand circular polarizations.

The MCSA performs a complex Fourier transform which yields the real and the imaginary amplitude for each bin, which are squared and added to yield the actual power. If the power exceeds a predetermined threshold, the signal is flagged for further tests. The level of the threshold is set high enough to minimize false alarms from a gaussian distribution of noise signals, but also low enough to maintain the sensitivity of the system to external signals. Sophisticated signal recognition algorithms are now in the R & D stage at the Ames Research Center and at the Jet Propulsion Laboratory, the two NASA centers that share the responsibility for the NASA SETI program. Emphasis is placed on the ability to detect pulsed signals and signals that display a frequency drift because of the relative motion of the transmitting and the receiving sites. A major effort is made to develop on-line processing because of the large volume of data that will be coming out from an 8.25 million spectrum analyzer.

The NASA SETI program, which is expected to go into full swing around 1990 and will probably last beyond the turn of the century, will consist of two search modes that try to maximize two key parameters of the search space: Solid Angle, i.e., sky coverage, and Signal Strength, i.e., sensitivity to weak signals. Both modes will also try to explore as much as possible of the frequency space within the time limitations of the program. One of these two search modes is called the "Sky Survey" and will try to cover the entire sky in the 1 to 10 GHz frequency range with a 32 Hz frequency resolution. The other is called the "Targeted Search" and will focus on 800-1,000 specific targets in the 1.2 to 2.0 GHz range, i.e., the range around the water hole, with a frequency resolution of 1 Hz. These targets will include the 773 F,G, and K sun-like stars within a distance of 25 parsec (81.5 l.y.) from our Sun contained in the Royal Greenwich Observatory Catalogue. Also a variety of other targets such as stars with peculiar spectra, galaxies, etc.

The Targeted Search plans to use many of the large radio telescopes around the world, including the 305 m Arecibo, the 53 m (equivalent) Ohio State University antenna, the 64 m radiotelescopes of the NASA's Deep Space Stations in California (DSS 14, Goldstone) and in Australia (DSS43, Tidbinbilla), the 91 m NRAO at Green Bank West Virginia, and possibly the 100 m Bonn antenna in West Germany and the Deep Space Station's 64 m antenna in Spain. For an approximate calculation the Targeted Search will examine close to 1000 targets spending about 1000 seconds on each target for each 8 MHz frequency band. For an over all frequency range of 100 8MHz bands (1.2 - 2.0 Ghz), the total time will be $10^3 x 10^3 x 10^2 = 10^8$ sec = 3.3 years. Adding time for moving the telescope, reobservation of interesting cases, telescope maintenance, etc, would bring the total time to about 5 years of telescope time.

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The All-Sky Survey plans to use the 5 or 6 smaller, 35m radiotelescopes of NASA'S Deep Space Stations with approximately the same total time. It will have a lower spectral resolution (32 Hz) but will cover a wider frequency range (1-10 GHz). It will scan the entire sky (4π steradians) with a half power beam width (HPBW) of approximately (λ/D), where λ is the observing wavelength and D the diameter of the antenna. This implies that the antenna will have to examine approximately $4\pi/(\lambda/D)^2 \sim 10^6$ locations. Spending approximately 1 second per location (the time to scan through a HPBW) per frequency band of about 100 MHz, composed of several MCSA's and some pseudobinning, it will take approximately 10^8 sec to complete the entire Sky Survey, and with the unavoidable time losses it will come again close to 5 years of telescope time.

These two modes of searching complement each other optimizing certain trade-offs at the expense of others. The Sky Survey has roughly 1000 times greater sky coverage and 10 times greater frequency coverage, while the Targeted Search has 32 times better frequency resolution and approximately 10^4 higher sensitivity. The total telescope time required for both surveys is approximately 10 years, which using 5 to ten different radio telescopes at about 10 - 20% of their time can be completed in about 10 years. Thus allowing five more years for the completion of the 8,25 million channel MCSA and for building several additional copies, plus the development of all the required signal recognition algorithms and related hardware, we can anticipate with some optimism that this major search program organized by NASA will start around 1990 and will be completed by the year 2,000.

Parallel to the NASA SETI program there are several other programs in progress, or in the development stages, which follow alternative search approaches based on more restrictive assumptions and/or different search philosophies. Preeminent among these is the current Project Sentinel and its successor Project META (Megachannel Extra-Terrestrial Assay) which is expected to go into operation within 1985. META will have an 8.4 million spectrum analyzer which will expand the total bandwidth of the system from the present 2 kHz to 420 kHz, thus removing certain restrictive assumptions which were necessary for Project Sentinel. Exciting is also the second generation (Serendip II) of the parasitic receiver and data processor being built by Stuart Bowyer and Dan Werthimer of the University of California-Berkeley which will be able to analyze random radio data for SETI without using valuable telescope time since it will operate in a piggyback mode. Important are also the studies of Walter T. Sullivan III and Stephen H. Knowles who are trying to eavesdrop on other stars for leaking radio signals by analyzing a wide range of frequencies for narrowband signals using computer software rather than MCSA hardware. Significant finally is the forthcoming entrance of Japan into the SETI experimental community with the new 45m Nobeyama microwave radiotelescope. Thus in the next 10-20 years we can expect a major SETI effort spearheaded by NASA and supplemented by several other projects most of them the products of ingenious leadership and high technology. These other projects will not only enhance the spectrum of the search effort, but will also expand the involvement of the scientific community in this new field.

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The Co-Chairmen of the corresponding Session at the Symposium were Frank D. Drake of Cornell University and George Marx of Eotvos University, Budapest, Hungary.

The first paper of this Section is a comprehensive review of the entire NASA SETI program by Bernard M. Oliver of the NASA Ames Research Center. Barney, as Dr. Oliver is known to his friends and colleagues, has been a sustaining force in the SETI effort from the very beginning. As Vice President for Research of the Hewlett Packard company, he spearheaded the NASA study for Project Cyclops in the early 1970's, he has personally helped with funds, instruments and technical advice different SETI projects, and has recently taken over as the Director of the NASA SETI program. In this review paper he describes the bimodal search approach planned by NASA with its Targeted and Sky surveys, the development of the 8.25 MCSA at Stanford, and the development of the necessary signal recognition algorithms for the proper processing of the signals obtained.

Paul Horowitz of Harvard University with his colleagues John Forster and Ivan Linscott describes his new 8.4 million channel spectrum analyzer now under construction, which is expected to become operational within 1985. It will replace the two 65,000 channel spectrum analyzers of the current Project Sentinel which are used for the simultaneous processing of LHC and RHC polarized signals of the same frequency. Each of the two MCSAs of Project Sentinel has a Unit Instantaneous (total) Bandwidth (UIB) of 2 kHz with a 0.03 Hz bandwidth per channel.
The new MCSA will do the two polarizations sequentially in time and with a 0.05 Hz bandwidth per channel will have an instantaneous bandwidth of 420 kHz, which represents an increase of more than 200 times in the total bandwidth. This will lift the strong restriction which currently requires that the extraterrestrials must correct their signals for all Doppler effects, i.e., not only for those in their own solar system but also for the relative motion of their star to our Sun, which also implies that they must be beaming their signals exclusively to us. The radial component of the peculiar velocity of nearby stars is of the order of 20 km/sec which produces a Doppler shift at about 100 kHz at 21 cm. Including also a component for the differential rotation of stars in the Galaxy ($\pm$ 75 kHz/kpc), the total becomes of the order of 100-200 kHz, which the new 420 kHz bandwidth can easily accommodate. The new system will be observing a magic frequency, e.g. the 1.420 MHz hydrogen line, sequentially in our local standard of rest and perhaps in their heliocentric frame, in the reference frame of the galactic center, and finally in the Big Bang rest frame, i.e., the frame in which the 3° K background radiation is isotropic. In each of these frames the LHC and the RHC polarized signals will be measured sequentially, so that the system will process 6 or 8 different signals in each 2.5 minute interval, i.e., in the time period any source will remain within the half power beam width of the 84 ft. antenna of the Harvard-Smithsonian Oak Ridge Observatory.

Allen Peterson of Stanford University with his colleagues Kok Chen and Ivan Linscott, describe the new 8,257,536 channel MCSA now being built at the Space, Telecommunications and Radioscience Laboratory of Stanford University under a contract with NASA. It will consist of 112 units each with 73,728 channels, the first of which has been completed and will be undergoing tests during 1985. The memory capacity of the entire system will be 43 Megabytes and is obtained through the use of dynamic random-access memory circuits. It will be able to provide simultaneously output bandwidths of approximately 1 Hz, 32 Hz, 1024 Hz, and 74 kHz over a spectrum that is about 8 MHz wide. Most of the processing for signal recognition at each of the two polarizations will be done in real time. Given the large volume of data and the variety of tests the signals must be subjected to, this will be a very demanding task.

D. Kent Cullers of the NASA Ames Research Center discusses the signal recognition algorithms that are being developed for the 8.25 million channel MCSA. A key concept is to set the signal detection threshold low enough to enhance the sensitivity while keeping low the rate of false alarms from noise. Signal detection algorithms have already been developed for the detection of three general types of signals: narrowband carriers, single pulses of variable lengths, and pulse trains. A more general pulse detection algorithm capable of detecting unsynchronized pulses by summing into pseudobins pulses found in adjacent samples is now approaching completion. All pulse detection algorithms allow for frequency drifts and in general do not require that pulses be synchronized with the sampling time. They also allow for missing pulses. Drifting CW signals can in principle be incoherently detected using the same algorithms used for non-drifting CW's, but require a very large memory. A new approach, which is capable of greatly reducing the demands for memory and computing time, has been proposed by Oliver and is now under study. It selects drifting CN signals by successive tests in a manner analogous to that used for pulses. The development of an optimum drifting CN detection algorithm is one of the key tasks for the next few years.

The next four papers describe different aspects of the NASA SETI Program. Charles L. Seeger and John H. Wolfe of the NASA Ames Research Center describe the Targeted Search approach. They note that the limited time available for SETI on large telescopes could stretch the program to undesirable lengths. A solution, they point out, would be the development of a broadband feed system for the Arecibo and other large radiotelescopes and the use of 10 or more of the 8 MHz MCSA units in parallel to cut the time required for the search by a factor of ten.

Michael J. Klein and Samuel Gulkis of the NASA Jet Propulsion Laboratory discuss the overall search problem and focus on the second approach of the bi-modal NASA SETI program, the Sky Survey. They note that because large telescopes have small size beams it takes them longer to scan the entire sky. In addition, time on these major facilities is at a premium and therefore the Sky Survey will probably use smaller antennas. This will set the sensitivity of the Sky Survey several orders of magnitude below the sensitivity of the Targeted Survey, but will allow it to be completed in a period of 3-5 years gaining in sky coverage what is lost in sensitivity. They also note that the Sky Survey will be able to catalogue more than 50,000 radio sources over a wide frequency range (1-10 GHz) and therefore will also be of considerable importance to Astronomy in general.

Edward T. Olsen, Anotoly Lokshin and Samuel Gulkis of the NASA Jet Propulsion Laboratory expand on the all sky survey and describe a strategy to achieve a uniform sensitivity (within 0.5 db) of $6x10^{-23}$ W/m^2 which will require dividing the sky in small areas to be scanned individually. They also discuss the excessive memory needs of about $8x10^8$ words of memory, and of processing power approaching 10^9 floating point operations per second. They suggest the consideration of alternative signal processing methods, such as the one they call "scalloping", which are capable of reducing substantially the signal processing time with a relatively small loss in the uniformity of the sensitivity of the survey.

Samuel Gulkis of the NASA Jet Propulsion Laboratory analyzes the probability of detecting randomly distributed CW transmitters in a Sky Survey. Given a fixed time interval, he compares the alternatives of spending more time on fewer sky locations and thus achieving higher sensitivity in these limited areas, or spending less time per location but covering the entire sky, of course with reduced sensitivity. He concludes that in most cases the all sky coverage is preferable.

Woodruff T. Sullivan, III and Kenneth J. Mighell of the University of Washington give a brief summary of their recent study on optimal radio search strategies. Considering a wide variety of radio luminosity functions and assuming that the density of transmitting civilizations is proportional to the stellar density, they conclude that in a non-targeted search it is preferable to simply concentrate in the inner galactic plane. This will bring a gain of about a factor of 10 in time over an all-sky survey, which if the time is available may be used to increase the sensitivity of the survey. In a targeted search of N stars, on the other hand, they recommend choosing only about 10% of them to be the nearest stars in all directions, while the other about 90% to be stars only within a 10 degree range of the galactic plane.

Dan Werthimer, Jill Tarter and Stuart Bowyer of the University of California at Berkeley, describe their Serendip II system, which as the earlier (1980) Serendip I, is designed to perform real time SETI work in a piggyback mode analyzing the signals obtained by a radiotelescope in a non-SETI-related project. The new system has a 65,536 channel fast Fourier transform processor, with an instantaneous bandwidth of 128 kHz and a 2 Hz bandwidth per channel, which is used to search for narrowband peaks above a 6 sigma threshold throughout the entire IF band of the radiotelescope. The search is conducted in 100 kHz increments, each taking 10 seconds, at the end of which a frequency synthesizer moves it to the next 100 kHz increment of the IF. In this manner the entire 30 MHz IF band is covered in 50 minutes. Unidentified peaks, together with all the other pertinent data, are recorded for further investigation. The system is fully automated to be able to operate unattended on a 24 hour basis. It thus provides a high sensitivity, low cost approach to SETI, which in the long run can cover large portions of the sky with no imposition on valuable telescope time.

The last paper of this Section is by Hisashi Hirabayashi of the Tokyo Astronomical Observatory, and describes the facilities at the new Nobeyama Radio Observatory (NRO). The main instrument is a 45 m radiotelescope, now in operation. It has a pointing accuracy of 0.001

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degrees and a surface accuracy of 0.2 mm (rms), which allows it to be effective all the way to the mm region. They also have a supersynthesis inteferometer consisting of five 10m antennas. The 45 m radiotelescope is equipped with two Acousto-Optical Spectrometers (AOS), one with 16,384 channels and a 2 GHz total bandwidth, and one with 8,192 channels and a 160 MHz total bandwidth. It also has a direct Fourier transform spectrometer with 4.096 channels for a 40 MHz to a 600 kHz total bandwidth. Japan is planning to enter soon the active SETI community using the Nobeyama radiotelescope to search for radio signals at the 4.83 GHz (6.21 cm) line of Formaldehyde (H_2CO), one of the so called "magic frequencies". This absorption line has the distinctive feature of being the narrowest of all the known lines, and because of an anti-maser effect it has a temperature below the 3 degree background radiation. Consequently it must be well suited for interstellar communications. The plan is to look for signals at the formaldehyde line in stars which, as seen from us, appear to be standing in front of dark clouds that enhance this anti-maser effect.

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