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Working Group Report**

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ERRATA

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SETI Science Working Group Report

Edited by Frank Drake, John H. Wolfe, and Charles L. Seeger

October 1983

Title page: Words "Edited by" to precede list of names

Page 54: Equation (3) should read

$$= s^2 + 2sn + n^2$$

Page 56: Equation (30) should read

$$s(t) = [A + a(t)] \cos \omega t + b(t) \sin \omega t$$

Page 59: Second line above equation (60a) should read

and if we let  $x = \sqrt{r} \cos \theta$ , and  $y = \sqrt{r} \sin \theta$ , then the result

Page 60: Line above equation (62) should read

For  $r \ll 1$ ,  $p(\theta) \rightarrow [1/(2\pi)] [1 + \sqrt{\pi r} \cos \theta]$  so that

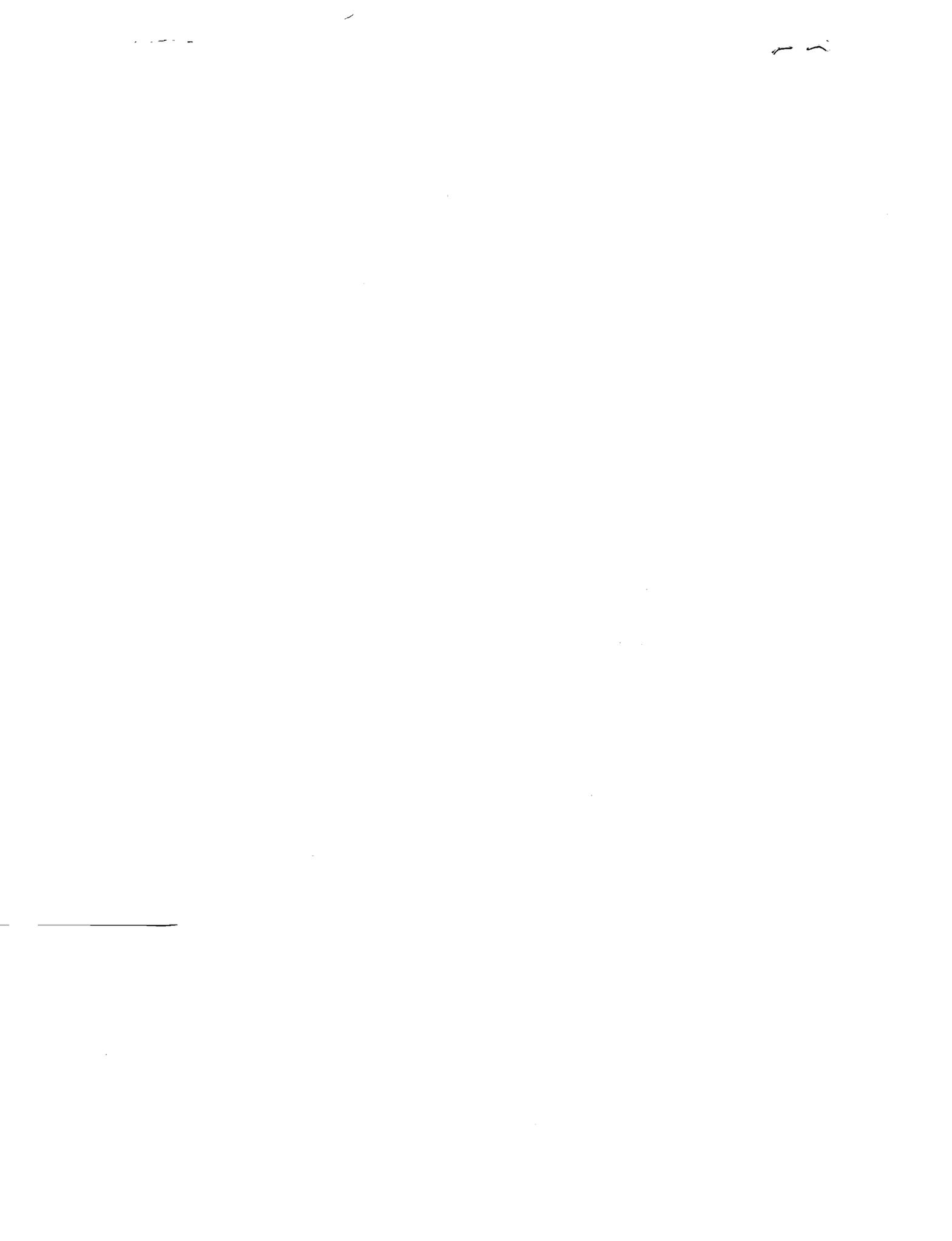
Page 63: Last line of paragraph ending after equation 81 should read

$(\sin \delta / \delta) f_{10}(\delta - \gamma)$  as a function of  $\delta$  when  $\gamma = \pi/2$ .

First line of following paragraph should read

Although we have not proved it generally, we have

COSATI page: Item 7 should include John H. Wolfe's affiliation: (Ames Research Center, Moffett Field, Calif.)





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# SETI Science Working Group Report

*Edited by*

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**NASA**

National Aeronautics  
and Space Administration

**Scientific and Technical  
Information Office**

1984



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## FOREWORD

The detection and study of other civilizations in space is one of the most tantalizing and potentially rewarding enterprises open to contemporary society. It is possible that intelligent and technological life can occur elsewhere in space; indeed, most would say it was very probable, although some argue for a paucity of intelligent life in the cosmos. The contemplation of other civilizations must be, for the time being, very much an experimental science. Only after much study may the subject become the grist for hard theorizing. Fortunately, we now have instruments which can make meaningful searches for other civilizations, and conduct such searches at a cost that is extremely modest. We believe that it is time to proceed with serious efforts to detect the existence of other intelligent beings in space.

This subject is not new. There have been two major studies in the last decade, both concluding that it is timely and promising to conduct a search for other civilizations by testing for the presence of short-wavelength radio transmissions from them. In the present plan, as described in this report, this same approach has been favored. What has changed is our technology. In the 10 years since the original studies, which produced the seminal Project Cyclops report, data processing technology has improved enormously. This is of the utmost importance to SETI, for it has long been recognized that our greatest weakness in searching the "cosmic haystack" for radio signals may not be, after all, the size of our telescopes or the sensitivity of our radio receivers, but rather our ability to sort through the immensity of the radio spectrum. Now it is possible.

Thus in this, the third major effort to study the problem, the last requirement for a viable SETI program is satisfied. A versatile and powerful radio spectrum analyzer is designed which offers the ability, at last, to search the radio spectrum in a thorough and timely manner.

Having seen a way to achieve the desired instrumentation, it is possible to design a detailed observing program, and it is given here. This very general program calls for searching selected nearby regions for weak signals and the entire sky for stronger signals. Thus we not only address the possibility that most civilizations have radio transmitters no more powerful than our own, but also the possibility that there are perhaps a few civilizations which transmit particularly strong signals. The program calls for the development of unusually sensitive computational procedures which can search the data collected by our radio telescopes for many forms of radio signals. Together, the observational and analytic programs create an overall cosmic search which is vastly more thorough than the sum of all previous searches. And the cost is reasonable and realistic.

For one fundamental reason it is important that the programs described here begin at the very earliest possible time. Each passing day sees the radio brightness of our own civilization take another leap in intensity, further increasing the greatest technical obstacle to searching for faint signals from the depths of space. Many of the loud signals of Earth unavoidably enter our instruments, blanking out parts of the spectrum and, in other parts, causing confusion, wasted effort, and delay. Any substantial delay in the SETI search could quite possibly decrease the prospects for success so greatly that the potential chances for success could be restored only through such heroic measures as observing from deep in space, shielded from the Earth by a natural or artificial body.

Frank D. Drake  
Goldwin Smith Professor of Astronomy  
Cornell University  
Ithaca, New York



## PREFACE

In the summer of 1970, a small group of scientists at the NASA Ames Research Center met to discuss two provocative questions. First, is there a valid scientific basis for the supposition that intelligent life may be widely distributed in the Universe? Second, do we now have the technological capability to detect the existence of extraterrestrial intelligent life? The group concluded that the answer to both questions was "yes," and they recommended intensive studies of both questions.

Over the next 10 years a variety of studies were carried out on different aspects of both questions. In 1971 Bernard Oliver conducted a thorough engineering systems design study of a system for detecting extraterrestrial intelligent life, Project Cyclops. In 1973 the Interstellar Communications Study Group was formed at the Ames Research Center. In 1976 scientists from the Jet Propulsion Laboratory (JPL) joined the endeavor, which became known as the Search for Extraterrestrial Intelligence, or SETI. 1977 saw the publication of the report (NASA SP-419) of the SETI Science Workshops under the chairmanship of Philip Morrison. Engineering studies of possible designs for data processing systems began at Stanford University under Allen M. Peterson. More detailed design studies were conducted by Ames and JPL in the late 1970s.

In 1980, the National Academy of Sciences began the deliberations on those key programs which should represent major national thrusts in astronomy and astrophysics through the 1980s. Their recommendations, published in 1982, included SETI as one of seven moderate new programs which should be carried out in the coming decade.

Also in 1980, the Ames-JPL SETI Program Team, in concert with NASA Headquarters, decided that the program should be carried out with the continuing input at a working level from leading radio scientists in the academic community. Accordingly the SETI Science Working Group (SSWG)

was formed, under the chairmanship of John Wolfe of Ames and Sam Gulkis of JPL. Details of the mandate and membership of the Group are given in pages that follow.

This document is the first report of the SSWG.

A very considerable amount of work has gone into this volume. I must acknowledge the leading roles played by the editors Frank Drake of Cornell University, John Wolfe of Ames Research Center, and Charles Seeger of San Francisco State University. Sam Gulkis and his colleagues at JPL have made significant contributions. The assembly of the material into the report, with necessary attention to the thousand details involved, was carried out by Vera Buescher and Lorraine Mitvalsky, while Jill Tarter and Peter Backus were our scientific proofreaders. Correspondingly the Ames Technical Information Division people, under Paul Bennett, and particularly the Graphics and Publications experts, were responsible for the translation of the document into its final printed form.

Last but not least I must thank the many authors, from Ames, JPL, and the SSWG, for all their hard work in producing such a thorough technical document. It is their report.

As the SETI Program matures, I expect that the SSWG will continue its intimate relationship with all aspects of the endeavor. I expect also that this report will be the first of a series, published over the years, which will chronicle the technical progress of SETI as the program develops into its fully fledged state.

John Billingham  
Chief, Extraterrestrial Research Division  
Ames Research Center  
Moffett Field, California



## BACKGROUND

Serious scientific concern with SETI was first enunciated in 1959. In a paper in *Nature* entitled "Searching for Interstellar Communications," Cocconi and Morrison<sup>1</sup> proposed that transmissions in the neighborhood of the line of neutral hydrogen (1420 MHz) might be a means by which civilizations communicate with each other over interstellar distances. In 1963 a collection of papers by Bracewell, Dyson, Morrison, Oliver, Sagan, Shklovskii, and others was published by Cameron under the title, "Interstellar Communication." In 1966 Shklovskii and Sagan published a comprehensive analysis, "Intelligent Life in the Universe." In 1971 there appeared a translation of a Soviet collection of papers under the heading, "Extraterrestrial Civilizations: Problems of Interstellar Communication," edited by S. D. Kaplan. "Project Cyclops: A Design Study of a System for Detecting Extraterrestrial Intelligent Life" was published in 1972 by Oliver and Billingham. In 1971 a large-scale meeting on SETI, jointly sponsored by the academies of science of the U.S. and the U.S.S.R., was held at Byurakan in Soviet Armenia. The proceedings of this joint meeting were published in 1973 under the title "Communication with Extraterrestrial Intelligence," edited by C. Sagan. In 1974 a series of papers, originally presented at the NASA Ames Research Center in 1970, was published by Ponnampertuma and Cameron under the title "Interstellar Communication: Scientific Perspectives." A summary of the state of knowledge in the field of interstellar communication was published in 1975 by Sagan and Drake in the *Scientific American*. At the 1979 General Assembly of the International Astronomical Union, Montreal, Canada, there was a joint commission session on SETI. The proceedings, edited by M. Papagiannis, were published in 1980 under the title "Strategies for the Search for Life in the Universe." A comprehensive bibliography of SETI, assembled by Mallove, Connors, Forward, and Paprotny, was published in March 1978 by NASA Ames Research Center as NASA Reference Publication 1021. Finally, much of the history of the concept of life in the Universe is covered in the Selected SETI References and Reading List following appendix M of this report.

The essence of the scientific arguments developed in these papers and in many others is as follows. Modern astrophysical and astronomical theory predicts that planets are a natural part of the star formation process and may well num-

ber in the billions in our galaxy alone. Given a suitable location and environment, theories of chemical evolution and the origin of life predict that life may begin. Once life has been established, and given a period of billions of years of comparative stability on the planet, it is argued, life will sometimes evolve intelligence. In some cases, the next step may be the emergence of a technological civilization. While we believe ourselves to be an example that this complex path was followed at least once, there is no broad agreement as to how many other technological civilizations might currently exist in our galaxy. The joint discussion of this topic at the 1979 International Astronomical Union General Assembly showed the "optimists" and "pessimists" to be separated by at least six orders of magnitude in their estimates. On that occasion, as he had done 20 years earlier in his pioneering paper in *Nature*, Morrison urged that a search be conducted to experimentally determine (or to at least bound) the number of other technological civilizations, as it cannot be calculated from first principles without far more information than we now possess.

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

A series of SETI Science Workshops, chaired by Philip Morrison of the Massachusetts Institute of Technology (MIT) and supported by the NASA Office of Space Science, was conducted as part of a 2-year feasibility study. The results of the Workshops were published in 1977 as NASA SP-419, "The Search for Extraterrestrial Intelligence - SETI," and reprinted by Dover Publications in 1979. The conclusions of the Workshops were

1. It is both timely and feasible to begin a serious search for extraterrestrial intelligence.

2. A significant SETI program with substantial potential secondary benefits can be undertaken with only modest resources.

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<sup>1</sup>See reference section after appendix M for this and other references.

3. Large systems of great capability can be built if needed.

4. SETI is intrinsically an international endeavor in which the United States can take a lead.

The proposed SETI effort is an integrated program incorporating the proposals generated by the Science Workshops under Conclusion 2. The plan recognizes the timeliness of Conclusion 1, not only in terms of available technology, but also in terms of the very serious problem of human-caused interference at radio frequencies. For a SETI program to require only modest resources, it must be ground-based, yet still have access to those portions of the radio spectrum in which the search for potentially weak signals is to be accomplished. The most recent allocations of the microwave spectrum to numerous users worldwide serve to emphasize the need to proceed with a SETI exploration as soon as possible. The pressures exerted by all nations for increasing access to the satellite radio spectrum is enormous.

In accord with Conclusion 2 above, a significant SETI program can be carried out without new radio telescopes by equipping existing telescopes with powerful instruments unavailable to previous explorers of the spectrum. Recent

electronic developments offer the opportunity to conduct more efficient searches with higher sensitivity and with broad sky and frequency coverage. Key aspects are the ability to simultaneously process tens of millions of separate frequency channels; to use ultralow-noise cryogenic receivers having wide bandwidth and tunability; and to provide sophisticated on-line, real-time signal processing and identification systems.

Starting with Drake's Project Ozma, which began early in 1959 and made its SETI observations in 1960, there have been some 31 separate radio searches for ETI signals, some of them still continuing today. Although these searches represent an impressive effort, they covered only a minute fraction of the parameter space in which we believe an ETI signal might be expected. The program described there should lead to a *10 millionfold* increase in search space coverage, compared to the sum of all previous searches.

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

## THE SETI SCIENCE WORKING GROUP

The SSWG was constituted in early January 1980 and held its first meeting at NASA Ames Research Center on January 23 and 24, 1980. The principal purpose of the SSWG is to help the NASA SETI Program Office in the definition of the key scientific requirements for a projected SETI effort. The SSWG was chartered to assess and critique SETI ideas and concepts, and to participate in the definition of a detailed SETI program plan. In particular, the SSWG was required to

1. Identify the crucial scientific objectives of a SETI program
2. Examine alternatives in the development of a search strategy and identify a preferred approach
3. Discuss the translation of the preferred approach into an observational plan
4. Discuss the resulting duration and scale of a SETI project

5. Discuss the significance of nondetection of ETI as a result of this particular SETI initiative

6. Discuss the design requirements for data acquisition systems, data analysis systems, and data dissemination plans needed to implement a program

7. Determine those signal characteristics, such as periodicity, polarization, and coherence, the use of which would optimize the approach to signal recognition with respect to sensitivity, generality, cost, or other criteria

8. Explore ways in which these requirements can be met in terms of on-line and off-line hardware and software

9. Examine the objectives of, approach to, and results of SETI field tests

10. Suggest ways in which SETI activities and hardware can assist radio astronomy and other disciplines

11. Examine ways in which the scientific community might participate in a SETI program

12. Prepare summary reports of their deliberations and conclusions

### SSWG Membership

The constituent members of the SSWG are:

John H. Wolfe, Chairman  
SETI Program Scientist  
NASA Ames Research Center  
Moffett Field, Calif.

Samuel Gulkis, Cochairman  
Deputy SETI Program Scientist  
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Astronomy Department  
University of California  
Los Angeles, Calif.

#### Additional Participants

The following visitors and other members of the SETI Team contributed to the SSWG activities:

John Billingham, Chief, Extraterrestrial Research Division, and Acting Chief, SETI Program Office, NASA Ames  
Michael J. Klein, Deputy Chief, SETI Program Office, JPL  
Peter R. Backus, Dudley Observatory and University of Massachusetts  
Allen L. Berman, Operations Manager, SETI Program Office, JPL  
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Jill C. Tarter, Deputy Operations Manager, Space Sciences, University of California, Berkeley  
Robert M. Taylor, SETI Program Office, JPL  
Calvin C. Teague, Electrical Engineering, Stanford University

## SSWG Meetings

The first six meetings of the SETI Science Working Group were held on the following dates and at the locations listed below:

| Meeting | Dates         | Location                  |
|---------|---------------|---------------------------|
| 1       | 1/23, 24/1980 | NASA Ames Research Center |
| 2       | 3/19, 20/1980 | NASA Ames Research Center |
| 3       | 6/2, 3/1980   | Jet Propulsion Laboratory |
| 4       | 9/3-5/1980    | Snowmass, Colorado        |
| 5       | 1/29, 30/1981 | Stanford University       |
| 6       | 4/27, 28/1981 | NASA Headquarters         |

Logistical support for the meetings was provided by the American Institute of Biological Sciences (AIBS). Donald R. Beem (AIBS) was facilitator and recording secretary.

## Conclusions and Recommendations

1. The discovery of other civilizations would be among the most important achievements of humanity.
2. Continuing advances in our knowledge in astronomy, the planetary sciences, chemistry, and biology have led in recent years to the conclusion that life may be widespread in the Universe.
3. In some cases, intelligence, culture, science, and technology may have emerged on the planets of other stars, as they did on the Earth.
4. The existence of extraterrestrial intelligent life might be demonstrated by the detection of signals that they generate in the electromagnetic spectrum.
5. After many years of study, we conclude that the best place to initiate the search for extraterrestrial intelligence is in the microwave region of the spectrum. Other regions, particularly the infrared should receive continuing study with regard to their possible use in the future.
6. Two dozen pioneering searches over the past 20 years have been able to cover only a minute fraction of the total search space.
7. Recent advances in the technology of spectral analysis and signal processing now allow an increase in the rate of coverage of search space by many orders of magnitude, and at reasonable cost.
8. A 5-year research and development program to exhaustively test a prototype signal detection system has been proposed by the NASA Ames/JPL SETI Program Team. We endorse this program. It should be carried out.
9. The 5-year research and development program would be followed by the construction of several optimum SETI data processing systems for use at several existing large radiotelescopes in a definitive search expected to take 4 to 5 years. The search would examine likely nearby target stars and survey the whole sky in a carefully planned program.
10. In parallel with this program, other possible approaches to SETI should be examined on a continuing basis, to ensure that the types of search selected in the future represent the best possible strategies at all times.
11. The Ames/JPL team should continue to work closely with the entire scientific community on all aspects of SETI. Specific arrangements should be made to provide funds for outside scientific investigators to participate in the program.
12. It is expected that there will be useful byproducts for radio astronomy and other disciplines. It is important, for this reason alone, that there should be continuing interaction with the scientific community as the program develops.
13. While NASA should remain as the focal point for a well-structured SETI program, other sources of support should be examined. Correspondingly, various avenues of international cooperation should be explored.
14. There is an urgency to the implementation of a SETI program because of the progressive buildup of radio frequency interference by transmissions of terrestrial origin.
15. The program described in this volume should be viewed as an inherent and important part of life in the Universe studies as a whole.
16. The final resolution of differences between various concepts regarding the nature and distribution of intelligent life can be achieved only by the unequivocal detection of the existence of other intelligent species.
17. It is recommended that the search for extraterrestrial intelligence be supported and continued at a modest level as a long-term NASA research program.



## GLOSSARY

|                       |  |                   |  |
|-----------------------|--|-------------------|--|
| <b>A/D</b>            | Analog to digital  | <b>EIRP</b>       | Equivalent isotropic radiated power (watts) of a transmitting antenna system; product of the antenna directional gain and the real transmitted power |
| <b>ALU</b>            | Arithmetic Logic Unit  |                   |  |
| <b>ANT</b>            | Antenna; a device for collecting or launching electromagnetic waves of radio wavelengths   | <b>ET</b>         | Extraterrestrial   |
| <b>Ames</b>           | NASA Ames Research Center, Mountain View, Calif.   | <b>ETI</b>        | Extraterrestrial intelligence (-ent)   |
| <b>AO</b>             | Announcement of Opportunity; a formal procedure used by NASA to invite participation by members of the larger community in specific activities | <b>FFT</b>        | Fast Fourier Transform   |
|                       |  | <b>FIR</b>        | Finite impulse response (filter)   |
| <b>beacon</b>         | An omnidirectional, continuous, or regularly intermittent signaling device to get the attention of parties unknown                             | <b>GHz</b>        | Gigahertz; $10^9$ hertz; billion (U.S.) hertz  |
|                       |  | <b>HI</b>         | Neutral atomic hydrogen (gas)  |
| <b>binwidth</b>       | Half-power resolution bandwidth of a multi-channel spectral analyzer output channel (bin)  | <b>HPBW</b>       | Half-power beamwidth   |
|                       |  | <b>Hz</b>         | Hertz, a unit of frequency; equivalent of earlier term cps or c/sec (cycle per second) no longer used, by international agreement                    |
| <b>bpi</b>            | Digital-bit density on a magnetic tape record  |                   |  |
| <b>CSIRO</b>          | Commonwealth Scientific and Industrial Research Organization, Australia  | <b>IF</b>         | Intermediate frequency   |
|                       |  | <b>J</b>          | Joule; international standard unit of energy; watt-second  |
| <b>CTRL</b>           | Control  | <b>Jy</b>         | Jansky, $10^{-26}$ W/m <sup>2</sup> Hz   |
| <b>CW</b>             | Continuous wave; an essentially single-frequency electromagnetic wave  | <b>JPL</b>        | Jet Propulsion Laboratory of the California Institute of Technology, Pasadena, Calif.  |
| <b>CZT</b>            | Chirp Z transform  |                   |  |
| <b>dB</b>             | Decibel; a logarithmic (base 10) measure of power ratio  | <b>K</b>          | Kelvin; international standard (SI) unit of thermodynamic temperature  |
|                       |  | <b>k</b>          | Kilo-; 1000  |
| <b>DFT</b>            | Discrete Fourier Transform   | <b>k</b>          | Boltzmann's constant; $1.38 \times 10^{-23}$ J/K   |
| <b>Doppler effect</b> | The apparent frequency change of radiant energy, varying with the relative velocity of the source and the observer                             | <b>LC</b>         | LCP, left circular polarization  |
|                       |  | <b>light year</b> | Distance light travels in a year in free space; $9.46 \times 10^{12}$ km   |
| <b>DSN</b>            | Deep Space Network (NASA/JPL)  |                   |  |
| <b>DSS</b>            | Deep Space Station; a particular installation, such as the 64-m receive/transmit system DSS 14 at Goldstone, Calif.                            | <b>LO</b>         | Local oscillator   |
|                       |  | <b>ly</b>         | Light year   |

|                  |  |                            |  |
|------------------|--|----------------------------|--|
| <b>M</b>         | Mega-; $10^6$ ; million  | <b>RC</b>                  | RCP, right circular polarization   |
| <b>m</b>         | Meter; international standard (SI) of length   | <b>RCV</b>                 | Receiver   |
| <b>MAC</b>       | Multiplier-accumulator   | <b>R&amp;D</b>             | Research and development   |
| <b>MCSA</b>      | Multichannel spectrum analyzer   | <b>RFI</b>                 | Radio frequency interference   |
| <b>Milky Way</b> | A band of brightness in the night sky; another name for our island Universe, the galaxy  | <b>RGO</b>                 | Royal Greenwich Observatory  |
| <b>MIPS</b>      | Million instructions per second  | <b>ROM</b>                 | Read only memory   |
| <b>MIRA</b>      | Monterey Institute for Research in Astronomy   | <b>sensitivity</b>         | Reciprocal of $\phi_{\text{minimum}}$ , the minimum detectable signal flux with acceptable false alarm probability   |
| <b>NAIC</b>      | National Astronomy and Ionosphere Center   | <b>service</b>             | This term has a special meaning in radio spectrum management parlance; a broad class of radio transmitting operations, such as TV, FM, radio location, mobile  |
| <b>NAR</b>       | Noise Adding Radiometer (JPL); a type of receiver  | <b>SETI</b>                | Search for extraterrestrial intelligence by means of radio wavelength exploration of the spectrum of signals incident on Earth; terminology developed by the 1975-76 Science Working Group chaired by Philip Morrison, to distinguish between the effort to discover an ETI signal and any later effort to communicate with an extraterrestrial species (CETI) |
| <b>NOCC</b>      | Network Operations Control Center (JPL)  | <b>S/N</b>                 | Signal to noise ratio  |
| <b>NRAO</b>      | National Radio Astronomy Observatory, Green Bank, W.Va.  | <b>square law detector</b> | A device producing an output current or voltage which is proportional to the power of the complex input signal; that is, proportional to the square of the input signal voltage  |
| <b>NSF</b>       | National Science Foundation  | <b>SSWG</b>                | SETI Science Working Group   |
| <b>Ops</b>       | Operations   | <b>sr</b>                  | Steradian; solid angle   |
| <b>OSTDS</b>     | Office of Space Tracking and Data Systems (NASA)   | <b>Tidbinbilla</b>         | Australian site of a major DSN communications center   |
| <b>OSU</b>       | Ohio State University, Columbus, Ohio  | <b>TV</b>                  | Television   |
| <b>OSURO</b>     | Ohio State University Radio Observatory  | <b>zoom</b>                | As used in this report, short for greatly increasing the frequency resolution during an observation  |
| <b>Ozma</b>      | Project Ozma; pioneering attempt (by F. D. Drake and NRAO) to receive signals from neighborhood of (two) nearby stars, in 1961 | $\lambda$                  | Common symbol for wavelength   |
| <b>Parkes</b>    | Site of CSIRO (Australia) 64-m radio telescope complex   | $\phi$                     | Symbol used for signal flux at Earth; watts/m <sup>2</sup> , or W/m <sup>2</sup>   |
| <b>parsec</b>    | Parallax second; a distance; $\sim 3.26$ ly  |                            |  |
| <b>pc</b>        | Parsec   |                            |  |
| <b>PDF</b>       | Probability density function   |                            |  |
| <b>POCA</b>      | Programmable Oscillator Control Assembly (JPL)   |                            |  |
| <b>RA</b>        | Radio astronomy  |                            |  |
| <b>RAM</b>       | Random-access memory   |                            |  |

## EXECUTIVE SUMMARY

This report covers the activities and deliberations of the SETI Science Working Group (SSWG) over the period from early 1980 through the spring of 1981. The report is divided into two parts: (1) the main text, consisting of seven chapters representing the SSWG consensus, and (2) 13 appendixes which reflect the thoughts of the individual contributors.

The SSWG confirmed the consensus of others, who have deliberated over the last 10 years, that the microwave region of the electromagnetic spectrum is the most logical and promising place to begin searching for signals of extraterrestrial intelligent (ETI) origin.

The search strategy that has been developed employs a bimodal approach consisting of a high-sensitivity *targeted search* and a less sensitive *all-sky survey*. The targeted search will examine all known solar-type stars within about 80 light years (ly) distance, over the 1- to 3-GHz frequency range, with 1-Hz resolution, and integration periods up to 1000 sec per star per frequency band. It will utilize the largest collecting areas available, including the 1000-ft-diam radiotelescope at Arecibo, Puerto Rico. The all-sky survey will examine the sky over the 1- to 10-GHz frequency range with 32-Hz resolution and integration periods up to 3 sec. The sky survey will utilize the 34-m subnet of NASA's Deep Space Network (DSN).

The SETI Program envisages a 5-yr research and development (R&D) effort in which prototype instrumentation is designed, developed, and thoroughly tested at the DSN site at Goldstone, California, and at Arecibo, Puerto Rico. A vital subsystem of the SETI instrumentation is the multi-

channel spectrum analyzer (MCSA) which is already under development at Stanford University. At present, the prototype MCSA is a 74-kHz spectrum analyzer to be interfaced with a small, general-purpose computer for signal processing via software. It is planned that the targeted search will look for pulses and drifting, narrowband carrier-like signals of ETI origin, whereas the sky survey will search for continuously present, nondrifting signals. Signal processing algorithms will be fully tested and optimized, then gradually realized in hardware, and the MCSA will be expanded to dual polarization and increased bandwidth.

Field tests, using the prototype hardware and software, will evaluate instrumentation capabilities and efficiencies, particularly in the presence of human-caused radio frequency interference (RFI). The field tests will include some limited SETI observations and will also be used for a variety of exploratory radio astronomical studies. During the 5-yr R&D activities, new technology will be evaluated for its applicability to SETI, and it is anticipated that the SETI program will involve extensive participation by the scientific community. At the end of the R&D phase, it is expected that a fully functional SETI instrument will be available with about 4-MHz bandwidth and dual polarization.

To accomplish the targeted search and sky survey will require about 32 MHz of bandwidth at 1-Hz resolution, 256 MHz of bandwidth at 32-Hz resolution, dual polarization, and a period of 4 to 5 yr. The exact method of realizing the SETI instrumentation to accomplish this will depend upon the findings and technological developments of the R&D phase and upon available resources.



## INTRODUCTION

One very practical test of the idea that intelligent life exists beyond our solar system is based on the postulate that other civilizations have transmitted electromagnetic signals which we can receive and recognize. The physical laws of the Universe, a relatively mature microwave technology, recent digital solid-state achievements, and a minimum number of reasonable assumptions have permitted the development of a promising set of exploratory strategies for the detection of a range of possible electromagnetic signals of ETI origin. As a result, NASA Ames Research Center and the Jet Propulsion Laboratory are now carrying out a 5-yr R&D program using existing radio telescopes and advanced electronic techniques. The objective is to develop powerful instrumentation with which to *detect* the presence of one or

more signals generated by other intelligent beings, if they exist.

This 5-yr R&D phase is a necessary prelude to the definitive SETI observing program described in some detail in this report. Chapters one through seven give the essence of the SETI endeavor as visualized by the SSWG and the Ames/JPL SETI Team. The 13 authored appendixes (A through M) discuss both current and future R&D and various technical and observational concerns. While these discussions are, strictly speaking, individual contributions, they were requested by the SSWG because of the authors' known interests and expertise in matters of importance to the Group as a whole.



## CHAPTER 1

### FUNDAMENTAL CONCEPTS OF MICROWAVE SEARCHES FOR EXTRATERRESTRIAL INTELLIGENCE

#### Abstract

*This chapter presents fundamental relations involved in the transmission and reception of signals across interstellar distances. The sensitivities of a targeted search and an all-sky survey are compared. Examples show the powers needed for beamed signals are modest even with present receivers and antennas, but that detection of omnidirectional signals will require very large transmitter powers or a very large receiving antenna area. Nevertheless, searches for both types of signal are justified.*

Twenty years of SETI studies have repeatedly indicated that searching in the microwave spectral range is a very promising approach. Appendix A gives a brief review of the thinking which leads to this conclusion and appendix L briefly discusses some alternative possibilities. Existing terrestrial microwave radio telescope technology is sufficiently sensitive to detect reasonable signals, those no stronger than some leaving Earth, from distances of 1000 ly or more. Within that distance are more than a million sunlike stars, and many researchers feel that there may be at least one detectable civilization among such a large stellar population. Here we give the quantitative relations governing the detectability of interstellar microwave transmissions.

#### Detection Range Equations

Suppose a transmitter radiates a power  $P$  isotropically. Then at a distance  $R$  an antenna of effective collecting area  $A_r$  will receive a power

$$P_r = PA_r/4\pi R^2 \quad (1)$$

We define the detection range limit  $R_d$  as the value of  $R$  that makes  $P_r = mkTb$ , where  $T$  is the system noise temperature and  $kTb$  is the noise power per channel of binwidth  $b$ . The parameter  $m$  is the factor by which the detection threshold must exceed the mean noise power in order for a tolerable false alarm probability (say  $10^{-12}$ ) to be achieved. Thus

$$R_d = (A_r P / 4\pi m k T b)^{1/2} \quad (2)$$

Since the effective area of a circular antenna is  $A_r = \eta \pi d^2 / 4$ , where  $d$  is the diameter and  $\eta$  is the aperture efficiency, we have

$$R_d = (d/4)(P\eta/mkTb)^{1/2} \quad (3)$$

As an example of the application of this relation, the Arecibo planetary radar has an equivalent isotropic radiated power (EIRP) of about  $10^{13}$  W. Assume that an extraterrestrial (ET) transmitter radiates this power, and that our radio telescope system has a bandwidth of 1 Hz (per channel), a system noise temperature of 16 K, and an aperture efficiency of 80%. Taking  $m = 1$  we find  $R = 5d$ , where  $R$  is in light years and  $d$  is in meters. A 64-m antenna could detect this ETI signal at a range of 320 ly ( $\sim 100$  pc) in a few seconds, which is striking.

Equation (2) shows that for the greatest range we want the largest collecting area,  $A_r$ , and the lowest system noise temperature,  $T$ . The Cyclops study (Oliver and Billingham, rev. ed. 1973) proposed that, starting with a single antenna,  $A_r$  be increased with time as needed by adding antennas to form a phased array. This is feasible and may ultimately be necessary. The best modern receivers add very little noise to the natural sky background, so no great breakthrough can be expected in reducing  $T$ . All we can and should do is select the spectral region in which the sky noise is least; i.e., the terrestrial microwave window (see fig. A-1, appendix A). The question of desirable receiver bandwidths is discussed below.

If the transmitting antenna radiates only into a solid angle  $\Omega$ , the transmitter power  $P_t$  need be only

$$P_t = P\Omega/4\pi \quad (4)$$

Assuming  $\eta = 1$ , the antenna gain is

$$g = P/P_t = 4\pi/\Omega \quad (5)$$

But  $4\pi/\Omega$  is the number of directions,  $n$ , in which the antenna must be pointed to cover the sky, so

$$n = g \quad (6)$$

The collecting area,  $A_o$ , of an isotropic antenna is

$$A_o = \lambda^2/4\pi$$

On axis, an antenna of effective area  $A$  collects  $A/A_o$  times as much power as an isotropic antenna and so has a gain

$$g = A/A_o = 4\pi A/\lambda^2 = (\pi d/\lambda)^2 \quad (7)$$

Thus gain ( $g$ ) and directivity ( $n$ ) are equal and are proportional to the antenna area in square wavelengths. Small modifications are necessary in this result when  $\eta < 1$ .

Making use of equations (5) and (7), equation (1) may be written in several equivalent forms:

$$\begin{aligned} R &= (1/\lambda)[A_t A_r (P_t/P_r)]^{1/2} = [g_t A_r (P_t/P_r)/4\pi]^{1/2} \\ &= [A_t g_r (P_t/P_r)/4\pi]^{1/2} = (\lambda/4\pi)[g_t g_r (P_t/P_r)]^{1/2} \end{aligned} \quad (8a)$$

Let us now examine these equations assuming  $P_t/P_r$  is fixed. If the realizable antenna area were independent of wavelength, the first form would be appropriate and the range would be proportional to frequency. If all linear dimensions of a structure are scaled by a factor  $s$ , the deformations under gravity or thermal strain scale as  $s^2$ . Since the tolerable deformations are proportional to  $\lambda$ ,  $s$  can be proportional to  $\lambda^{1/2}$ , which makes the area  $A = s\lambda$  for single structures. If we use arrays we are limited in gain only by phase errors, and thus by our ability to point the beam. There does not appear to be any reason why the maximum practical directivity (and hence gain) should be a function of frequency. We can therefore rewrite equation (8a) as

$$R = s(P_t/P_r)^{1/2} = [g_s \lambda (P_t/P_r)/4\pi]^{1/2} = (\lambda g/4\pi)(P_t/P_r)^{1/2} \quad (8b)$$

where the first expression applies for two single-unit antennas, the second for one single unit and one array, and the third for two arrays. We can find no basis in these results to prefer frequencies above the microwave window, and it remains a very promising spectral region for searches.

### Likely Signals

Signals we may receive fall into two classes: those generated for the "society's" own use (leakage), upon which we "eavesdrop," and signals intended for the reception of others (beacons). Leakage signals may be pulsed or be subject to other complex modulations. In the latter case, only the

monochromatic carriers (if any) may be detectable. Beacon signals may be monochromatic or nearly so; in which case, as for leakage carriers, very narrow search channels are called for because, ideally, the channel width should be the reciprocal of the observing time. But other considerations argue for pulsed signals. For example, by rotating a fan beam antenna one can generate a pulsed beacon using the same average power as the omnidirectional, continuous wave (CW) signal, but each pulse received now contains the same energy as the CW signal provided in the entire pulse period. An advantage to this method is that broader receiver channels can be used and the complexity of the data processing hardware can be decreased. Further, because of the higher pulse power, detection is improved and less *average* power is needed for a given range and receiving system. With pulses, information could be carried by polarization modulation without lessening their detectability (see appendix C, section 5).

From the above considerations, it is felt that we should be prepared at least to detect signals or components of signals where the energy is concentrated in frequency (e.g., CW carriers) and signals with their energy concentrated in time (pulses). Since we have no *a priori* notion of a preferred pulse length or repetition period, we should provide matched or nearly matched filters for a wide range of pulse lengths and periods. Fortunately, this is not difficult.

For CW signals, bandwidths as narrow as 0.1 Hz are easily realized. There are then  $3 \times 10^9$  channels in the frequency range 1.4 to 1.7 GHz (the microwave "Waterhole," see appendix A) each to be examined for at least 10 sec, but preferably for 100 sec or more. Thus a single channel receiver would take about 10,000 yr to search the Waterhole for each selected star. With an MCSA having  $10^7$  channels or bins, this figure drops to  $3 \times 10^4$  sec or about 8 hr per star. Clearly an MCSA is an essential element of any SETI system.

### Doppler Drift

Planetary rotation and orbital motion, if uncompensated, will cause periodic frequency shifts in a CW signal at a rate proportional to its frequency. The absolute offset is of little consequence, but the rate of drift limits the useful narrowness of the MCSA channel. If the drift rate of a narrowband CW signal is  $\dot{\nu}$  Hz/sec and the channel width is  $b$ , the time  $\tau$  required to drift through each channel is simply

$$\tau = b/\dot{\nu} \quad (9)$$

This time must be equal to or greater than the response time  $\sim 1/b$ . Thus

$$1/b < b/\dot{\nu} \quad (10)$$

or, the minimum bandwidth,  $b_m$ , is

$$b_m > \sqrt{\dot{\nu}} \quad (11)$$

But  $\dot{\nu}$  is proportional to the operating frequency  $\nu$ , so

$$b_m \propto \sqrt{\nu} \quad (12)$$

The total noise per channel is  $kTb$ , so for CW detection we should tilt the noise temperature versus frequency curves corresponding to all natural contributors to the microwave background noise (see appendix A) by multiplying by  $\sqrt{\nu}$  to obtain the curves of figure 1-1. Now the Waterhole appears to be at the very best part of the entire spectrum. (See appendix L for an alternative viewpoint.)

Doppler drift also complicates averaging  $n$  successive spectra to gain sensitivity. In order to be sure that the signal energy is concentrated into one bin in the sum, the  $n$  spectra must be added after being shifted by the nearest integer number of cells to the drift that might have occurred since the first sample. Assuming the maximum drift rate is  $\dot{\nu}_m$  Hz per sample time, the  $n$ th sample must be shifted by  $i\dot{\nu}_m$  Hz, where  $-n < i < n$ . The  $j$ th sample is shifted by the nearest integer number of cells to  $ji/n$ , a frequency shift of

$$\Delta\nu = \dot{\nu}_m [\text{int}(1/2 + ji/n)] \quad (13)$$

Thus the  $n$  spectra must be added  $2n + 1$  ways. If  $n$  is large, this represents a formidable amount of computation, even by today's standards.

We can correct for the doppler drifts caused by motions of the Earth because we know our own acceleration along the line of sight. Similarly, "they" can correct for their doppler drift if their signal is being beamed at us. Thus the

only time the above dedrifting of successive spectra would be needed is for leakage signals and perhaps for omnidirectional beacons.

### Sky Survey Relations

If instead of searching only certain likely stars one searches the entire sky, one must of necessity accept a lower sensitivity than can be achieved by looking in only a few directions and for the same total observing time. For a CW signal, the received energy is

$$W = A_r \phi \tau \quad (14)$$

where  $\phi$  is the signal flux in  $\text{W}/\text{m}^2$  and  $\tau$  is the observing time. In a sky survey,  $\tau$  is the time needed for the source to pass through the antenna beam. If  $t_s$  is the total time for one complete sky scan and  $n$  is the number of scan directions needed to cover the sky, we have

$$\tau = t_s/n = t_s/g \quad (15)$$

and

$$W = \phi t_s A_r / g = \phi t_s \lambda^2 / 4\pi \quad (16)$$

The received energy is independent of antenna area and is the energy that would be received by an isotropic antenna in the time  $t_s$  needed to scan the sky. We note that this

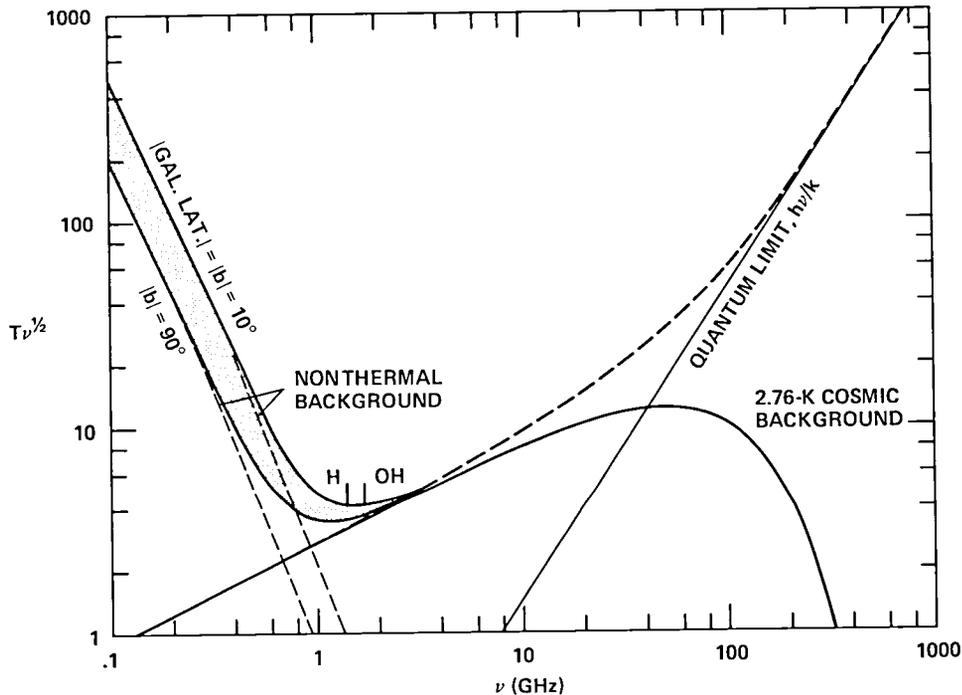


Figure 1-1.— Free space temperature bandwidth index.

energy is proportional to  $\lambda^2$  and therefore that the low end of the terrestrial microwave window allows sky surveys with 100 times the sensitivity of those at the upper end.

At first glance, equation (16) seems to indicate that large antennas are not needed for a sky survey. This is not the case. The larger the antenna

1. The more precisely we know the direction of arrival of the signal.
2. The greater the on-axis gain and hence discrimination against off-axis RFI.
3. The shorter and more intense the received pulse (due to our scanning the sky) the smaller  $\tau$  becomes and the greater the bandwidth  $b$  of the matched filter becomes. This reduces the number of channels,  $M$ , required to cover a given total bandwidth  $B = Mb$  in the MCSA.

Setting  $W = mkT$  in equation (14), we find for the faintest detectable signal

$$\phi_{\text{limit}} = mkT/A_r\tau \quad (17)$$

A figure of merit for a sky-survey system is the sensitivity-total bandwidth product  $SB$  where  $S \equiv 1/\phi_{\text{limit}}$  and  $B = Mb$ . Taking  $b = 1/\tau$  we find

$$SB = MA_r/mkT \quad (18)$$

which shows it is equally important to increase  $M$  and  $A_r$  and to reduce  $T$ .

If  $b\tau = n$ , the loss due to averaging  $n$  samples is similar to the pseudo-binning losses discussed in appendix C, section 5. The average should be a weighted running average with the weighting having the shape of the power curve of the antenna beam.

### Search Volume

Assume that a system with an isotropic antenna can detect a certain signal out to a range  $R_o$ . It will then be effective in detecting that signal anywhere in a volume of space  $V_o = 4\pi R_o^3/3$ . If we replace the isotropic antenna with one having a gain  $g$ , it will detect signals of the same intrinsic intensity within a solid angle  $\Omega = 4\pi/g$  out to a range  $R = R_o\sqrt{g}$ . The search volume is now

$$V = \Omega R^3/3 = 4\pi R_o^3(\sqrt{g})/3 = V_o\sqrt{g} \quad (19)$$

In spite of its directivity, a large antenna *pointed in one direction only* searches a volume of space  $\sqrt{g}$  greater than an isotropic antenna. Of course, if we then scan all directions in  $g$  times the nominal time of a single observation, the volume is increased to  $V_o g^{3/2}$ .

Search volume is proportional to the solid angle covered and to the 3/2 power of the sensitivity. Let us compare the

search volume of an all-sky survey capable of detecting  $10^{-23}$  W/m<sup>2</sup> with a targeted search of a number of stars,  $N_*$ , of 1000. In the latter case we assume an antenna of gain  $g = 10^7$  and a system capable of detecting  $10^{-27}$  W/m<sup>2</sup>. We find, for signals of the same intrinsic intensity in each search, the ratio of the volume searched in the targeted search,  $V_t$ , to that in the all-sky survey,  $V_s$ , is

$$V_t/V_s = (N_*/g)(S_t/S_s)^{3/2} \quad (20)$$

where  $S$  is the sensitivity and reciprocal to the minimum detectable flux. In spite of the limited coverage of the targeted search,  $10^{-4}$  of the whole sky, the search covers 100 times the volume of space. This raises the question: which is more important, to cover all directions or to search a larger volume? Despite the apparently correct answer (the search of a larger volume), this conclusion is not clear-cut. If there happens to be one or a few particularly powerful signals coming from directions not observed in the targeted search, they could be detected by the sky survey. Based on this fact, it is clearly prudent to employ the dual search strategy which has been designed for the NASA SETI Program.

### Energy Comparisons

Even if we have selected the best part of the spectrum, is the interstellar radio search feasible, and does it make a reasonable search for plausible and reasonable extraterrestrial transmissions? We cannot engage here in an exhaustive analysis of various possible systems; we will merely assume a practical system and a few variations of it to determine the transmitter powers which become detectable with the system. Conservatively assume that *they* have only the equivalent of NASA's Deep Space Network so that at both ends we would have the following (arbitrary but modest) system parameters:

|  |            |
|--|------------|
| Antenna diameter ( $d$ )                   | 64 m       |
| Operating frequency ( $\nu$ )              | 1.5 GHz    |
| System noise temperature ( $T$ )           | 12 K       |
| Resolution bandwidth ( $b$ )               | 1 Hz       |
| Probability of false alarm ( $p_{fa}$ )    | $10^{-12}$ |
| Probability of missing signal ( $p_{ms}$ ) | $10^{-2}$  |
| Antenna gain ( $g$ )                       | $10^6$     |

If we assume the use of a CW signal and that we average 100 samples, implying an overall observing time of 100 sec, then from the statistics of a normal square law detection and the values of  $p_{fa}$  and  $p_{ms}$  (see appendix C) we find  $m = 1.29$  and, from equations (3) and (5) that

$$P_t = (mkTb/g)(4R/d)^2 \cong 750 \text{ kW} \quad (21)$$

for a range,  $R$ , of 100 ly. Because  $P_t \propto R^2$ , we can now immediately construct the solid line of figure 1-2. If instead, the signal is a 1-sec-long pulse repeated once each 100 sec, we must attain the same  $p_{fa}$  and  $p_{ms}$  from a single sample and this requires  $m = 47$ , for a peak power of  $(750 \text{ kW})(47/1.29) \approx 27.5 \text{ MW}$ . But since our duty cycle is now 0.01, the average power drops to 275 kW, or a little over one-third as much as for the CW case (see the dashed line in fig. 1-2). This reduction comes about because we are now using the detector at a high signal-to-noise (S/N) ratio, where it is almost as efficient as a synchronous detector.

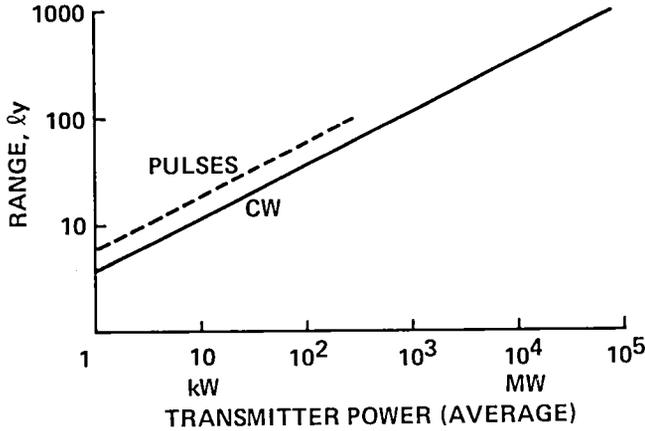


Figure 1-2.— Performance of a DSN SETI system.

Note that the average powers presently required to detect signals from Alpha Centauri with such a system are 1440 W CW and 520 W pulsed. These are very small and are typical of modest amateur radio transmitters. When we compare these with the  $\sim 10^{22}$  J required for interstellar space-ships which travel at an appreciable fraction of the speed of light, as discussed in appendix A, we see that for the same energy expenditure we could keep a useful pulsed beacon operating for 600 billion years, or 40 times the age of the Universe. Such examples illustrate the attractiveness and power of radio technology for interstellar contact.

Another important figure is the power needed to illuminate all likely stars out to some range,  $R$ . We take the number of likely stars within a range  $r$  to be

$$n(r) \approx (r/r_0)^3 \quad (22)$$

Astronomical data indicate  $r_0$  to be about 8 ly. We assume we use the same antenna design to transmit to each star and vary only the transmitter power appropriately to transmit a detectable signal. Then each star at a distance  $r$  will require a power  $P_1 r^2$ , where  $P_1$  is the power needed at 1 ly. The total power required is then

$$P = \int_0^R P_1 r^2 (dn/dr) dr = (3P_1/5r_0^3)R^5 \quad (23)$$

Taking  $P_1 = 75 \text{ W}$  from a manipulation of equation (21) or figure 1-2,  $r_0 = 8 \text{ ly}$ , and  $R = 100 \text{ ly}$ , we find  $n = 2000$  and  $P = 900 \text{ MW}$  total for the 2000-CW beacons. Pulsed beacons would require 300 MW, which is about the average electric power consumption of an American city of 300,000 people.

If instead we transmit omnidirectionally, the power needed is

$$P_O = gP_1 R^2 \quad (24)$$

When we compare equations (23) and (24), it is evident that for ranges less than some limiting range,  $R_2$ , less power is needed if the beamed beacon approach is used; for greater limiting ranges an omnidirectional beacon demands less energy supply. When we equate equations (23) and (24), we find the range which separates one region from the other to be

$$R_2 > r_0(5g/3)^{1/3} \approx 950 \text{ ly} \quad (25)$$

For greater limiting ranges, omnidirectional radiation would be more efficient. At this range the total radiated power required would be  $68 \times 10^{12} \text{ W}$ , or the output of 68,000 typical nuclear power plants. The number of stars illuminated would be over 2 million.

Our assumed receiver for the targeted search has a minimum detectable signal level of  $4mkTb/\pi d^2 = 6.6 \times 10^{-26} \text{ W/m}^2$ , whereas the proposed sky survey has a best sensitivity of  $10^{-23} \text{ W/m}^2$ . The following table shows the power needed in various types of signals to be detectable at a range of 100 ly. It is assumed in the beamed signals that the transmitting antenna is a 64-m reflector with  $g = 10^6$  and that the peak pulse power in pulsed emissions is 100 times the average power.

| Signal type   | Averaged power to be detectable by |            |
|---------------|------------------------------------|------------|
|               | Targeted search                    | Sky survey |
| Beamed pulses | 275 kW                             | 40 MW      |
| Beamed CW     | 750 kW                             | 110 MW     |
| Omni pulses   | 275 GW                             | 40,000 GW  |
| Omni CW       | 750 GW                             | 110,000 GW |

To many people, it seems unreasonable to expect a civilization to pour into space four to ten times the total energy consumption of Earth in the hope of receiving an answer after at least a century and probably after much, much longer. Thus it seems plausible that the targeted search portion of the present SETI effort will detect signals beamed at us. However, exceptionally powerful signals, as in the table, even though very rare, would be detected by the sky survey but not by the targeted search if the signals originate from sources not near a nearby star or from ranges greater than 100 ly. (Beyond 100 ly, stellar catalogs rapidly decrease in completeness.)

As a provocative speculation, if one solar luminosity of power were converted into a beacon, it would be detectable

by the sky survey from a distance of 200 million ly, a distance far beyond that of the Virgo cluster of galaxies. A volume of this radius contains at least 10 million billion stars. If even one of these were used to power such a beacon, it would be detectable. It could be that such very rare but powerful signals outnumber the weaker, detectable signals originating within 100 ly of the Sun. If so, the sky survey will find them. Again, prudence calls for this bimodal search scheme.

### Conclusion

It appears from our existing knowledge that an intelligent civilization might announce or accidentally reveal its existence to other advanced cultures while utilizing the least energy if signals are radiated in the terrestrial microwave window. Thus this frequency band is presently the preferred

part of the spectrum in which to conduct a first major search. The lower-frequency portion of the window is preferred over the high and is marked by the symbolic spectrum lines of H and OH. Signals of only modest radiated power can be detected by a targeted search if these signals are being beamed at us continuously by large antennas. These signals can be expected to be coherent with at least some components concentrated in either frequency or time. Unless they are intrinsically much more powerful than anything we radiate, leakage signals will be detected only by a much larger receiving area than is presently available on Earth.

A sky survey, which examines a million or more directions rather than a thousand stars and, in addition, covers a wider frequency band, is perforce much less sensitive than a targeted search. It will discover transmissions only if there are one or more of very high power, but they can originate within a huge volume which includes our own galaxy and many other galaxies.

## CHAPTER 2

### GENERAL SEARCH STRATEGY

#### Abstract

*A general search strategy should address the problems of choosing search directions in space, frequency coverage, and frequency and time resolution coverages. The ranges chosen for these parameters will be influenced greatly by the qualities of available electronics and telescopes. In choosing these parameters, it still seems most reasonable to assume our civilization is typical at our present evolutionary technological epoch and to emphasize searches for civilizations similar to ours but much more advanced. The consequence of such an approach is a dual strategy: survey for stronger signals on many frequencies and over the whole sky (the sky survey), and a more sensitive examination of nearby solar-type stars over a smaller frequency range (the targeted search).*

In designing an overall strategy for the SETI program, the goal is to identify the combination of search parameters, such as radio frequencies and directions to be searched in the sky, that seems most likely to produce the greatest probability of detecting an extraterrestrial radio transmission. In principle, an accurate determination can be made only if we know the spatial density of civilizations of various types and their expected radio spectra. Such knowledge is clearly out of reach until SETI has succeeded. In the meantime, however, our civilization – and the arrangement of the Universe – allow us to deduce a general strategy we believe should facilitate even the detection of civilizations which operate quite differently from how our theories or intuition might suggest; as long as these species actively exploit what we may call microwave broadcast technology. The SSWG has once again dealt with this problem and contributed to the evolution of an overall strategy for the search. Its components, and its rationale, are as follows.

#### General

Circumstances limit the present SETI program to the use of existing radio telescopes because large telescopes are unduly costly in the present financial climate, and because it does seem possible to share the use of existing large instruments in a manner allowing a first major search to be carried out in perhaps 3 to 7 years – once the proper instrumentation has been developed and installed. Since the availability of time on the large telescopes is limited, whereas other technical components of a SETI system can be purchased or built as needed (within reasonable bounds, of course), this aspect of search strategy deserves the most careful attention.

#### Search Directions

The cosmos allows us no unique answer when it comes to the question, “Where should we look?” Perhaps we are typical, and the right place to look is at single stars like the Sun. But perhaps other kinds of stars, even multiple star systems, not only possess civilizations, but those civilizations might be in even greater abundance than those around solar-type stars. This has led to two approaches in the choice of directions in which to explore:

*The targeted search*— In this approach it is assumed that we and the solar system are typical. Thus the most productive strategy is to search with the highest feasible sensitivity for radio signals of the type we radiate but of much higher power coming from the direction of the nearest solar-type stars. These transmissions could be either radio leakage or radio beacons to attract the attention of emerging civilizations such as ours. High sensitivity is required because from the distance of these stars, even duplicates of most of our strongest signals would be exceedingly difficult to detect. Sensitivity can be maximized by observing with the largest telescopes for long periods of time. So the strategy is to observe for long enough time intervals at the highest reasonable resolution on the largest available antennas. Since this tends to require excessive time on heavily subscribed instruments, the number of stars to be examined will have to be limited so that total telescope time requested and total search duration will not be unreasonable.

*The sky survey*— Although it is perhaps natural and seems reasonable to many to assume that we and the solar system are typical, we realize full well that there may be

enough planetary variety in the Milky Way and enough cosmic time to lead to the evolution of creatures, civilizations, and technological levels far different from ours. In particular, it seems (so far) to be technically possible that some civilizations might radiate signals many orders of magnitude stronger than those of Earth. One can only speculate as to what these might be. They could, for example, be signals which are beamed at us or extremely powerful beacons from an extraordinarily successful species. Were even one or a few ETI species engaged in such activities, their signals might be easier to detect than those from any civilizations, only modestly advanced over ours, which might be nearer to us. Since such unusual civilizations might well be rare, we would expect them to be most likely at a great distance and perhaps associated with a star which is just one of the multitude of faint, uncatalogued stars, or even a star not visible from Earth. In this scenario there is little guidance as to directions in which to look. Thus it is important to search the entire sky, but with emphasis toward the central plane of the galaxy where the stellar population is concentrated. However, because of the greater number of search directions ( $\sim 10^4$ ) which must be examined, compared with the targeted search, it is obviously necessary to search the whole sky with much lower sensitivity.

### Radio Frequency Coverage

The reasons for performing an initial exploration for ETI signals in the terrestrial microwave window, and particularly in its lower portion – the Waterhole – were developed in chapter 1. These conclusions are based on our experience and to some extent on our guesses about possibly universal cost influences on technology. (The conservative use of energy resources may well be a serious and continuous concern for most technological species.) Thus, although a mainly objective application of physical laws leads us to microwave frequencies for our search, we recognize that other civilizations may manifest themselves prominently in quite different ways for reasons we cannot yet fathom. For our present purposes, this situation implies that we should conduct our first searches at microwavelengths, but that we should also realize that other civilizations may be easily detectable at other wavelengths or by means of other physical phenomena yet to be fully understood. Therefore it is important and desirable to support other practical means of exploring for evidence of extraterrestrial life.

Thus the SSWG endorses such additional approaches to the SETI problem. Towards this end the Group encourages the participation of the general scientific community not only in the program proposed here but also in other possible forms of SETI which are scientifically credible.

Taking the above into account, the frequency coverage proposed here is:

*The targeted search*— Although it would be desirable to observe at all frequencies at which a given telescope operates well, this would require more observing time than can be made available on existing large telescopes in a 3- to 7-yr period, so it is proposed to limit the program to a spectral region about 2 GHz wide, 1.2–3 GHz, a region which includes the minimum noise portion of the terrestrial microwave window. The astronomical information which will be produced as a byproduct may be significant, though opinions vary on this (see appendix H). It also includes the Waterhole frequency band which many SETI experts feel is promising because it is bounded on the low-frequency side by the unique radio frequency line of interstellar atomic hydrogen and by the prominent lines of the OH radical on the high side. These two ions, H and OH, are fragments of the water molecule (hence the name “Waterhole” for this 300-MHz-wide band), and it is a commonly held opinion that water may be vital to most living things elsewhere.

*The sky survey*— As in the targeted search, frequency coverage is exchangeable with sensitivity when all other parameters are fixed. However, since the sky survey is inherently less sensitive than the targeted search, it is planned to emphasize frequency coverage. Since small antennas can search the sky more quickly than large antennas and so can cover more frequencies in a given time, and smaller antennas are more available than larger ones, smaller antennas are suggested for this program. This leaves the largest available antennas for the targeted search. Taking into account the size and availability of suitable smaller antennas and the 3- to 7-yr observing period, a frequency range of 1.2–10 GHz is possible, with perhaps spot-band coverage up to as high as 25 GHz.

### Frequency and Time Resolutions

In both the targeted and all-sky approaches, it is desirable to use a spectrum analyzer that provides a small number of different, but high-resolution, output streams for the following reasons. First, the purpose of SETI is just to detect on-line a totally unknown ETI signal – not to understand it – and to do this with sensitivities close to the theoretical limits imposed by fundamental parameters such as background noise and observing time. From the discussion in appendix C, section 5, one clearly would like to provide a wide range of resolution bandwidths ranging from, say, 0.1 Hz to  $10^5$  Hz in 10% steps. A wide range of signals would then be receivable along with nearly a minimum of confusing background noise. But a multichannel spectrum analyzer with 145 separate, simultaneous output resolutions is not yet practical. One must settle for just a few binwidths and then create algorithmic approximations to recoup as much of the lost sensitivity as seems reasonable.

A second reason stems from the prime characteristic which distinguishes an intelligent signal from so-called "natural" or "astrophysical" signals — the high degree of coherence exhibited in one or more of the parameters of an electromagnetic wave in space: amplitude, phase, polarization, and time. In our experience, these coherences often produce prominent signal components more easily detectable by themselves than the whole signal, when properly observed. That is, their spectral power density is noticeably higher than that of the rest of the signal, and they tend to be relatively narrow in bandwidth and/or in time. Thus it is with carriers in many broadcast systems; e.g., amplitude-modulated sound and TV, and with the repetition rates of pulsed transmission services. Because the information content is quite unknown, the "message" must be considered to be just another form of unwanted noise superimposed on a coherent signal structure, and to be excluded as much as may be practical.

Now let us further consider a typical amplitude-modulated terrestrial broadcasting system. Besides the CW carrier with a coherence time of many tens of seconds, there is also a sharply defined coherence between corresponding higher and lower sideband (transient, informational) signal elements, a quadrature relationship between the carrier and the sidebands, and the transmitted wave is close to 100% plane-polarized. The situation is qualitatively similar with just about all types of intelligent human signals ever put on the air, and for an impressive reason that may well be shared by ETI species that exploit the radio spectrum. A signal employing a high degree of coherence of the right kind is power-efficient, can be used to conserve spectrum usage as well,<sup>1</sup> and can be used to minimize capital costs at both ends of a communication circuit. (There are some uncommon exceptions, of course, and notably so where coherence is established through an auxiliary communications mode, either a circuit or another prearrangement.)

In principle, useful bandwidths may be as small as the minimum bandwidth propagated without serious alteration through the interstellar medium. This varies with radio frequency and with distance traveled and is typically on the order of 0.01 Hz for the frequencies considered here. Unfortunately, bandwidths this narrow would require an unacceptably expensive multichannel spectrum analyzer, or would lengthen the search time far beyond what is felt to be feasible. Thus minimum bandwidths have been chosen to permit the various searches to be carried out over the prescribed frequency spectrum and within the time limits set for each search. These are:

*The targeted search*— The minimum instantaneous observational bandwidth, or binwidth, should be about 1 Hz. This provides high sensitivity for carrier-type signals, and is a

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<sup>1</sup>There is only one electromagnetic spectrum in free space, and ETI species also may have service-allocation spectral problems.

bandwidth of about the same order as that of some of the strongest transmissions leaving Earth. This minimum bandwidth also permits the search to be carried out using reasonable times on the world's largest radio telescopes. The spectrum analyzer should also produce simultaneously a small number of increasingly larger binwidths from which many approximate or pseudobandwidths may be constructed on-line. These will provide better matches to broader (but still relatively narrow) signal types such as moderately slowly pulsed signals.

*The sky survey*— The selected resolution bandwidth is about 32 Hz. This permits the entire sky to be surveyed for essentially continuous signals with good sensitivity over the frequency range 1–10 GHz, the region of minimum sky brightness temperature, within about a 3-yr period. A small hierarchy of broader channels should also be provided to assist efficient signal detection and recognition, and further assistance should be available in the form of a fair number of 1-Hz channels, or resolution "zoom" capability.

## Signal Types

The antenna models and sky scan rates presently contemplated for use in the sky survey provide a "look" time in any one direction and frequency range with a duration of only 0.3 to 3 sec. Thus the sky survey can be fairly characterized as being on the whole most sensitive to essentially constant signals that are always present, compared to the targeted mode in which dwell times in a given direction may be as long as 0.25 hr, thus maintaining good sensitivity for signals of a wider range of intermittency. But neither approach is anywhere near optimum for signals which behave like our TV carriers, which may be visible from distant star systems for about 2 hr twice each day.

An exploration such as SETI should be highly sensitive to as wide a range of signal types as can be managed within the bounds of available resources and the duration of the proposed overall effort. But whatever the signal detection and recognition capabilities may be, they should be clearly and quantitatively understood.

Studies in this innovative area have been increasing in intensity in recent years because it holds the greatest immediate promise to improve the likelihood of an ETI signal discovery. It also seems to be an area in which members at large in the scientific community may make outstanding contributions. While this effort will level off in the relatively near future, it is not likely to decrease; rather, it will continue indefinitely because of two factors in addition to the enormous variety of possible signals. Steadily improving digital technology continually makes feasible more powerful on-line devices for a SETI system capable of growth in an economical fashion. Second, this field of study is relatively new, and as theory and algorithmic capability expand, one

can expect new and more powerful methods of signal detection and recognition to appear.

Finally, we note that the SETI system is required to recognize a range of beacon-like signals, intentional or not, and to be able to eavesdrop on much of the wide range of signal types we now produce, at least as far as may be feasible. For further related discussion, see appendix H.

#### **Flexibility of the SETI System**

Because of the concerns just outlined, and because there is as yet no observational experience using such a concep-

tually powerful device, the entire SETI signal processing system is required to be (1) designed with unusually great algorithmic flexibility and (2) easily expandable, as major objectives. Thus wherever feasible, the signal processing hardware is programmable, not hard-wired, and compilers are being provided to facilitate experimentation and improvement. A spinoff from this approach may be beneficial to astronomers and to scientists in other fields who may wish to experiment with this unusual system when it is not in use for SETI.

## CHAPTER 3

### DETAILED SEARCH STRATEGY

#### Abstract

*Many programmatic decisions have been made regarding a large number of options in order to arrive at a specific proposal to conduct the bimodal observational program favored by a consideration of the general search strategy in the previous section. Major options are discussed and the pros and cons and the course of action proposed are summarized. Telescope times required for the target search and the sky survey observations are given in a form allowing explicit scaling according to the identified options.*

Given the general strategy of chapter 2, it is necessary to construct a detailed strategy optimized to what is believed will produce the best chance of success, taking into account not just scientific and engineering concerns, but also practical matters such as funding availability and projected annual expenditure rates; the numbers, sizes, and limitations of available telescopes; and the abilities of contemporary digital instrumentation and computer technologies to cope with SETI needs. The telescopes to be used are particularly important, of course, and their availability and frequency coverage will strongly influence the program design.

What follows summarizes observational options considered while developing the proposed Ames/JPL bimodal observing program. The overall program has been arranged to be consistent with typical continuing R&D programs. We start with the most general of program tradeoffs, money versus time, as follows.

| TRADEOFFS                                 |  |
|---|--|
| Money                                     | vs Time                                      |
| Sensitivity<br>and<br>Signal<br>Character | vs<br>Spatial<br>and<br>Spectral<br>Coverage |

For a project such as SETI, which must be admitted to be potentially a long-term endeavor, it is tempting to argue that time can effectively be substituted for money; hardware can be built at a slower rate or in smaller quantity, and the same program can be carried out by fewer personnel over a longer period of time. As with all research endeavors, this is true for SETI – but only up to a point.

There are three important reasons why time is not a relatively unlimited, cost-free resource for SETI.

1. An economical search over frequencies between 1 and 10 GHz has long been proposed for scientific and engineering reasons, but it is rapidly becoming much more difficult to search for faint signals within much of this spectral range from Earth's surface. *Before the close of this decade*, human-caused RFI from fixed, mobile, airborne, and satellite transmitters operating in this broad band may well require that SETI be carried out using multiple antennas in an interferometric mode (appendix K) or from a space platform. Yet the increased hardware replication costs, the increased functional complexity of the interferometric mode, and the increased difficulty of scheduling time on heavily subscribed multiple antenna systems may preclude this ground-based approach. Space-based operations, of course, will continue to be more costly and technologically demanding than their Earth-based equivalents for the foreseeable future.

2. Unique instrumentation providing significant capabilities previously unavailable requires block capital investment for its construction. Recent laboratory and industrial experience with complex digital systems provides impressive evidence that construction of powerful instrumentation employing advanced technologies is not cost-effective when it is completed slowly over a protracted period of time.

3. Personnel talented enough to conceive, construct, and optimally put to use superior instrumentation cannot be retained in an environment in which achievement of any primary objective is stretched into the uncertain, distant future and/or the funding profile is so low as to preclude even interim satisfaction via achievement of significant secondary objectives.

The remaining tradeoffs have been evaluated in light of the conclusion that both time and money must be constrained in any particular SETI observational program and, further, that any particular program should not be viewed as

the only SETI effort that should be undertaken. The observing phase of this proposed program is estimated to last about 4 to 5 yr.

Tables 3-I and 3-II describe the options embodied in these tradeoffs. The sky survey and targeted search modes are presented separately, although they are intimately interconnected in this bimodal program. The main characteristics of both the wideband (sky survey) and narrowband (targeted search) SETI systems are highlighted. The only important questions remaining concern the number of systems to be replicated and the precise nature of the zoom capability for the wideband system.

Finally, it is assumed that no new collecting area will be built as part of this program although existing telescope facilities might be upgraded in some appropriate manner.

The question of the availability of observing time on existing radio telescopes is a major concern for the observa-

tional program. Figures 3-I and 3-II give the times required to complete the targeted search and sky survey sequences. The scaling factors shown correspond to each of the observing options displayed. These figures can be used as a guide for assessing the impact of a particular strategy on the telescope time required.

Table 3-III shows one possible scenario for the target search in order to give an example of the impact that a systematic SETI program might have on the RA community through the use of their facilities by SETI.

Table 3-IV lists telescopes around the world that are of particular interest to a systematic SETI program, either because of their large collecting area or because the *potential* facility has a large amount of time that might be available to a SETI program. *Presenting this list does not imply any commitment by these facilities that they may be used for SETI.* Rather, the list should be regarded only as a "wish list."

TABLE 3-I.— TARGETED SEARCH: OBSERVATIONAL OPTIONS

| Option                     | Advantages  | Disadvantages  | Proposed 10-yr program  |
|----------------------------|---|--|---|
| Use of NASA telescopes     | A NASA program can claim time on DSN telescopes and OSTDS support. The three 64-m DSN telescopes offer global coverage.   | 64 m is size of the largest antennas, and these are heavily loaded by satellite tracking needs.  | Issue announcement of opportunity (AO) to solicit participation by many of largest non-NASA telescopes plus any which offer a dedicated facility. Use many sites so time per site is acceptable to RA users. Use Tidbinbilla 64-m antenna to supplement only large southern non-NASA telescope at Parkes. Determine vehicle for international facility use, and encourage same. |
| vs                         | vs  | vs   |   |
| Use of non-NASA telescopes | Largest telescopes are non-NASA. Dedicated site may exist. More certain inclusion of science community. Possibility of NASA funds for upgrades of mutual interest to RA and SETI. More chance to do RA. | Direct competition for limited time on large antennas. Scheduling will not be under control of NASA. Requires complex agreement between NASA, NSF, and/or other agencies. May be international problems. |   |
| $\nu_1 = 1.2$ GHz          | Front end engineering constraints set value as far below HI line as cost effective.   |  |   |
| $\nu_2 = 3$ GHz            | Limiting $\nu_2$ improves $\phi$ per star. Covers "Waterhole" plus some. Drift, pointing, etc., is easier.  | May miss signal.   | Continuous frequency coverage will be 1.2-3 GHz. However, spot bands in 3- to 10-GHz range will be searched at selected frequencies. Receiver will be continuously tunable, 1.2 to 10 GHz, therefore can accommodate RA in this frequency range.  |
| vs                         | vs  | vs   |   |
| $\nu_2 \geq 10$ GHz        | Increased $\nu_2$ does increase probability of success. More interesting radio astronomy.   | Largest non-NASA telescopes will not work to 10 GHz. Large upgrade costs.  |   |

NOTE:  $\nu_1$  = lowest frequency observed.  $\nu_2$  = highest frequency observed.  $\phi$  = minimum detectable flux.

TABLE 3-I.— CONTINUED

| Option  | Advantages   | Disadvantages   | Proposed 10-yr program  |
|---|--|---|---|
| Select all known solar-type stars                     | Samples the largest population of likely candidates.   | For same total observing time, $\phi$ per star is poorer.   | Solar-type stars from RGO catalogue, which is volume complete to 25 pc, will be primary targets. Of these, the 22 stars within 20 ly will be observed longer to achieve better $\phi$ . A limited number (~20) of special directions will be included as primary targets. Both single and multiple stars are represented.   |
| vs  | vs   | vs  |   |
| Only close solar-type stars, e.g., within 20 or 80 ly | Can detect weaker signals. Fewer identification errors.  | If N is small, may not be any civilizations that close. Signal may not be associated with a star.   |   |
| vs  | vs   | vs  |   |
| Other <i>a priori</i> interesting directions          | Many “targets” in beam at once. Find signal from star too distant to be optically identified. Some RA could be done in parallel.   | Will be sensitive only to super-strong signals if distance is large. For same total observing time, $\phi$ per star is poorer.  |   |
| Observing time per band per star = 100 sec            | Covers <i>all</i> primary targets over $\nu_1 \rightarrow \nu_2$ band during 4- to 5-yr observing program without unreasonable burden on any site ( $\leq 5\%$ time at any nondedicated facility).   | May miss entirely plausible low rep-rate pulsed signals. $\phi$ is not as good as might be achieved for limited set of targets.   | Observing time at any nondedicated site will be restricted to $\leq 5\%$ . All stellar targets within 20 ly will be observed for 1000 sec; all other F, G, K dwarf stars within 25 pc and visible from nondedicated sites will be limited to 100 sec/band. Dedicated site required, and all targets visible from this site will be observed for $\geq 1000$ sec/band.   |
| vs  | vs   | vs  |   |
| $\geq 1000$ sec                                       | Improves $\phi$ by factor $\geq 3$ per target. Offers sensitivity to pulsed signals of lower rep-rate. Allows smaller telescopes to achieve $\phi$ as good as larger at 100 sec.   | 4- to 5-yr observation program can only examine a few targets unless undue burden is placed on site, $\geq 50\%$ time, so requires dedicated facility to do many targets.   |   |
| Use of single dish                                    | Cheapest, most readily available without new construction. Offers possibilities for dedicated site.  | Susceptible to RFI. Confusion with extended astrophysical sources (greatly enhanced background).  | It is assumed that with only an 8-MHz input to a narrowband MCSA and a discrete set of targets to be covered over 1.2–3 GHz, that any site-specific RFI can be avoided by appropriate scheduling, and data lost to unpredictable events can be reclaimed at a later time without generating an unacceptably high “look-back” time factor. Therefore, targeted search will be conducted by single dishes, but the hardware design should not exclude the interferometry option, should experience disprove the above assumption. |
| vs  | vs   | vs  |   |
| Some form of multiplying interferometer               | Increased collecting area and $\phi$ . Fringe frequency suppression on nearly all RFI. Lower false alarm rate allows more sophisticated real-time signal identification tasks. Provides matched filter to point source moving at sidereal rate. Removes confusion due to extended astrophysical sources. | Simultaneous scheduling very difficult. Larger costs due to front end replication. More difficult signal-processor hardware design. No dedicated site possible. Number of possible non-NASA sites is small and linkage upgrade costs high. Loss of RA data which might come from single-dish operation. |   |

TABLE 3-I.— CONCLUDED

| Option                                    | Advantages  | Disadvantages   | Proposed 10-yr program   |
|---|---|---|--|
| Construct single narrowband SETI system   | Cheapest; therefore easier to fund.   | Much time lost to transport, set up, and repair. Unavailable for RA uses. Lacks operational flexibility.  | Three separate narrowband SETI systems will be constructed. The first 8-MHz system is intended for Arecibo Observatory and will be upgraded to 16 MHz within 6 mo to allow maximum sensitivity to be achieved using this unique collecting area. The second 8-MHz system is intended for the southern hemisphere and will be shared between the DSN 64-m antenna at Tidbinbilla and a large southern telescope, e.g., Parkes. This second system is to be the most transportable and may be brought to the northern hemisphere to facilitate the scheduling of the entire target list. The third 8-MHz system will be placed at a dedicated site where at least 80% of all observing time could be spend on SETI, e.g., Ohio State University (OSU). |
| vs  | vs  | vs  |  |
| Construct several narrowband SETI systems | Less time lost to transport, set up, and repair. Eases schedule problems. Allows easier simultaneous confirmation of suspect signals. Allows use of processors to reduce data off-line. Allows much greater access and availability for RA uses. Shortens overall duration of program. Allows simultaneous use of dedicated and nondedicated facilities. Narrowband system for DSN 64-m antenna could serve as zoom for sky survey. | More expensive. Might replicate design concept errors since construction occurs early in observing program.   |  |
| A search for signal types which are:      | A CW signal is an obvious candidate for an artificial beacon since it has no known astrophysical counterpart.   | CW may drift through channels at unknown rate, making integration and recognition more complex. Data rate is modest. Easily susceptible to common, human-caused RFI.  | There is sufficient time during targeted search to attempt detection of CW signals at an S/N of $\sim 1$ and drift rates of $\dot{\nu}/\nu \leq 10^{-9}$ using 1-Hz resolution channels. And to search for pulses having durations in the range 0.25 msec to many tens of seconds and rep-rates up to one-fifth the single observation time, using the power output signals and the "pseudobins" constructed from the 1-, 32-, and 1024-Hz resolution channels. A gain stability, $\Delta G/G$ , of about $10^{-5}$ is desired over time scales of $\sim (100-1000)$ sec for total power mode detection of astrophysical and other complex signal types.   |
| Narrow (CW)                               | Linear improvement in S/N can be achieved by narrowing channel width until problems develop due to $\Delta G/G$ or costs.   |   |  |
| vs  | vs  | vs  |  |
| Pulsed                                    | For a given investment in current "smarts," a <i>given</i> signal <i>energy</i> is more likely to be easily recognized against a noise background, than is CW, if the signal is pulsed at a low duty-cycle rate.  | There is no <i>a priori</i> way to construct a matched filter. Pulses may be highly dispersed, making coherent integration more difficult. For recognition, must detect at least 4 pulses per observation.  |  |
| vs  | vs  | vs  |  |
| Complex                                   | May be most general type of signal. For maximum sensitivity, one depends on just recognizing the most prominent signal component(s); in amplitude, phase, polarization, and time.   | Not possible to construct more than a small range of approximately matched filters for a range of more likely signal components. System must have high gain, phase, and polarization stability. Some signal types might be confused with astrophysical signals. |  |

TABLE 3-II.— SKY SURVEY: OBSERVATIONAL OPTIONS

| Option  | Advantages   | Disadvantages   | Proposed 10-yr program   |
|---|--|---|--|
| At each frequency telescope pointed to achieve: |  |   |  |
| Constant $\phi$ per beam                        | $\phi$ independent of frequency. Time per beam area is independent of frequency, therefore sensitive to uniform class of signals.  | Majority of time spent at highest frequencies:<br>$t_{\text{total}} \sim \nu_2^3 - \nu_1^3$   | Sky survey will cover $4\pi$ sr. It will run at the constant drive rate of $\omega \cong 0.2^\circ/\text{sec}$ . In addition, certain regions of the sky of special interest to both SETI and RA, e.g., the galactic plane, will be scanned at a slower rate, $\omega \sim 0.01^\circ/\text{sec}$ , the "dwell mode" (see appendix H).                   |
| vs  | vs   | vs  |  |
| Constant drive rate $\omega$ across sky         | Operationally easy. Proportionally more time spent at lower frequencies:<br>$t_{\text{total}} \sim \nu_2^2 - \nu_1^2$  | $\phi \sim \sqrt{\nu}$ . Time per beam varies, so detectable class of signals varies with frequency. If $\omega$ is too high, may get mechanically unreliable program, e.g., readout errors, and little useful RA data. |  |
| vs  | vs   | vs  |  |
| Constant beam size at all frequencies           | Time is uniformly spread over frequencies:<br>$t_{\text{total}} \sim \nu_2 - \nu_1$  | $\phi \sim \nu$ . Requires multiple antennas or feed-horns with illumination patterns which narrow with increasing frequency.   |  |
| Use of NASA telescopes                          | A NASA program can claim DSN telescope time and OSTDS support. A large number of contiguous hours over several years should be available, given load forecasts. $4\pi$ sr available. DSN experienced in wide-band, low-noise front ends and in precision observing techniques. | Spacecraft will always have first priority. Planetary missions may increase, thus diminishing available time. Current plans put S- and X-band transmitters next to DSN receiving antennas.                              | Sky survey will be conducted using one of "listen only" 34-m telescopes for $\sim 16$ hr/day. DSN sites at Goldstone and Tidbinbilla will be needed for global coverage. Madrid site will be used if scheduling problems are thereby minimized. If $\omega = 0.2^\circ/\text{sec}$ , time per half-power beamwidth will be $\sim (3/\nu\text{GHz})$ sec. |
| vs  | vs   | vs  |  |
| Non-NASA telescopes                             | Greater access to RA community. Greater flexibility.   | Large time needs require a dedicated facility. Sky coverage limited.  |  |

TABLE 3-II.— CONTINUED

| Option                                  | Advantages  | Disadvantages  | Proposed 10-yr program  |
|---|---|--|---|
| $\nu_1 = 1.2$ GHz                       | Front end engineering constraints set the value as far below HI line as is cost effective.  |  |   |
| $\nu_2 = 10$ GHz                        | Can achieve a reasonable $\phi$ in $\sim 3$ – $4$ yr. Covers quietest part of terrestrial microwave window. Pointing problems are tolerable.  | May miss signal.   | Sky survey will be conducted throughout 1.2–10-GHz band. 0.2 to 0.25 of observing time will be spent investigating “spot bands” at higher frequencies. The receiver will be continuously tunable to at least 25 GHz.  |
| vs                                      | vs  | vs   |   |
| $\nu_2 = 25$ GHz                        | Covers more frequencies and H <sub>2</sub> O line. Greater detection probability. More interesting to RA community.   | May miss signal. Takes far too long to complete survey to reasonable $\phi$ . More background noise.   |   |
| Use of a single dish                    | Cheapest. Scheduling problems are minimized. Well understood operational mode.  | Confusion from extended astrophysical sources.   | The RFI picture is far less predictable than in the case of the targeted search. The sky survey will initially be carried out with a single dish and wide-band instrumentation designed to accommodate the presence of strong RFI signals, so that much of the band can still be used. The processing hardware must not exclude the possibility of multiple beams or interferometry. If the RFI problem is restricted to particular bands and cannot be scheduled around, use of the interferometer may be required. If the problem pervades many bands, multiple-beam solutions may be the only viable approach. |
| vs                                      | vs  | vs   |   |
| Some form of multiplying interferometer | Increased collecting area, lower $\phi$ . Depending on the time per beam, fringe-rate averaging may suppress many sources of RFI. Removes confusion due to extended sources. Links already exist between 34-m antennas. For same total collecting area and same total time to survey, interferometer is more sensitive to transient signal. | Increased costs due to replication of front ends. Potentially more difficult back-end signal-processor hardware design. Unlikely that many hours of contiguous observations could be scheduled and realized on two of the 34-m antennas at any site. Simultaneous slewing to required accuracy may be difficult. |   |
| vs                                      | vs  | vs   |   |
| Multiple beams in single feed           | May provide adequate anti-coincidence suppression of RFI. Cheaper than interferometer. Eases scheduling problems.   | Degradation in gain due to off-axis positioning. Requires same back-end complexity as interferometer. As yet unproven.   |   |

TABLE 3-II.— CONCLUDED

| Option   | Advantages  | Disadvantages   | Proposed 10-yr program   |
|--|---|---|--|
| Construction of an 8-MHz narrowband system for zoom capability | Provides full capability for doing target search with 64-m antenna via a data link. Can serve as confirmation for other targeted search sites. Allows further analysis of suspect signals in real time. | Expensive.  | This wideband machine will be constructed with ~300 MHz bandwidth and 32-Hz, 1024-Hz and 74-kHz resolutions, and with 1-Hz zoom capability over any one 74-kHz band. Programmable oscillators will be used to slide the bandpass until the suspect signal falls usefully into this narrower band of high-resolution channels, where it can be examined in more detail. |
| vs   | vs  | vs  |  |
| Construction of a 74-kHz narrowband zoom capability            | Can often serve as confirmation for other targeted search sites. Allows further analysis of suspect signals in real time.   | Does not allow range of signal recognition processing power found in 8-MHz narrowband systems. Therefore cannot be used for target search or, perhaps, for signal confirmation. |  |

$$T_{\text{ALL TARGETS}} = 176 \text{ DAYS} \left[ \frac{N^*}{773} \right] \left[ \frac{\nu_2 - \nu_1}{3 \text{ GHz} - 1 \text{ GHz}} \right] \left[ \frac{8 \times 10^6}{N} \right] \left[ \frac{100\text{m}}{D} \right]^4 \left[ \frac{10^{-26} \text{ W/m}^2}{\phi} \right]^2$$

$$\nu_1 \rightarrow \nu_2 @ \phi$$

**773 SOLAR TYPE STARS WITHIN 25 pc (≈ 81 light years)**  
**22 SOLAR TYPE STARS WITHIN 20 light years**  
**REQUIRES MULTIPLE SYSTEMS AT MULTIPLE OBSERVATORIES SO THAT**  
**% TIME AT ANY OBSERVATORY ≲ 5%**  
**ALLOW SYSTEMS TO BE USED FOR OFF-LINE DATA REDUCTION FROM OTHER SOURCES**  
**ALLOW SYSTEMS TO BE USED FOR RADIOASTRONOMY**

$\phi = 10^{-26} \text{ W/m}^2$   
 $D = 100\text{m}$   
 $\nu_2 = 3 \text{ GHz AND } \nu_1 = 1 \text{ GHz}$   
 $N^* = 773$

$\left. \begin{array}{l} \phi = 10^{-26} \text{ W/m}^2 \\ D = 100\text{m} \\ \nu_2 = 3 \text{ GHz AND } \nu_1 = 1 \text{ GHz} \\ N^* = 773 \end{array} \right\} \sim 87 \text{ sec/STAR/8 MHz BAND, FOR S/N} = 1$

**A "DEDICATED" FACILITY IS REQUIRED TO ALLOW OBSERVING TIMES**  
**~1000 sec/STAR/8 MHz BAND TO IMPROVE PULSE DETECTION**

Figure 3-1.— Target search.

$T_{\text{COMPLETE SKY}} = 584 \text{ DAYS} \left[ \frac{D}{34\text{m}} \right] \left[ \frac{256 \text{ MHz}}{Nb} \right] \left[ \frac{0.2^\circ/\text{sec}}{\omega} \right] \left[ \frac{\nu_2^2 - \nu_1^2}{(10 \text{ GHz}^2 - 1 \text{ GHz}^2)} \right]$

$\nu_1 \rightarrow \nu_2$

REQUIRE LARGE AMOUNT OF TIME ON TELESCOPES CAPABLE OF WORKING UP TO HIGH FREQUENCIES

USE NASA TELESCOPES WITH LIGHT LOAD FORECAST

THE 34m NETWORK IS A GOOD CHOICE

ASSUME { 16 hours/day ON ONE 34m DISH  
 LOOK BACK FACTOR AND MAINTENANCE  $\leq 25\%$

COMPLETE SKY SURVEY IN 3 YEARS OVER 1  $\rightarrow$  10 GHz WITH A SENSITIVITY

$\phi \sim 2.2 \times 10^{-23} \sqrt{\nu_{\text{GHz}}} \text{ W/m}^2$ , for S/N = 9

Figure 3-2.— Sky survey.

TABLE 3-III.— OBSERVATIONAL SCENARIO FOR TARGET SEARCH

| Site                           | Time, %    | Time/target/frequency | No. of targets | $\phi \text{ W/m}^2$                             |
|--------------------------------|------------|-----------------------|----------------|--|
| Arecibo                        | 3          | 100-sec<br>(1000)     | 243<br>(7)     | $2.3 \times 10^{-27}$<br>$(7.3 \times 10^{-28})$ |
| CSIRO and<br>DSS 43            | 4<br>and 5 | 100<br>(1000)         | 172<br>(12)    | $1.3 \times 10^{-26}$<br>$(4.0 \times 10^{-27})$ |
| OSU                            | 80         | 1000                  | 307            | $2 \times 10^{-26}$                              |
| DSS 14 or 63<br>or NRAO 300-ft | <1         | 100                   | 53             | $1.3 \times 10^{-26}$                            |

TABLE 3-IV.— POSSIBLE CANDIDATE SITES BASED ON COLLECTING AREA AND/OR AVAILABILITY

| Telescope                        | Size, m |
|----------------------------------|---------|
| DSN 34-m network                 | 34      |
| DSN 64-m network                 | 64      |
| Arecibo Observatory, Puerto Rico | 213     |
| NRAO 300-ft, West Virginia       | 93      |
| OSU, Ohio                        | 53      |
| CSIRO, Australia                 | 64      |
| Effelsberg MPIFR, Germany        | 100     |

## CHAPTER 4

### THE SETI EXPERIMENTAL PROGRAM

#### Abstract

*A detailed observing plan is described for the detection of signals of ETI origin. The major focus is a search in the microwave region of the electromagnetic spectrum to cover a well-defined region of search space. Existing radio telescopes instrumented with advanced digital multichannel spectrum analyzers and signal processors comprise the basic instrumentation. The underlying strategy is bimodal in character to cover a wide range of possibilities. In one mode, the entire sky would be surveyed between 1 and 10 GHz with resolution binwidths down to 32 Hz. In the other mode, more than 700 nearby solar-type stars and other selected interesting directions would be searched between 1 and 3 GHz with binwidths down to 1 Hz. Particular emphasis would be placed on solar-type stars within 20 ly of Earth.*

A detailed observing plan was formulated by the Ames/JPL SETI Program Office and presented to the SSWG to promote discussion, critical analysis, and suggestions for improvements. The two previous chapters discuss the trade-off studies and options considered while constructing this plan. Here, the principal features of the resulting plan are summarized.

The major focus of the observing plan is a search in the microwave region of the spectrum to cover a specifically defined region of search space. Existing radio telescopes instrumented with state-of-the-art data acquisition and analysis systems comprise the basic instrumentation for the search.

The search strategy embodied in the plan is bimodal in character in order to cover a wide range of possibilities. One objective of the program is to survey the entire sky over a wide frequency range and at a constant scan rate. This survey ensures that all potential life sites are observed to some limiting equivalent isotropic radiated power (EIRP) depending upon their distance. The sky survey will search the entire celestial sphere over the frequency range  $1.2 \leq \nu \leq 10$  GHz and as many spot bands between 10 and 25 GHz as time and instrumentation permit. In addition, lengthy observing times will be assigned to directions in which a large number of stars lie within the telescope beam. These include especially the galactic plane and the galactic center region. The 1- to 10-GHz frequency coverage spans the flat minimum of the terrestrial microwave window. Resolution binwidths down to 32 Hz will be used in this mode. This sky survey will be about 300 times more sensitive and cover 20,000 times more frequency space than all surveys to date.

The second objective is to survey a set of potential transmission sites selected *a priori* to be especially promising, achieving very high sensitivity over a smaller frequency range than the sky survey. This targeted search is designed to observe 773 stars within 25 pc of the Sun which have been identified to be of spectral type F, G, or K and luminosity Class V, as well as a number of other regions of special interest such as the galactic center and external galaxies. The frequency range to be covered will be 1.2–3 GHz and as many spot bands between 3 and 10 GHz as time permits. This spectral region includes the Waterhole, 1.4- to 1.7-GHz, which has been suggested as a preferred frequency band for an interstellar search (see appendix A). Using resolution binwidths down to 1 Hz, the targeted search will nearly match in sensitivity the most sensitive search to date, but it will extend the number of targets by a factor of four and the range of frequencies covered by a factor of  $3 \times 10^6$ . Furthermore, it will be sensitive to a much wider range of signal types.

The search will be sensitive (in varying degrees) to three general classes of signals:

1. Signals which are compressed within the frequency domain of the receiver, an obvious example being a continuously present CW signal (drifting or nondrifting).
2. Signals which are compressed in the time domain and within the temporal windows of the detector, the simplest example being a regularly pulsed signal.
3. Signals so complex as to exhibit little or no fine structure over the temporal and spectral windows of the detector. Many kinds of intercepted transmissions may belong to this class.

TABLE 4-I.— PRINCIPAL OBSERVING PARAMETERS

| Parameter                       | Sky survey  | Targeted search  |
|---------------------------------|---|--|
| Coverage                        | 4π sr   | ~800 beam areas  |
| Sensitivity                     | ~10 <sup>-23</sup> (ν <sub>GHz</sub> ) W/m <sup>2</sup> | ~10 <sup>-25</sup> to 10 <sup>-27</sup> W/m <sup>2</sup> |
| Frequency range                 | 1.2-10 GHz<br>+ spot bands                              | 1.2-3 GHz<br>+ spot bands                                |
| Spectral resolution             | 32 Hz   | 1 Hz   |
| Integration <i>t</i> /beam-area | 0.3-3 sec   | 100-1000 sec   |
| Survey duration                 | ~3 yr   | ~5 yr  |
| Aperture                        | 34 m  | ≥64 m  |

Two types of instrument systems are needed to perform the search: a wideband system for the sky survey and a narrowband system for the targeted search. These systems are described in the following chapter.

Table 4-I summarizes the principal observing parameters of the sky survey and the targeted search.

### The Sky Survey

The sky survey observing plan calls for using the NASA DSN 34-m subnet of antennas and one transportable wide-band SETI spectral analysis instrument with 32-Hz resolution binwidth and some zoom (1-Hz) capability. Initially the spectral analysis hardware would be installed on a 34-m telescope at the Goldstone Test Station near Barstow, Calif. Later it would be moved to Tidbinbilla, Australia, to complete the sky coverage. Since Goldstone is the busiest complex in the DSN, it may be necessary to carry out part of the survey of the northern hemisphere at the DSN complex in Spain.

The sky survey will be conducted by driving the telescope across the sky at a constant rate, ω. The time required to move the telescope through a half-power beamwidth (HPBW) is

$$\xi = 70c/D\omega\nu \quad (1)$$

and the sensitivity achieved in this manner is

$$\phi = (4\alpha kT_s/\pi\eta)(\omega b\nu/70cD^3)^{1/2} \quad (2)$$

The amount of time required to survey a fraction of the sky at one frequency is

$$T^f = 70G\pi^2\nu D\eta/c\omega\epsilon \quad (3)$$

and the total time to survey between the frequency limits is

$$T = (70G\pi^2\eta D/2Nb\epsilon\omega)(\nu_2^2 - \nu_1^2) \quad (4)$$

The quantities appearing in equations (1) through (4) are

ξ = time to scan through HPBW, sec

φ = limiting detectable flux, W/m<sup>2</sup>

T<sup>f</sup> = time to survey one frequency setting, sec

T = time to survey frequency range, ν<sub>1</sub> to ν<sub>2</sub>, sec

c = speed of light, 3×10<sup>8</sup> m/sec

D = diameter of parabolic radio telescope, m

ω = antenna drive rate, deg/sec

ν = frequency of observation, Hz

α = numerical multiplier to ensure sufficiently low false alarm rate

k = Boltzmann's constant, 1.38×10<sup>-23</sup> J/K

T<sub>s</sub> = system noise temperature, K

η = aperture efficiency

ε = beam efficiency

b = binwidth, single-channel instantaneous resolution, Hz

N = number of channels with binwidth, b. Thus Nb is the instantaneous bandwidth of the receiving system

G = fraction of sky surveyed

Table 4-II presents numerical values of the relevant parameters and the resulting sensitivity and survey times for the 34-m subnet, assuming the facility is equipped with a

TABLE 4-II.— NUMERICAL VALUES OF DSN 34-m SUBNET

| DSN 34-m subnet parameter              | Value   |
|--|---|
| Number of telescopes                   | 9   |
| Sky coverage, %                        | 100   |
| $T_s$ (K), 1-10 GHz                    | 10 to 30  |
| Maximum antenna drive rates (deg/sec): |   |
| Hr angle                               | 0.4   |
| Declination                            | 0.4   |
| $\omega$ , deg/sec                     | 0.2   |
| $\eta$                                 | 0.5   |
| $\epsilon$                             | 0.75  |
| $b$ , Hz                               | 32  |
| $N$                                    | 7,864,320   |
| $\phi$ , W/m <sup>2</sup>              | $2.5 \times 10^{-24} \alpha (\nu_{\text{GHz}})^{1/2}$ |
| $\xi$ , sec                            | $3.1/\nu_{\text{GHz}}$                                |
| $T'$ , days                            | $3(\nu_{\text{GHz}})$                                 |
| $T$ , days                             | $5.9(\nu_2^2 - \nu_1^2)$ , $\nu$ in GHz               |

wideband SETI System. It shows that a sky survey over the frequency range 1.2-10 GHz could be conducted with 1.6 yr of 34-m observing time. Assuming observations will be carried out 16 hr/day and a look-back factor (fraction of time required to check possible signals and to account for time lost due to equipment failure, transportation, and inclement weather) is about 25%, the physical time required to carry out the survey over this frequency range is  $1.6 \times 1.25 \times 3/2 = 3$  yr. Over a 4-yr period, there would be enough time to carry out several surveys in spot bands above 10 GHz (for example, bands centered upon interstellar lines due to H<sub>2</sub>O and NH<sub>3</sub>). In addition, or as an alternative, the limited area of the sky containing the galactic plane could be scanned more slowly or repeatedly in order to increase the sensitivity and/or duty cycle coverage for the majority of the stars in our Galaxy.

The sensitivity achieved in the sky survey will depend on the threshold value of  $\alpha$  chosen, as indicated in table 4-II. If  $\alpha$  is chosen so that the false alarm rate per HPBW is constant, then  $\alpha$  will be frequency-dependent. For example, the number of independent samples which can be accumulated during the time it takes to scan one HPBW is  $\sim 100$  at 1 GHz and  $\sim 10$  at 10 GHz. In the absence of RFI, Gaussian noise alone will produce one channel out of  $8 \times 10^6$ , which exceeds the threshold for each accumulated spectrum unless the threshold is set at ( $>7$  for 1 GHz) or ( $>9$  for 10 GHz)  $\times$  (mean power per channel). A sensitivity goal corresponding to  $\alpha \cong 9$  and a continuous frequency coverage from 1.2-10 GHz represent the major observational objectives of the sky survey. Setting  $\alpha = 9$  and assuming  $T_s = 25$  K, the estimated sky survey sensitivity for the 34-m subnet would be

$$\phi = 2.2 \times 10^{-23} (\nu_{\text{GHz}})^{1/2} \text{ W/m}^2 \quad (5)$$

An  $\alpha$  of 9 corresponds to one false alarm per 10 beam areas at 10 GHz, but only about one out of 100,000 at 1 GHz.

Figure 4-1 shows the minimum detectable EIRP as a function of distance for a typical sky survey carried out with a 34-m telescope. Also shown are typical results for the targeted search, discussed next.

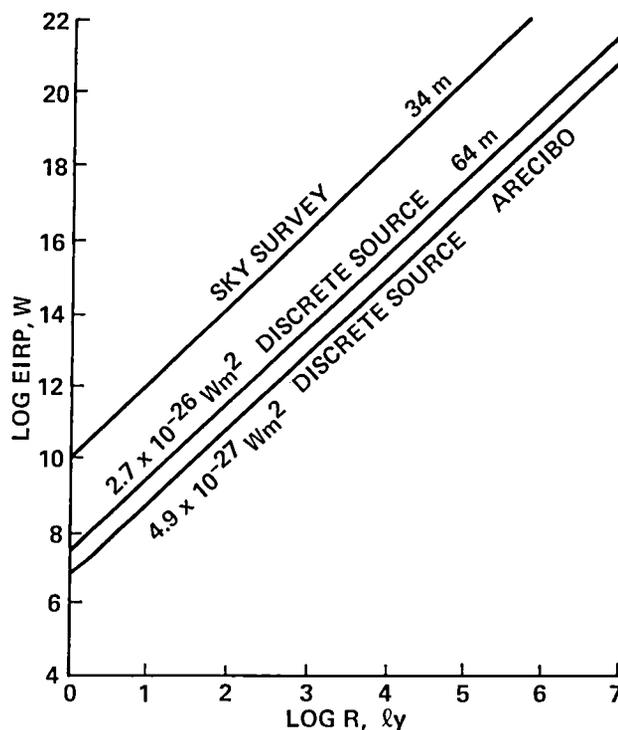


Figure 4-1.— Minimum detectable EIRP as a function of distance.

The targeted search uses the largest available collecting areas to gain very high sensitivity for the search for signals originating from the direction of nearby solar-type stars. In addition, sensitivity to very narrowband signals (or signal components) is much enhanced by using real and pseudo-instantaneous resolution binwidths down to 1 Hz. The targeted search is to be conducted in the 1.2- to 3-GHz range, plus spot-bands if time allows.

The candidate stellar target list for these observations will be drawn from the "Royal Greenwich Observatory Catalogue of Stars within 25 Parsecs of the Sun" (Wooley et al., 1970). This catalogue contains entries for 1744 stellar systems which have trigonometric or spectroscopic parallaxes exceeding 0.04 sec of arc, and is the most volume-complete star catalogue available at this time. The target list will be updated as the SETI Program continues, to allow inclusion of new stellar census studies such as those being carried out by R. Humphreys et al., at the University of Minnesota, and similar studies at the Monterey Institute for Research in Astronomy (MIRA). From the RGO catalogue, 773 dwarf stars of spectral type F, G, or K (similar to our Sun) have been identified. Of these, 488 show no indication of multiplicity in terms of the catalogue entries. It is anticipated, however, that further study will reveal a number of multiple systems among these 488 stars, particularly as members of the wide binary systems. In addition to those stars within 20 ly, stars which continue to be judged single will form the highest-priority target list. Those members of binary systems whose separations appear to allow a solution for stable planetary orbits (Harrington, 1977), within which there might exist a habitable zone around the solar-type star, will also be included as high-priority targets. The target list will also include some stellar aggregations, such as globular clusters, nearby galaxies, and other selected directions such as toward the galactic center.

The targeted search is conducted by observing each candidate object for a time,  $\tau$ . The sensitivity achieved through integration for  $\tau$  sec is

$$\phi = (4\alpha k T_s / \pi \eta D^2) (b/\tau)^{1/2} \quad (6)$$

which may be rewritten to give the time required to achieve a given limiting flux

$$T_\phi = b(4\alpha k T_s / \pi \eta D^2 \phi)^2 \quad (7)$$

Thus, the time required to survey  $N_*$  targets to a limiting flux,  $\phi$ , for one frequency is

$$T' = N_* T_\phi \quad (8)$$

and the total time required to survey these stars over the frequency range  $\nu_1 \leq \nu \leq \nu_2$  is

To estimate the antenna time required to perform a high-sensitivity search for realistic limiting flux levels, the following telescopes were considered: The 305-m antenna at the Arecibo Observatory of the National Astronomy and Ionosphere Center (NAIC); the three 64-m antennas of the Deep Space Stations (DSS 14, DSS 43, and DSS 63), and the Commonwealth Scientific and Industrial Research Organization (CSIRO) 64-m antenna at Parkes, Australia (an example of a large southern hemisphere site); the National Radio Astronomy Observatory (NRAO) 300-ft antenna (an example of a large northern hemisphere site); and the Ohio State University (OSU) Radio Observatory meridian telescope (an example of a dedicated site). For these purposes, CSIRO, Parkes, is identical to DSS 43, and both will be assumed to be available to obtain coverage of the southern stars. The following observing scenario was chosen: (1) All stars and stellar aggregates visible from Arecibo were assigned to be observed with that instrument at the highest sensitivity; (2) all targets visible from OSU, but not visible from Arecibo, were assigned to that instrument; (3) all southern targets not visible from the previous two sites were assigned to DSS 43 and Parkes in Australia; and finally, (4) those few stars too far north to be visible from OSU were assigned to either the 300-ft antenna at NRAO (assuming the southern hemisphere narrowband system would be transported) or to DSS 14 or to DSS 63 (assuming the wideband zoom capability can be used during the northern sky survey). In table 4-III, the assumed parameters for each site are given along with the sensitivities which can be achieved for either 100- or 1000-sec integration times. Also given are the times to complete a survey of the given number of stars at each site.

Figure 4-1 shows the minimum detectable EIRP as a function of distance for the targeted search and sky survey. The targeted search results are shown for a 64-m antenna and for Arecibo. We see from this figure that the Arecibo telescope can detect  $10^8$  W (EIRP) out to about 4 ly, the distance to the nearest stars. Transmitters at the level of the strongest TV stations,  $10^5$ - $10^7$  W (EIRP), can be detected only if they are situated less than 2 ly away. A transmitter equivalent to the most powerful radar systems used on Earth,  $10^{13}$  W (EIRP), can be detected by the sky survey at a distance of 20 ly and by the targeted search at a distance of 1400 ly.

## Reference

- Wooley, R.; Epps, E. A.; Penston, M. J.; and Pocock, S. B.: Royal Greenwich Observatory Catalogue of Stars within 25 Parsecs of the Sun. *Observ. Ann.*, no. 5, Herstmonceux, England, 1970.

TABLE 4-III.— CALCULATION OF OBSERVING TIME REQUIRED TO DO A HIGH-SENSITIVITY SEARCH

| Site location |  | Arecibo         | DSS 43 and Parkes | OSU*          | NRAO 300 ft  | or | DSS 14       | or | DSS 63        |
|---------------|--|-----------------|-------------------|---------------|--------------|----|--------------|----|---------------|
| Parameter     |  | Puerto Rico     | Australia         | Ohio          | W. Va.       |    | Calif.       |    | Spain         |
| $D$           | Diameter, m  | 213             | 64                | 53            | 91.4         |    |              |    | 64            |
| $T_s$         | System temperature, K  | 30              | 15                | 50            | 30           |    |              |    | 15            |
| $\eta$        | Aperture efficiency, %   | 50              | 50                | 50            | 50           |    |              |    | 50            |
| $B$           | Inst. bandwidth, MHz   | 7.9 & 7.9       | 7.9 & 7.9 zoom    | 7.9           | 7.9          |    |              |    | 7.9 zoom      |
| $\phi$        | Limiting flux,<br>$\alpha(b_r)^{1/2} \times 10^{-26} \text{ W/m}^{-2}$   | 2.3             | 12.6              | 61.4          | 12.6         |    |              |    | 12.6          |
| $N_*$         | Stars visible at site:<br>all stars<br>[single stars only]   | 243<br>[149]    | 696<br>[442]      | 545<br>[331]  | 499<br>[305] |    | 610<br>[407] |    | 676<br>[384]  |
| $N'_*$        | Stars assigned:<br>all stars<br>stars within 20 ly   | 243<br>{7}      | 172<br>{12}       | 305<br>{2}    | 53           | or |              |    | 53<br>{1}     |
| $t_*$         | Total observing time<br>per star, hr   | 6.4<br>{64}     | 6.4<br>{64}       | 58<br>{64}    | 6.4          |    |              |    | 6.4<br>{64}   |
| $\tau$        | Observing time per star<br>in one frequency band,<br>$B$ , sec   | 100<br>{1000}   | 100<br>{1000}     | 900<br>{1000} | 100          | or |              |    | 100<br>{1000} |
| $\phi^*$      | Sensitivity achieved,<br>$b = 1 \text{ Hz}$ , for assigned<br>stars, $\alpha \times 10^{-26} \text{ W/m}^{-2}$ | 0.23<br>{0.073} | 1.3<br>{0.40}     | 2.0<br>{1.9}  | 1.3          |    |              |    | 1.3<br>{0.4}  |
| $T'$          | Time to observe all<br>assigned stars per fre-<br>quency band, $B$ , hr  | 6.6<br>{1.9}    | 4.4<br>{3.3}      | 75.8<br>{0.5} | 1.5          | or |              |    | 1.5<br>{0.3}  |
| $T$           | Total time to observe all<br>assigned stars over<br>frequency range of<br>1.2-3 GHz, days                      | 32<br>{9}       | 43<br>{3}         | 726<br>{5}    | 14           | or |              |    | 14<br>{3}     |
|               | Period of operation, yr  | 3.5 & 4         | 1.7 & 3           | 2.5           |              |    |              |    |               |
|               | Percentage observing<br>time at site over<br>period of operation   | 3%              | 5% and 4%         | 80%           |              |    |              |    |               |

NOTES:

Square brackets, [ ], contain values for single stars only.

Braces, { }, contain values for stars closer than 20 ly.

$\alpha$  is the multiple of the rms noise power required to establish a signal-recognition threshold providing adequate false alarm probability calculated on the basis of Gaussian noise statistics.

$b$  is the MCSA frequency resolution, or binwidth, and is nominally 1 Hz in this search mode.

\* It is assumed that the OSU Radio Observatory will be upgraded to implement tracking and polarization capabilities.



## CHAPTER 5

### THE PROTOTYPE SETI INSTRUMENTATION

#### Abstract

*The Prototype SETI instrumentation consists of an intermediate-frequency down-converter, a spectrum analyzer, a signal processor, and a PDP-11/44 computer. The main challenge in the development of the SETI instrument is to provide efficient signal processing equipment to handle the very high data rates (~8 Gbytes/sec). This chapter describes the design approach and offers a view of the prototype hardware under development.*

#### Introduction

The targeted search and sky survey instruments will be designed to be among the most sensitive broadband radio telescope systems yet developed. With high-efficiency antenna feeds, cryogenically cooled preamplifiers, high-resolution spectrum analyzers, and special-purpose signal processors, the utmost care will be taken to deliver optimum performance. The engineering task requires considerable resources, but is within the state of the art. The greatest SETI technical development challenge is to process the massive data output in real time.

The data processing requirement could be met with general-purpose computers, but only at exorbitant expense. Therefore, SETI instrumentation will use a few, specially designed, high-speed digital processors to carry out a small set of algorithms which produce outputs at dramatically reduced data rates. Determining appropriate algorithms and evaluating their efficiencies when implemented in hardware is the main task being accomplished during the SETI prototype development. Despite the differing requirements of the sky survey and targeted search observations, a high degree of instrumental commonality is expected in the two operational systems.

#### The SETI Prototype Observing System

The SETI receiving system is a combination of well-understood radio frequency technology and brand new signal processing technology still under theoretical and laboratory development. The signal processor is a rather simple device, from a functional point of view. From an engineering point of view, however, it is a fast, large-scale, highly specialized digital computer which manipulates partitioned broadband data on-line through hundreds of parallel algorithmic streams

which interact with each other at various levels. Because of the functional simplicity and high degree of parallelism, it is possible to build and test a breadboard about 1% as large as the final processor, yet containing at least one example of each type of board and function required by the ultimate device. Furthermore, starting with a section of the MCSA, the breadboard can grow economically function by function with thorough testing at each stage of development. In this way the system design can be validated in a low-risk situation, and improvements can be introduced at low cost until the design is frozen and replication begins. Since breadboard development is projected to last several years, when the design is finally set it should be technologically up to date in a field in which technology is changing rapidly and is expected to do so well into the future.

The design and construction of an item of observing apparatus is not complete until the item has been tested (and has survived) in an appropriate observatory environment. Therefore it was decided to design and arrange for a SETI Prototype Observing System, or "protosystem," which could absorb and act as a test bed for each new piece of software and hardware as it was developed. Furthermore, the system should be controllable from on-site or via telephone connections to remote terminals at, for example, JPL or Ames.

Figure 5-1 gives a functional overview of the protosystem. To save costs, it will share the use of the antenna, microwave front end, low-noise traveling-wave maser, and S-band receiver of an R&D, DSS, and the existing feeds and amplifiers at the Arecibo Observatory to provide input signals to test the proof-of-concept signal-processing system being developed for SETI. The MCSA is a minimal portion of the final system; initially, only 74,000 1-Hz channels in a single polarization are available, instead of the 8 million dual-polarization 1-Hz or 32-Hz channels proposed at this time for the final instruments. Each prototype output buss, however, operates at the 20-Mbyte rate required of the full system, so

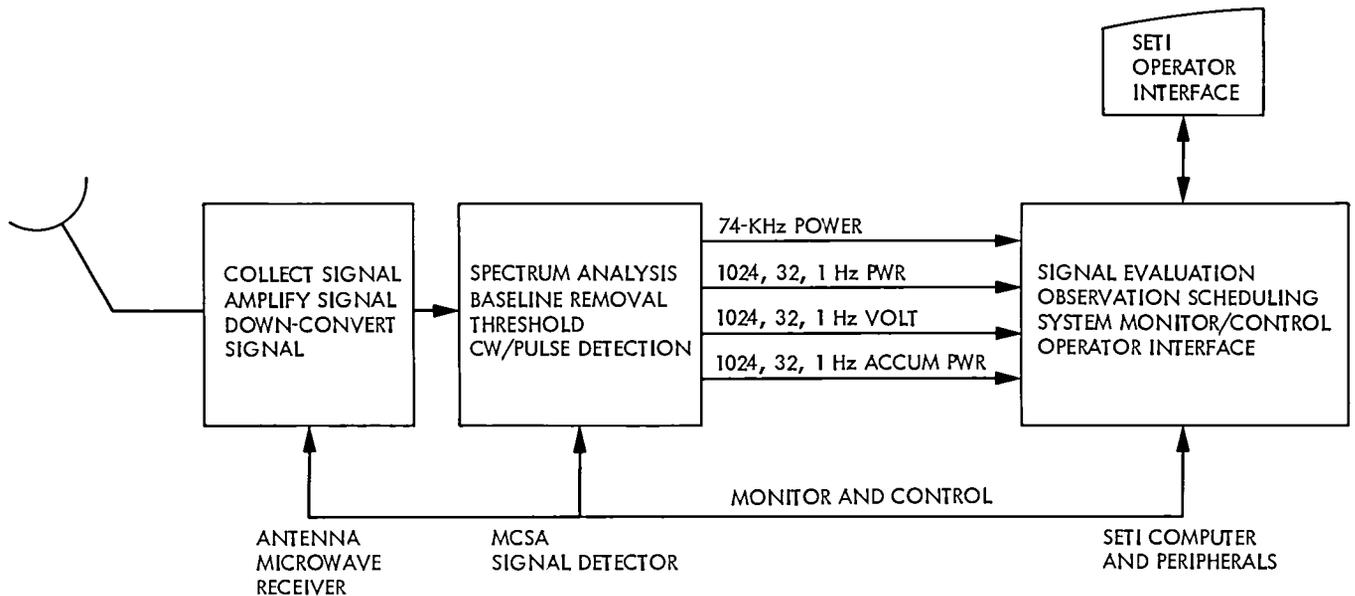


Figure 5-1.— Functional block diagram of the SETI prototype instrument.

the 74-kHz output data appear not as a continuous data stream but in brief bursts. The economy, the high-speed operation, and the large throughput of the MCSA must be matched in the final machine by the performance of the signal-extracting and data-compacting processors which follow the MCSA. The demand for economy and high speed generates a major engineering problem and is a prime justification for the development of the prototype.

The approach being pursued is to use the SETI computer (a PDP 11/44 for the prototype development stage) to take a snapshot of the data — a few tens of seconds of data recorded on tape or disk — and then operate off-line on that data to develop efficient algorithms to determine the data baseline and gain fluctuations, to threshold, and to provide signal recognition and identification. As these routines are developed, it is planned to convert the most successful software algorithms into efficient, high-speed digital hardware that will perform their functions in real time.

Another major objective of the prototype effort is to reduce operating costs by thoroughly automating routine system operation. This is especially important since the proposed sky survey will take some 3 yr of 16-hr/day operation for completion.

In order to facilitate software evolution, the prototype system has been arranged as shown in figure 5-2, where it is configured for operation at a DSN station which is, for the present, DSS 13. As indicated in the figure, this DSN station has been equipped for either local or remote control of the entire installation. The Network Operations Control Center (NOCC) in Pasadena can send commands to DSS 13 via modems (MOD), a normal telephone circuit, and the DSS 13 link control. These commands are accepted by the Star Switch Controller, a priority-controlled multiplexer, and passed to the desired control element; for the antenna (ANT)

and noise-adding radiometer (NAR), the test transmitter (XMT) and the Block III receiver (RCV) and programmable oscillator control assembly (POCA). Control of DSS 13 can be passed to a local terminal (DSN OP CTRL) or to the SETI computer and terminals, local, at JPL, or at Ames. The SETI breadboard installation is shown boxed in the lower right corner of figure 5-2. Thus the SETI project will be able to use the standard S- and X-band equipment typically used for tracking and data acquisition in the DSN; and, using “real” signals, will be able to polish the performance of the breadboard. A corresponding arrangement will be established when the breadboard is taken to the Arecibo Observatory.

The long-term objective of the SETI program is to develop the technology and instrumentation required to carry out two complementary searches for ETI. The targeted search is a particularly high-sensitivity one focusing on 773 solar-type stars. The other search will survey the entire sky over a broader frequency range at lower resolution and less sensitivity (table 5-I). Both these searches require handling very large quantities of high-speed data; thus both require special-purpose hardware.

The proposed 5-yr supporting research and technology program is directed at building a representative model of the SETI instrumentation so that the required R&D can be done and low-risk, minimum-cost searches can be achieved.

This algorithm and instrumentation development for SETI has been divided into four phases. During phase 1, the breadboard will provide only a narrow frequency coverage and will depend almost exclusively on off-line data processing to evaluate the various signal-recognition schemes (table 5-II and fig. 5-3). As algorithms are developed, they will evolve into hardware in later phases. Further, as the signal-processing matures, the instantaneous system

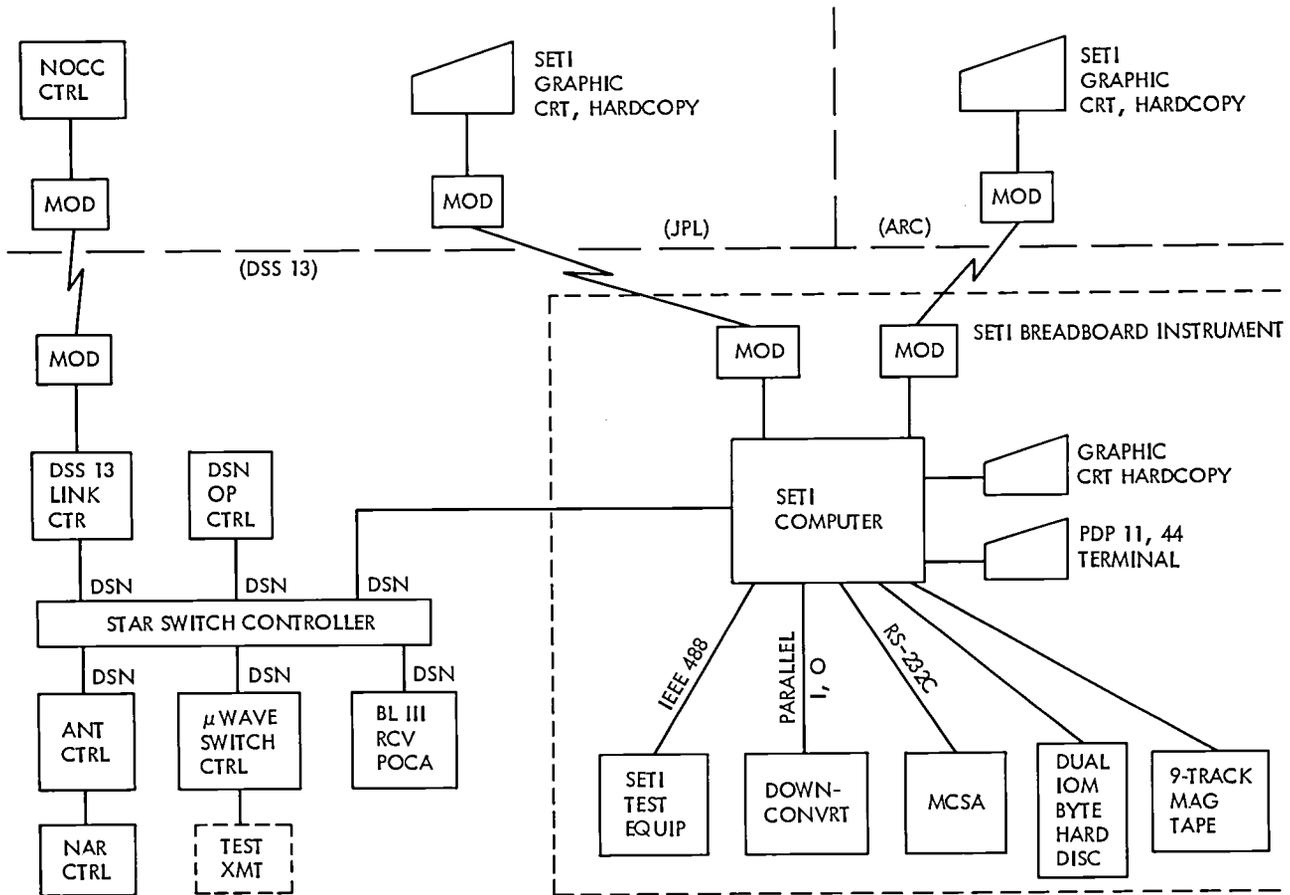


Figure 5-2.— Detailed block diagram of the DSS 13 SETI prototype instrument configuration.

TABLE 5-I.— SETI SEARCH GOALS

| Parameter                            | Target search                                    | Sky survey |
|--------------------------------------|--|------------|
| Area coverage                        | 773 solar-type stars                             | All-sky    |
| Frequency coverage (continuous), GHz | 1.2-3.0  | 1.2-10     |
| Frequency coverage (spot bands), GHz | 3.0-10   | 10-25      |
| Spectral resolution, Hz              | 1024, 32, 1                                      | 1024, 32   |
| Instantaneous bandwidth, MHz         | 8  | 256        |
| Signal search                        | Pulses   | CW         |
|                                      | Drifting CW                                      |            |
| Polarization                         | Dual (RC and LC)                                 |            |
| Gain stability                       | $\Delta G/G \leq 10^{-5}$ in $10^2$ - $10^3$ sec |            |
| Frequency stability                  | $\Delta \nu/\nu \leq 10^{-13}$ in $10^3$ sec     |            |
| Drift rate detection                 | $\dot{\nu}/\nu \leq 10^{-9}$                     |            |

TABLE 5-II.— PHASE 1 BREADBOARD

MCSA:  
 Bandwidth — 74-kHz (single polarization) resolution outputs —  
 74 kHz, 1024 Hz  
 32 Hz/1 Hz

Signal processor:  
 PDP 11/44 SETI computer  
 Baseline, threshold, and signal identification accomplished in software

Field tests at Goldstone and Arecibo in FY 83

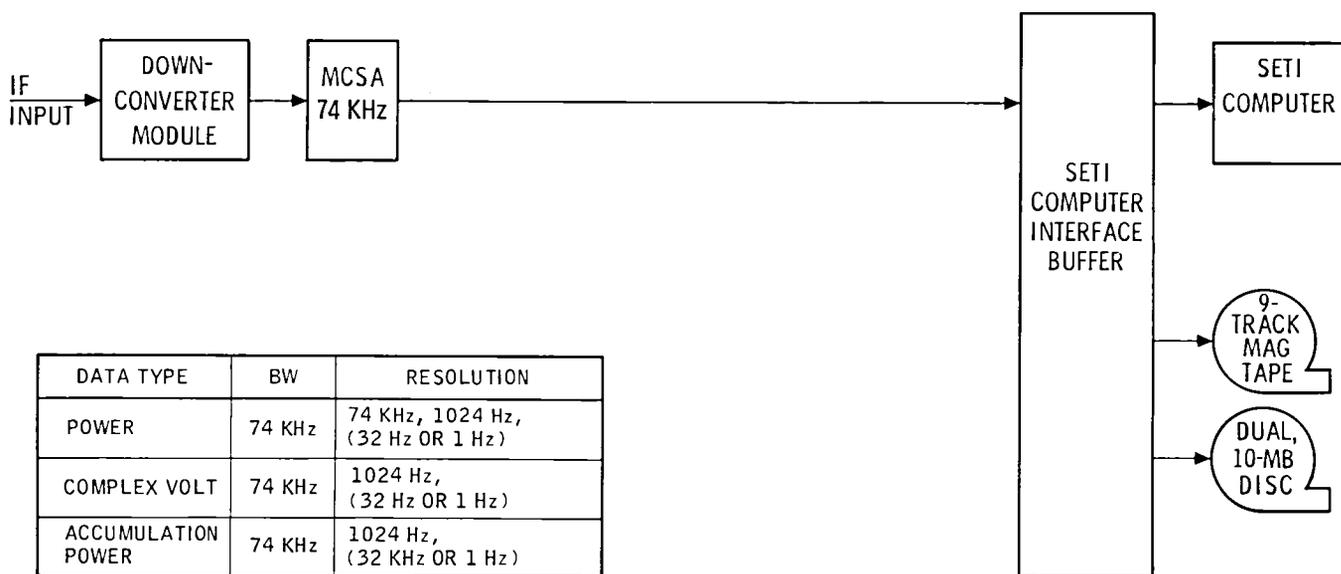


Figure 5-3.— SETI breadboard data configuration, phase 1.

bandwidth will be expanded to properly test the designs (see tables 5-II through 5-V and figs. 5-3 through 5-6).

The SETI systems are intended also for use by many scientists outside the SETI program. To optimize the user interface, software necessary to control each system and many components will be provided as part of the system. Figure 5-7 is a software flow diagram for the SETI protosystem. The design of an observational experiment will consist of the software of the desired sequence of events coming after INIT and before TERMINATE EXPT. All experimenter decisions (e.g., choices in sequence of events) will be made prior to running the experiment; however, data-driven decisions will be capable of changing the sequence of events in real time. For each experiment, a set of files will be developed that will control the detailed operation of each element in the SETI subsystems (e.g., these files will contain high-level inputs that define where to point the antenna, what scan rate and scan pattern to use, what receiver frequency

band to observe, and what data to take from the spectrum analyzer). The same experiment (i.e., sequence of events) can be used with any number of user-developed experiment files (i.e., to do the same SETI experiment on  $n$  stars requires compiling the program once, and generating  $n$  files).

A brief description of the flow diagram shown in Figure 5-7 follows:

*INIT.* The INIT routine is intended to determine the operational status of the equipment. The first task is to poll all the system elements (i.e., down-converter, spectrum analyzer, disk, magnetic tape, etc.) to determine that they are controllable from the SETI computer. Next, each element is instructed to perform a self-test. If all self-tests run satisfactorily, a system test is performed. The results of the test are displayed and recorded on magnetic tape.

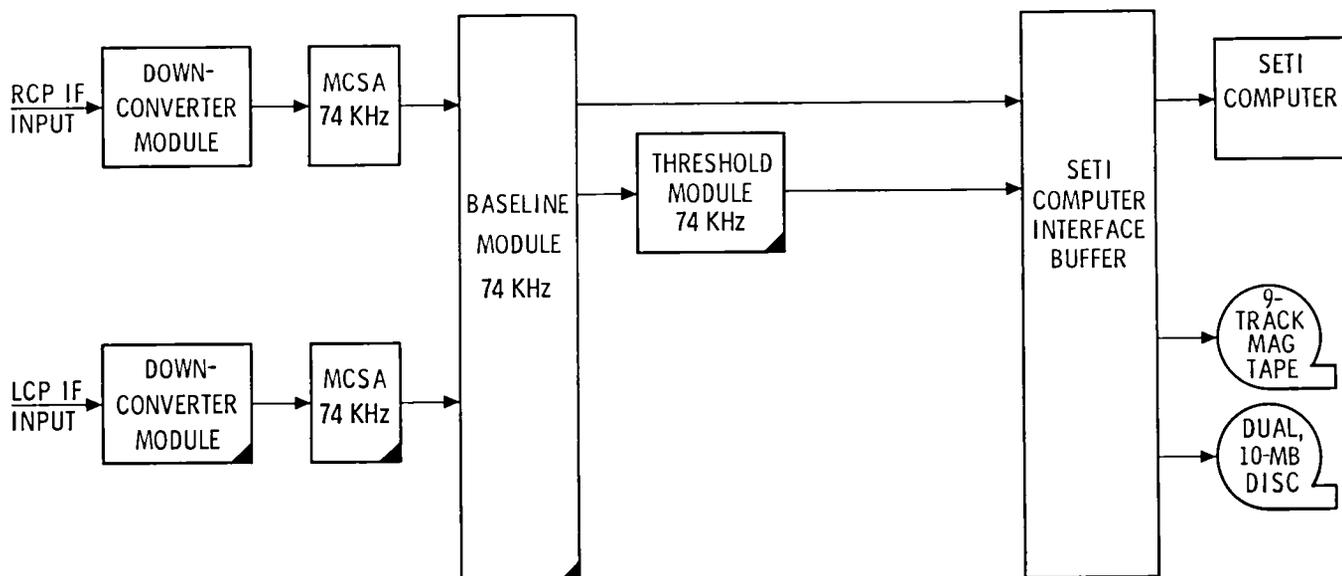
*SET-UP EXPT.* This routine prompts the experimenter to enter the file name for this trial. The program then moves the appropriate files from a disk to a reserved area in the

TABLE 5-III.— PHASE 2 BREADBOARD

Upgrade MCSA  
 Add simultaneous 32-Hz and 1-Hz resolutions  
 Add dual polarization (74 kHz)  
 Add baseline and threshold hardware

Develop signal-processor software  
 Pulses  
 Drifting CW

Field tests at Goldstone and Arecibo in calendar year 1986



| DATA TYPE          | BW     | RESOLUTION                   |
|--------------------|--------|------------------------------|
| POWER              | 74 KHz | 74 KHz, 1024 Hz, 32 Hz, 1 Hz |
| COMPLEX VOLT       | 74 KHz | 1024 Hz, 32 Hz, 1 Hz         |
| ACCUMULATION POWER | 74 KHz | 1024 Hz, 32 Hz, 1 Hz         |

▲ = UPGRADE

Figure 5-4.— SETI breadboard data configuration, phase 2.

computer “common” storage. The system elements are then configured by calling the appropriate input/output routines from the common areas and sending the data to the appropriate system elements.

**RUN EXPT.** This routine will be written by the experimenter and will contain the desired sequence of events and real-time data-decision logic utilizing the high-level monitor and control routine to control the hardware.

**ANALYZE DATA.** This routine to analyze the data will also be written by the experimenter. Decision flags will be set that will be used to control RUN EXPT.

**M&C TASK.** This collection of high-level routines will be provided with the SETI system to control and monitor all system elements.

**TERMINATE EXPT.** This routine performs the same tests performed in INIT. Test results are displayed and recorded on magnetic tape.

**EXPT MON.** This concurrent task will allow periodic system status to be displayed. During the early prototype stages, the equipment configuration and storage status will be displayed. Later, as more elements are added and a complete SETI station is available, the status will periodically

TABLE 5-IV.— PHASE 3 BREADBOARD

Expand phase 2 hardware to 4-MHz bandwidth, dual polarization, at 32-Hz resolution

Develop signal processor for 74-kHz dual polarization  
Pulses  
Drifting CW

Field tests and observations at Goldstone and Arecibo in calendar year 1987

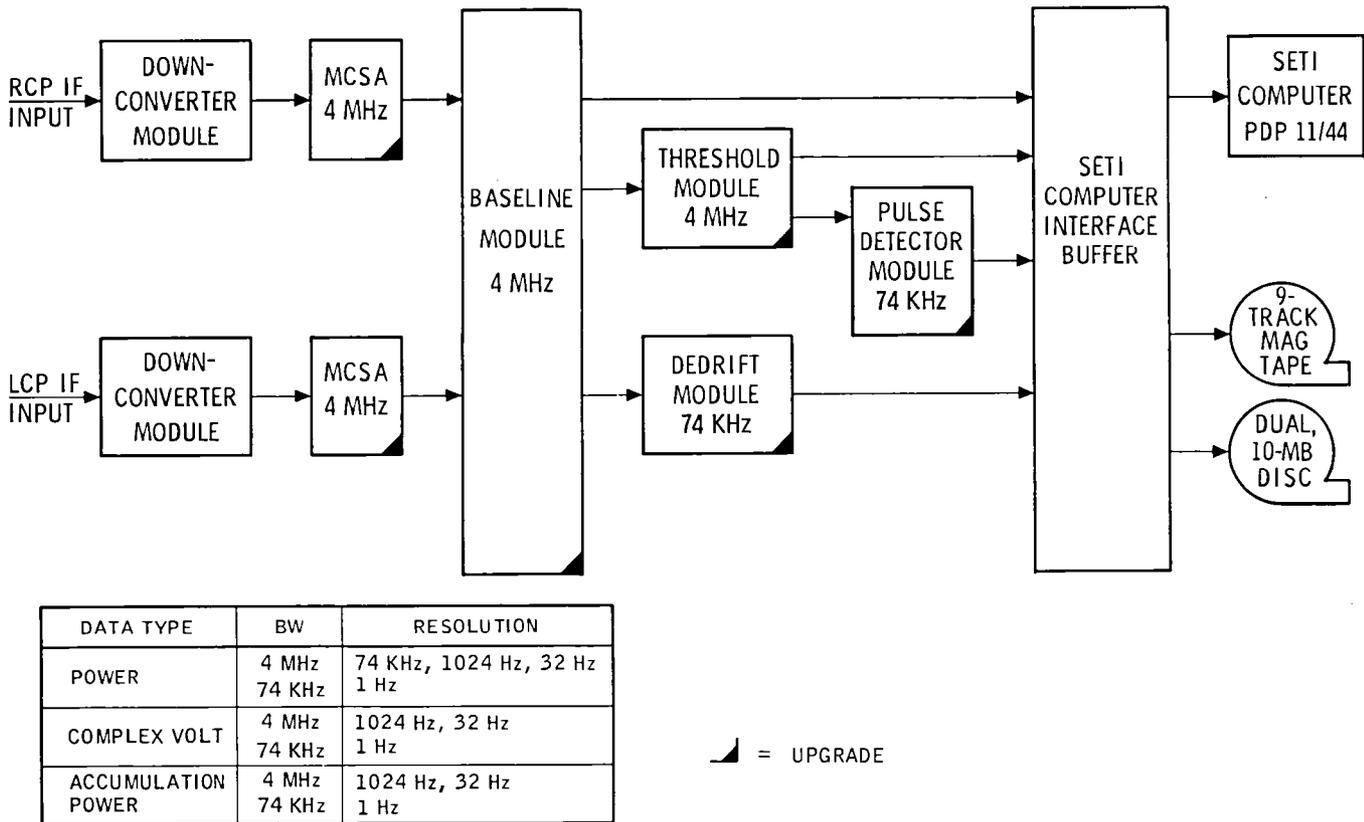


Figure 5-5.— SETI breadboard data configuration, phase 3.

display antenna position, receiver frequency, system temperature, etc.

The plan calls eventually for the computer to command and monitor the performance of all the components of the protosystem, including its own subsystems. Presently, it calls for the deployment of the phase 1 protosystem in the winter of 1982, and for the next 2 years to be spent evaluating various signal-recognition software algorithms, some of

which may later be turned into compact high-speed hardware.

### Proposed Schedule

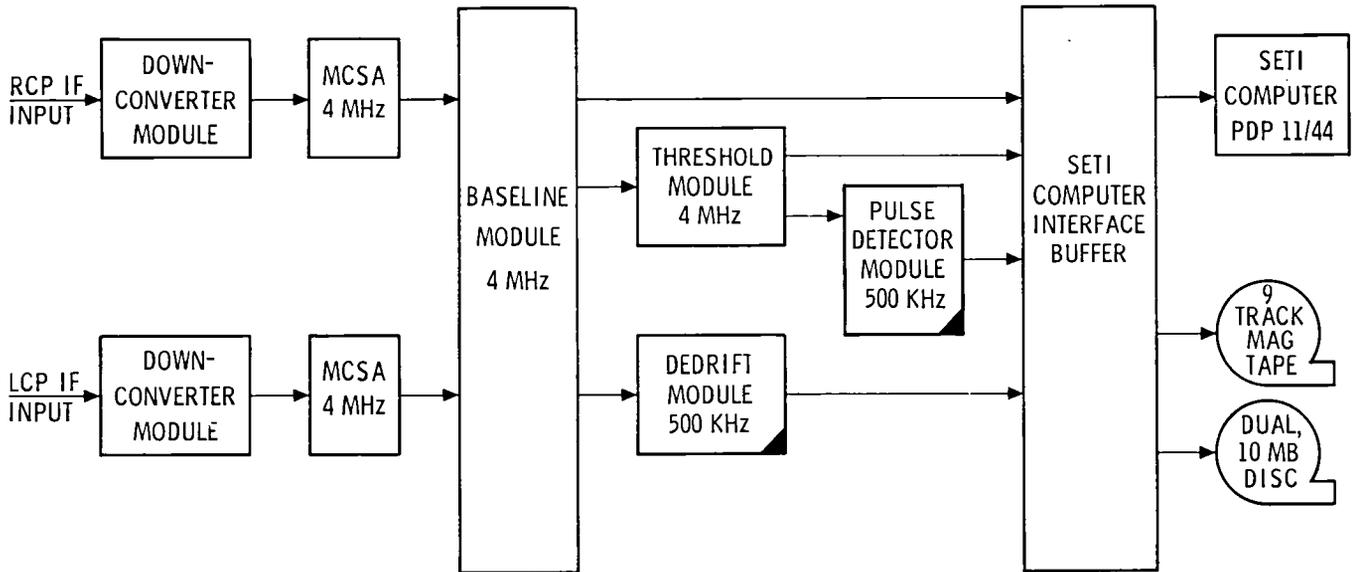
The proposed milestone schedule for the 5-yr R&D plan is given in figure 5-8.

TABLE 5-V.— PHASE 4 BREADBOARD

Expand phase 3 hardware to 500-kHz, dual polarization, at 1-Hz resolution

Expand signal processor to  $5 \times 10^5$  channels, dual polarization

Observations at Goldstone and Arecibo in calendar year 1988



| DATA TYPE          | BW               | RESOLUTION                     |
|--------------------|------------------|--------------------------------|
| POWER              | 4 MHz<br>500 KHz | 74 KHz, 1024 Hz, 32 Hz<br>1 Hz |
| COMPLEX VOLT       | 4 MHz<br>500 KHz | 1024 Hz, 32 Hz<br>1 Hz         |
| ACCUMULATION POWER | 4 MHz<br>500 KHz | 1024 Hz, 32 Hz<br>1 Hz         |

▲ = UPGRADE

Figure 5-6.— SETI breadboard data configuration, phase 4.

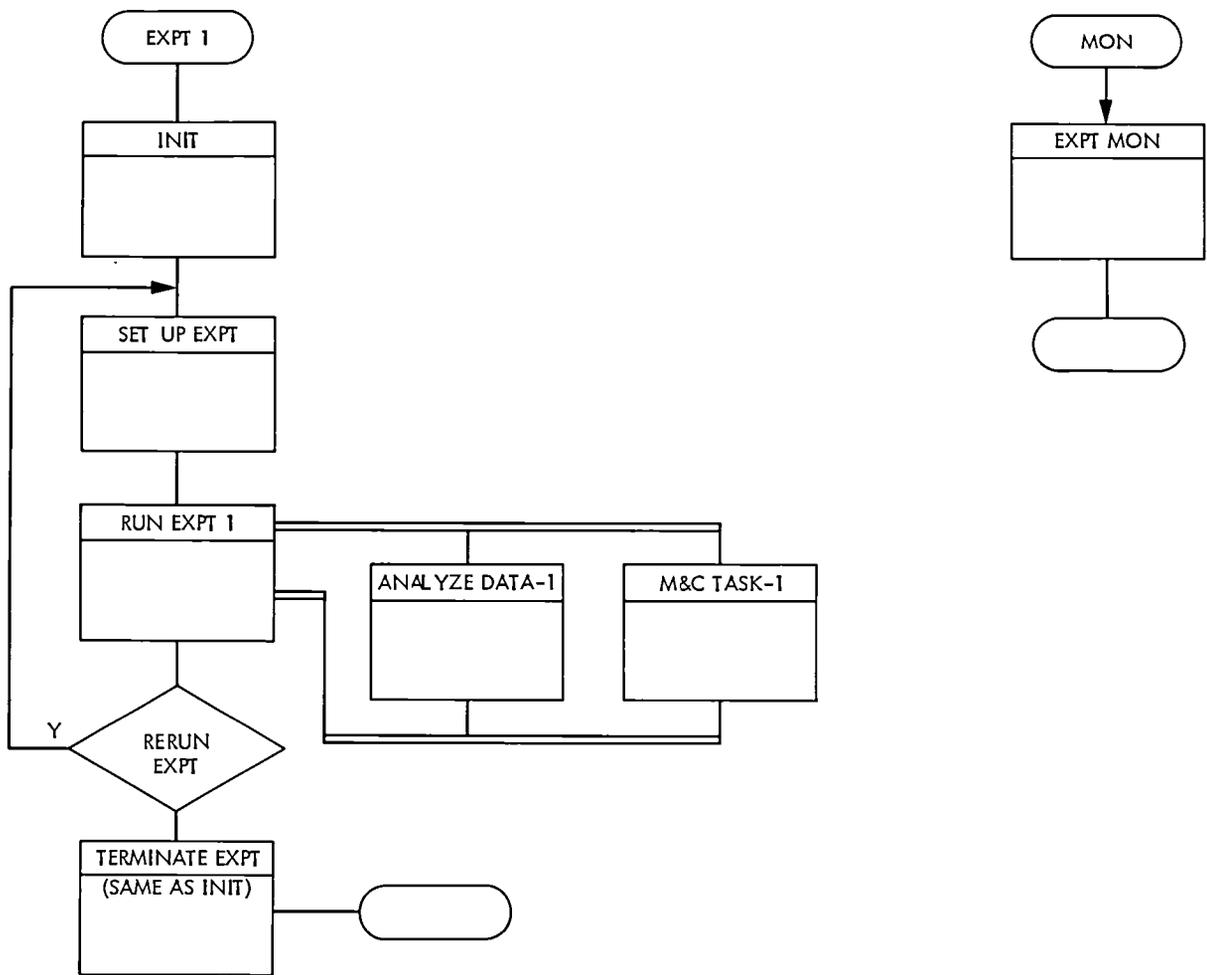


Figure 5-7.— SETI experiment no. 1.





## CHAPTER 6

### POTENTIAL ASTRONOMICAL RESULTS FROM THE SETI PROGRAM AND ITS EQUIPMENT

#### Abstract

*The proposed systematic SETI observational program will employ sensitive receivers viewing much of the sky over a prolonged period of time. If modest additional effort is expended, valuable continuum and spectral line survey data can be collected for the RA community in a manner which may even enhance the prospects for detection of an ETI signal. These surveys represent a formidable investment for the individual astronomer and, therefore, one can anticipate that only a small portion of the survey data would be collected in the absence of an organized effort such as SETI. Close and continuing cooperation between the external scientific community and the SETI program is necessary to determine that the data are collected and archived in a form which ensures that they will be useful.*

The SETI program plan calls for two major observing modes: the sky survey and the targeted search. The targeted search is not expected to give useful astronomical continuum data. In contrast, the combination of high sensitivity and high spectral resolution and full sky coverage of the sky survey will produce, in addition to the SETI data, a wealth of astronomical data as well. For the most part, the astronomical results will consist of systematic catalogues of line and continuum emission from both galactic and extragalactic sources. Because of the necessary lengthy observing times required with state-of-the-art instrumentation on large radio telescopes, it is unlikely that RA survey programs, which have historically provided basic astronomical data, will be done with conventional radio telescope systems. Furthermore, it is possible to utilize the equipment of the SETI program to make a host of important new observations. The time and cost impact on the overall program would be minimal.

Although the primary scientific spin-off is expected to be fundamental survey data and other special observations, entirely new discoveries are possible. Whenever sizeable portions of the sky have been surveyed to a greater sensitivity, with higher time or spectral resolution, or at new frequencies, important discoveries have resulted. The history of RA is full of such unanticipated discoveries, and it is unlikely that we have already recognized all types of objects radiating significantly at microwavelengths. Nevertheless, whether or not SETI instrumentation will be sensitive to presently unknown phenomena must remain an open question until these systematic studies are made.

We now describe some of the potential for new scientific results from the SETI program and its equipment. For convenience, we start with continuum observations and spectral line studies which will derive directly from the SETI observations.

#### Continuum Source Surveys

A main feature of the SETI effort will be a sky survey which covers the frequency band 1.2–10 GHz and spot-bands up to 25 GHz. Full-sky surveys in this range have been made only at 6 and 21 cm (5 and 1.4 GHz). The SETI survey will be of particular interest at the shorter wavelengths where relatively little work has been done. At these wavelengths the sky is dominated by compact, flat-spectrum sources commonly associated with quasars, BL Lac objects, and active galactic nuclei.

Because of the multifrequency nature of the survey, spectral information will be available for all sources, which will allow their classification into spectral types. Since flat-spectrum (compact) sources and steep-spectrum (extended) sources exhibit very different morphologies, data of this type are essential to cosmological studies of radio source evolution. As there are so few strong sources in the sky, statistical uncertainties often dominate present analyses. Time-consuming full-sky surveys of even the strongest sources are essential to the analysis of the radio luminosity function, as well as the spatial distribution and evolution of radio galaxies and quasars.

In addition to the survey of extragalactic sources, the SETI survey may be expected to concentrate on the region near the galactic plane, and in particular the galactic center region. Although galactic continuum surveys have been made at longer, centimeter wavelengths, they cover only the region within a few degrees of the galactic plane. The SETI survey will cover a much wider area, and will extend the surveys to shorter wavelengths. New objects expected to be found in the galactic plane survey include compact HII regions and supernova remnants, as well as the variable compact radio sources associated with X-ray and binary stars, and exotic objects such as SS 433.

Assuming system parameters given in the proposed SETI Program Plan, a unit survey covering the whole sky with a bandwidth of  $\sim 250$  MHz will take  $\sim 3(\nu_{\text{GHz}})$  days to complete and will contain all sources down to approximately  $0.014\sqrt{(\nu_{\text{GHz}})}$  Jy at the  $5\sigma$  level. Averaging data for a full gigahertz will reduce this by a factor of two without significant loss of spectral resolution, at least for  $\nu \geq 8$  GHz. This will yield a catalogue of positions and spectra for  $\sim 1000$  flat spectrum and  $\sim 300$  steep spectrum sources.

At the shortest wavelengths, an insignificant number of steep spectrum sources will be found, but a large number of flat spectrum sources will be detected. Many of these will be catalogued already, as a result of existing long-wavelength surveys, but the full-sky survey is still needed in order to compile a complete catalogue. Because of the need for state-of-the-art instrumentation and lengthy observing times, it is unlikely that any systematic surveys at the shorter wavelengths will be made using conventional RA facilities.

Thus an opportunity exists for the SETI sky survey to make a significant contribution to continuum RA in the form of a short-wavelength-source survey. No additional observing time is needed, and the data acquisition and archiving requirements are small compared to those of the main SETI program. The required total power measurements would probably be recorded anyway for engineering purposes.

Consider the following system parameters, applicable to the 34-m DSN observations:

$$T_s = 25 \text{ K (system temperature)}$$

$$B = 250 \text{ MHz (bandwidth)}$$

$$\tau = 1 \text{ s}/\nu_{\text{GHz}} \text{ (three samples per beamwidth)}$$

For a total power receiver, the noise is

$$\begin{aligned} \Delta T &= T_s/\sqrt{B\tau} \\ &= 1.5 \text{ mK at 1 GHz} \\ &= 5 \text{ mk at 10 GHz} \end{aligned}$$

and the required gain stability is

$$\Delta G/G = 3 \times 10^{-5} \text{ for } \sim 10 \text{ sec at 1 GHz}$$

and

$$\Delta G/G = 10^{-4} \text{ for } \sim 1 \text{ sec at 10 GHz}$$

The DSN 34-m antennas provide  $1/6$  K/Jy, in two polarizations, so for a 5:1 S/N the minimum detectable flux density is

$$\begin{aligned} S_{\text{min}} &= 30 \text{ mJy at 1 GHz} \\ &= 100 \text{ mJy at 10 GHz} \end{aligned}$$

Note that the 34-m telescopes are confusion-limited at 1 GHz, reducing somewhat the value of the survey at such low frequencies.

If about 16 surveys over, say, 6-10 GHz can be recorded and averaged, then the noise goes down by  $\sqrt{16}$  to give

$$S_{\text{min}} = 25 \text{ mJy}, \bar{\nu} = 8 \text{ GHz}$$

and this compares extremely favorably with, for example, the NRAO/Bonn 6-cm all-sky survey, for which  $S_{\text{min}} \geq 500$  mJy. The number of detectable sources should be almost 100 times greater than in the NRAO/Bonn survey.

There are several potential problem areas requiring further study. The SETI program does not require the 0.01% gain stability needed in the continuum total power survey. However, the required time scale is short ( $\sim 1$  sec), and with careful engineering this may not represent a serious limitation. Survey registration must be adequate to permit alignment and averaging of the 16 data sets, taken at widely spaced intervals in time and under varying conditions. The requirements are only a little more severe than those needed to be able to retarget a suspected SETI source, and the known positions of strong radio sources will help with alignment.

The data rate is very slow, about 40 byte/sec plus perhaps 20% overhead, or about one 1600-bpi (bits per inch) tape every 2 weeks. Special equipment requirements, assuming adequate gain stability is achieved, are minimal. A wide-band detector feeding an analog-to-digital converter is needed for each polarization, and a separate minicomputer and tape drive for this program would make it independent of the complex data processing associated with the main SETI search.

In spite of the slow data rate, the data analysis effort is nontrivial. Source surveys of this type have typically required the concerted full-time effort of several experienced people for 3-10 yr. Careful advance planning would be required to minimize this effort.

Interferometry, if selected for the SETI observations, would significantly enhance (and complicate) the continuum survey. It would improve sensitivity, reduce confusion, provide accurate positions, and greatly reduce interference susceptibility. Sensitivity to extended sources would be reduced, but these make up only a small fraction of the sources at short wavelengths. If desired, both total power and interferometric data could be recorded and analyzed.

### Other Continuum Projects

The targeted search data should be monitored for unusual wideband fluctuations, although it is unlikely that the SETI program stars will produce flares. Polarization data from the all-sky survey, particularly Faraday rotation over the wide frequency range observed, might prove to be useful. Such observations would require the construction of a polarimeter to provide all four Stokes parameters from the input circular polarizations. The calibration problems for such a polarization search would be much more severe than for the total power survey, and the likelihood of obtaining useful results is probably not very high. Nevertheless, this possibility should be examined in detail since such an all-sky survey is unlikely to be repeated in the foreseeable future.

As already mentioned, careful monitoring of the continuum data provides useful engineering information on the health of the front-end electronics; cooperative arrangements between the operations and scientific teams are important here.

Overall, the add-on costs and the impact of continuum research on the SETI program are probably minimal.

### Spectral Line Survey

For the first time, the SETI survey will give high spectral resolution data over the whole sky for all of the strong, well-known, molecular species, as well as for atomic hydrogen. The astronomical value of the molecular data will depend to a large extent on the degree to which the SETI survey concentrates on the galactic plane. The scientific implications of these surveys are described only briefly below because of the complexity of the spectral line field. A detailed discussion of this subject is given in appendix H. All other things being equal, SETI surveys should be concentrated near these bands.

*Neutral hydrogen*— A full-sky survey lasting about 1 yr will detect point sources stronger than  $\sim 0.6$  Jy, assuming a velocity dispersion of 10 km/sec and extended line emission with  $T_B \geq 0.1$  K. This will allow the detection of new HI clouds and dwarf galaxies within the Local Group, and will lead to an estimate of the HI content in the Local Group. This is important in understanding the dynamics of the Local Group and galactic evolution.

The SETI search will also allow the detection of HI in spiral galaxies which are visibly obscured. New spiral galaxies

may be discovered in this way out to a distance of 30 Mpc, or twice the Virgo cluster distance.

*H<sub>2</sub>CO*— The 6-cm SETI survey will cover the H<sub>2</sub><sup>13</sup>CO as well as the H<sub>2</sub>CO formaldehyde band in addition to the  $\pi_{1/2}$ , J = 1/2 triplet of OH. The rms noise will be on the order of a few tenths of a degree in a 1-km/sec bandwidth if the survey lasts approximately 1 yr and covers the whole sky. Similar sensitivity can be reached for the 2-cm H<sub>2</sub>CO line if the data are smoothed to the 6-cm beam.

*NH<sub>3</sub>*— The (1,1), (2,2), and (3,3) transitions of NH<sub>3</sub> can be observed simultaneously, but minimum detectable signals will be  $\sim 0.3$  K, even if 6 mo are spent covering a few-degree-wide strip centered on the galactic plane (see appendix H).

*H<sub>2</sub>O*— A SETI survey of the galactic plane at the H<sub>2</sub>O wavelength lasting a few months or more would be a valuable complement to existing OH and H<sub>2</sub>CO surveys.

### Use of the “Dwell Mode”

The original concept of the relationship between RA and SETI considered two extremes: pure SETI observations with RA use of the data, and RA use of SETI equipment on its own time, possibly even with different telescopes. These ideas are still valid (e.g., the continuum survey), but another promising concept, the so-called “dwell mode” observation, has emerged, in which SETI and radio astronomy share the results.

This concept arose from simple calculations indicating that SETI sky survey observations scan too fast (a bandwidth being scanned in a time of about 1 sec) to provide an adequate S/N for RA; and they spend most of the time *not* looking at regions and/or on frequencies normally of astronomical interest. Hence most of the interesting RA can come only from increased integration time (through reduced scan speed or through repeated mapping) on a few selected frequencies and/or from a few regions of the sky.

It turns out that once such observations become available they are of interest to SETI as well. For example, pulsed signal searches are limited if the beam spends only about a second per beam area, as is planned in the main survey. They become more interesting if the dwell time in a given direction is increased. Then, too, for many types and ranges of possible ETI signals, sensitivity is increased as well.

One approach to implementing the dwell mode is to budget a 5–20% lengthening of the sky survey and to solicit project suggestions for this time which are selected on a peer review basis. Possible projects were discussed at the fourth SSWG meeting; all suggestions to date are for atomic or molecular line surveys at selected frequencies. These are discussed in detail in appendix H. The eventual assignment of observing time to the dwell mode will have to await the existence of an active observing program.



## CHAPTER 7

### SCIENTIFIC COMMUNITY INTERACTION WITH THE SETI PROGRAM

#### Abstract

*In this section several avenues for interaction between the scientific community at large and the NASA SETI program are presented. A few represent a continuation or expansion of previous successful activities, but some require new commitments from the NASA SETI program and commensurate allocation of funds. In each case the suggestions are intended to ensure that innovative (and possibly cost-saving) new concepts can be encouraged and incorporated into the ongoing program to the benefit of the astronomical or ETI signal-detection research.*

The SETI program as now envisioned is primarily oriented toward microwave searches of a large volume of space and to covering a significant fraction of the microwave spectrum. A continuing program of development of more sensitive instrumentation and improved signal extraction techniques is also included.

Large-scale searches of the radio frequency spectrum which have a reasonable degree of completeness will be very time-consuming and will extend over a significant length of time. Attention will be given to the problem of maintaining uniformity throughout the course of the full search. Nevertheless, constructive innovations are sure to occur. From past experience, many such innovations may come from outside the project staff, if the scientific community at large is informed of goals and needs. Thus it is very desirable that there be a good linkage between the astronomical community and any SETI program. Such an approach, utilizing talented visiting scientists, has already been successful at Ames.

Moreover, because of the large scale of the search task, we must seek out any compelling limitations on the space, or frequencies, which are promising to search. Such limitations can be expected to shorten the necessary search time and reduce the cost by a significant amount. Discovery of other natural limitations which might influence the search techniques could have an extremely important effect upon the outcome and time scale of the SETI program. Again, the development of such concepts could well arise in the general community if the community is informed. Means must be provided to encourage development of these ideas and their incorporation into the SETI program.

In summary, strong community interaction with SETI programs will have the following benefits.

1. Community interest in the SETI program will be maintained through personal involvement of many scientists.

2. Attention may be given to searching additional regions in the electromagnetic spectrum. For instance, it might be shown that certain infrared wavelengths offer excellent opportunities for interstellar communication.

3. SETI searches could be made on data acquired during normal radio astronomical observations. The effort required is relatively small.

4. Alternative or more powerful search strategies may be developed that can be included in all the SETI searches.

5. Innovative instrumentation and data handling techniques may be developed outside the SETI program that could be of great benefit to the program.

There are three requirements for good communication between the SETI program and the scientific community. First, the community must be encouraged and supported to participate in SETI, even if only in a minor way. Second, new ideas and developments must be disseminated widely among all SETI investigators. Third, the large ETI search programs must be encouraged to adopt and put into use appropriate new technologies and search algorithms developed outside their institutions.

There are excellent reasons why the major search programs should be done by an institution which has SETI as a major priority. Continuity and long-term commitment are vital to the successful completion of a large search. But within the overall SETI program there must be a well-defined section in which participation by outside scientists is not only possible but encouraged. Funds should be included within the program plan to support a program of grants based on peer-reviewed proposals. Such a program should not be limited to searches in the microwave spectrum. All wavelengths and all aspects of SETI should be eligible for support. In order to avoid conflicts of interest, this support program should have a formal system for obtaining peer review outside the central program.

The SSWG works on a continuing basis with the Ames/JPL SETI Program Office to pursue all aspects of SETI. In particular, the non-NASA members of the Group serve as an effective information channel to present ideas from the community at large. This has been effective, in our view, and it is very desirable to continue to provide this service to the program, either through this or a similar group.

The SSWG can also help to spread information about the NASA SETI program throughout the community by produc-

ing reports such as this one. We recommend that such reports be developed periodically and that they receive wide distribution.

It is important to be sure that the members of the SSWG are highly regarded in the scientific community so that their activities, carried out jointly with the NASA team, may be seen by others in the scientific community to reflect a broad consensus of outside opinion.

## APPENDIX A

### CONCEPTS SUPPORTING MICROWAVE SEARCHES AS THE PREFERRED APPROACH TO SETI

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#### Abstract

*A realistic examination of the costs of interstellar travel, interstellar probes, and other communication media reveals that detection of ETI signals in the microwave region is by far the least energy consuming, and therefore most cost effective method of establishing contact.*

Let's stop kidding ourselves. It is very unlikely that we are going to travel to the stars, or that other creatures will travel to us. Looking at the situation here on Earth, it's not that our technology isn't up to the task (which it isn't), it's that physical law makes it impossible to cross interstellar distances in a human lifetime without a politically prohibitive energy expenditure. Consider the least case: a crew of 10 is willing to devote its entire life from age 20 to age 65 traveling to Alpha Centauri and back. This means the ship must cruise at one-fifth the speed of light. At that speed every colliding grain of interstellar dust is a miniature A-bomb (1 lb of TNT per  $\mu\text{g}$ ), but we will ignore this problem. Even with 100% efficient rocketry, the energy required to produce four velocity increments of 0.2 c would supply the entire U.S. with electric power for several thousand years. It is hard to imagine our Congress (or theirs) approving such a mission.

An interstellar probe can, in principle, be much slower. But if the generation launching the probe is to learn of the outcome, the probe must travel at one-tenth the speed of light on a one-way trip and radio back its findings. Also it can be much lighter, perhaps one-hundredth the weight of an inhabited spacecraft. Nevertheless it would be a formidable mission costing far more than Apollo and would sample only one star. The simple fact is that we are going to discover other life in the Universe not by hurling tons of matter through space, but by detecting radiation emitted by that life.

Of all the possible forms of radiation, only particles with zero rest mass deserve consideration. An electron traveling at half the speed of light has 100 million times the energy of a millimeter wave photon and, since we require the same number of either particle per bit, signaling with electrons would require that much more power if we could aim them as well.

But charged particles are deflected by the galactic magnetic field and cannot be aimed at all. As to the other neutral particles, the graviton has not yet been directly detected even from events on a cosmic scale (although the existence of gravity waves has been inferred from the orbital decay of the binary pulsar 1913+16), while the neutrino is costly to generate and practically impossible to detect. Photons are cheap, easy to generate, and easy to detect. The first indications of other life will almost surely be brought by electromagnetic waves.

Must we then search the entire spectrum? Freeman Dyson has suggested that advanced societies might transform planetary matter into shells of orbiting habitats so numerous as to practically block the star's radiation, or rather to convert most of it to the infrared. He feels that we should be on the alert for stars with excess infrared radiation and try to detect artifacts around them. Others, taking note of the enormous energies needed for astro-engineering,<sup>1</sup> feel that advanced societies will have been able to limit their population and enjoy their home planet for eons. In either case, the final proof of the existence of advanced life is most likely to come from detecting signals it radiates for its own uses or else from beacons intended to attract our attention. Either type of signal will be easiest to detect in the frequency range where the sky is quietest, i.e., in the spectral region from about 1-60 GHz. Here the only noise received from space is the 2.7 K cosmic background: the relict radiation of the Big Bang. Below 1 GHz the synchrotron radiation of the galaxy rises rapidly with decreasing frequency, while above

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<sup>1</sup>To disassemble an Earth-sized planet would require all the energy of the sunlight that has fallen on Earth since the age of the dinosaurs.

60 GHz the “quantum noise” due to spontaneous emission in linear amplifiers dominates. The spectral power density of this noise is  $h\nu$  corresponding to one interfering photon per reciprocal receiver bandwidth. Thus, above the microwave window the received power must increase proportional to frequency, as shown in figure A-1.

The same is true if we do not use linear amplifiers but merely count photons. Since we need at least one photon to detect a signal, and some number  $n$  if we are to determine its nature, the received energy will decrease with decreasing frequency until we begin to receive spurious thermal photons from the cosmic background. Then we must increase  $n$  inversely proportional to frequency to keep the S/N constant. The sole advantage of quantum detection is that, far above the thermal region, we can widen our receiver bandwidth without increasing the background noise provided we are not pointing at a star or other infrared source. However, the necessary received (and transmitted) energy per bit is much greater than in the microwave window. In essence, we are led to the microwave window in trying to minimize the energy needed to establish interstellar contact.

The microwave window is still approximately 60 GHz wide in space and 10 GHz wide from the surface of the Earth. The search would be easier if we could narrow the

spectrum further. There are several reasons to prefer the low end of the window. For example:

- Larger single-unit antennas are possible at lower cost.
- Lower Doppler drift rates permit longer coherent integration times.
- Higher-power single-unit transmitters are possible.
- For large arrays, the beams are broader, so pointing errors are less serious.

At the low end of the microwave window are the hydrogen line and the hydroxyl lines, spectral emissions of the dissociation products of water. Water is believed to be essential to the origin and existence of life, so, in a sense, these markers are symbolic of life. Cocconi and Morrison (1959) called attention to the hydrogen line as a natural communication frequency; the Cyclops team decided we might find other species at the Waterhole, the 300-MHz band embracing the H and OH lines.

Considerations such as the above have led us to the conclusion that a search at microwave frequencies is the optimum approach, utilizing existing or proposed technology, to the detection of other civilizations. Emphasis in the search should be placed on the Waterhole, but other frequencies should be tested for signals also. These conclusions have formed the basis for the selection of the SETI programs proposed here.

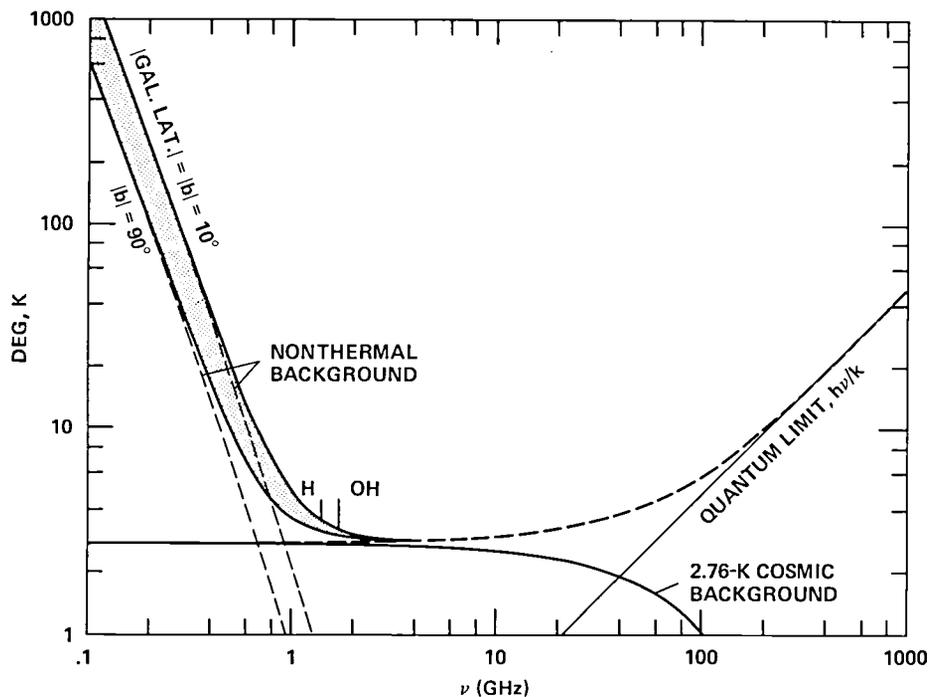


Figure A-1.— Free-space microwave window.

## APPENDIX B

### THE MULTICHANNEL SPECTRUM ANALYZER

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#### Abstract

*The MCSA is a special-purpose digital signal processor. Its main function is to filter a wide-band signal into many narrower bands, so that each of the output bands has a bandwidth that is a better match to the signal being searched for.*

*The basic MCSA provides simultaneous output bandwidths of approximately 1 Hz, 32 Hz, 1024 Hz, and 74 kHz over a spectrum that is about 8 MHz wide. The input to the MCSA consists of a complex signal sampled at 10 MHz, and the outputs consist of either complex samples or power (square-law-detected) samples. In addition, the MCSA provides an accumulator for taking the integral of the power of the output bands for periods up to 1000 sec.*

*The MCSA hardware is constructed using wire-wrap technology. The implementation of the hardware is done with the aid of a computer program developed specifically for the design of the MCSA. Care has been taken in the MCSA design to ensure that engineering tradeoffs do not adversely affect the performance of the system.*

#### General Description

Instead of using a single large Fast Fourier Transform (FFT), the MCSA derives its narrow bands by cascading two stages of digital bandpass filters with moderate-sized Discrete Fourier Transforms (DFT). FFT operations do not yield convenient signals for deriving the intermediate bandwidths that the MCSA delivers. Furthermore, it is possible to provide better RFI rejection with the bandpass filter technique. An FFT has a worst-case sidelobe (adjacent bin) response that is only 13 dB below the response of the main lobe. A bandpass filter can be designed to give more than 70 dB of adjacent channel rejection.

The first bandpass filter splits the input signal into 112 bands, each approximately 74 kHz wide. Each of these 74-kHz-wide signals is then filtered by a second bandpass filter which further subdivides the signal into 72 bands. Each of the resultant bands is about 1024 Hz wide.

The 1024-Hz signals are then fed either to a 36-point DFT or to a 1152-point DFT to form the final 32-Hz or 1-Hz outputs, respectively.

Each of these bandwidths (1 Hz, 32 Hz, 1024 Hz, and 74 kHz) is available as an output of the MCSA. The magnitude squared value of each output sample is computed and is available as the square-law-detected power output. Except

for the 74-kHz bandwidth, the complex signals from the other bands are also available as outputs.

The memory required to do real-time transforms is equal to twice the size of the transform – one block of memory being required to buffer a block of data while the second block is having the transform operations done to it. By using relatively small transform sizes in the final DFTs, the need for a main memory that is twice the size of the MCSA bandwidth can be avoided. Thus, a substantial saving in memory cost is made by applying the bandpass filter/DFT technique compared to a single large FFT, offsetting the extra cost needed to implement the bandpass filters.

Internal to the MCSA, the sampling frequency of a given signal is kept a fraction larger than its analysis bandwidth to prevent additional noise from aliasing into the band of interest. If this were not done, it would be impossible to avoid a substantial degradation of the S/N near the extremes of the band, however sharp the cutoff of the filter is. A sharper filter reduces the size of the region that gets severe aliasing, but could not prevent a 3-dB loss of S/N at the edge of the band due to aliasing. The sampling frequencies used were chosen such that for each filter, the additional aliased noise is kept below 0.1 dB.

The use of oversampling causes the DFT transform sizes to come out to be non-power-of-two's. This is not a

disadvantage, however. Through the use of newly developed DFT algorithms (called the Generalized Winograd DFT Algorithms), the computational efficiencies achieved are comparable with those of power-of-two FFT algorithms. Hardware complexity has increased (more hardware is needed in some cases, faster hardware is needed in others) because of oversampling. This, however, is unavoidable unless a substantial loss in S/N can be tolerated.

### Bandpass Filter 1

The first bandpass filter (see section, Digital Bandpass Filter) operates on a complex input that is sampled at 10 MHz. Each of the real-imaginary pair of samples is made up of a pair of 8-bit binary numbers taken by an analog-to-digital (A/D) convertor subsystem that precedes the MCSA.

Before being given to the bandpass filter, each 8-bit sample is further quantized into a 4-bit representation to reduce the arithmetical complexity of this very-high-speed stage. It was found that, with a signal that has Gaussian statistics, the loss in S/N due to the quantization of the signal to 4 bits is no more than 0.05 dB. Coarse quantization of a signal has been a necessity in many systems that are required to operate at high speeds. However, careful analyses have shown that very low S/N losses can indeed be achieved without having to quantize the signal into very fine levels, providing the quantization parameters are held to some given values (see section, Digital Bandpass Filter).

The first bandpass filter is implemented as two identical banks of filters. Alternate 74-kHz passbands appear at the outputs of either of the two filters – the even 74-kHz bands appearing at the outputs of the first filter bank and the odd 74-kHz bands appearing at the outputs of the second filter bank. The basic filter bank separates its input into 72 bands, of which 16 are discarded, retaining 56 of the bands as outputs. The 16 discarded bands represent the part of the input signal that has substantial amounts of noise aliased into it by the sampling process.

The input signal, following the 4-bit quantization, is applied directly to the input of the first filter bank. Before being applied to the second filter bank, the input signal is shifted in frequency by 74 kHz. The frequency shifting is achieved by the multiplication of the input signal by a complex sinusoid at the appropriate frequency, done digitally. The output of the frequency shifter, quantized to 4 bits, is then applied to the input of the second filter bank.

Each of the two filter banks consists of a 288th order Finite Impulse Response (FIR) filter and a 72-point DFT. The 72-point DFT is implemented with an 8-point FFT followed by a 9-point DFT.

The 8-point FFT is realized with hard-wired pipelined logic circuits. A table-lookup Read-Only Memory (ROM) is used to implement the only multiplication, the scaling of a value by  $\sqrt{2}$ , required to perform an 8-point FFT. The

number representation at this stage (and successive stages) is kept at 16 bits.

The 9-point DFT is implemented with eight special-purpose programmable processors (see section on DFT Processor) working in parallel. A single microprogrammed controller controls all eight DFT Processors (also the 8 DFT Processor in the other bank of the filter).

The multiplication by the filter weights of the FIR filter is done with table lookups using ROMs. The FIR filter taps are partitioned into four sets of taps. One table is used for each of these sets of coefficients. For each table, a datum from tap (4 bits) and the index of one of 72 filter coefficients (7 bits) form the address to the table. The output of the table-lookup is a 16-bit number which represents the product of the datum and the filter coefficient pointed to by the 7-bit index. This implementation resulted in substantial savings in hardware which would otherwise be needed if actual multiplications were performed.

As a consequence of using the table lookup technique to perform multiplications, the input data need not be the result of a uniform quantization of the input signal. Each 4-bit datum can be merely some known representation of the signal value, the actual conversion of the representation to its actual value taking place within the table-lookup process itself. Nonuniform quantization provides both a better S/N and less susceptibility of the S/N to changes in the system gain.

### Bandpass Filter 2

Each of 112 74-kHz-wide signals at the output of the first bandpass filter is further filtered into bands that are 1024 Hz wide. Conceptually, this is done with 112 bandpass filters. In actual implementation, this is done with only 28 separate filters, each filter capable of performing the task of bandpass filtering four different 74-kHz-wide signals.

Each of the second-stage bandpass filters consists of a 2016th order FIR filter together with a 144-point DFT.

The FIR filters in the second bandpass filter are implemented with actual multiplications rather than with lookup tables. The representation of the signal at this point is a 16-bit quantity, making any lookup table prohibitively large. The summation of the 14 active taps (eq. (2) of the section, Digital Bandpass Filter) is performed within an integrated circuit multiplier-accumulator (MAC). Since the MAC maintains a 35-bit internal accumulator, no precision is lost through the arithmetical operations even though the number of active taps is high. This enables us to implement filters which have stopband rejections that are better than 70 dB.

The 144-point DFT is performed by microprogramming the same special-purpose processor that is used in the first bandpass filter. The transform algorithm consists of a 16-point DFT followed by a 9-point DFT.

The signal at the input of this stage is oversampled by a factor of 2. Thus, of the 144 bands available at the output of each of the second bandpass filters, half are discarded, retaining only 72 bands, each 1024 Hz wide.

### Main Memory

The main memory is logically partitioned into blocks of 384k bytes (96k complex words, 16-bit real and 16-bit imaginary components) each. Each block provides enough memory to process a 74-kHz slice of the spectrum in real time. The entire 8-MHz bandwidth (8,257,536 channels, at the 1-Hz resolution) is covered with 112 memory banks, making up approximately 43 Mbytes (10.75 million complex words) of memory. The memory uses dynamic random-access memory circuits. Data are written into the memory from the output of the second bandpass filter (bandwidth of 1024 Hz). The stored data are then read out of the memory and forwarded to the final DFT Processors, in the order that they are expected. Thus, the function of the main memory can be envisioned as a permutation operation on the data.

### 36- and 1152-point Discrete Fourier Transforms

Two sets of DFT Processors are used to filter the 1024-Hz signals into the final 32-Hz and 1-Hz bins. Fourteen processors are used in parallel to perform the transforms required to produce the 32-Hz outputs, and 28 processors are required for the transforms which result in the 1-Hz output bins.

The first set of DFT Processors is programmed to implement 36-point Fourier Transforms. The 1024-Hz signals are oversampled by a factor of 1.125. After the 36-point transform, four of the output bins are discarded, leaving 32 bins, each covering 32 Hz of bandwidth. The second set of processors is programmed to perform 1152-point transforms. Only 1024 of the output bins, representing 1024 Hz worth of bandwidth at the resolution of 1 Hz, are retained.

### The DFT Processor

A special-purpose microprogrammable processor, which we have called the DFT Processor, is used throughout the MCSA to implement the various transforms. In the first bandpass filter, it is programmed to perform a 9-point DFT. In the second bandpass filter, it is programmed to perform a 144-point DFT. For the final transforms, the DFT Processor is programmed for either a 36- or 1152-point DFT.

Although designed with the efficient implementation of the Generalized Winograd DFT algorithms in mind, the DFT Processor can also be programmed to perform other arithmetic-intensive tasks.

The DFT Processor is designed as a pipelined processor, with two Arithmetic-Logic Units (ALU) and a hardware Multiplier-Accumulator (MAC). The processor cycle-time of the DFT Processor is 167 nsec, corresponding to the processor clock frequency of 6 MHz. The two ALUs and the MAC are capable of concurrent operation — with proper programming, this gives the DFT Processor the equivalent capability of an 18-MIPS (million instructions per second) machine. The processing elements themselves need perform no input-output operations — the local memory is doubly buffered; while data are being read into one section of the memory from the previous stage, the data in the second section of the local memory are processed by the arithmetical elements. The DFT Processor outputs are handled in a similar manner. All the input-output operations are performed concurrent to actual computations; all compute cycles are therefore usable.

The program (microcode) for the DFT Processor resides in random-access memories (RAM) on a DFT Controller module. A single DFT Controller is used to control the DFT Processors that perform an identical task (such as the 28 DFT Processors performing the 1152-point DFT). The microcode for each DFT Controller can be downloaded from floppy disks by an LSI-11/23 microcomputer, used as the MCSA controller. It is possible to change algorithms in the field by reloading the microcode. The DFT Processors doing the 1152-point transforms, for example, may be reprogrammed to process the 1024-Hz signals in a different way.

### Design Aids

Much of the tedious work in the MCSA design is alleviated by a computer program which produces the wire-wrap tables. The program has access to a database of all the integrated circuit types used in the MCSA. A designer using this program could ignore the details of the integrated circuits such as physical pin positions, input loadings, and output drive capabilities. The aim of this program is to allow a designer to concentrate on the functions of a board rather than to keep track of every single detail. It provides the designer a tool analogous to what a high-level language provides a computer programmer.

The input to the program is a file of circuit descriptions. The integrated circuits used are declared, much like variable declarations in computer programming languages, giving their types and locations on the wire-wrap board. After that, each node in the design is defined by the symbolic name of the integrated circuit, as defined by its declaration, and the mnemonic representing a given pin on the integrated circuit, defined by a database entry for the particular integrated circuit type. The actual location on the board of each pin is kept track of by the program. To relocate an integrated circuit on a board, for example, one simply changes its declaration line, and the input file is resubmitted to the program.

In addition to symbolic module names, symbolic signal names can also be declared. The wire-wrap program creates interconnections between nodes that reference the same signal name.

A macro facility is provided for making repetitive commands, such as the wiring of data and address buses, less laborious. In addition to having the designer spend less time defining the circuit, errors are minimized and checking is also simplified.

The program provides an output file that can be written onto a magnetic tape which can be directly processed by an automatic wire-wrapping machine. In addition to the output tape, the program provides a printout of the circuit board layout, a cross-reference listing, and a signal run list. The latter items aid in debugging the design in addition to providing a uniform set of documentation for the MCSA. Thus, from a file of circuit descriptions typed in by the designer, the result is a completely wired board from a wire-wrap machine.

The wire-wrap program is implemented in the C Programming Language and currently runs on the DEC SYSTEM-20, using about 150k bytes of memory.

### Digital Bandpass Filter

The digital bandpass filter in the MCSA is implemented by combining the operations of a finite impulse response filter with an inverse DFT.

An  $n$ th order FIR filter (also known as a transversal filter or a tapped delay-line filter) consists of a delay-line of length  $n$ . Each of the delay stages has a tap brought out and multiplied by a gain constant. These weighted taps are then summed together at a single common node, forming the output of the FIR filter.

Consider an input sequence to the FIR filter that is in the form of a single impulse at time  $t_0$ . As time increases, the impulse appears at successive taps of the delay-line. Since the output is simply the sum of the weighted taps, the response of the FIR filter to a single impulse is just the time-ordering of the weights of the FIR filter, which, by definition, is the impulse response of the filter. Notice that the impulse response is identically zero before time  $t_0$  and after time  $t_{n-1}$  ( $n - 1$  time units later) — which leads to the term finite impulse response filter.

For an arbitrary input sequence  $x_\nu$ , the output sequence of an  $n$ th order FIR filter with weights  $h_\mu$ ,  $\mu = 0, 1, \dots, n - 1$  is given therefore by

$$y_\nu = \sum_{\mu=0}^{n-1} x_{\nu-\mu} h_\mu \quad (1)$$

A linear time-invariant filter is uniquely determined by its frequency response, which is just the Fourier transform of its impulse response. Thus, by an appropriate choice of the weights for the FIR filter, we can approximate various filter responses — in particular, lowpass filter responses, which are of primary interest here.

Various techniques exist for the determination of the FIR filter weights (impulse response) for realizing lowpass filters. The filters in the MCSA were designed with the Remez algorithm and the application of Dolph-Chebyshev windows.

Now, consider a FIR filter of order  $nm$ , for integers  $n$  and  $m$ , defined by its filter weights  $h_\lambda$ ,  $\lambda = 0, 1, \dots, nm - 1$ .

Given an input sequence  $x_\nu$ , we define  $y_\nu^k$ ,  $\kappa = 0, 1, \dots, n - 1$  by

$$y_\nu^k = \sum_{\mu=0}^{m-1} x_{\nu-\mu n-\kappa} h_{\mu n+\kappa} \quad (2)$$

This is a slight variant from the simple FIR filter in that there are  $n$  outputs, each computed as a sum of a subset of the taps of the delay-line. Each of the  $m$  components of the impulse response  $h_\mu$  in equation (2) is termed an active tap of the filter. From this, we take the  $n$ th order inverse DFT of  $y_\nu^k$ , to obtain the sequence  $z^k$ , i.e.,

$$z_\nu^k = \sum_{\mu=0}^{n-1} y_\nu^\mu e^{i(2\pi\mu\kappa)/n} \quad (3)$$

Defining

$$H_\mu^k = h_\mu e^{i(2\pi\mu\kappa)/n} \quad (4)$$

equations (2) and (3) can be combined and rewritten as

$$z_\nu^k = \sum_{\mu=0}^{nm-1} x_{\nu-\mu} H_\mu^k \quad (5)$$

Notice that equation (5) has the same form as equation (1), except for a different impulse response for each index  $\kappa$ . From equation (4), we see that each of the impulse responses  $H^k$  is simply the impulse response of the prototype filter,  $h$ , that has been translated in the frequency domain by the amount  $\kappa/n$ .

Thus, if the prototype filter were a lowpass filter, each output signal  $z^k$  would be a bandpass-filtered output of the input signal  $x$ , the location of the passband being a function of  $\kappa$ . If the prototype lowpass filter has a bandwidth of  $1/n$ , then the  $\kappa$  outputs would represent passbands which are non-overlapping and span the bandwidth of the input signal  $x$ .

Furthermore, given that each band is precisely  $1/n$  in width, by undersampling each of the output signals by a

factor of  $1/n$ , each signal is folded precisely into a lowpass (baseband) signal that is  $1/n$  wide, but representing its original bandpass. This implies that the entire arithmetical operation need be done only once each  $n$  time units. The computational complexity of an  $n$  band bandpass filter has thus been reduced approximately to that of a single FIR filter together with an  $n$ -point inverse DFT, at a computational rate of one iteration per  $n$  time units.

It should be pointed out that the inverse DFT is used here in an operational sense and not in the manner the inverse DFT is usually interpreted to be. Notice from equation (5) that even though the input signal has gone through a DFT, the signal  $z^k$ , for each  $k$ , remains a time-domain signal; i.e., for a given  $k$ ,  $z_n^k, z_{n+1}^k, z_{n+2}^k, \dots$  form a time sequence.

### Signal-to-Noise Ratio Loss Due to Quantization

Given a signal with Gaussian statistics that gets quantized to a 1-bit representation (i.e., only the polarity of the signal is preserved), it has been shown that there is no loss of spectral information, except for a degradation in the S/N of about 2 dB. This well-known fact has been applied to systems which require high-speed arithmetical operations.

Here, we shall derive the S/N loss for a general  $n$ -bit quantizer, given that the signal has Gaussian statistics. We shall also require that the quantizer be linear (but not necessarily uniform). Other constraints will be introduced at the appropriate times.

Let  $x(t)$  be a Gaussian process. Then the random variables  $x(t_1)$  and  $x(t_2)$  are jointly Gaussian with the joint probability density function of

$$f(x_1, x_2) = \frac{1}{2\pi\sigma^2\sqrt{1-\rho_x(\tau)}} \exp\left\{-\frac{x_1^2 + x_2^2 - 2\rho_x(\tau)x_1x_2}{2[1-\rho_x^2(\tau)]\sigma^2}\right\} \quad (6)$$

where

$$\begin{aligned} x_1 &= x(t_1) \\ x_2 &= x(t_2) \\ \tau &= |t_1 - t_2| \end{aligned}$$

Without any loss of generality, we can assume the variance  $\sigma^2$  to be unity. If we also assume that  $\rho_x(\tau) \ll 1$  for  $\tau \neq 0$ , then equation (6) can be approximated as

$$f(x_1, x_2) = \frac{1}{2\pi} \exp\left[-\frac{x_1^2 + x_2^2 - 2\rho_x(\tau)x_1x_2}{2}\right] \quad (7)$$

The second assumption implies that the power of any coherent signal is much smaller than the total power of the process  $x(t)$ .

Let  $\hat{x}(t)$  be the process which results from passing  $x(t)$  through a quantizing function  $\Xi(\cdot)$ ; i.e.,  $\hat{x}(t) = \Xi[x(t)]$ . We shall impose the restriction that  $\Xi(\cdot)$  be a bounded function. The autocorrelation function  $R_{\hat{x}}(\tau)$  of the process  $\hat{x}(t)$  can then be written as

$$R_{\hat{x}}(\tau) = \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 \Xi(x_1)\Xi(x_2)f(x_1, x_2) \quad (8)$$

In the limit  $\rho_x(\tau) \rightarrow 0$ , and using equation (7),

$$\begin{aligned} R_{\hat{x}}(\tau) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 \Xi(x_1)\Xi(x_2) \\ &\quad \times (1 + \rho_x(\tau)x_1x_2)\exp\left(-\frac{x_1^2 + x_2^2}{2}\right) \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 \Xi(x_1)\Xi(x_2)\exp\left(-\frac{x_1^2 + x_2^2}{2}\right) \\ &\quad + \frac{\rho_x(\tau)}{2\pi} \int_{-\infty}^{\infty} dx_1 \int_{-\infty}^{\infty} dx_2 x_1x_2\Xi(x_1)\Xi(x_2) \\ &\quad \times \exp\left(-\frac{x_1^2 + x_2^2}{2}\right) \end{aligned} \quad (9)$$

For an odd-valued quantizer function  $\Xi(\cdot)$ , the first term on the right hand side of equation (9) vanishes, leaving

$$R_{\hat{x}}(\tau) = \frac{2}{\pi} \left[ \int_0^{\infty} dx x\Xi(x)\exp\left(-\frac{x^2}{2}\right) \right]^2 \rho_x(\tau) \quad (10)$$

By definition,

$$\begin{aligned} R_{\hat{x}}(0) &= \int_{-\infty}^{\infty} dx \Xi^2(x)f(x) \\ &= \sqrt{\frac{2}{\pi}} \int_0^{\infty} dx \Xi^2(x)\exp\left(-\frac{x^2}{2}\right) \end{aligned} \quad (11)$$

From equations (10) and (11), we obtain the normalized autocorrelation function

$$\rho_{\hat{x}}(\tau) = \frac{R_{\hat{x}}(\tau)}{R_{\hat{x}}(0)} = \sqrt{\frac{2}{\pi}} \frac{\left[ \int_0^{\infty} dx x \Xi(x) \exp\left(-\frac{x^2}{2}\right) \right]^2}{\int_0^{\infty} dx \Xi^2(x) \exp\left(-\frac{x^2}{2}\right)} \rho_x(\tau) \quad (12)$$

Thus we see that the normalized autocorrelation function  $\rho_{\hat{x}}(\tau)$  of the quantized process has changed with respect to autocorrelation function  $\rho_x(\tau)$  of the original signal by a constant factor

$$\xi = \frac{\rho_{\hat{x}}(\tau)}{\rho_x(\tau)} = \sqrt{\frac{2}{\pi}} \frac{\left[ \int_0^{\infty} dx x \Xi(x) \exp\left(-\frac{x^2}{2}\right) \right]^2}{\int_0^{\infty} dx \Xi^2(x) \exp\left(-\frac{x^2}{2}\right)} \quad (13)$$

The power spectrum  $S_x(\omega)$  of a signal  $x(t)$  is simply the Fourier Transform of its autocorrelation function. By normalizing the autocorrelation function in the above equations, we have kept the total power of the process constant, independent of the quantizer function. We see from equation (13), that by doing this, the autocorrelation function, thus the power spectrum, of a quantized process has suffered a loss in gain with respect to the total power (signal + noise) of the process; i.e., by quantizing a signal, we have suffered a factor of  $\xi$  loss in the S/N.

Given any bounded function  $\Xi(\cdot)$ , we can compute  $\xi$  from equation (13). A 1-bit quantizer can be described by  $\Xi(x) = \text{sgn}(x)$ . With this, equation (13) evaluates to  $2/\pi$ , which is precisely the value previously obtained for the S/N loss for the hard-limiting quantizer.

For quantizer laws that are piecewise-constant (such as A/D convertors), equation (13) can be further simplified. Let a piecewise-constant quantizer be described by

$$\Xi(x) = \Xi_i \quad \text{for } x \in (\sqrt{2}x_{i-1}, \sqrt{2}x_i), i = 1, 2, \dots, n$$

and

$$\Xi(x) = -\Xi(-x) \quad \text{for } x < 0$$

where  $0 = x_0 < x_1 < \dots < x_{n-1} < x_n = \infty$ . Then the SNR loss is given by

$$\xi = \frac{2}{\pi} \frac{\left\{ \sum_{i=1}^n \Xi_i [\exp(-x_{i-1}^2) - \exp(-x_i^2)] \right\}^2}{\sum_{i=1}^n \Xi_i^2 [\text{erf}(x_i) - \text{erf}(x_{i-1})]} \quad (14)$$

where  $\text{erf}(\cdot)$  is the error function.

Given an  $m$ -bit uniform quantizer (i.e.,  $x_n - x_{n-1} = \alpha$  for  $i = 1, 2, \dots, 2^{m-1}$ ), we can vary the quantizer step size,  $\alpha$ , to obtain a minimum  $\xi$  from equation (14). This would then represent the optimal uniform quantizer for a signal with Gaussian statistics with a variance  $\sigma^2 = 1$ . (The optimal quantizer step size for a nonunit variance signal is scaled accordingly.)

The following is a listing of the S/N losses sustained by optimal  $m$ -bit quantizers:

| $m$ | S/N loss, dB |
|-----|--------------|
| 1   | 1.961        |
| 2   | .550         |
| 3   | .166         |
| 4   | .050         |
| 5   | .015         |
| 6   | .005         |
| 7   | .001         |

It should be noted that an ordinary A/D convertor does not satisfy the constraint that the quantizer law be an odd-valued function unless a bias equal to half a bit is introduced.

## APPENDIX C

### SIGNAL RECOGNITION

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#### Abstract

*This appendix discusses the set of algorithms which must examine the data coming from the MCSA. These algorithms, presently in software, will be implemented in hardware once they have been thoroughly tested, understood, and optimized for on-line operation.*

Although the algorithms described later in this appendix are now programs residing on the PDP 11/44 computer, they are not by any means necessarily final. Some of them, such as the Pulse Detection Algorithm have relatively firm theoretical support. Others are in the preliminary stages, comprising little more than optimization procedures with a few general requirements. An example of this is drifting CW, which is to be a table look-up algorithm, but in which the table is not yet specified. Still a third class is in between and contains elements of several time-tested procedures. Examples are the Baseline and Threshold Algorithms. Ultimately, the final form of all algorithms will be decided on the basis of field tests, simulation studies, and hardware implementation requirements.

This appendix has five major divisions. *SECTION 1* contains a rationale for optimizing detection algorithms for specific signal types, and an outline of these algorithms. *SECTION 2* summarizes the procedure now being used to develop a drifting CW detector using digital data. *SECTION 3* shows how to calculate the false alarm rate and the probability of missing a signal for the regular-pulse detector. *SECTION 4* relates a regular-pulse detector to one which searches for isolated large pulses. For those unsatisfied with the degree of rigor so far, *SECTION 5* is a careful treatment of the concepts in pulse detection as well as other problems related to SETI signal detection.

#### SECTION 1: INTRODUCTION

The range of possible signal types which may plausibly be transmitted by an ETI is large, and many classes of signals are practically indistinguishable from random noise unless the modulation scheme is known. Thus a decision was made early in the program to consider only those classes which were deliberately made easy to detect, principally by use of Fourier Transform techniques. In particular, algorithms were to be constructed for detecting signals which (1) are relatively narrowband, (2) are highly polarized, (3) are continuously present, or regularly pulsed, and (4) occur at a fixed frequency, or at a few fixed frequencies, or may be drifting by no more than a few Hz/sec. It was also decided that the algorithms should allow data of interest to RA to be preserved.

Five basic algorithms have been implemented in the phase 1 SETI Prototype System: BASELINE, HISTOGRAM, THRESHOLD, CW DETECTION, and PULSE DETECTION. Each algorithm has several modes of operation, or options, and may be exercised in an interactive as well as an unattended mode. The philosophy pursued during their creation was that field tests of the system and algorithms would lead to a selection of the most desirable options, which might then be incorporated into the hardware in later phases of the

SETI Prototype. Depending upon the operational circumstances and the limits dictated by the computing power of the PDP 11/44, these signal-processing algorithms may be exercised in real time, nearly real time, or off-line. What follows is a general description of the primary system algorithms and their interactions. The relative statistical power of the single pulse and regular pulse detectors is explained in some detail following the general system description. It should be pointed out that the description is a logical flow and may not correspond to the actual software implementation.

### BASELINE

The purpose of this algorithm is to determine the slowly changing background power level in each channel of the MCSA output and to prepare the individual MCSA sample arrays so that a meaningful threshold test may be applied. At the same time, the RA utility of the data must not be compromised. Given the diverse requirements of the sky survey, the targeted search, and RA, the baseline algorithm software package allows the investigator to choose any of the following options:

1. Determine the gain and zero-offset channel-by-channel by injecting a standard noise-power reference signal.
2. Use low-resolution data (e.g., 1-kHz) to define a baseline.
3. Use past channel-by-channel history to define current spectrum baseline with uniform or exponential averaging over time.
4. Fit a polynomial to the spectrum.
5. Apply a filter to remove unwanted frequency components from the spectrum.
6. Smooth the spectrum by averaging over frequency.

### HISTOGRAM

The purpose of this algorithm is to determine the system noise spectral density of residuals after the baseline algorithm has been applied and to compare this density with stored functions such as a Gaussian, Gamma Function, or another observed spectrum. Statistical tests by which the data will be compared to the stored functions are chi square, Kulbac, and Kolmogorov tests. HISTOGRAM also calculates the probability of missing a signal ( $p_{ms}$ ) as a function of the assumed S/N and the false alarm probability ( $p_{fa}$ ).

### THRESHOLD

The purpose of this algorithm is to identify channels in a spectrum in which signals may be present, consistent with a predetermined noise density,  $p_{fa}$ , and  $p_{ms}$ . It continuously

tests the noise statistics for consistency with the density function and passes along those channels exceeding threshold ( $\equiv$  a hit) to the CW and PULSE detection algorithms for further processing.

THRESHOLD makes use of BASELINE and HISTOGRAM and is in turn used by both CW and PULSE. It tests for residuals which exceed the background level by a predetermined multiple of the rms residual over a specified window. After some experience in the field, THRESHOLD will also incorporate an RFI discriminator.

### CW DETECTION

The purpose of this algorithm is to determine if there is a continuously present narrowband signal within the frequency interval being observed during the time the antenna is pointed at one portion of the sky. The signal may be fixed in frequency, or slowly drifting (but no more than a few Hz/sec).

This algorithm may be operated in several modes, depending upon the observing technique and rate of data acquisition. It makes use of the more basic algorithms (BASELINE, HISTOGRAM, and THRESHOLD) and applies them to individual spectrum samples or to accumulated spectra. The nondrifting CW detection may be carried out in real time in the phase I Prototype during target survey tests and slow sky survey tests, but it is not known whether this is possible for drifting CW. A drifting CW detection algorithm which uses a table look-up procedure to assign values to signals based on their frequency and drift rate will be tested in real time in phase I. The high speed and known scaling parameters of this algorithm make it a good candidate for use in a larger machine.

Once a hit has been passed on by the threshold algorithm, the tests to be applied depend on the observing technique. In a targeted search, the antenna tracks a point on the celestial sphere. Every spectrum or every accumulated spectrum is tested for hits. The investigator may choose to

1. Report the events on a monitor and magnetic tape.
2. Automatically shift the intermediate-frequency bandpass by a few channels in order to discriminate against intermediate-frequency interference.
3. Request the telescope operator to acquire a position on the celestial sphere which is slightly offset from the currently tracked position in order to discriminate against local RFI.
4. Record the spectrum for further off-line analysis.

In a sky survey, the antenna is continuously moving relative to the celestial sphere. In this case, the investigator will specify a coherence time over which a fixed point on the celestial sphere will remain in the beam, which depends on the antenna half-power beamwidth and scan rate. This algorithm will test the hits passed to it and report only those which have a duration less than or equal to the coherence

time specified. Depending on the scan rate, the algorithm may allow the investigator to request an automatic "wobble" of the intermediate-frequency bandpass in order to discriminate against intermediate-frequency interference. Otherwise, the investigator has the following options:

1. Report the events on a monitor and on magnetic tape.
2. Request a new scan over the suspected portion of the sky.
3. Request a target mode study over the suspected portion of the sky.
4. Record the spectra for off-line analysis.

If data rates are too high to carry out real-time analysis, a nearly-real-time mode of operation is available. Here the changing spectrum during a sweep across the sky is recorded directly on disk. The observing program then pauses while the algorithms are applied to the stored data at a rate acceptable to the PDP 11/44. A report is made and a new observing request appears on the monitor screen.

## PULSE DETECTION

This algorithm searches data for isolated occurrences of strong pulses, and for weaker but regularly spaced pulses having a minimum number of repetitions. Pulses may be defined in practice by either specifying one threshold for all spectra or by providing a variable threshold which produces a constant number of pulses per spectrum. Strong pulses so stand out above the noise that the associated  $p_{fa}$ s are adequately low. Weak pulses have poor individual  $p_{fa}$ s, but when they occur with some sort of regularity in the frequency-time-polarization plane, it takes only a few successive appearances to develop a good group- $p_{fa}$ . Requiring coherence in a low-duty-cycle pulse train allows a detector to work at appreciably higher sensitivity. In Fourier Transform terms, a single pulse is conjugate to a nondrifting carrier. If the carrier energy in, say, 100 samples with an S/N of  $\sim 1.3$ , is compressed into one sample, it can be easily identified after square-law detection. The energy stands out far more sharply against the noise in one sample than it did when it was distributed over 100 samples. Also, the pulse-train detector should be less susceptible to many kinds of RFI than a CW detector of equal energy sensitivity. The statistical background of this pulse detector is fully discussed later in this appendix.

One way to make a pulse-emitting beacon is to rotate a fan-beam antenna fed by a CW transmitter. Like a rotating lighthouse beam on the seashore, such a system provides a regular pulse train with effective peak power much higher than that of the CW transmitter.

## SECTION 2: DRIFTING CW

The development of a practical CW algorithm for the signal processor has proceeded by identifying the broad characteristics expected of an optimal algorithm, noting possible tradeoffs and limitations, and specifying details of an apparently attractive, but not necessarily optimal, implementation for the Prototype configuration.

### Definitions

1. A *bin* is one frequency channel for which the MCSA provides a complex report at regular time intervals.
2. A *spectrum* is composed of a large number of bins, contiguous in frequency, and all produced from the same unit-time-interval raw-data string.
3. A *signal*, for the purpose of *this discussion*, is considered to have the following characteristics:
  - a. Coherent over at least several unit time intervals.
  - b. Changes frequency linearly with time and by no more than a binwidth in a unit time interval.
  - c. Has approximately constant power which is mostly concentrated in one bin or in two adjacent bins of each spectrum.
4. *Noise*, at the output of the MCSA, has the following characteristics:
  - a. With, on the average, equal power in all bins of a time-frequency plot, bin power is exponentially distributed.
  - b. Phase not correlated from one bin to the next.
  - c. Phase not correlated from one spectrum to the next.
5. *Signal to noise ratio* (S/N) is the ratio of signal power to average noise power in one bin after detection.
6. A *bin report* is the complex number produced by the MCSA to represent that component of the received signal that falls within one frequency channel.
7. *Bin history* is a number incorporating several abbreviated bin reports. Phase quadrant and channel changes are obtained from the strongest related set of preceding bins.
8. A *state* is a number characterizing a complex bin report.

### Design Considerations

For  $S/N \geq 1$ , signal detection is easy. Therefore the algorithm design effort concentrates on marginally detectable signals. There is little advantage in being able to detect strong signals faster than weak signals and, in fact, slow but sure detection may weed out some types of RFI.

If a marginal signal is present, only a small amount of information about it is contained in one bin report. Most of the information in a bin report goes to define the noise that is present. Algorithm sensitivity depends strongly on the

total amount of information that can be retained from spectrum to spectrum for use in discriminating against unpromising signal paths.

### Algorithm Implementation

The algorithm attempts to concentrate the useful information from one bin report into a choice between only a few states. This information, which constitutes the retained history of any signal present, is combined with bin reports from the next spectrum. This larger sum of information is stored as a choice between a larger number of states, and the process can be continued. For each state, there is in principle a function which gives the probability that the observed state has occurred by chance. The longer the signal history that a state represents, the more sharply defined the probability density function (PDF) may be, and the more precisely signal parameters may be inferred. The number of states grows exponentially with the number of spectra, but by the time a few thousand states are defined, any new states required are adequately approximated by one of the previous states. The algorithm uses this determination of states both as an initial filter to find a manageable number of possible signals, and as a predictor of phase angle for continued coherent addition.

With each state there are expected bin reports for each of the three adjacent bins in the next spectrum where a signal, if present, should be found. The algorithm correlates these expected bin reports with the actual reports in order to achieve coherent addition. The addition may be continued as long as necessary to achieve the desired false alarm rate. Note that the phase of the expected report needs only to be accurate within about  $\pm\pi/4$  to achieve good results.

### Implementation Details

The best way to represent a bin report with a few bin states is not clear, but the following is a plausible trial solution.

1. Set a threshold midway between the mean expected amplitudes with and without the weakest signal the algorithm is expected to detect.
2. If the amplitude of a bin report is below threshold, bin state is defined to be 5.
3. Otherwise, let bin states 1 through 4 designate within which sector the bin report falls.

The computation that is done at run time is mostly just a matter of looking up new values in tables that use old and new values as indexes. One table translates from state to state, a second table provides expected bin reports, and a third normalizes accumulator sums. These tables may be laborious to construct and optimize, but once done they can be used indefinitely. The table containing bin history with state numbers and the table containing expected bin reports are relatively large. Both tables are indexed by (1) the old bin

history state number, (2) the current bin state number, and (3) an index ranging from 1 to 3 which designates the bin in the next spectrum through which the signal path must pass.

Several smaller tables are used to translate bin reports into bin states and complex products into accumulator increments. *Signal histories* consist of (1) bin history state number and (2) accumulator value.

In the Prototype implementation, one signal history is maintained for each bin. When updating the signal histories from spectrum to spectrum, there are several new signal histories generated for each location. The one with the highest accumulator value is the one actually retained. Note that accumulator values are scaled and normalized to be approximately linear with the negative log of the false alarm probability, independent of the number of spectra accumulated (see section 4). This allows direct comparisons between short, strong histories and long, weak histories. It also allows a single threshold for "bell ringing."

It should be pointed out that the justification for the foregoing implementation is essentially heuristic in nature. It is not mandated by a precise mathematical model. Therefore, though it is clear that table look-up is computationally efficient, the characteristics of the tables involved in CW detection will be refined by guided trial and error. As yet, this type of sequential detection strategy is optimized using simulation, since no general procedure exists.

## SECTION 3: REGULAR PULSES

The pulse-detection scheme presently implemented on the PDP-11/44 depends on the recognition of regular patterns of pulses having powers above a given threshold. A pulse may be defined by specifying either the threshold or the number of pulses per spectrum. Because broadband RFI is a likely signal type, the sort routine which finds the highest pulses in a spectrum is capable, in combination with a threshold, of specifying a peak power and bandwidth when many channels are involved. This can be used to save space in the pulse memory. If a pulse occurs in a cell of the standard frequency-time plot, it is represented by a 1, and a nonoccurrence by 0. A *channel* of the frequency-time plot consists of one spectral bin sampled at successive intervals. Call the number of cells in a channel  $N$ , and the probability of a 1 in a given cell  $p$ .

The probability  $p$  is determined by the pulse-detection algorithm and the signal strength, as well as the noise environment. It will be assumed for the present that  $p$  is known. Given  $p$  and  $N$ , we wish to compute the probability of a regular occurrence in one channel. A regular occurrence of length  $r$  is defined as a string of  $r$  1's having the same spacing between any two adjacent elements. There may be 1's between elements of the string, and the string may be longer than length  $r$ . For example, if  $r = 3$  and  $N = 7$ , the strings

“1010101” and “1110101” both qualify as regular. The string “1001100” does not.

For the case in which only Gaussian noise is present, the probability that a regular pattern will appear by chance ( $pfa$ ) can be calculated. The probability of  $x$  hits in a channel of length  $N$  is

$$f(x) = C(N,x)p^x q^{N-x}$$

where

$$q = 1 - p$$

and

$$C(N,x) = N!/(N-x)!x!$$

From this relation it follows that

$$f(x+1) = f(x)(p/q)(N-x)/(x+1)$$

This defines a recurrence relation for  $f(x)$ . In order to count the number of regular patterns, it will be necessary to generate them using a recurrence relation.

If there are  $r$  hits in a channel of length  $N$ , the number of regular patterns using all of these hits is

$$g(r) = \sum_{i=1}^{\ell} N - i(r-1)$$

where  $\ell(r-1) \leq N-1$ . That is, the sum includes no negative terms, but all possible positive terms. Therefore,  $\ell = \text{INT}[(N-1)/(r-1)]$ . Performing the summation gives

$$g(r) = N\ell - (r-1)\ell(\ell+1)/2$$

If  $\ell(r-1) = N-1$ , then

$$g(r) = N\ell - (N-1)(\ell+1)/2$$

If  $r=2$ , this result reduces to the correct answer for the number of combinations of two 1's with any spacing. If  $N \gg 1$ , then  $\ell \cong (N-1)/(r-1)$ , and

$$\begin{aligned} g(r) &= \ell(N-r+2)/2 \\ &\cong N^2/2(r-1) \end{aligned}$$

Assume that the first regular pattern of  $r$  hits is created, and that all hits thereafter are distinguishable from those filling the first pattern. Under this assumption, the probability of a regular pattern is

$$h(x,r) = g(r)C(N-r,x-r)(p^x q^{N-x})$$

where  $q = 1 - p$ . Note that  $h(x,r)$  overcounts the number of patterns since some are not really distinguishable.

$$h(x,r)/f(x) = g(r)[(N-r)!/N!] [x!/(x-r)!]$$

$$h(x,r) \leq g(r)f(x)$$

This sets an upper bound on the probability of a regular pattern.

It follows from the formula for  $h(x,r)$  that

$$h(x+1,r) = h(x,r)(p/q)(N-x)/(x-r+1)$$

It follows from this that if for any given  $x$  and  $r$

$$(p/q)(N-x)/(x-r+1) \leq 1$$

terms for larger  $x$  quickly approach zero. In particular, if  $Np \ll 1$

$$\sum_{x=r}^N h(x,r) \cong h(r,r) = g(r)p^r q^{N-r}$$

This limit is the typical case in the calculation of low false alarm rates. Substituting for  $g(r)$

$$h(r,r) \cong [N^2/2(r-1)]p^r q^{N-r}$$

It should be noted that the method outlined above does not yield the probability of a regular pattern if  $Np \geq 1$ . In such a case, which occurs when one is trying to calculate the probability of missing a signal which is actually present in the data, a different technique is required. Fortunately, in this case it is not necessary to calculate the probability of all regular patterns, but only that of the pattern present in the signal.

The S/N determines the probability of  $p$ . The string length  $N$  is the number of samples in which the signal may actually be detected. For a given  $p$  it is easier to detect a pulse with a high repetition frequency since the number of opportunities for detection is greater. Given the meanings of  $N$  and  $p$ , the probability of detection is the probability of detecting  $r$  1's in a row in the string  $N$ . This can be calculated using a recurrence relation developed as follows. Define a function  $j(k)$  on the string  $N$  such that  $j(k)$  is the probability that the elements of the string through  $k$  contain  $r$  1's in a row.  $r$  1's can occur for the first time in the  $(k+1)$ th place only if there is a 1 in this place, there is a 0 in the  $(k-r)$ th place, and all the places in between contain 1's. From this we have

$$j(k+1) = j(k) + [1 - j(k-r)]p^r q$$

In summary, this section has outlined the procedures for calculating false alarm statistics for the pulse detector. In the case of low false alarm probability, the number of regular patterns is given by a counting procedure. In the case where a signal is present, the probability of missing the signal is given by a recurrence relation. In intermediate cases the statistics can best be obtained by simulation since computational procedures of the type listed above become extremely cumbersome.

#### SECTION 4: PRELIMINARY STATISTICAL CONSIDERATIONS

The regular pulse and single pulse detectors can be analyzed using elementary statistical theory. This analysis is especially simple in the high S/N regime where detector behavior is determined solely by false alarm rate. The analysis also shows why incoherent CW detection is less efficient than pulse detection.

One voltage sample of either an in-phase or quadrature channel can be represented as:

$$v = s + n \quad (1)$$

where  $s$  is the signal voltage and  $n$  is a Gaussian noise voltage. The power in the sample is

$$p = v^2 \quad (2)$$

$$= s^2 + 2sn + n^2 \quad (3)$$

If  $s \gg n$  and  $\langle n^2 \rangle = 1$ , then  $n^2$  can be neglected in equation (3), yielding

$$p = s^2 + 2sn \quad (4)$$

Thus,  $p$  is a Gaussian variable with mean  $s^2$  and standard deviation  $2s$  if the noise power is normalized to unity. In general, if  $N$  independent samples are added, the total power  $p_t$  is a Gaussian variable with mean  $p_s$  and standard deviation  $2\sqrt{p_s}$ . Here,  $p_s$  is the total signal power.

To obtain a low false alarm rate for a single channel in the presence of noise alone, one must require a large voltage or power relative to the average noise level. For purposes of setting the false alarm threshold, power and voltage are equally good descriptions of the data channel. If the noise is that of equation (1), the power probability density is

$$f_1(p) = [1/\Gamma(1/2)] p^{-1/2} e^{-p} \quad (5)$$

where  $\Gamma(1/2)$  is the gamma function of  $1/2$ . If the convolution theorem and the characteristic function are used, it follows that the probability density function for the sum of  $N$  independent noise samples is

$$f_N(p) = [1/\Gamma(N/2)] p^{N/2-1} e^{-p} \quad (6)$$

where  $p$  is the total noise power. Since each MCSA power sample is the sum of the squares of an in-phase and quadrature voltage component, equation (6) yields the well-known result that one power sample of the MCSA is exponentially distributed.

If one considers only cases where an integer number  $Q$  of power channels is added

$$f_{2Q}(p) = [1/\Gamma(Q)] p^{Q-1} e^{-p} \quad (7)$$

Integration of this expression yields the probability of exceeding a given power  $p$  as

$$F_{2Q}(p) = \sum_{i=0}^{Q-1} [p^i/\Gamma(i+1)] e^{-p} \quad (8)$$

In the important case where  $N = 1$ , an approximation for the area of a Gaussian tail gives

$$F_1(p) = f_1(p) \quad (9)$$

Thus, for all of these distributions one may write a relation of the form

$$F_N(p_N) = g_N(p_N) e^{-p_N} \quad (10)$$

where  $g$  has a power-law form.

If two detectors summing different numbers of samples  $j$  and  $k$  have equal false alarm rates, then

$$g_j(p_j) e^{-p_j} = g_k(p_k) e^{-p_k} \quad (11)$$

Taking the logarithm of both sides

$$p_j - \ln(g_j) = p_k - \ln(g_k) \quad (12)$$

As  $p_j$  and  $p_k$  become large, the logarithmic terms can be neglected so that

$$p_j = p_k \quad (13)$$

This makes intuitive sense because the average power contribution from a few noisy samples is small compared to the threshold. If the threshold approaches the average noise and/or the number of samples becomes large, the detector is less efficient. This is why incoherent single pulse detection is more efficient than incoherent CW detection of the same total signal energy. In the high S/N limit, a pulse power detector is as efficient as a one-sample synchronous detector.

It can be seen from the argument following equation (4) that for large signals a 50% probability of missing the signal occurs when its power equals the threshold. To decrease this probability, one must have a signal such that

$$p_s = p + 2k\sqrt{p_s} \quad (14)$$

where  $p$  is the threshold value while  $k$  is found by using the inverse normal distribution and determines the probability of missing a signal. Dividing by  $p_s$  in equation (14) yields for large signals

$$p/p_s = 1 \quad (15)$$

This completes the proof that the threshold  $p$  describes detector behavior in the high signal limit and that in this limit the single pulse detector is ideal.

As long as the exponential term in equation (8) dominates, the regular pulse detector is also ideal. If the probability of one pulse exceeding threshold varies as  $e^{-p}$ , the probability of  $N$  pulses in a specified sequence doing so is

$$F_{\text{reg}} \sim (e^{-p})^N = c e^{-Np} \quad (16)$$

As before, the signal power must approximately equal the threshold power for detection in this high signal limit. If the total signal energy is split between the pulses equally, then

$$Np = p_s \quad (17)$$

Therefore

$$F_{\text{reg}} = c e^{-p_s} \quad (18)$$

This is the same form as that of the one pulse power detector, depending only on the total pulse energy. It is true, of course, that as signal power decreases or the number of regular samples required becomes large, the efficiency of this detector degrades toward that of incoherent detection. However, the detector is ideal for high S/N situations. In this limit, a regular pulse detector gains a factor of  $N$  in sensitivity over a single pulse detector, where  $N$  is the required length of the regular string, as can be seen from equation (16).

## SECTION 5: THEORETICAL CONSIDERATIONS IN SETI SIGNAL DETECTION

The central problem in SETI is the detection of the presence of a signal in a very wide band of thermal noise. (The signal may be of extraterrestrial origin or it may be ordinary RFI, so another important problem is to distinguish the two as nearly automatically as possible, but we will not consider that problem here.) To be readily detectable the signal should possess some form of temporal coherence that distinguishes it from the noise or other "natural" signals. Because most of our own transmitters radiate monochromatic (CW) carriers, because such signals are unknown in

nature, because they are, in a sense, the simplest type of signal, and because they are always present, much attention has been given in SETI to the detection of CW signals. However, as we shall see, pulses offer some advantages in that they reduce the problem of Doppler drift, permit polarization modulation (between right- and left-hand circular) pulse to pulse without affecting their detectability, and, perhaps most important, they require less average power. In a sense, we are always detecting pulses, for even a CW signal appears as a rectangular pulse whose duration is the observing time.

In the usual communication situation, a signal is known to be present in a certain frequency band and the task of the detector is to determine some property of the signal, say its amplitude, with the greatest possible S/N in the output. In SETI the signal is almost certainly not present in any given channel, and the task of the detector is to confirm its absence or detect its presence reliably with the least possible input S/N. Because of the vast number of channels in the microwave window (or even in the Waterhole) and because of the large number of directions to be interrogated in a sky survey, or of stars in a targeted search, it is necessary to automate the detection process as completely as possible. Practically, this means setting a threshold in each channel that will rarely be exceeded by noise alone to give a false alarm, but will be exceeded by a CW signal of sufficient power or a pulse of sufficient energy. Of course we want this power or energy to be as small as possible to minimize the probability of missing the signal. The criteria are thus different for the communications and SETI applications and so are the relative performances of different detectors. Nevertheless it is instructive to examine the communications case first.

### Matched Gating and Filtering

Let  $f(t)$  be a signal of finite duration and let  $n_k(t)$  be the added noise received on the  $k$ th sample. An optimum detection procedure is to multiply  $f(t) + n_k(t)$  by the proper gating function  $g(t)$  and to integrate the product to obtain

$$q_k = \int_{-\infty}^{\infty} g(t)[f(t) + n_k(t)] dt \quad (19)$$

$q_k$  will contain a signal "power"

$$q_s^2 = \left[ \int_{-\infty}^{\infty} g(t)f(t) dt \right]^2 = \left[ \int_{-\infty}^{\infty} G(\nu)^* F(\nu) d\nu \right]^2 \quad (20)$$

where  $*$  denotes the complex conjugate, and a mean "noise" power

$$\overline{q_n^2} = \text{Ave}_k \left[ \int_{-\infty}^{\infty} g(t)n_k(t) dt \right]^2 = \int_{-\infty}^{\infty} \psi(\nu)|G(\nu)|^2 d\nu \quad (21)$$

In these expressions  $\nu$  is cyclic frequency, the capital letters are the Fourier Transforms of their lowercase counterparts, and  $\psi(\nu)$  is the two-sided spectral power density of the noise. It is a straightforward problem in the Calculus of Variations to show that  $q_s^2/q_n^2$  is greatest if

$$G(\nu) = \lambda \frac{F(\nu)}{\psi(\nu)} \quad (22)$$

where  $\lambda$  is an arbitrary multiplier. If the noise is white thermal noise,  $\psi(\nu) = kT/2$  and

$$G(\nu) = \mu F(\nu) \quad (23)$$

so

$$g(t) = \mu f(t) \quad (24)$$

where  $\mu = 2\lambda/kT$  is another arbitrary multiplier. The gate now weights the contribution to  $q_k$  at each instant in proportion to the expected signal amplitude. The gate is open widest when the signal amplitude is greatest, is positive or negative along with the signal, and is shut when there is no signal.

If we precede the gating operation with a linear filter of transmission  $K(\nu)$ , then in equation (22)  $F(\nu)$  is replaced by  $F(\nu)K(\nu)$ , and  $\psi(\nu)$  is replaced by  $\psi(\nu)|K(\nu)|^2$  with the result

$$G(\nu)K(\nu)^* = \lambda \frac{F(\nu)}{\psi(\nu)} \quad (25)$$

Only the product  $G(\nu)\overline{K(\nu)}$  is specified. Deficiencies in either the gate shape or filter shape can be corrected by the other (except for zeros at real frequencies).

If we simply sample the output at  $t = 0$ , then  $g(t) = \delta(0)$ , and  $G(\nu) = 1$  so

$$K(\nu) = \frac{F(\nu)^*}{\psi(\nu)} \quad (26)$$

This matched filter weights the contribution at each frequency in proportion to the ratio of signal amplitude to noise power density at that frequency. The conjugacy causes all the Fourier components in the output to peak at  $t = 0$ , thereby producing the greatest ratio of peak signal to rms noise.

Substituting the condition of equation (22) into equations (20) and (21), we find that with a matched gate or matched filter-gate pair the S/N is given by

$$S/N = \frac{q_s^2}{q_n^2} = \int_{-\infty}^{\infty} \frac{|F(\nu)|^2}{\psi(\nu)} d\nu \quad (27)$$

Again, if the noise is white thermal noise,  $\psi(\nu) = kT/2$  and

$$S/N = \frac{2W}{kT} \quad (28)$$

where  $W$  is the pulse energy. This result shows that the pulse detectability depends only on the total pulse energy and is independent of how that energy is distributed in frequency or time. But this is true only if we know that distribution in advance so that we can construct a matched gate or filter. In SETI we have no such foreknowledge.

### Synchronous Detection

If the signal is a radio frequency (RF) pulse, then by equation (24) the gate will also be an RF pulse of the same envelope shape and phase. We can, of course, separate this operation into two steps: synchronous detection with a local oscillator of the same frequency and phase as the pulse, followed by a gating operation at baseband using a pulse having the shape of the RF pulse envelope. In SETI we do not know the RF frequency or phase in advance, and so we cannot use synchronous detection while searching. However, we can do so once the signal is found and, in any case, it is useful to know how far below the ideal our actual process falls.

Let us assume a CW signal  $A \cos \omega t$  and represent the noise as  $a(t)\cos \omega t + b(t)\sin \omega t$  where  $a(t)$  and  $b(t)$  are two statistically independent Gaussian variables of zero mean and equal variance (see fig. C-1). We then have

$$p(a) = \frac{1}{\sigma\sqrt{2\pi}} e^{-a^2/2\sigma^2} \quad (29a)$$

$$p(b) = \frac{1}{\sigma\sqrt{2\pi}} e^{-b^2/2\sigma^2} \quad (29b)$$

and

$$s(t) = [A + a(t)]\cos \omega t + b(t)\sin \omega t \quad (30)$$

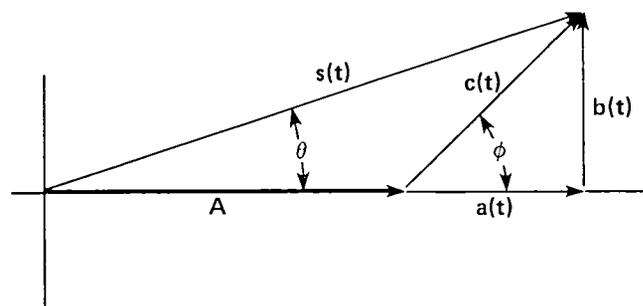


Figure C-1.— Vector relations between a signal,  $A$ , and the in-phase,  $a(t)$ , and quadrature,  $b(t)$ , components of the noise.

The signal power in equation (30) is  $S = (A \cos \omega t)^2 = A^2/2$  and the noise power is

$$N = \overline{(a(t)\cos \omega t)^2} + \overline{(b(t)\sin \omega t)^2} = \frac{\overline{a^2} + \overline{b^2}}{2} = \sigma^2 \quad (31)$$

so the input S/N is

$$\frac{S}{N} = \frac{A^2}{2\sigma^2} \quad (32)$$

Upon multiplying equation (30) by  $\sqrt{2} \cos \omega t$  we have

$$\sqrt{2}s(t)\cos \omega t = [A + a(t)] \frac{1 + \cos 2\omega t}{\sqrt{2}} + b(t) \frac{\sin 2\omega t}{\sqrt{2}} \quad (33)$$

We now filter out the double-frequency terms to obtain

$$\overline{\sqrt{2}s(t)\cos \omega t} = \frac{A + a(t)}{\sqrt{2}} \quad (34)$$

The noise  $b(t)$  does not appear in the output. After detection the signal power is  $S_1 = A^2/2$ , and the noise power is  $N_1 = \overline{a^2}/2 = \sigma^2/2$  for an output S/N of

$$\frac{S_1}{N_1} = \frac{A^2}{\sigma^2} = 2 \frac{S}{N} \quad (35)$$

The noise  $N$  is spread over two bands centered at  $\pm\omega$  with spectral density  $kT/2$ . The noise  $N_1$  is spread over one identical band centered at zero frequency. Thus we have half the noise power spread over half the bandwidth, which leaves the noise power spectral density unchanged.

Frequently two synchronous detectors are used with local oscillator inputs differing by  $90^\circ$  in phase. Let these inputs be  $\sqrt{2} \cos(\omega t - \phi)$  and  $\sqrt{2} \sin(\omega t - \phi)$  and let the signal be as before in equation (30). Then the in-phase and quadrature outputs will be

$$I = \frac{A + a(t)}{\sqrt{2}} \cos \phi + \frac{b(t)}{\sqrt{2}} \sin \phi \quad (36a)$$

$$Q = -\frac{A + a(t)}{\sqrt{2}} \sin \phi + \frac{b(t)}{\sqrt{2}} \cos \phi \quad (36b)$$

In a phase-locked detector the output  $Q$  is used to control the frequency of the local oscillator in such a way as to drive  $\phi$  to zero, whereupon  $I$  becomes the output (eq. (34)) of a

synchronous detector. Once the presence of a CW signal was detected in SETI, this technique would be used to improve the S/N.

If we form the quadratic sum  $I^2 + Q^2$  we obtain

$$I^2 + Q^2 = \frac{A^2}{2} + Aa(t) + \frac{a^2(t) + b^2(t)}{2} \quad (37)$$

which is exactly the output  $\overline{s^2(t)}$  of a square-law detector (see eq. (50)). There is thus no predetection advantage to using a pair of synchronous detectors in quadrature.

In calculating the statistics of the output, it is convenient to normalize all variables to the rms noise level. Thus we let

$$x(t) = \frac{A + a(t)}{\sigma} \quad \text{and} \quad h = \frac{A}{\sigma} \quad (38)$$

The probability density function of  $x$  is then found by replacing  $a^2/\sigma^2$  by  $(x - h)^2$  in equation (29a) and normalizing the result

$$p_1(x) = \frac{1}{\sqrt{2\pi}} e^{-(x-h)^2/2} \quad (39)$$

If we average  $n$  samples we find

$$p_n(x) = \sqrt{\frac{n}{2\pi}} e^{-n(x-h)^2/2} \quad (40)$$

The probability that noise alone exceeds a threshold  $T_n$  is found by setting  $h = 0$  in equation (40) and integrating from  $T_n$  to  $\infty$ . This is the probability of a false alarm in any one channel in the time corresponding to the reciprocal bandwidth. Thus

$$\begin{aligned} p_{fa} &= \sqrt{\frac{n}{2\pi}} \int_{T_n}^{\infty} e^{-nx^2/2} dx \\ &= \frac{1}{\sqrt{2\pi}} \int_{T_n}^{\infty} e^{-(\sqrt{nx})^2/2} d(\sqrt{nx}) \end{aligned} \quad (41)$$

Let the function

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\lambda^2/2} d\lambda \quad (42)$$

Then, letting  $\lambda = \sqrt{nx}$ , we see from equation (41) that

$$T_n = \frac{Q^{-1}(p_{fa})}{\sqrt{n}} = \frac{T_1}{\sqrt{n}} \quad (43)$$

The probability,  $p_{ms}$ , of missing the signal is the integral from  $-\infty$  to  $T_n$  of equation (40) which is 1 minus the integral from  $T_n$  to  $\infty$ . Thus

$$1 - p_{ms} = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{n}(T_n - h_n)}^{\infty} e^{-[\sqrt{n}(x-h)]^2/2} d[\sqrt{n}(x-h)] \quad (44)$$

Again, letting  $\lambda = \sqrt{n}(T_n - h_n)$ , we see from equation (42) that

$$\sqrt{n}(T_n - h_n) = Q^{-1}(1 - p_{ms}) \quad (45)$$

or

$$h_n = \frac{Q^{-1}(p_{fa}) - Q^{-1}(1 - p_{ms})}{\sqrt{n}} = \frac{Q^{-1}(p_{fa}) + Q^{-1}(p_{ms})}{\sqrt{n}} \quad (46)$$

$h_n$  is the normalized signal amplitude needed for the assumed  $p_{fa}$  and  $p_{ms}$ . Since the input noise power  $N = \sigma^2$ , the required threshold is

$$10 \log \frac{T_n^2}{2} = 20 \log T_1 - 10 \log 2n \text{ dB} \quad (47)$$

above the input noise level, and the required input S/N is

$$10 \log \frac{h_n^2}{2} = 20 \log h_1 - 10 \log 2n \text{ dB} \quad (48)$$

Equations (47) and (48) show a linear relation between dB and  $\log n$ . Both the threshold and the required S/N decrease 3 dB for every doubling of  $n$ . This is consistent with the doubling of  $W$  in equation (28) since we can regard a string of pulses twice as long as a single signal  $f(t)$  of twice the energy whose matched gate is a string of pulses twice as long.

It will be seen that the calculation of  $Q^{-1}$  is an iterative procedure. Fortunately, we need calculate only one  $Q^{-1}$  for each  $p_{fa}$  and each  $p_{ms}$ . Further, by making the set of  $p_{fa}$  include  $p_{ms}$  or  $1 - p_{ms}$ , we can compute the curves for all  $p_{fa}$  and all  $p_{ms}$  from one set of  $Q^{-1}$ .

### Square Law Detection

A square law detector is a square law device followed by a filter that removes all double-frequency RF terms. If the input is  $s(t)$  as given by equation (30), the output of the square law device will be

$$s^2(t) = [A + a(t)]^2 \frac{1 + \cos 2\omega t}{2} + [A + a(t)] f(t) \sin 2\omega t + b^2(t) \frac{1 - \cos 2\omega t}{2} \quad (49)$$

and, after filtering

$$\overline{s^2(t)} = \frac{A^2}{2} + Aa(t) + \frac{a^2(t) + b^2(t)}{2} \quad (50)$$

The first term in equation (50) is the signal power, the last term is the "instantaneous" noise power, and the second term is the cross product of the signal and in-phase noise amplitudes. The second and third terms fluctuate and thereby contribute noise to the output. The mean square value of the second term is

$$A^2 \overline{a^2(t)} = A^2 \sigma^2 = 2SN \quad (51)$$

Let  $P_1 = [a^2(t) + b^2(t)]/2$ . Then  $\overline{P_1} = N = \sigma^2$ . As we shall see later,  $P_1$  is exponentially distributed. Thus the mean square departure from the mean

$$\overline{(P_1 - N)^2} = \overline{P_1^2} - N^2 = 2N^2 - N^2 = N^2 \quad (52)$$

(See eqs. (68) through (71) with  $n = 1$ .)

The output  $\overline{s^2(t)}$  of a square law detector is the *amplitude* of some variable: a current, a voltage, or a temperature. In expressing the output S/N *power* ratio we take the ratio of the square of the component due to the signal to the mean square fluctuation due to the noise. Thus we take  $S_2 = (A^2/2)^2$  and  $N_2 = 2SN + N^2$  and obtain for the output S/N

$$\left( \frac{S_2}{N_2} \right) = \frac{(S/N)^2}{1 + 2(S/N)} \quad (53)$$

For  $S/N \gg 1$  the output S/N is half the input S/N: 3 dB worse rather than 3 dB better, as we found for the synchronous detector. For  $S/N \ll 1$ , the output S/N is the square of the input S/N. For example, an input S/N of -20 dB will produce an output S/N of ~-40 dB. The reasons for this behavior can be seen by comparing the multiplication involved in synchronous detection or matched gating with that in square law detection. Reverting to our original notation with  $f(t) = A \cos \omega t$  (or  $A(t) \cos \omega t$ ) and  $n(t) = c(t) \cos[\omega t + \phi(t)]$  where  $c^2(t) = a^2(t) + b^2(t)$  and  $\phi(t) = \tan^{-1}[b(t)/a(t)]$  (see fig. C-1), we have for synchronous detection or matched gating,

$$f(t)[f(t) + n(t)] = f^2(t) + f(t)n(t) \quad (54)$$

while for square law detection:

$$[f(t) + n(t)] [f(t) + n(t)] = f^2(t) + 2f(t)n(t) + n^2(t) \quad (55)$$

Of course in synchronous detection or matched gating, the gate, which appears as  $f(t)$  in equation (54), does not vary as the signal amplitude changes and the detection is therefore linear, but the S/N would be unaffected if it did.

At high S/Ns, when the last term in equation (55) becomes negligible, we see that the cross-product noise term has twice the *amplitude* of the noise term in equation (54). Regarding the first factor on the left of equations (54) and (55) as the gate, we see that the square law detector does its own gating, but with a correlated noisy gate. At high S/Ns the penalty is 6 dB, but at S/Ns less than unity the noise becomes the gate and the signal is suppressed.

### Linear (Absolute Value) Detection

A linear, or absolute value, detector may be thought of as a square law detector followed by a device that restores linearity by taking the square root of the output. From equation (50) we see that the output will be

$$\sqrt{s^2(t)} = \left( \frac{A + a(t)}{\sqrt{2}} \right) \sqrt{1 + \left( \frac{b(t)}{A + a(t)} \right)^2} \quad (56)$$

For high S/Ns

$$\sqrt{s^2(t)} \approx \frac{A + a(t)}{\sqrt{2}} + \frac{1}{2\sqrt{2}} \frac{b^2(t)}{A + a(t)} \quad (57)$$

and we see that the quadratic noise is suppressed, leaving the S/N almost as good as with synchronous detection – and 6 dB better than with square law detection. The reason for this is apparent from figure C-2, which shows the transfer characteristics of a square law detector as the parabola  $S'OS$  and of an absolute value linear detector  $L'OL$  which matches the output signal amplitude at the operating points  $P'$  and  $P$ . The slope of the parabola at  $P'$  and  $P$  is twice that of the straight lines. Thus input noise amplitude fluctuations about the signal level produce twice the output amplitude fluctuations in the square law case.

So far as detecting the presence of a signal, however, the linear detector offers no advantage over the square law since the same statistics are merely remapped on a new scale which is the square root of the original. This leaves the monotonicity for points relative to the threshold unaffected.

### Phase and Magnitude Statistics

Referring to figure C-1 and equation (29), we see that, because  $a(t)$  and  $b(t)$  are statistically independent, the proba-

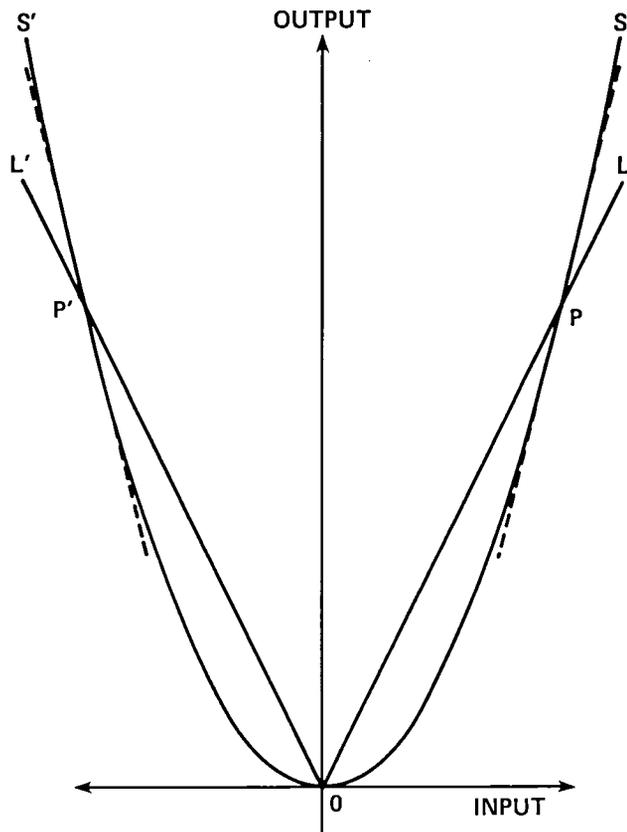


Figure C-2.— A square-law device has twice the slope of a linear (absolute value) device at the operating point  $P$  and hence doubles the amplitude of small modulations due to noise.

bility that  $a$  lies in the range  $a$  to  $a + da$  and that  $b$  lies in the range  $b$  to  $b + db$  is

$$p(a)da \times p(b)db = \frac{1}{2\pi\sigma^2} e^{-[(a^2+b^2)/2\sigma^2]} da db \quad (58)$$

Since  $a^2 + b^2 = c^2 = A^2 + s^2 - 2As \cos \theta$  and  $da db = s ds d\theta$ , the probability density as a function of  $s$  and  $\theta$ , as shown in figure C-1, is

$$p(s,\theta) = \frac{s}{2\pi\sigma^2} e^{-[(A^2+s^2-2As \cos \theta)/2\sigma^2]} \quad (59)$$

The probability density as a function of  $\theta$  is found by integrating equation (59) over all  $s$ . If we let  $q = s^2/2\sigma^2$  be the instantaneous total power to average noise power ratio,  $r = A^2/2\sigma^2 = S/N$  be the signal power to noise power ratio, and if we let  $x = \sqrt{r} \cos \theta$ , and  $y = \sqrt{r} \sin \theta$ , then the result is (Grubner and Hofreiter, 1950)

$$p(\theta) = \frac{1}{2\pi} [e^{-r} + \sqrt{\pi x} e^{-y^2} \operatorname{erfc}(-x)] \quad (60a)$$

Making use of 7.16 in Abramowitz and Stegun (1964)

$$p(\theta) = \frac{1}{2\pi} [e^{-r} w(x) + \sqrt{\pi} x e^{-y^2}] \quad (60b)$$

where

$$w(x) = 1 + \frac{2x^2}{1} \left( 1 + \frac{2x^2}{3} \left( 1 + \frac{2x^2}{5} \left( 1 + \dots \right) \dots \right) \right) \quad (61)$$

For  $r \ll 1$ ,  $p(\theta) \rightarrow \left[ \frac{1}{\sqrt{2\pi}} \right] [1 + \sqrt{\pi r} \cos \theta]$  so that

$$\frac{p(0)}{p(\pi)} \rightarrow \frac{1 + \sqrt{\pi r}}{1 - \sqrt{\pi r}} \rightarrow 1 + 2\sqrt{\pi r} = 1 + \sqrt{2\pi} \frac{A}{\sigma} \quad (62)$$

This ratio varies linearly with signal amplitude and is therefore a sensitive early indicator of the presence of a signal. The problem, as usual, is that we do not know  $\theta$  in advance. Figure C-3 shows  $p(\theta)$  for various values of  $r$ .

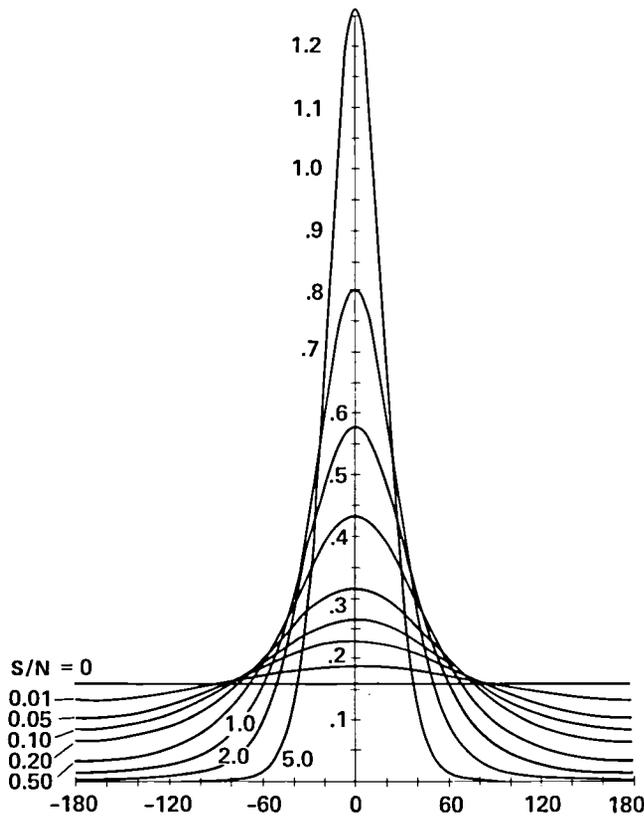


Figure C-3.— Probability density distributions of the phase of random Gaussian noise plus an added sine wave of zero phase.

The probability density as a function of  $s$  is found by integrating equation (59) over all  $\theta$  with the result

$$p(s) = \frac{r}{\sigma^2} e^{-(A^2+s^2)/2\sigma^2} I_0 \left( \frac{Ar}{\sigma^2} \right) \quad (63)$$

Where  $I_0$  is the zero-order modified Bessel function of the first kind. If we replace the variables in equation (63) with our normalized variables  $q$  and  $r$ , we obtain

$$p(q) = e^{-(r+q)} I_0(2\sqrt{rq}) \quad (64)$$

The characteristic function (Fourier Transform) of equation (64) is

$$C(\omega) = \frac{e^{i\omega q/(1+i\omega)}}{1+i\omega} \quad (65)$$

If we add  $n$  independent samples, the resulting distribution is the  $(n-1)$ -fold convolution of  $p(q)$  and is the inverse transform of  $C^n(\omega)$ : If we then replace  $q$  by  $z = q/n$ , we get the distribution of the *average* of  $n$  samples

$$p_n(z) = n e^{-n(r+z)} \left( \frac{z}{r} \right)^{(n-1)/2} I_{n-1}(2n\sqrt{rz}) \quad (66)$$

Making use of the ascending series for  $I_{n-1}$ , this can be written:

$$p_n(z) = \frac{n^n z^{n-1} e^{-n(r+z)}}{(n-1)!} \left[ 1 + \frac{n^2 r z}{1n} \left( 1 + \frac{n^2 r z}{2(n+1)} \left( 1 + \dots \right) \dots \right) \right] \quad (67)$$

If we set  $r = 0$  in equation (67) we find

$$p_n(z) = \frac{n^n z^{n-1} e^{-nz}}{(n-1)!} \quad (68)$$

which is the probability density function for the average of  $n$  samples of noise alone. The mean value of  $z$  is

$$\bar{z} = \int_0^\infty z p(z) dz = \int_0^\infty \frac{(nz)^n e^{-nz}}{n!} d(nz) = 1 \quad (69)$$

while the mean square value is

$$\begin{aligned} \overline{z^2} &= \int_0^\infty z^2 p(z) dz = \frac{1}{nn!} \int_0^\infty (nz)^{n+1} e^{-nz} d(nz) \\ &= \frac{(n+1)!}{nn!} = \frac{n+1}{n} \end{aligned} \quad (70)$$

Thus the mean square fluctuations about the mean are

$$\overline{(z - \overline{z})^2} = \overline{z^2} - \overline{z}^2 = \frac{n+1}{n} - 1 = \frac{1}{n} \quad (71)$$

The probability of a false alarm is the integral of equation (68) from the threshold  $T_n$  to infinity:

$$p_{fa} = e^{-nT_n} \sum_{k=0}^{n-1} \frac{(nT_n)^k}{k!} \quad (72)$$

Since equation (72) cannot be inverted to give  $T_n$  explicitly, one must find  $T_n$  by iteration. The probability,  $p_{ms}$ , of missing the signal is then the integral of equations (66) or (67) from 0 to  $T_n$ . Since this integral does not appear to be known in closed form, it is necessary to integrate equation (67) numerically. Finally, since we are interested in the value of  $r$  that gives  $p_{ms}$  some assumed value, the numerical integration, each ordinate of which involves summing the series equation (67), must itself be iterated. These lengthy calculations have been performed, and the results are available, giving, for selected values of  $n$  from 1 to 1600, the threshold in dB above the noise level needed to achieve  $p_{fa} = 10^{-i}$  ( $i = 1, 2, 3, \dots, 20$ ) and with these thresholds the S/N needed for  $p_{ms} = 0.99, 0.9, 0.5, 0.1, 0.01$ . We will present here only a few of the results in graphical form.

Figure C-4 shows in dB above or below the input noise level the threshold settings required to achieve false alarm probabilities of  $10^{-4}, 10^{-8}, 10^{-12}, 10^{-16}$ , and  $10^{-20}$ . Also shown are the input S/Ns needed to have no more than a 50% chance of missing the signal with each of these thresholds. The abscissa is the number of samples averaged, ranging from 1 to 1000. For example, if 100 samples are averaged, and we wish a false alarm probability of  $10^{-12}$ , we must set the threshold 2.7242 dB above the noise level. Then a signal 0.5706 dB below the noise will have a 50% chance of detection.

Figure C-5 shows, for this same false alarm probability, the input S/Ns needed versus  $n$  for probabilities of missing the signals of 0.99, 0.9, 0.5, 0.1, and 0.01. We note that if we have only one sample, a change in signal level of 5.71 dB takes us from having only a 1% chance of detecting the signal to only a 1% chance of missing it. At 1024 samples a change of 3.36 dB covers the same range.

Figure C-6 compares the detection performance at  $p_{fa} = 10^{-12}$  and  $p_{ms} = 0.5$  of a square law detector and a

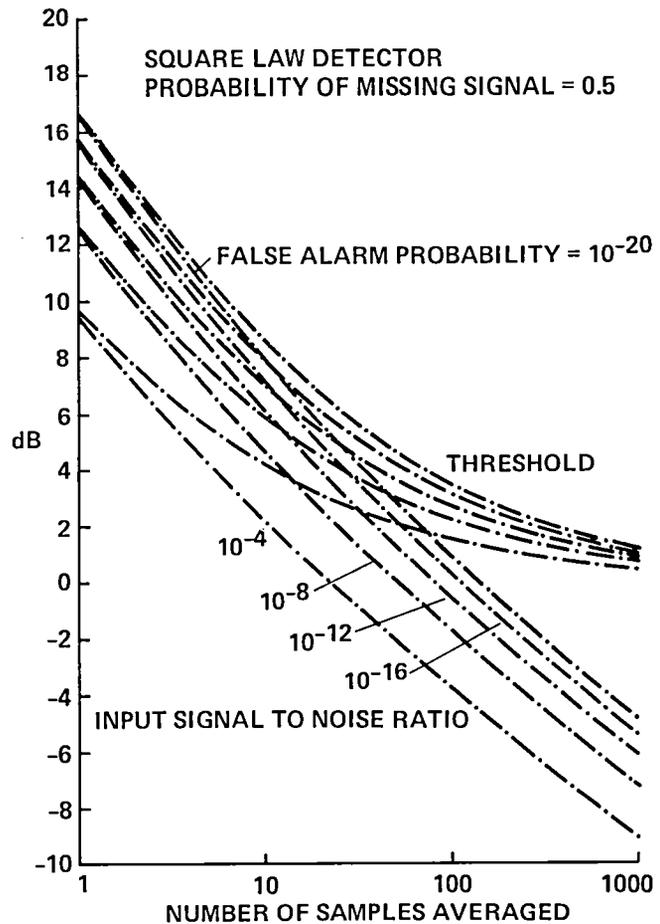


Figure C-4.— Effect of averaging  $n$  samples upon the threshold required to achieve false alarm probabilities of  $10^{-4}, 10^{-8}, 10^{-12}, 10^{-16}$ , and  $10^{-20}$ , and upon the S/N required to exceed that threshold with probability  $1/2$ .

synchronous detector. We see that at the high S/Ns required for the detection of a signal with only a few samples averaged, the performance of the square law detector is within a fraction of a dB of the synchronous detector. At the low S/Ns possible when many samples are averaged, the square law detector is considerably poorer.

Figure C-6 also illustrates an advantage of pulses over CW signals. To detect (with 50% probability and  $p_{fa} = 10^{-12}$ ) a CW signal in a single sample requires a S/N of 14.3344 dB. If we average 100 samples, the required S/N drops to -0.5706 dB for a 14.9-dB improvement. However, if the entire energy received in the 100 samples in the latter case had been radiated in a pulse received as a single sample, the S/N would have been  $20 - 0.5706 = 19.4294$  dB or 5.095 dB above the S/N for 50% detectability. This means that the original performance could be achieved with 31% as much average power as for the CW case. (We of course assume, in this example, that a pulse is sent every 100 samples.)

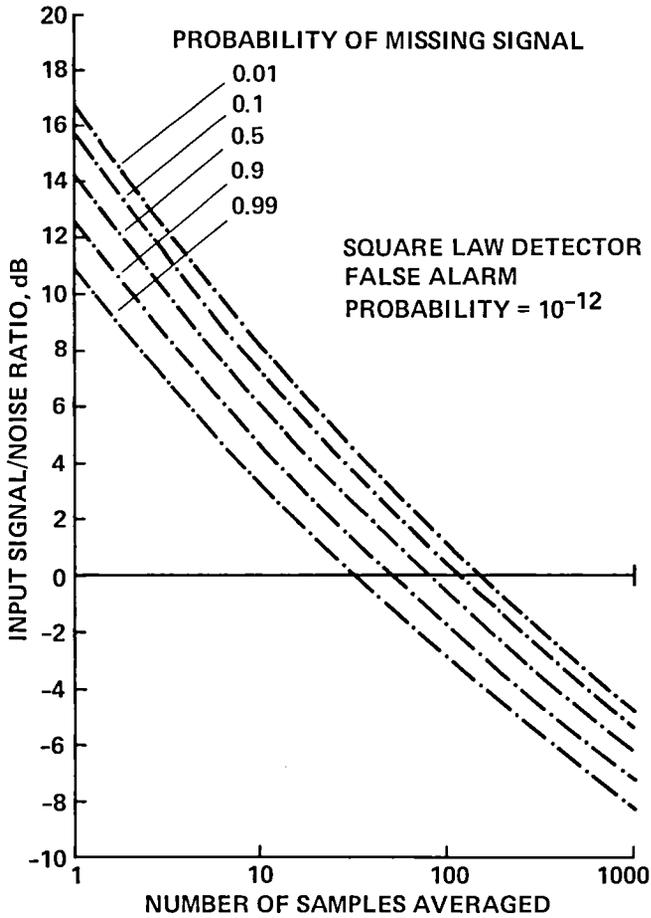


Figure C-5.— Effect of averaging  $n$  samples on the  $S/N$  needed to achieve probabilities of missing the signal of 0.99, 0.9, 0.5, 0.1, and 0.01 when the threshold is set to give a false alarm probability of  $10^{-12}$ .

We use this same technique in mundane applications. Every time the lighthouse beam sweeps past us, we receive as much energy as from the bare bulb in the time of one revolution, but the flash is more detectable.

### MCSA Detection

The narrow bandwidth needed to approximate a matched filter to a CW signal or to long pulses, together with the enormous bandwidth of the microwave window or even the Waterhole, has been one of the problems of SETI since the beginning. The Cyclops study proposed the use of many optical Fourier transformers, each converting a megahertz of spectrum into  $10^6$  channels 1 Hz wide or  $10^7$  channels 0.1 Hz wide. During the early 1980s it has become increasingly feasible to do megapoint digital Fourier Transforms

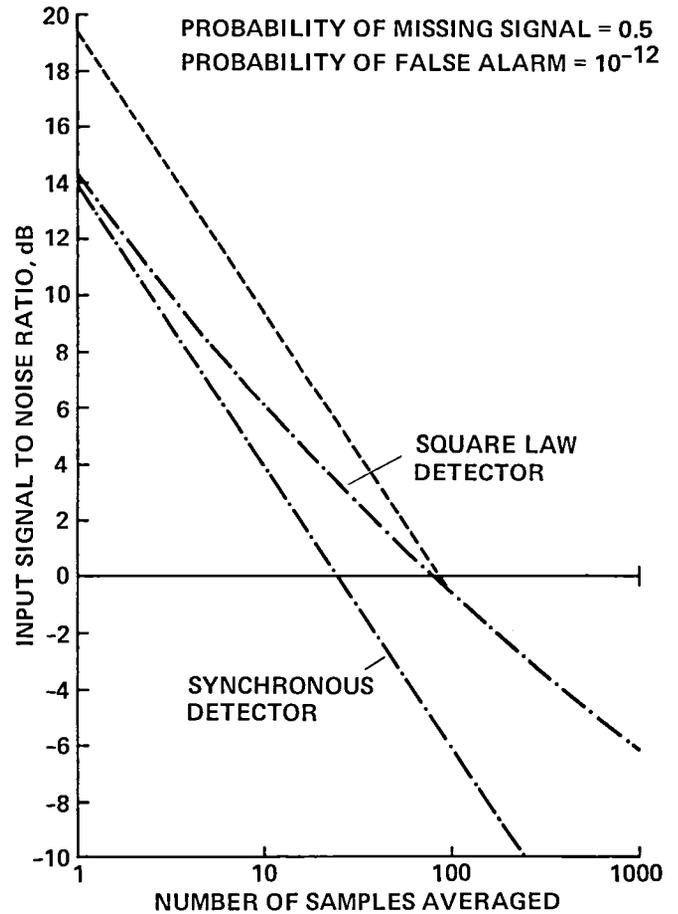


Figure C-6.— Comparison of the effect on the required  $S/N$  of averaging  $n$  samples with synchronous vs square law detection. For high  $S/N$ s, the square law detector is nearly as good as a synchronous detector. With square law detection it is better to take the energy received in  $n$  samples and send in a pulse received in one sample, as shown by the dashed line for  $n = 100$ .

using large-scale integrated circuits. This is the preferred technology for SETI today.

An MCSA has a large number,  $N$ , of channels, or bins, each of bandwidth  $b$ , giving a total bandwidth  $B = Nb$ . Typically  $B \sim 10^7$  Hz, and  $b$  may be as wide as a kilohertz or as narrow as 1 Hz or less. In effect, the MCSA multiplies the received signal by  $\cos \omega_i t$  and  $\sin \omega_i t$  and integrates the products for a time  $\tau = 1/b$  to obtain an in-phase amplitude,  $I$ , and a quadrature amplitude,  $Q$ , for bin  $i$ , where  $\omega_i$  is the center frequency of bin  $i$ . If the signal is  $A \cos(\omega t + \phi)$  and  $\eta \cos(\xi t + \psi)$  is a sinusoidal noise component, then  $I$  and  $Q$  are given by

$$\left. \begin{matrix} I \\ Q \end{matrix} \right\} = \int_{-\tau/2}^{\tau/2} [A \cos(\omega t + \phi) + \eta \cos(\xi t + \psi)] \frac{\sqrt{2}}{\tau} \begin{pmatrix} \cos \\ \sin \end{pmatrix} \omega_i t dt \quad (73)$$

where we have introduced the factor  $\sqrt{2}/\tau$  to keep the results consistent with our earlier equations. If we retain only difference frequencies from the multiplications in equation (73), and if we let

$$\gamma = (\omega - \omega_i)\tau/2 \quad (74a)$$

$$\delta = (\zeta - \omega_i)\tau/2 \quad (74b)$$

be the phase shifts that accrue in a half integration time from the frequency offsets of  $\omega$  and  $\zeta$  from the bin center frequency  $\omega_i$ , then we find

$$I \Big\} = \pm \left[ \frac{A}{\sqrt{2}} \frac{\sin \gamma}{\gamma} \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix} + \frac{\eta}{\sqrt{2}} \frac{\sin \delta}{\delta} \begin{pmatrix} \cos \psi \\ \sin \psi \end{pmatrix} \right] \quad (75)$$

where all upper and lower alternatives are taken together. Now let  $P = I^2 + Q^2$ . We then find

$$P = \frac{A^2}{2} \frac{\sin^2 \gamma}{\gamma^2} + A\eta \cos(\psi - \phi) \frac{\sin \gamma}{\gamma} \frac{\sin \delta}{\delta} f_n(\delta - \gamma) + \frac{\eta^2}{2} \frac{\sin^2 \delta}{\delta^2} \quad (76)$$

where for the single sample we have been considering  $f_1(\delta - \gamma) = 1$ . If we now average  $n$  successive samples in time, the first and third terms are formally unaltered though the statistics of the third term change. For the middle term we find

| $n$ | $f_n(\delta - \gamma)$   |
|-----|--|
| 1   | 1  |
| 2   | $(1/2)[2 \cos(\delta - \gamma)]$   |
| 3   | $(1/3)[1 + 2 \cos 2(\delta - \gamma)]$   |
| 4   | $(1/2)[\cos(\delta - \gamma) + \cos 3(\delta - \gamma)]$                           |
| 5   | $(1/5)[1 + 2 \cos 2(\delta - \gamma) + 2 \cos 4(\delta - \gamma)]$                 |
| 6   | $(1/4)[\cos(\delta - \gamma) + \cos 3(\delta - \gamma) + \cos 5(\delta - \gamma)]$ |

If we call  $S = A^2/2$  the signal power, then  $\overline{\eta^2}/2 = kT \Delta f$  is the noise power in  $\Delta f$ , and the mean value of the third term in equation (76), when integrated over all frequencies, is

$$N = kT \int_{-\infty}^{\infty} \frac{\sin^2 \delta}{\delta^2} df = kT \frac{1}{\pi\tau} \int_{-\infty}^{\infty} \frac{\sin^2 \delta}{\delta^2} d\delta = kTb \quad (77)$$

If  $P_1$  is the instantaneous value of the third term integrated over all frequencies, then the statistics of  $z = P_1/N$  are given by equation (68), and the mean square fluctuations about the mean are therefore

$$P_3 = \frac{(kTb)^2}{n} = \frac{N^2}{n} \quad (78)$$

Since  $\psi$  is uniformly distributed, the mean square of  $\cos(\psi - \phi)$  is  $1/2$ . Thus the mean square fluctuations of the cross product term are

$$P_c = 2S \frac{\sin^2 \gamma}{\gamma^2} \frac{kT}{\pi\tau} \int_{-\infty}^{\infty} \frac{\sin^2 \delta}{\delta^2} f_n^2(\delta - \gamma) d\delta \quad (79)$$

When  $n = 1$

$$P_c = 2S \frac{\sin^2 \gamma}{\gamma^2} kTB = 2SN \frac{\sin^2 \gamma}{\gamma^2} \quad (80)$$

If  $\gamma = 0$  (signal is at center of bin), it is easy to show that the integrand in equation (79) becomes

$$\frac{\sin^2 n\delta}{(n\delta)^2} \quad (81)$$

or, in other words, that the noise bandwidth is inversely proportional to the total integration time. When  $\gamma \neq 0$  the transmission peaks in the spectrum are shifted and the noise spectrum becomes more complex. Figure C-7 shows  $(\sin \delta/\delta)f_{10}(\delta - \gamma)$  as a function of  $\delta$  when  $\gamma = \pi/2$ .

Although we have not proved it, generally, we have shown that for  $n = 1, 2, 3, 4$  the integral in equation (79) is independent of  $\gamma$ . We therefore assume that

$$P_c = \frac{2SN}{n} \frac{\sin^2 \gamma}{\gamma^2} \quad (82)$$

Again, if we call  $[(A^2/2)(\sin^2 \gamma)/\gamma^2]^2$  the output signal power in equation (76) and  $P_c + P_3$  the noise power, we find

$$\left( \frac{S_2}{N_2} \right) = \frac{(S/N)^2 (\sin^4 \gamma)/\gamma^4}{1 + 2(S/N)(\sin^2 \gamma)/\gamma^2} n \quad (83)$$

which is exactly our old result (eq. (53)) for the square law detector except for the inclusion of the filter factor in the signal power and for the factor  $n$ , which represents the benefit from averaging  $n$  samples. Remember that this is the improvement in *output* S/N with averaging, not the improvement in signal detectability.

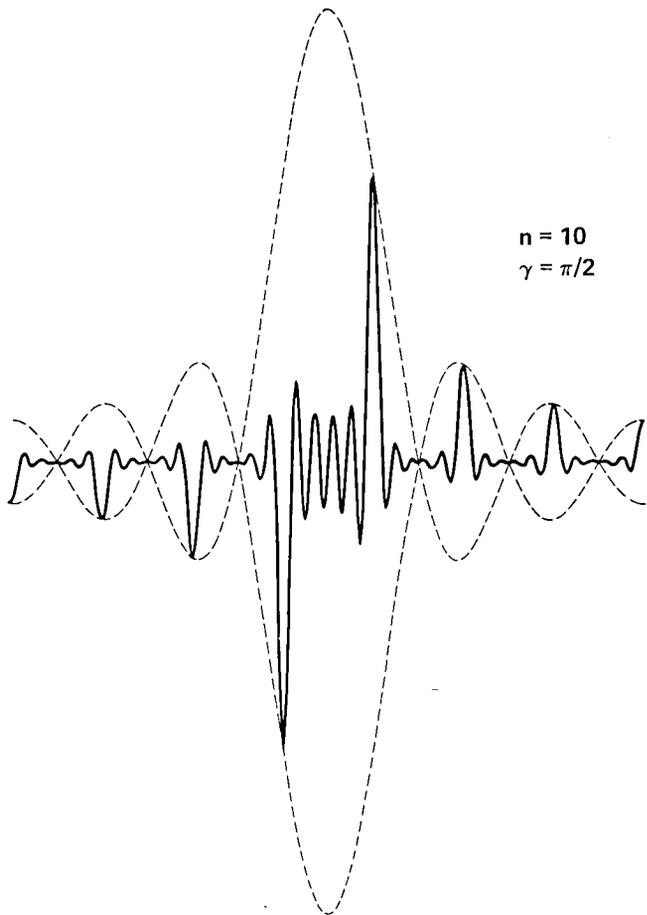


Figure C-7.— Noise cross power coefficient  $[(\sin \delta)/\delta] f_n(\delta - \gamma)$  as a function of  $\delta$  when 10 samples are averaged ( $n = 10$ ) and the signal is at the bin edge ( $\gamma = \pi/2$ ).

To summarize, each channel in an MCSA delivers an in-phase and quadrature pair of numbers representing the integral of the product of the signal with sine and cosine carriers centered in the channel. The numbers are equivalent to independent samples of the product signals taken after passing through  $(\sin x)/x$  filters of noise bandwidth  $b = 1/\tau$ . The detection statistics, except for the filter loss  $(\sin^2 \gamma)/\gamma^2$ , which must be added to the required S/N, are identical to those derived previously for square law detection. At the center of each bin this filter loss is 0 dB; at the bin edges it is  $-20 \log(2/\pi) = 3.92$  dB.

Other filter characteristics may be obtained by “windowing” the input or, equivalently, by forming weighted sums of the in-phase amplitudes and of the quadrature amplitudes in adjacent bins. For example,  $\pi/4$  times the sum of the amplitudes in any bin and the next higher bin produces the filter:

$$\frac{\pi}{4} \left[ \frac{\sin \gamma}{\gamma} + \frac{\sin(\gamma - \pi)}{\gamma - \pi} \right] = \frac{\pi}{4} \frac{\cos(\gamma - \pi/2)}{\gamma(1 - \gamma/\pi)} \quad (84)$$

Figure C-8 shows the two  $(\sin x)/x$  filters that are added and  $\pi/4$  times their sum. We see that the new filter peaks at  $\gamma = \pi/2$  or at the nominal edge of the bins that were added. Now the minimum transmission occurs at  $\gamma = \pi(1 - \pi/4)$  and is 0.9259 or  $-0.668$  dB rather than  $-3.92$  dB. Thus the inclusion of these sums can greatly reduce the bin-to-bin “scalloping.”

The transmission (eq. (84)) is the transform of  $(\pi/2)\cos \pi(t/\tau)$  with  $|t| < (\tau/2)$ . In effect, the input has been “windowed” (i.e., gated) by this function. This is because the contributions to the amplitudes in the two bins are equal and opposite at  $t = \pm(\tau/2)$  and are equal at  $t = 0$ . The noise bandwidth of equation (84) is  $\pi^2/8$  as compared with unity for  $\sin \gamma/\gamma$ . Thus we lose another 0.91 dB for a CW signal from this cause.

### Pseudobinning and Pulse Detection

Suppose we have bins of width  $b$  and our integration time is  $\tau$ , and a rectangular pulse occurs of length  $2\tau$ . For a single sample our sensitivity would be increased 3.01 dB if we went to a bin  $b/2$  in width and an integration time of  $2\tau$ . (This assumes our integration starts and stops with the pulse.) If instead we merely add two successive “power” samples, and if our false alarm probability is  $10^{-12}$ , we will gain 2.63 dB. In other words, we are down only 0.38 dB with respect to the proper matched bin. If we add four successive samples, we will gain 5.14 dB rather than 6.02 dB for a mismatch loss of 0.88 dB. The “mismatch” loss, defined as  $10 \log n - [S/N(1) - S/N(n)]$  where the S/Ns are in dB, is shown in figure C-9 for several values of  $p_{fa}$ .

For  $(\sin x)/x$  pulses and a synchronous  $(\sin x)/x$  window, the same mismatch losses apply for the addition of the powers in adjacent bins to achieve wider bins. For rectangular pulses the losses are slightly greater. For example, with  $p_{fa} = 10^{-12}$  and with a  $\tau/2$  pulse centered on a bin, the mismatch loss when the two bins on either side are added in with equal weight is 1.09 dB, rather than 0.38 dB. In the addition of successive samples in time, the effective time sample was matched to the pulse shape. In the adjacent bin addition the effective spectrum sample is not matched to the spectrum. It would be better to add adjacent bin powers with weighting factors proportional to the expected power, but this adds complications. With Gaussian pulses, the formation of pseudobins by the addition of successive samples in time and adjacent bins in frequency should have roughly equal mismatch losses, intermediate to those given above.

In the proposed MCSA, true DFT outputs are provided at bandwidths of 1024, 32, and 1 Hz. By forming running sums of these outputs up to four bins wide and 4 samples deep in time, crudely matched filters are then generated for pulses whose duration is from 1/4096 to 4 sec. Thus although there seems to be no “natural” length for a pulse, we can nevertheless be prepared for a large range of possible lengths.

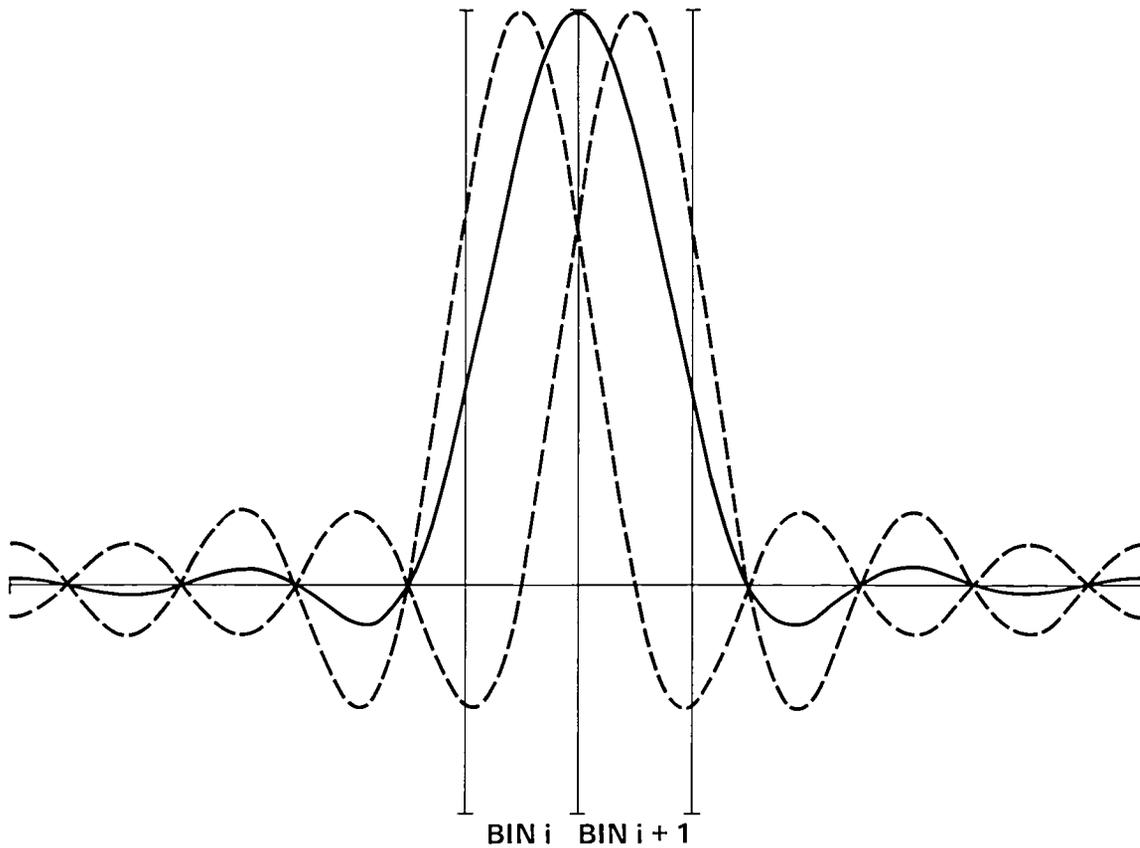


Figure C-8.— Frequency characteristics (dashed lines) of two adjacent bins and of the effective shifted bin produced by adding their complex amplitudes (solid line).

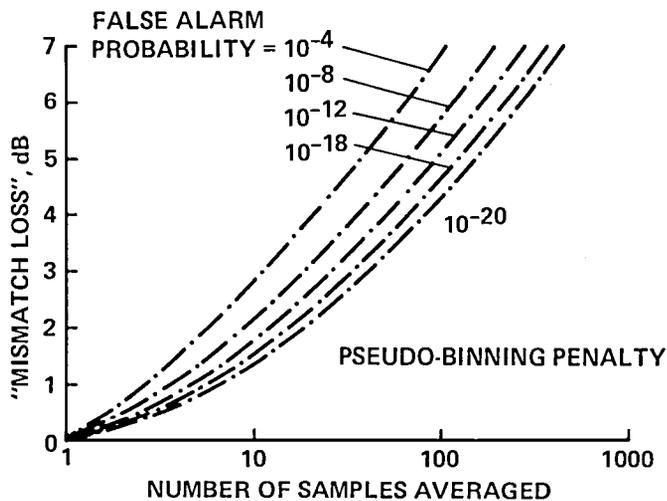


Figure C-9.— Pseudobinning loss. Adding the powers of  $n$  successive samples to produce a “pseudobin”  $1/n$  times as wide produces only a small loss when the false alarm probability is small (and hence the  $S/N$  is high).



## APPENDIX D

### ESTIMATES OF THE RELATIVE PROBABILITY OF SUCCESS OF THE SETI SEARCH PROGRAM

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#### Abstract

*Under certain, perhaps reasonable, assumptions, it is possible to derive an expression for the probability of success of a SETI search program. Without knowledge of the ETI luminosity function, it is not possible to calculate absolute probabilities of success, but it is possible to derive precisely the relative probabilities of different programs searching for the same signals with different instrumental parameters such as telescope size, bandwidth, frequency coverage, etc. As expected, the results show that (1) there is great advantage to using larger telescopes; (2) it is even more important to utilize the lowest noise detectors; (3) it is equally important to minimize sources of false alarms, such as RFI; (4) using a large number of frequency channels is very desirable; (5) the use of small bandwidths is very valuable, providing there are ETI signal components of similar bandwidths. The quantitative advantages accruing from optimizing each of these parameters are given. It is found that even a small number of observing hours on a large telescope, such as that at Arecibo, can create as much chance of success as many more hours on smaller telescopes.*

The compilation of at least the relative probabilities of success of various proposed SETI search programs is highly desirable because it permits an informed adoption of the program or programs which are most promising or cost effective. As shown below, the compilation is possible if only one important assumption is made, namely that radio emitting civilizations are spread nearly uniformly and relatively frequently throughout the galaxy. The results are then applied to the targeted search and sky survey programs.

First we derive the expression giving the absolute probability of success of a generalized SETI program. We assume the SETI program instrumentation can detect a minimum radio flux  $S_m$ . Although the galaxy is a highly flattened disk system, we make the solar neighborhood assumption that signals from civilizations radiating an equivalent isotropic radiated power (EIRP),  $P$ , are originating from points spread uniformly with a density  $\rho$  throughout a sphere of radius  $R \leq 1$  kpc. Then the system can detect all civilizations within the range  $R_{\max}$  given by

$$S_m = P/4\pi(R_{\max})^2; \text{ or, } R_{\max} = \sqrt{(P/4\pi S_m)}$$

and all civilizations with a volume

$$V = (4\pi/3)(P/4\pi S_m)^{3/2}$$

The total number of detectable signals then is

$$N_{\text{det}} = \rho V = (4\pi\rho/3)(P/4\pi S_m)^{3/2} \quad (1)$$

The dependence on  $S_m^{-3/2}$  is valid almost no matter what the luminosity function may be. If in the real galaxy the distribution of numbers of signals of power  $P$  in range  $dP$  is given by  $\rho(P)dP$ , then we replace  $\rho P^{3/2}$  in the above relation with  $\overline{\rho(P)P^{3/2}}$ , giving

$$N_{\text{det}} = \overline{[\rho(P)P^{3/2}]} / [3(4\pi)^{1/2} S_m^{3/2}] = K_0 S_m^{-3/2} \quad (2)$$

where  $K_0 = \overline{[\rho(P)P^{3/2}]} / 6\sqrt{\pi}$ . This result is well known in RA. We, of course, would like to know  $K_0$ ; indeed it is a prime goal of SETI research.

Turning now to the probability of success of a search program, we assume all directions in the sky have the same probability of revealing a signal. Unless there are very many signals, the probability of success of any given observation in the program is given by

$$p = (\Omega_s/\Omega_c)C(B_s/B_c)N_{\text{det}}$$

where

$\Omega_s$  = solid angle of the antenna beam of the search telescope

$\Omega_c$  = solid angle of celestial sphere

$C$  = number of radio channels in the search system

$B_s$  = bandwidth of single channel of the search system

$B_c$  = total bandwidth in radio spectrum within which signals are confined

The probability of failure of each observation is

$$(1 - p) \quad (3)$$

The probability of failure of an entire search program of  $M$  observations is

$$(1 - p)^M \quad (4)$$

and the probability of success is

$$1 - (1 - p)^M \quad (5)$$

Thus, the probability of success,  $p_s$ , of the SETI program is

$$p_s = 1 - [1 - (\Omega_s/\Omega_c)(B_s/B_c)CK_0S_m^{-3/2}]^M \quad (6)$$

Again, the only unknown parameter is  $K_0$ , and its presence prevents the computation of quantitative values of  $p_s$ .

If the probability of success of a single observation is very small, which is surely a very good assumption, then an approximate form for  $p_s$  is

$$p_s \approx MCK_0(\Omega_s/\Omega_c)(B_s/B_c)S_m^{-3/2} \quad (7)$$

As expected, the probability of success is proportional to the number of observations and to the total frequency coverage  $CB_s$ . The probability is very sensitive to the minimum detectable flux.

We can incorporate the relation for  $S_m$

$$S_m = (4\alpha kT_s/\pi D^2)\sqrt{(B_s/\tau)} \quad (8)$$

where

$\alpha$  = numerical multiplier to ensure sufficiently low false alarm rates

$k$  = Boltzmann's constant

$T_s$  = system noise temperature

$D$  = effective diameter, or equivalent effective diameter, of the telescope used

$\tau$  = integration time of each observation

This gives

$$p_s = K_1 CM\lambda^2 DB_s^{1/4} \tau^{3/4} / (\alpha T_s)^{3/2} \quad (9)$$

where  $K_1 = K_0 \pi^{1/2} / 2\Omega_c B_c k^{3/2}$ .

This result points out that the probability of success is directly proportional to the telescope diameter. It is even more strongly dependent on  $T_s$  and  $\alpha$ , and there is strong reason to make major efforts to reduce the system noise and any avoidable sources of false alarms. On the other hand,  $B_s$  is not very important (although in practice  $C$  will often depend on it, giving  $B_s$  more influence on  $p_s$ ).

Now consider two SETI search programs, 1 and 2. The relative probability of success is

$$p_{s_1}/p_{s_2} = \frac{1 - [1 - (\Omega_{s_1}/\Omega_c)(B_{s_1}/B_c)C_1 K_0 S_{m_1}^{-3/2}]^{M_1}}{1 - [1 - (\Omega_{s_2}/\Omega_c)(B_{s_2}/B_c)C_2 K_0 S_{m_2}^{-3/2}]^{M_2}} \quad (10)$$

which is intractable unless  $K_0$  is known. However, if we use the approximate form for  $p_s$  we obtain the simple and useful result

$$p_{s_1}/p_{s_2} = \frac{C_1 M_1 B_{s_1} \Omega_{s_1} S_{m_1}^{-3/2}}{C_2 M_2 B_{s_2} \Omega_{s_2} S_{m_2}^{-3/2}} \quad (11)$$

This relation can be used to compare various search plans if they are searching for the same types of signals.

It is interesting to apply this formulation to the proposed targeted search (Search 1) and the constant angular scan rate sky survey (Search 2). From an early program plan for SETI and assuming a search for carrier signals only, the proposed parameters are

| Parameter  | Search 1 (targeted search)                                     | Search 2 (sky survey)  |
|------------|--|--|
| $D$        | 53 to 213 m  | 34 m; $\eta = 0.5$   |
| $M$        | 773  | $6 \times 10^4 (\nu_{\text{GHz}})^2$                               |
| $\nu$      | 1.2-3.0 GHz  | 1.2-10.0 GHz   |
| $\Omega_s$ | 2.6-260 arc-min <sup>2</sup>                                   | $2343/(\nu_{\text{GHz}})^2$<br>arc-min <sup>2</sup>                |
| $S_m$      | $7 \times 10^{-28}$ to $2 \times 10^{-26}$<br>W/m <sup>2</sup> | $2.2 \times 10^{-23} (\nu_{\text{GHz}})^{1/2}$<br>W/m <sup>2</sup> |
| $CB_s$     | 1.8 GHz  | 8.8 GHz  |

The computations are complicated somewhat by the obvious fact that the basic parameters vary within each search. In the targeted search the use of six different radio telescopes is

proposed. Each telescope is assigned a subset of the 773 directions in space to be searched. Some directions are given more integration time, changing the value of  $S_m$  accordingly. To carry out the calculations it is necessary to compute the value of  $M\Omega_s S_m^{-3/2}$  for each subset of sensitivities and directions. The fact that  $\Omega_s$  is frequency-dependent must be taken into account. The sum of the results for all the subsets provides a value to insert in equation (11). With the sky survey,  $M$ ,  $\Omega_s$ , and  $S_m$  are all frequency-dependent, but the product  $M\Omega_s$  is frequency-independent, and it is necessary to compute  $S_m^{-3/2}$  by making the appropriate integration over frequency. When these calculations are made and the results inserted in equation (11), one obtains

$$p_{s_1}/p_{s_2} = p_{\text{target}}/p_{\text{all-sky}} \simeq 40$$

This large factor in favor of the targeted search is entirely due to the  $10^3$  to  $3 \times 10^5$  difference in  $S_m$  for the two observing modes. Because of the strong dependence of  $p_s$  on  $S_m$ , this more than compensates for the fact that all the other parameters favor the sky survey.

It is possible to break down the contributions to possible success of various parts of the proposed program and show that of the overall probability of success, whatever it may be,

2.4% is provided by the all-sky survey

39.3% is provided by the observation of 250 beam areas at the Arecibo Observatory

58.3% is provided by the observation of 523 other areas in the remainder of the targeted search.

These calculations, where an S/N of one was assumed for the targeted search and nine for the sky survey, emphasize once again the importance of achieving the best practical  $S_m$ .

It should be noted that as the parameters of the various search programs are altered, the relative contributions to possible success will change and, therefore,  $p_{s_1}/p_{s_2}$  may change substantially from the above figure. Indeed, since  $S_m$  is proportional to  $\alpha T_s$ , the relative value of a search may be highly site-dependent. Sites with high levels of RFI will have much reduced contributions to possible success. Because of the high sensitivity and frequency coverage of the SETI systems, the false alarm problem may not be well understood until the searches are in progress.

There are a number of situations which can cause the above formulation of the probabilities to be incorrect. Among the more obvious, it has been assumed that there is an equal probability of radio signals at all radio frequencies.

Any variation in that probability will change the relative chances of various searches which do not cover the same frequency ranges. For example, if signals are much more probable above 3.0 GHz, then this increases the relative value of the sky survey. Also, if there is one or a few exceptionally strong signals being radiated at all times which produce a flux detectable by either search, the problem is no longer a statistical one. Obviously, in this case, the sky survey will certainly succeed, whereas the targeted search may not. The fact that a targeted search is concentrated in directions where for some reasons it is postulated that there is a better chance of success will increase its probability of success if the "reasons" are valid.

A nonuniform distribution of civilizations in the galaxy will also strongly influence the actual probabilities. One expects nonuniformity on some scale, due to the flatness of the galactic disk; and, of course, there may be other nonuniformities caused by such matters as the evolution of galactic demography. All that can be said is that the probabilities would appear to be enhanced by utilizing lines of sight which are close to the galactic plane.

Finally, it should be noted that the preceding calculations ignore the fact that in the 1980 proposal the targeted search would be equipped with signal-recognition systems capable of noticing a wider range of signal formats than was assumed to be practical for the sky survey. This is simply due to the fact that the longer dwell times planned for any given search direction in the targeted search permitted exploring for a range of intermittent signals, as well as for continuous carrier-like signal components, as in the sky survey. Though the effect of this procedural difference on the actual probabilities of success is indeterminate, it does seem desirable in both approaches to employ at all times the widest range of signal processing that seems reasonable as a consequence of our communications experience, and manageable within the limitations set by such arbitrary matters as telescope availability and funding level.

In conclusion, the above considerations show that it is informative to quantify the relative probabilities of success of various SETI radio searches, although this does involve making assumptions about an as yet unknown reality. Moreover, these calculations have demonstrated the basic fact of SETI. There is an exceptionally strong dependence of the probability of success on the minimum detectable flux. Every practical and reasonable effort should be made to make this flux as low as possible.



## APPENDIX E

### ANTENNA FEEDS FOR THE ARECIBO TELESCOPE

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#### Abstract

*The Arecibo telescope is expected to play a prime role in the NASA SETI program, but to do so the telescope will have to be equipped with antenna feeds which provide reception over the full band of frequencies to be covered in the SETI targeted search. One way to do this is to construct some 20 new waveguide feeds using the same technology which is normally used to build antenna feeds for the Arecibo telescope. The cost of this would range from about \$100,000, if only one polarization is to be received, to more than \$1 million if two polarizations are to be received. An alternative would be to construct a proposed Gregorian feed system using two large reflecting mirrors. This system would not only provide the desired frequency coverage, but would more than double the sensitivity of the telescope. However, it is a new technology and would cost between \$1 and \$2 million.*

The Arecibo telescope is destined to play a key role in the proposed SETI program and in many future SETI programs. It is important to take any cost-effective steps which will enhance the usefulness of this telescope for SETI. Antenna feeds are an important area to consider in this respect.

The Arecibo telescope consists of a 1000-ft-diam, fixed, spherical reflector and a triangular platform some 500 ft above the reflector which provides support and alt-azimuth motion for equipment near the reflector focus. The spherical shape of the reflector permits pointing the beam anywhere within  $20^\circ$  of the zenith through motion of the feed only, but in turn requires correction of the spherical aberration.

#### Wave-Guide Feeds

Slotted wave-guide feeds are currently used to provide the required control of aperture illumination and phase correction. The length of the feed determines the sensitivity, usable bandwidth, and vignetting properties of the feed. A 16-ft feed illuminates a 450-ft-diam circle; provides a 200-MHz, 3-dB bandwidth; and is nonvignetting. A 96-ft feed illuminates the full 1000-ft aperture, has a 10-MHz bandwidth, and begins vignetting just off the zenith, dropping to about 40% of its zenith efficiency at  $20^\circ$  zenith angle. A

40-ft line-feed illuminates a 700-ft-diam region, provides a 50-MHz bandwidth, and begins vignetting at  $10^\circ$  zenith angle. The 40-ft line-feeds provide a workable compromise in sensitivity, bandwidth, vignetting properties, and cost, and are the ones most commonly in current use. They provide a sensitivity of 6-8 K/Jy, depending on the illumination pattern (1 K/Jy equals  $2760 \text{ m}^2$  effective aperture).

Both single- and dual-polarization feeds have been used successfully. They differ significantly in cost, complexity, and performance. Flat feeds consisting of shallow-height waveguides provide only a single sense of linear polarization, but are inexpensive and are relatively straightforward to manufacture. Circular feeds consist of dozens to hundreds of individually machined conical sections which provide orthogonal polarizations. Linear or circular polarization may be selected by adjusting the turnstile junction at the top of the feed. The 2380-MHz circular feed used with the S-band transmitter was manufactured commercially for \$50,000 in 1974. The cost of producing such a feed in-house is estimated at \$20,000, but this may underestimate the labor and indirect costs. In contrast, the single-polarization feeds cost about \$2,000 to \$5,000 each, in-house.

The performance of the feeds differs principally in their polarization property, but there are other important differences as well. The single-polarization feeds add approximately 30 K to the system noise temperature. The noise

from the circular waveguide feed is due almost entirely to atmospheric, galactic, and isotropic background radiations, and to thermal radiation received through feed spillover beyond the edge of the dish. The linear feeds receive these noise radiations plus approximately 10 K more due to ohmic loss within the feed structure itself. The values given are for 1400 MHz. Ohmic loss increases approximately as (frequency)<sup>3/2</sup>.

At present the linear feeds provide lower sidelobes than the circular feeds. The latter have a beam shape which includes a ringlobe surrounding the main beam containing some 20% of the available directivity. In a program such as the targeted search, the parameter of most importance is the peak forward directive gain. In spite of the ringlobe, the present circular feeds provide somewhat higher peak sensitivity at the zenith (8 K/Jy at 1400 MHz, vs 6.5 K/Jy for the flat feed), but this is primarily due to different choices for the feed's illumination taper. Recent work (unpublished) by Lynn Baker (NAIC) has tentatively identified the source of the ringlobe problem in the circular feeds as a deviation of the geometric optics theory from the more accurate diffraction theory, and it may now be possible to construct improved (though still expensive) circular feeds.

Both flat and circular feeds have a restricted instantaneous bandwidth (50 MHz for 40-ft feeds) which is set by waveguide propagation characteristics and is nearly independent of feed center frequency. Fortunately, feeds may be tuned over about twice their instantaneous bandwidth by lowering them some distance below the paraxial focus (about 0.5 in./MHz at 1400 MHz). Using this property, only 20 rather than 40 feeds are required to cover the 1- to 3-GHz frequency range.

If waveguide feeds are to be used in the SETI program, a difficult choice must be made. Some 20 feeds must be constructed, assuming the 1- to 3-GHz range is to be covered using a 700-ft aperture. Although dual circular polarization data are considered optimum, such feeds cost approximately 10 times as much as their linear counterparts. Given only a single spectrometer, the question is simpler, since only one polarization can be analyzed at one time. Even with two spectrometers, both can be fully utilized by sampling neighboring 8-MHz frequency bands. Such observations would, in fact, make more efficient use of the telescope, as each target would be observed twice as long, reducing the fraction of total time spent slewing the telescope. The imponderable factor concerns the relative importance of polarization-comparison algorithms vs longer integration.

### Gregorian Feed Systems

A completely different approach to aberration-correcting feeds for the Arecibo reflector is being given renewed attention. In this approach, correction of the

spherical aberration and the creation of a desirable illumination pattern are simultaneously achieved through the use of two large reflectors mounted near the paraxial focal sphere of the telescope.

Figure E-1 shows the geometry of the reflecting surfaces for one such system which would operate extremely well with the Arecibo telescope. In this system there is a large quasi-elliptical reflector, as in a Gregorian telescope, and there is a smaller quasi-hyperbolic reflector, as in a Cassegrainian telescope. Such a system can provide a highly efficient and convenient feed for the spherical main reflector. There are no inherent frequency limitations for frequencies greater than 1 GHz, other than dimensional tolerances, and the system can deal readily with any polarization.

In such a system, a conventional microwave feed horn is located in a convenient location in the "carriage house" of the telescope. This horn illuminates the smaller reflector as in a conventional Cassegrainian telescope. The shape of this smaller reflector is not, in fact, a precise hyperbola, but is an approximation to a hyperbola which redistributes the radiation from the horn in such a way that the eventual illumination pattern projected on the spherical primary mirror is a desirable one; i.e., a pattern of high gain, narrow beam width, low sidelobes, and less spillover. The radiation from the feed horn, then, is reflected from the smaller mirror with an altered angular power distribution as required by the geometry of the other two mirrors and the desired eventual primary illumination pattern. The second, larger

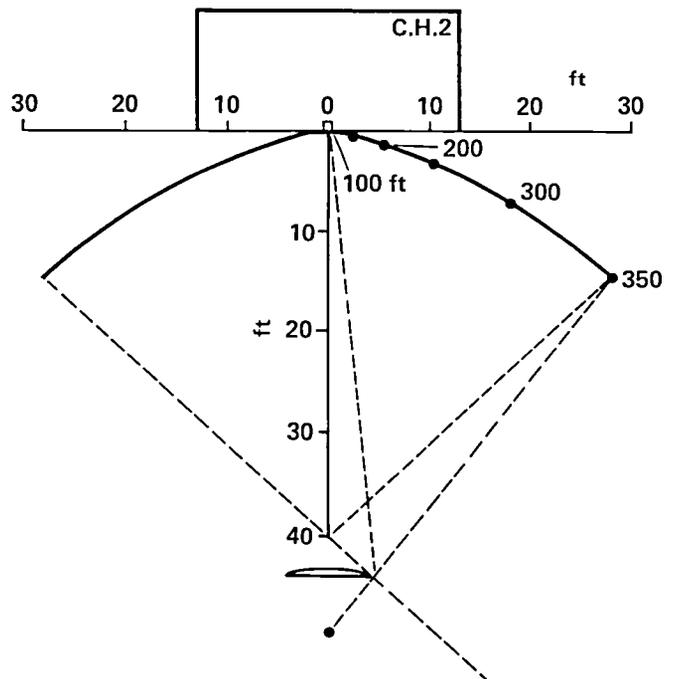


Figure E-1.— Geometry of reflecting surfaces for Gregorian feed system.

mirror is a quasi-ellipsoid which reflects the radiation from the smaller mirror onto the primary mirror. Its shape is such that it corrects for the phase error introduced by the deviation of the small mirror from a strictly hyperboloidal figure. In other words, this larger mirror corrects for the spherical aberration of the primary and the phase errors introduced by the precise shaping of the smallest mirror. Given a particular primary mirror and a desired final focal point, there is an extensive family of solutions, that is, pairs of mirrors, which achieve the above. The specific member of this family to be used is chosen to minimize mechanical problems and cost. The mathematics for defining these geometries is complicated but has been solved, and it is now possible to develop the mirror geometries with ease.

In the case of the Arecibo telescope, it is possible to improve performance by using an offset illumination pattern on the primary reflector. This is a result of the fact that the carriage house moves outward toward the edge of the primary reflector as higher zenith angles are required to achieve some desired pointing direction. This motion in zenith angle leads to vignetting of the illuminated area at some zenith angle, and the vignetting causes loss in illuminated area and increased pickup of Earth radiation, both of which degrade system sensitivity. An offset illumination pattern causes vignetting to set in at a higher zenith angle or not at all. A reflector feed system which achieves an offset illumination is shown in figure E-2, and a sketch of what such a system would look like on the Arecibo telescope is shown in figure E-3. The mathematics describing these asymmetrical designs is much more complicated than that for the symmetrical designs, and only approximate but useful solutions are presently available.

In all cases, the mechanical complexity and cost of these systems is much greater than a single-wave-guide line-feed system. However, the cost of the reflector system is about the same as the cost of a set of 20 circular waveguide feeds. In the end, the flexibility and the improvement in sensi-

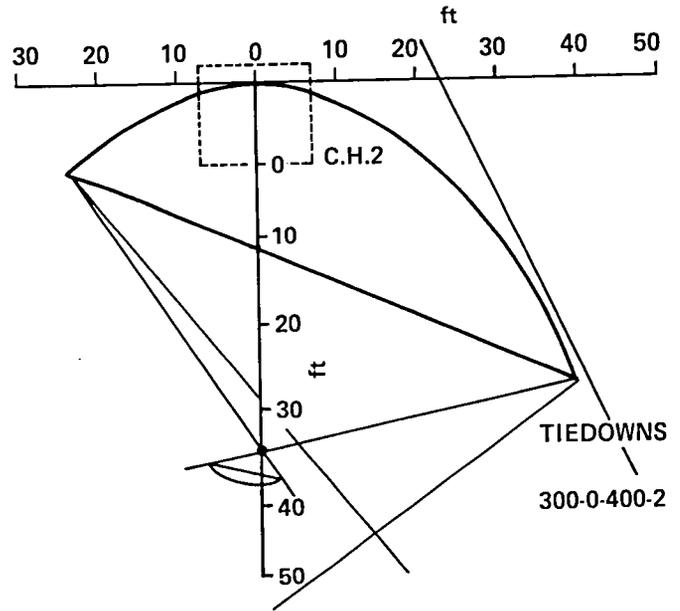


Figure E-2.— Reflector feed system which achieves offset illumination.

tivity provided, which is more than a factor of two, makes these systems very cost-effective.

Such systems would be extremely beneficial to the SETI program. They would provide much higher sensitivity, increasing the number of candidate stars within reach, assuming a given transmitter power, by a factor of perhaps four. Of equal importance, because the basic radiating device is a conventional microwave horn, the systems are as broadband as any found in radio telescopes. Thus the limitations to broadband operation are the same as in conventional radio telescopes.

Detailed engineering and cost analyses for these systems have not yet been done, but one can be hopeful that they will be done in any case because of the general benefits that would accrue to RA as well as to SETI.

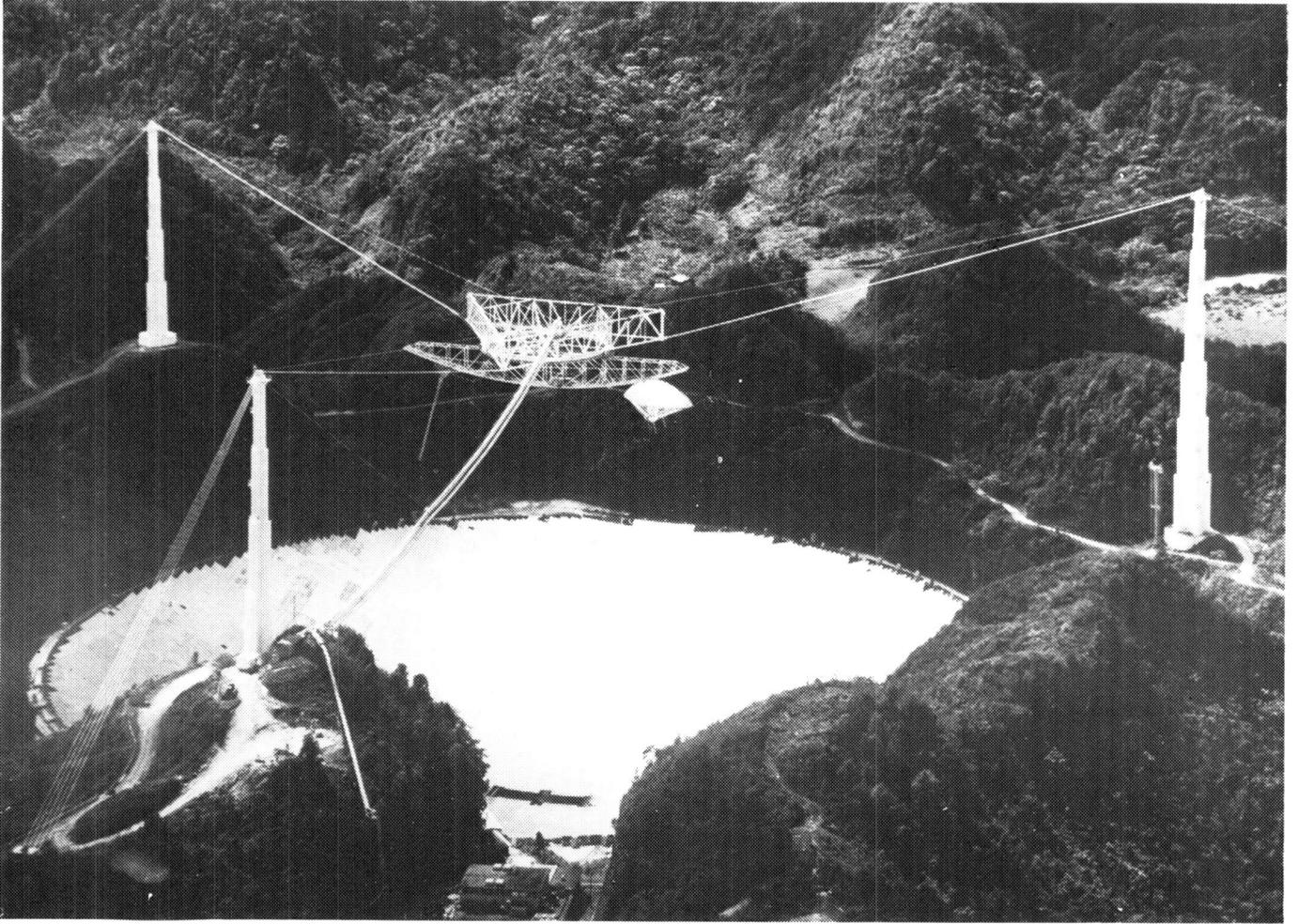


Figure E-3.— System on Arecibo telescope.

## APPENDIX F

### THE RADIO FREQUENCY INTERFERENCE PROBLEM

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#### Abstract

*Radio frequency interference from human-caused sources is a serious impediment to any SETI search, and becomes more serious each year. The most probable types of SETI signals are very similar to many kinds of RFI signals and therefore accurate procedures and algorithms for discrimination must be developed. Furthermore, SETI searches must be carried out at times, frequencies, and sites chosen to minimize the RFI problem.*

Of the various rationales for doing SETI *now*, most are concerned with the impressive capabilities of current RF and signal-processing technologies and with the importance of a comprehensive effort which takes advantage of lessons learned from experiments of the recent past. There is, however, one reason which gives great urgency to beginning SETI observations immediately, and that is the steadily increasing interference from terrestrial sources.

Quite often there are only subtle differences between predicted ETI signals and human-caused transmissions, and local narrowband signals can with ease totally mask signals of even extraordinarily powerful interstellar transmitters. Fortunately, much of the spectrum is not used for narrowband transmissions, but even wideband signals from nearby sources can cause severe degradation in the detection threshold of a SETI system. There is little reason to expect ETI signal fluxes as high as the flux levels commonly used in the ever-growing number of terrestrial communication, Earth-based and, particularly, space-based, and radar circuits.

RFI impinges on a microwave SETI in two ways. The first concerns the overall strategy for selecting sites, times, and frequencies as free of RFI as possible. The antenna *sites* used for RA and for deep-space tracking were originally chosen for their freedom from RFI, but the steadily increasing use of the radio spectrum has meant that most quiet sites now suffer RFI problems of one sort or another; and there is little that can be done about it. As to *times* for observing, RFI is generally least bothersome between midnight and 6:00 a.m. local time, so that much of the search may be limited to those few hours. In choosing specific *frequency bands* in which to observe, attention must be paid to national and international frequency allocations, particu-

larly with respect to satellite services. Ultimately, the RFI characteristics of various bands at a given site can only be ascertained by extensive monitoring at the site with a low-gain antenna and a broadband multichannel receiver.

Once the RFI environment at a specific site is broadly defined, some bands may be given up as hopeless, though many, perhaps most, should prove tractable with the application of proper techniques (see below). NASA SP-419 gives some details of the bands allocated to RA (I), Earthbound users (II), and airborne and satellite users (III), and documents the alarming present and the already planned future growth in RFI likely to be encountered over the next decade. Furthermore, it suggests a "triage-like" approach for establishing temporal priorities which seems basically sound. The first bands to be covered, other things being equal, should be those in Category III, since they are clearly the ones in which usage is growing fastest *and* it is these services which do the most harm. Category II services are also increasing rapidly, but constitute a lesser hazard for SETI. Category I can wait, assuming that these bands remain highly protected. However, one would not want to place last all work in Category I bands because, of course, this category includes some of the 1400- to 1700-MHz Water-hole region of the spectrum which is of special interest to SETI.

The second way RFI impinges on SETI concerns the techniques employed to distinguish a genuine ETI signal from RFI. The SSWG has emphasized that interferometric techniques in principle provide a powerful tool to this end. The use of interferometry necessitates appreciable additional costs even though several possible SETI sites already have two or more available antennas. Despite this, interferometry

may well prove its worth for those frequencies and sites in which RFI is the worst. In any case it is clear that once a single dish has discovered a promising candidate ETI signal; that is, one that has passed all single-dish discriminatory tests, it should be subjected to interferometric observation for further validation and for precision position determination.

The main purpose of the initial single-dish tests is to determine whether a candidate ETI signal is an artifact of one's own receiver, or of the local environment, or of known or easily recognized RFI, or is most likely of extraterrestrial origin. On-line algorithms will subject each candidate to an RFI-table look-up, an RFI search with a low-gain antenna, local oscillator offset switching, beam switching, modulation studies, etc. Most such tests are standard in RA

when unusual events occur, but the difference here is that signals of the expected narrowband or pulsed nature have seldom, if ever, been previously sought with such high sensitivities. Thus the RFI environment may be far more difficult to deal with than is usual in RA. Clearly, exploratory observations conducted with the MCSA prototype will be vital in defining this very serious RFI problem.

#### Reference

Morrison, Philip; Billingham, John; and Wolfe, John: The Search for Extraterrestrial Intelligence. NASA SP-419, 1977.

## APPENDIX G

### DATA ARCHIVES

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#### Abstract

*Any large-scale SETI program will initially produce great quantities of data, far more than it is reasonable to store in its entirety. A long-term data archive, perhaps in an amount equivalent to two standard magnetic tapes per day, should nevertheless be maintained for three purposes: (1) for radio astronomical studies using routine SETI data or other astronomical data taken with SETI instrumentation; (2) as a record of exactly what portion of the SETI "haystack" has been covered, and just how and when; and (3) as an RFI record and a record of the data on all tentative SETI candidate signals studied.*

An important part of the SETI program will be maintenance of extensive archives. The simple expedient of retaining all initially recorded data appears to be prohibitively expensive. Besides, most of the data simply represent background noise of negligible interest. Thus the SSWG has had to consider the difficult judgmental problem of striking the right balance between retaining data and paying the cost of doing so.

There are two primary purposes for maintaining a *long-term* data archive.<sup>1</sup> The first is to retain SETI data for later SETI investigations. The second is to retain data of astronomical significance. The SSWG considers about two magnetic tapes (about a gigabit) per day as a cost-effective amount of data which should be preserved indefinitely. This is also an amount considered reasonable by the most likely repository, the National Space Science Data Center at the Goddard Space Flight Center.

The SSWG has discussed at some length the possible and promising radio astronomical spin-offs from the proposed SETI program. The expected data of possible value, as discussed in appendix H, are primarily data on spectral lines (HI, OH, H<sub>2</sub>O, and perhaps others if a "dwell" mode is used in the galactic plane), an all-sky microwave radio source survey created by adding together data taken over a span of several GHz, and perhaps data on short-period pulsars. What serendipitous astronomical discoveries might occur is of

course speculative, but it would seem that such signals are only likely to be discovered during SETI observations if they somewhat mimic the kinds of signals thought most likely to be transmitted by ETI.

Given all this, one asks how much data are worth archiving and who will look at it in subsequent years? It is noteworthy that experience with other such national data archives shows that they are seldom consulted. (Yet it must be recalled that some archives, mainly private, have been of inestimable value many decades after initial storage.) One reason for not consulting old records is that not enough in the way of instrument calibrations is available, making the validity and interpretation of the old data uncertain. Thus an RA archive should be created only if it is kept in mind that later use will be by skeptics without prior and detailed contact with the observations and the procedures with which they were made. In other words, an RA data archive should *not* be created on the premise that, "well, someone someday is sure to use all this"; rather the researchers and their needs must be thoroughly identified in advance.

Of more practical importance is the question of how much of the MCSA data coming in at a rate of about 1 Gbit/sec should be archived for possible future SETI use. The bare minimum essentially comprises a logbook of the search space and instrumental conditions for each observation. But beyond this, how many suspect signals, rejected RFI signals, instrumental checks, etc., should be indefinitely archived even after intensive off-line analysis at the SETI data center? The final answer to this can come only from experience in the field, but it would seem that especially at

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<sup>1</sup>We are not discussing here which kind of or how much data should be saved from the MCSA output data stream for *short-term* (a few weeks?) intensive analysis back at the SETI data center.

the start of the program when one is still learning how best to search, parameters for *all* suspect signals, rejected RFI signals, instrumental checks, etc., should be preserved. In other words, it is estimated that about two tapes per day should probably be filled, assuming that enough suspect signals and RFI signals will likely exist above a statistically significant threshold; say, those having only one chance in 1000 of occurring in a given spectrum or time series (i.e., every 1000 spectra will probably contain one such signal which, however, in fact only represents a peak in the receiver noise). This archive would then be

1. Fodder for longer term studies of patterns of RFI and of internal electronic effects.

2. The place to consult for a synoptic history of a region of search space in which a suspect signal has been noticed later.

3. Data for use by any qualified "outsider" who wants to conduct a SETI in a different manner (although it would seem that most such interested parties would be better advised to "tap off" at the stage of the original analysis at the SETI data center).

*The level and mode of archiving should be considered still very much an open question and necessarily subject to extensive evolution.*

## APPENDIX H

### SPECTRAL LINE STUDIES USING SETI INSTRUMENTATION

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#### Abstract

*To be of use to RA the all-sky SETI search must be tailored to concentrate on a few selected regions such as the galactic plane. If 3 to 4 yr out of, say, a 10-yr search project are so tailored, then potentially very useful spectral line data should accrue to RA. Such time should definitely not be considered lost to SETI since most distant stars of likely SETI interest also lie in the galactic plane. Spin-offs from the targeted search program are likely to be minor.*

#### INTRODUCTION

SETI instrumentation will undoubtedly be of interest to spectral-line radio astronomers. However, the MCSA is quite different from a spectrometer optimized for pure RA applications. The total bandwidth of the wideband MCSA is comparable to the total bandwidth of multichannel filter banks currently employed at, say, the 12-m telescope of NRAO. The main advantage of the MCSA compared to this NRAO spectrometer and others at both centimeter and millimeter wavelengths is its excellent frequency resolution. However, most astronomers feel that resolutions better than a few hundred hertz at  $\lambda \sim 21$  cm and a few times 10 kHz at  $\lambda \sim 2$  mm will not be useful to spectral-line RA. Therefore, the highest-resolution capability of the MCSA is unlikely to prove valuable for conventional RA.

In light of the above it seems inappropriate to attempt to list all of the research areas in which astronomers might want to use the MCSA and SETI feeds and front ends. Therefore we limit our remarks to spin-offs to spectral-line RA that might occur in conjunction with the targeted search and the sky survey. Since these searches will consume many years of observation with the SETI instruments, possible gains to RA during this time should be considered seriously.

Spin-offs from the targeted search program are likely to be small, although there could be surprises. When the targeted search program is begun it would be of value to reexamine what data should be archived and studied for radio astronomical purposes (see appendix G).

The potential spin-offs to spectral-line RA from the sky survey are more promising. It seems worthwhile to tailor the sky survey to obtain these radio astronomical data chiefly because to do so does little or no obvious harm to the primary SETI goals and may well benefit the SETI program. Why this is so will be summarized after we outline the spectral-line studies that we deem most appropriate to carry out in conjunction with the sky survey. Input from about 20 spectral-line radio astronomers was obtained in order that the following remarks would be reasonably representative of the views of the astronomical community. Dr. Gill Knapp (Princeton University) was especially helpful in supplying useful input (see appendix I).

Table H-I summarizes those programs that seem most worthwhile to carry out in conjunction with the sky survey. The programs are arranged in order of decreasing priority. This ordering is based primarily on scientific interest except for the "dwell mode" where, in addition to scientific value, the fact that it most effectively utilizes the SETI instruments was also weighted in its favor. Of the programs listed in table H-I, all, except possibly the 2-cm H<sub>2</sub>CO survey, clearly seem worthwhile.

#### ASSUMPTIONS

We assume a 34-m-diam antenna that is driven across the sky at a constant rate independent of frequency. Then, for a program that lasts 10 yr and covers 10 GHz of the

TABLE H-I.— PROGRAMS IN SPECTRAL LINE RADIO  
ASTRONOMY TO BE CARRIED OUT IN CONJUNCTION WITH  
AN ALL-SKY SETI PROGRAM

| Program   | Regions examined  | Time required                                   |
|---|---|---|
| Dwell mode  | About 5 objects   | 10% at low end (20 cm)<br>1% at high end (2 cm) |
| 21-cm HI line and<br>1612-, 1665-, and<br>1667-MHz OH lines | All sky   | 1 yr  |
| H <sub>2</sub> O masers                                     | Galactic plane, $ b  \leq 1^\circ$<br>plus selected objects | 6 mo  |
| NH <sub>3</sub> [(1,1), (2,2)<br>and (3,3) doublets]        | Galactic plane<br>plus selected objects                     | 1 yr  |
| H <sub>2</sub> CO (6-cm doublet)                            | Galactic plane<br>plus selected objects                     | 6 mo  |
| CH ( $\Lambda$ -doubling<br>triplet)                        | Southern galactic plane,<br>galactic center                 | 6 mo  |
| H <sub>2</sub> CO (2-cm doublet)                            | Galactic plane<br>plus selected objects                     | 6 mo  |

spectrum, approximate values for some relevant parameters are given as follows:

## PROGRAMS

1. Total time ( $T$ ) spent at a given  $\lambda$  (cm):  $T = (1 \text{ yr})/\lambda$

### The Dwell Mode

2. Time ( $t$ ) spent per position at a given  $\lambda$  (cm):  
 $t = 0.4 \lambda \text{ sec}$

3. Number of pointing positions ( $N$ ) at a given  $\lambda$  (cm):  
 $N = 10^8 / \lambda^2$

Here we want to look at sources and regions of special interest at all frequencies, usually, and achieve high sensitivities always. The scientific motivation is primarily to discover new molecules and possible anomalies in the intensities of lines that have not yet been observed from known interstellar molecules. Suppose we consider five objects. These might be Orion, TMC 1, Sgr B2, a southern hemisphere object (?), and an evolved star (?). (Only the first three items of the list seem clearly worth doing.)

The SETI program seems sufficiently fluid, and the sensitivities that need to be reached for radio astronomical purposes are sufficiently imprecise, that a factor of 2 need not concern us at this time. In this spirit we estimate the system noise as

If we spend 10 hr per object, this amounts to roughly 2 days per frequency. Using No. 1, above, we see, as indicated in table H-I, that at a typical frequency a few percent of the total time available would be spent dwelling on the five sources. This seems quite reasonable.

$$\Delta T_{\text{rms}} = 2 T_{\text{sys}} / (BT)^{1/2}$$

which might be overly conservative by a factor of  $\sqrt{2}$  for at least some programs. Here  $T_{\text{sys}} = T_{\text{receiver}} + T_{\text{sky}} + T_{\text{source}}$ , and  $T_{\text{source}}$  = antenna temperature due to the continuum source in the main beam of the antenna.  $T_{\text{sky}}$  includes the cosmic background radiation and probably ranges from roughly 10 K at frequencies well removed from the 22-GHz atmospheric H<sub>2</sub>O line to two or three times that at frequencies near 22 GHz (good weather conditions assumed in all cases).  $T_{\text{receiver}} = 15 \text{ K}$ .

What sensitivity can be reached? Considering 6 cm a typical wavelength, we have the continuum source temperatures and velocity resolutions listed in table H-II. These resolutions are somewhat narrower than the full linewidths at half maximum power measured in these sources. The rms noises indicated are quite respectable. For example, in TMC 1, HC<sub>5</sub>N, HC<sub>7</sub>N, and HC<sub>9</sub>N antenna temperatures range between 0.1 and 0.03 K.

TABLE H-II.— RMS NOISE LEVELS ACHIEVABLE  
ON THREE REPRESENTATIVE SOURCES AT  
6 cm IN THE DWELL MODE

|   | Orion | TMC 1 | SGR B2 |
|---|-------|-------|--------|
| Continuum antenna temperature (K) due to source                         | 60    | 0     | 10     |
| Velocity resolution (km/s)  | 2     | 0.3   | 10     |
| After 10 hr integration, one has $\Delta T_{\text{rms}}$ ( $10^{-3}$ K) | 5     | 4     | 1      |

The dwell mode combines many of the advantages of the SETI instruments. It takes advantage of the wide frequency coverage and high spectral resolution. The telescope could be a bit larger, but even here one does not lose sensitivity provided that either the source is extended on the scale of the telescope beam size (which is true of TMC 1 at the higher frequencies) or  $T_{\text{source}}$  is greater than  $T_{\text{receiver}}$  (true of Orion).

#### Surveys at Selected Frequencies

We use the following criteria to decide what is worth doing.

1. Scientific interest.

2. Could it be done in a reasonable length of time with the 140-ft telescope of NRAO? This criterion sets a *lower* limit to the amount of time that is worth devoting to a survey project.

3. What is the *maximum* length of time that could reasonably be spent during the SETI program and not impact too badly on SETI itself?

Regarding the second point above, our assumption is that if a survey project can be done in a "reasonable length of time" with the 140-ft telescope, then someone will do it and we need not concern ourselves with it here. We assume that a reasonable length of time with the 140-ft telescope is less than about 1 yr. It is anticipated that the 140-ft telescope will soon be equipped with a series of up-converters that will cover the 1- to 16- and 18- to 25-GHz bands. The system temperature over this range will typically be 50 K and there will be a 1000-channel autocorrelation receiver with 80 MHz of total bandwidth. So the SETI system temperature will be about one-half of that at the 140-ft telescope except on continuum sources, where the ratio will be less favorable.

The 260-MHz bandwidth of the MCSA enables simultaneous coverage of multiple spectral lines, many of which may be of interest. This saves observing time. Table H-III lists the transitions of most interest for a survey program and indicates which can be covered simultaneously with the MCSA. There are a few other transitions from molecules

TABLE H-III.— SIMULTANEOUS COVERAGE OF  
MULTIPLE LINES POSSIBLE WITH THE MCSA

|   | Frequency, GHz |
|---|----------------|
| HI  | 1.420          |
| OH  | 1.612          |
|   | 1.665          |
|   | 1.667          |
| NH <sub>3</sub> (1,1)                                     | 23.694         |
| (2,2)   | 23.722         |
| (3,3)   | 23.870         |
| H <sub>2</sub> O masers 6 <sub>16</sub> - 5 <sub>23</sub> | 22.235         |
| Rapid scans only pick up maser lines                      |                |
| CH  | 3.263          |
|   | 3.335          |
|   | 3.349          |
| H <sub>2</sub> CO   | 4.830          |
| H <sub>2</sub> <sup>13</sup> CO                           | 4.593          |
| OH ( $\pi_{1/2}$ , J = 1/2)                               | 4.660          |
|   | 4.750          |
|   | 4.765          |
| H <sub>2</sub> CO   | 14.488         |

such as  $\text{HC}_7\text{N}$ ,  $\text{H}_2\text{CS}$ , and  $\text{CH}_3\text{CHO}$  that will be covered in some of these surveys, but with the modest integration times per position in the sky that are listed below, we do not anticipate that these molecules will be readily detected and, hence, do not consider them further at this time. Obviously, if a survey program ever does become a reality, then one should be aware of all transitions within the band of the SETI instrumentation.

Table H-III also shows that, except for the 2-cm  $\text{H}_2\text{CO}$  and the  $\text{H}_2\text{O}$  maser transitions, the broad bandwidth and many channels of the MCSA may give a SETI survey an advantage over a 140-ft survey in terms of the number of important lines that can be covered simultaneously. (This is not *necessarily* so since the NRAO autocorrelation receiver may be split into as many as four sections to cover different lines in the intermediate-frequency bandpass.) The considerations outlined above suggest that if the SETI-related survey is to achieve comparable sensitivity to a 1-yr, 140-ft survey, then, typically, at least 2-3 mo must be spent on the SETI survey at a given frequency.

#### Sky Survey for HI (and OH)

The scientific motivations for the HI survey are outlined in appendix I. The three lowest-frequency OH  $\Lambda$ -doublet lines at 18 cm can be included in the bandpass. This OH survey will not be competitive with Barry Turner's galactic plane survey. It may discover some new OH masers, but probably not too many, given previous surveys on larger telescopes (such as the NRAO 300-ft). Study of extragalactic OH with a 34-m antenna appears to be hopeless (Turner, private communication).

#### Survey of Galactic Plane and Selected Regions for $\text{H}_2\text{O}$ Masers

The scientific motivations are outlined in appendix I. It would seem worthwhile to spend 6-12 mo on this program. The sensitivity estimates have been carried out assuming a 34-m antenna. It is possible that the DSN antennas cannot be used at frequencies as high as 22 GHz. However, since the sensitivity of the survey for point-like sources scales only linearly with the telescope diameter, the flux estimates will not be wrong by more than a factor of two in either direction. Similar remarks hold for the  $\text{NH}_3$  survey described below, for which a 34-m antenna has been assumed.

#### Galactic Plane Survey of (1,1), (2,2), and (3,3) Transitions of $\text{NH}_3$

Ammonia is a widely observed molecule that is an especially useful probe of conditions (such as temperature)

in molecular clouds. This is because it possesses numerous inversion transitions that have nearly the same frequencies but very different excitation energies above the ground state.

If we assume a sky temperature of 20 K, 1 km/sec spectral resolution, and 25-sec integration time per point in the sky, then in 1 yr we can cover 2% of the sky with an rms noise level of  $\sim 0.05$  K. This sensitivity is comparable to that achieved by Schwartz et al. (1977) in a much more limited survey program. Two percent of the sky corresponds to a strip  $|b| \leq 1^\circ$  around the entire galactic plane ( $l = 0$  to  $360^\circ$ ). Barry Turner covered  $|b| \leq 1.5^\circ$  in his OH survey of the northern plane, and Dennis Downes et al. covered  $|b| \leq 1^\circ$  in their  $\text{H}_2\text{CO} + \text{H } 110\alpha$  survey of the northern plane.

#### 6-cm Galactic Plane Survey of $\text{H}_2\text{CO}$ , $\text{H}_2^{13}\text{CO}$ , and OH ( $\pi_{1/2}, J = 1/2$ ) Triplet

The  $1_{10}-1_{11}$   $\text{H}_2\text{CO}$  doublet is a line that is observed in many regions in the galaxy, including in dark clouds where it absorbs the cosmic background radiation. A sensitive galactic plane survey could be useful for galactic structure research and chemical abundance studies.

With 1 km/sec spectral resolution, one can integrate about 3 min per position in a 6-mo program that covers the galactic plane strip between  $|b| \leq 1^\circ$ . This would yield an rms noise of  $\sim 0.03$  K which is only slightly worse than the rms's achieved by Few (1979) and Downes et al. (1980) in much more limited surveys.

The opportunity to observe  $\text{H}_2^{13}\text{CO}$  at the same time may yield some valuable measurements of isotopic abundances. Also, new 6-cm OH maser sources may be discovered.

#### Galactic Plane Survey of the 2-cm $\text{H}_2\text{CO}$ Transition

This is a nice complement to the 6-cm  $\text{H}_2\text{CO}$  survey for measuring  $\text{H}_2\text{CO}$  excitation temperatures, but it is probably the scientifically least exciting of the surveys listed here. To do a complete galactic plane strip between  $|b| \leq 1^\circ$  would be possible in 6 mo, spending about 25 sec per position. This yields an rms noise of 0.05 K which is, at best, marginally adequate to observe lines in most directions.

#### Survey of CH Triplet in the Galactic Plane

This triplet has been studied extensively by the Swedish group, e.g., Hjalmanson et al. (1977). For dust clouds they integrated for  $\geq 3$  hr to detect lines as weak as 0.02 K with fair S/N.

Assuming 1 km/sec spectral resolution and spending 8 min per position, in 6 mo one could achieve an rms noise

of  $\sim 0.02$  K along a strip  $|b| \leq 1^\circ$ . This really would not be very competitive with the Swedish sensitivities (although they did not actually do such a strip). Observations of the galactic center and the southern Milky Way, neither of which is visible from Sweden, would perhaps be more valuable than a northern plane survey.

### SUMMARY

Based on the times given in table H-I, "dwelling" and surveying for the benefit of RA will take 3-4 yr out of an assumed 10-yr program. However, this should definitely not be regarded as time lost to SETI. Rather than scan the whole sky uniformly at many frequencies, it seems worthwhile to include at least one deep all-sky SETI survey – according to table H-I, this would be carried out at the Waterhole – and a few deep surveys of the galactic plane, since that is where the overwhelming bulk of population I stars resides. Many astronomers feel that concentrating on the galactic plane and a few other selected regions, such as nearby galaxies, makes good SETI sense completely independent of any considerations that relate to RA. By carrying out the surveys listed in table H-I we are having our cake and eating it too. The only

program in table H-I with little obvious value to SETI is the dwell-mode observations, but this only consumes a few percent of the total observing time.

### REFERENCES

- Downes, D.; Wilson, T. L.; Beiging, J.; and Wink, J.: H110 $\alpha$  and H<sub>2</sub>CO survey of Galactic Radio Sources. *Astron. Astrophys. Suppl. Ser.*, vol. 40, 1980, pp. 379-394.
- Few, Roger W.: Observations of Formaldehyde along the Galactic Plane. *Mon. Not. R. Astr. Soc.*, vol. 187, 1979, pp. 161-178.
- Hjalmarson, Å.; Sumi, A.; Elldér, J.; Rydbeck, O. E. H.; Moore, E. L.; Huguenin, G. R.; Sandqvist, Aa.; Lindblad, P. O.; and Lindroos, P.: Radio Observations of Interstellar Ch. II. *Astrophys. J. Suppl. Ser.*, vol. 35, 1977, pp. 263-280.
- Schwartz, P. R.; Cheung, A. C.; Bologna, J. M.; Chui, M. F.; Waak, J. A.; and Matsakis, D.: Observations of Ammonia in Selected Galactic Regions. *Astrophys. J.*, vol. 218, 1977, pp. 671-676.



## APPENDIX I

### HI AND H<sub>2</sub>O SURVEYS

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#### Galactic Survey for H<sub>2</sub>O Masers

It would be desirable to search the whole galactic plane plus several nearby dust clouds for H<sub>2</sub>O masers. The survey would find (1) the distribution, kinematics, and luminosity function of evolved stars which have H<sub>2</sub>O masers and (2) H<sub>2</sub>O masers associated with the processes of star formation. (I imagine that separating sources found in such a survey into these two groups will be difficult, if not impossible.) Looking at the intensities of H<sub>2</sub>O sources so far observed, a detection limit of 5 Jy would be desirable.

With a 34-m telescope of good efficiency, the HPBW is 1.6 arcmin and  $S = 6.1$  Jy/K. Assuming that the observations use a resolution of 1 km/sec, the time required to reach a  $5\sigma$  sensitivity of 5 Jy is 1.25 sec/beamwidth. To cover the whole galactic plane to  $|b| \leq 5^\circ$  would then require  $1.3 \times 10^7$  sec, or 5 mo. This survey is particularly important because nothing of the kind exists at present. All H<sub>2</sub>O observations to date have been spot observations,

almost always of infrared sources, compact HII regions, known infrared stars, etc.

Since several interesting regions would be missed by the coverage described above, they might be covered separately. Some of these regions are given in table I-I.

The times listed in table I-I have been worked out assuming that the desired sensitivity is still 5 Jy. It is probably worth surveying the galaxies to about 0.5 Jy, which would require  $\sim 70$  days.

#### HI in the Local Group

Here a whole-sky survey (41,253 square degrees) is appropriate. The aim is to search for HI clouds and dwarf galaxies in the Local Group and to measure, to some level, the total HI content of the Local Group. This work is of importance in considerations of the dynamics of the Local Group and of galactic evolution. A practical amount of observing time is 1 yr to survey the whole sky at the HI

TABLE I-I.— POSSIBLE REGIONS FOR H<sub>2</sub>O SURVEYS

| Selected region                          | Central position                     | Area    | Total time, sec      |
|--|--------------------------------------|---------|----------------------|
| Taurus clouds                            | 04 <sup>h</sup> 30 <sup>m</sup> +25° | 20°×10° | 3.5×10 <sup>5</sup>  |
| Orion complex                            | 05 <sup>h</sup> 40 <sup>m</sup> -2°  | 10°×10° | 1.8×10 <sup>5</sup>  |
| $\rho$ Oph clouds                        | 16 <sup>h</sup> 25 <sup>m</sup> -24° | 5°×5°   | 4.4×10 <sup>4</sup>  |
| M31 galaxy                               | 00 <sup>h</sup> 40 <sup>m</sup> +41° | 6°×3°   | 3.16×10 <sup>4</sup> |
| M33 galaxy                               | 01 <sup>h</sup> 31 <sup>m</sup> +30° | 3°×3°   | 1.6×10 <sup>4</sup>  |
| NGC253 galaxy                            | 00 <sup>h</sup> 45 <sup>m</sup> -26° | 3°×2°   | 1.1×10 <sup>4</sup>  |
| NGC185 galaxy                            | 00 <sup>h</sup> 36 <sup>m</sup> +48° | 30'×30' | 4.4×10 <sup>3</sup>  |
| M82 galaxy                               | 09 <sup>h</sup> 52 <sup>m</sup> +70° | 10'×10' | 49                   |
| IC342 galaxy                             | 03 <sup>h</sup> 42 <sup>m</sup> +68° | 20'×20' | 200                  |
| Total time = $6 \times 10^5$ sec = 7.5 d |                                      |         |                      |

frequency. Then the  $5\sigma$  detectability for a point source is 0.6 Jy if a bandwidth of 10 km/sec is assumed. For extended line emission, the upper limit on  $T_B$  in the same bandwidth is  $\sim 0.1$  K.

The outer edge of the galaxy can thus be surveyed to this limit, which corresponds to observing gas at a galactocentric distance of  $\sim 40$  kpc. The extent of the galaxy (or at least of its HI disk), the shape of the rotation curve, and the nature of the high-velocity clouds can all be examined.

The diameter of the Local Group is roughly 3 Mpc, with our galaxy at one edge. The limit of 0.6 Jy at a distance of 3 Mpc corresponds to  $\sim 4 \times 10^7 M_\odot$  of HI (assumed line width = 30 km/sec). The HI content of the Local Group can then be surveyed to this sensitivity, or better.

### Spiral Galaxies in the Zone of Avoidance

If a velocity resolution of 50 km/sec is assumed, the  $3\sigma$  detection limit for HI is  $\sim 0.16$  Jy. The largest amount of HI found in spirals is  $\sim 10^{10} M_\odot$ . If the line width of a hypothetical galaxy containing this amount of HI is 300 km/sec, such a galaxy can be seen to 30 Mpc, or about twice the Virgo cluster distance. The SETI observations will allow a search for gas-rich galaxies through the zone of avoidance out to a respectable distance.

None of the above work uses the unique capabilities of the SETI instrument, in particular the very fine frequency resolution. I suspect that if the instrument were to be made available as an RA facility, many proposals to use this high resolution would be made. Instead, the above suggestions use the possibility of acquiring whole-sky surveys in important lines and to reasonable sensitivities.

## APPENDIX J

### POTENTIAL USE OF SETI INSTRUMENTATION IN PULSAR RADIO ASTRONOMY

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#### Abstract

*The MCSA proposed for SETI will be a very attractive research instrument for the observations of pulsars. Pulsars have perhaps the highest brightness temperatures of all radio sources, primarily because of the narrow temporal features of their pulses. The pulsar emission mechanism that gives rise to these narrow features is not well understood, thus the observation of individual pulsar pulses with high time resolution is of particular interest. A technique is proposed here to convert the high spectral resolution of the MCSA into high temporal resolution for the observation of narrow pulsar pulses. When used in conjunction with a large radio telescope, both the breadboard MCSA and the completed 8-MHz system will be useful for studying galactic pulsars as well as for searching for extragalactic pulsars.*

Normally the high spectral resolution afforded by the MCSA would not be considered well suited to observing pulsars. Pulsar pulses are of very short duration with much of the radio energy concentrated in time intervals from milliseconds to perhaps less than a microsecond. Since a temporally concentrated pulse is by nature spectrally dilute, pulsars have their pulsed flux distributed over large bandwidths from some kilohertz to several megahertz. Consequently, frequency spectra of pulsar pulses are not expected to possess much in the way of strong, ultranarrow features and thus are not well matched to the MCSA's 1-Hz resolution.

Interestingly, a good match to the MCSA's properties can be made by taking advantage of the effects of interstellar dispersion. Radio waves do not propagate at constant velocity through the weakly ionized hydrogen clouds in the interstellar medium. Rather, if  $v_g$  is the group velocity of a wave packet, then the velocity of radio waves in the cold plasma clouds of interstellar space is (Rickett and Hankins, Meth. Comp. Phys. V14, 1975)

$$v_g(f) = c \frac{1}{1 + (f_p^2/2f^2)}$$

where  $c$  is the speed of light,  $f_p$  is the plasma frequency, and  $f$  is the nominal frequency of the packet. Typically  $f_p = 10$  kHz, and for most radio receivers the observing

frequency at which the pulses are observed is well above the plasma frequency.

As a pulsar pulse moves through interstellar plasma, the high-frequency components of the pulse travel faster than the low-frequency components. Consequently, the temporal width, or duration, of the pulse increases with distance from the pulsar. There is, however, a close correlation between the pulse's frequency components and their position within the pulse. In a receiver the pulse appears as a chirp, a signal that sweeps across the receiver's bandwidth.

The sweep rate  $df/dt$  depends on the amount of separation of the signal's frequency components. Using  $t_d = z/v_g$ , as the group delay  $t_d$  of the packet after traveling a distance  $z$ , the differential delay is

$$dt = \frac{z}{v_g(f+df)} - \frac{z}{v_g(f)}$$

and then the sweep rate is

$$\frac{df}{dt} = -\frac{f^3}{t_0 f_p^2}$$

where  $t_0 = z/c$ .

Since the frequency components of the pulse are typically well above the plasma frequency of the interstellar

plasmas ( $f_p$  order of 10 kHz), the sweep rate is nearly constant for bandwidths that are about 10% of the observing frequency. The constant nature of the sweep rate suggests that one means of observing a dispersion-free pulse is to mix the pulse's radio signal with a local oscillator (LO), that is swept at the same rate as the pulse. By timing the sweep of the LO to coincide with the mean arrival time for the pulse, each strong temporal feature, or subpulse, will sweep at a constant frequency offset from the LO. Then the spectrum of the mixed signals will contain strong, narrow components that correspond to each of the pulse's narrow temporal components. In this manner the temporal structure of the undispersed pulse will be mapped into the frequency spectrum of the received pulse.

The resolution time obtained in this manner depends on the LO sweep rate and thus depends on the dispersion measure of the pulsar. For moderate dispersion measures, like the PSR 0531+21 in the Crab nebula, the sweep rate  $g$ , at 430 MHz, is 140 kHz/msec. The minimum temporal resolution  $t_{\min}$ , is then

$$t_{\min} = \frac{f_{\min}}{g}$$

Choosing  $f_{\min} = 1$  Hz, gives  $t_{\min} = 7$  nsec, while for  $f_{\min} = 32$  Hz,  $t_{\min} = 200$  nsec.

A rich temporal structure is typically observed in the pulses from nearby pulsars. At time resolutions of 10  $\mu$ sec to a few msec, very bright, but unresolved, dispersion-broadened impulses have been observed previously. By using the MCSA to obtain temporal resolutions in the range from 0.01 to 1  $\mu$ sec, these impulses would likely be resolved, and the maximum brightness of the pulses could then be determined.

To take full advantage of the MCSA resolution, pulsar pulses that possess very narrow impulses should be observed. Impulses with a duration of about the inverse of the receiver's bandwidth will be mapped into just a few 1-Hz channels provided that the LO follows the sweep of the pulse for about 1 sec. Further, the pulse should be coherent across this bandwidth. Matching the sweep of the LO should present no serious technical difficulty. However, the noisy appearance of individual pulsar pulses suggests that their coherence bandwidth may be much smaller than typical receiver bandwidths.

On the other hand, some pulses from at least a few pulsars have broadband, coherent microstructure, and this microstructure has a temporal width of about 1  $\mu$ sec or less; i.e., compatible with an impulse in a 10-MHz receiver bandwidth. Further, these pulses sweep at rates which can be matched without serious technical difficulty. The pulsar in the Crab nebula, for example, occasionally emits giant bursts of RF energy which appear as a single impulse of 1  $\mu$ sec or less duration. These impulses appear to be coherent across bandwidths of 1 MHz or more. The giant pulses sweep at a

rate of 140 kHz/msec when observed at 430 MHz. In order to match the observation of these pulses to the MCSA, the receiver should be swept for 1 sec over a bandwidth of 140 MHz, which is possible at Arecibo with the frequency-agile receiver. This receiver has a relatively high noise temperature, and must be used with a low-efficiency, broadband feed. This is not a problem for the giant pulses, which appear on top of the roughly 1000-flux-unit noise from the Crab nebula.

A slower sweep rate would allow use of the narrower-bandwidth, but higher-efficiency feeds at Arecibo. A more attractive sweep rate from this point of view would be 10 kHz/msec, which would sweep over 10 MHz in 1 sec and would be well matched to the Arecibo receiver's bandwidth at 430 MHz. This sweep is slower by an order of magnitude or so, and implies that the pulses would have dispersions larger by a comparable amount. Higher dispersion would result from either a larger dispersion measure, or lower observing frequency, or both.

Interstellar dispersion depends on both the distance traveled by the pulse and the free electron density of the interstellar plasma over that distance. Within the plane of our galaxy the free electron density appears roughly constant (0.03 electrons/cc), and decreases roughly exponentially above the galactic plane. Thus a larger dispersion could be associated either with pulses from pulsars at larger distances, perhaps an order of magnitude farther than the Crab, perhaps from pulsars external to our galaxy, or from pulsars within or behind regions of greater ionization. Larger dispersions imply a correspondingly larger magnitude for interstellar scattering, which would in turn limit the coherence bandwidths. However, recent observations of the giant pulses from the Crab pulsar suggest that this need not be the case. Additional work is in progress on this question.

In taking advantage of the full resolution of the MCSA, enormous improvements in sensitivity over contemporary pulsar observations are possible. For example, when the MCSA is used to resolve a 1-Hz signal of constant frequency buried in noise, the gain in signal to noise  $G$  is equal to  $N$ , the number of channels in the spectrometer. For the proposed full MCSA,  $G = 8 \times 10^6$ . This gain is in effect a coherent integration of the signal within a matched filter. Sweeping the LO converts the MCSA into a matched filter for chirps. A gain of about  $10^6$  would more than compensate for the decrease in signal strength of pulsars in the neighboring external galaxies. Thus the MCSA appears to be a very attractive means of observing pulsars at great distance.

An additional difficulty associated with these observations is that the dispersions or rates of sweep of the pulses are not known a priori. Here again the features of the MCSA can be used to advantage. The final stages of the computation of the frequency spectrum in the MCSA are performed in a DFT processor that is microprogrammable. Instead of computing the DFT, in the last stage of the MCSA, the processors could be reprogrammed to compute the chirp  $Z$

transform (CZT) over a range of chirps. Even in the case in which the sweep rate is known, the pulse would likely not end up in a single 1-Hz channel, but in about 10 to 100 channels, due to inherent noise and degree of coherence in the pulse itself. Consequently a tradeoff between resolution and sweep rate is possible. By suitable reprogramming, the DFT processors could perform a variety of CZTs within the constraints of time and available memory space, and thereby search a limited range of chirps or dispersions.

A choice of the CZT algorithm suitable for an MCSA microprogram is possible because CZTs are very similar to the DFT. Both can be made very efficient. In fact, the CZT may be more efficient than the DFT if the size of the CZT is chosen carefully. The reason this is so is rather interesting and can be demonstrated by considering the mathematical properties of a chirp. By choosing the following representation for a chirp

$$a(t) = a_0 e^{2\pi i(f_0 t + b t^2)}$$

then there are two unknown constants,  $f_0$  and  $b$ . In this representation the constant  $f_0$  is, in some sense, the frequency in which the pulse appears within the band at the onset of data taking. The constant  $b$  is the sweep rate  $g$ . The magnitude of the signal is also not known, but for detection purposes,  $f_0$  and  $b$  are the ones which define the search space.

If  $b$  were zero, then an FFT would be all that would be needed to detect the signal. Since  $b$  is in general not zero, what is needed is a transform, like the FFT, that will compress this swept signal into a few channels. If for the moment  $f_0$  is assumed to be zero, then the CZT will produce this compression as follows. Let the CZT be represented by the kernel  $e^{2\pi i \alpha \Delta^2}$ , where  $\alpha$  indexes the chirp channels, and  $\Delta$  is the transform variable. This form of the CZT is easily made efficient by choosing the size  $N$  to be a number composed of mutually prime factors, and then factoring the transform matrix with a shuffle based on the prime factor algorithm. The following is an example of a small CZT to demonstrate the factoring.

In analogy with the Fourier Transform, define the CZT of a general sequence  $x_n$  as

$$X_k = \sum_0^{N-1} e^{2\pi i k n^2 / N} x_n$$

where this is now in discrete notation, and  $k$  labels the chirp rates. For the representation where  $x_n$  and  $X_k$  are considered vectors, then the transform is

$$X = (CZT)x$$

where (CZT) is a matrix operator of order  $N$ . To demonstrate the factoring of the matrix, the elements will be represented

as the product  $kn^2$  in the exponent of the operator. For demonstration purposes a small size, order 6, is chosen because its factors 3 and 2 are mutually prime. In general, if  $N = nm$ , and  $n$  and  $m$  are mutually prime; i.e., contain no common divisor, then a CZT of order  $N$  may be factored into outer products of smaller CZTs of order  $n$  and  $m$ . The CZT for these choices is

$$CZT = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 4 & 3 & 4 & 1 \\ 0 & 2 & 2 & 0 & 2 & 2 \\ 0 & 3 & 0 & 3 & 0 & 3 \\ 0 & 4 & 4 & 0 & 4 & 4 \\ 0 & 5 & 2 & 3 & 2 & 5 \end{pmatrix}$$

Because 6 has two prime factors,  $6 = (3)(2)$ , by the Chinese Remainder Theorem the matrix may be factored into two matrices of dimensions two and three, respectively. Right now the rows and columns are in the natural order, labeled (0,1,2,3,4,5). The factoring prescription based on the Chinese Remainder Theorem says change the order of the rows to (0,2,4,3,5,1) and the order of the columns to (0,4,2,3,1,5). Now the CZT transform matrix will be shuffled according to this prescription, and the shuffled operator  $CZT$  is obtained.

$$CZT = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2 & 2 & 0 & 2 & 2 \\ 0 & 4 & 4 & 0 & 4 & 4 \\ 0 & 0 & 0 & 3 & 3 & 3 \\ 0 & 2 & 2 & 3 & 5 & 5 \\ 0 & 4 & 4 & 3 & 1 & 1 \end{pmatrix}$$

The factors in  $CZT$  become obvious when  $CZT$  is chopped into quadrants.

$$CZT = \begin{pmatrix} 0 & 0 & 0 & . & 0 & 0 & 0 \\ 0 & 2 & 2 & . & 0 & 2 & 2 \\ 0 & 4 & 4 & . & 0 & 4 & 4 \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & 3 & 3 & 3 \\ 0 & 2 & 2 & . & 3 & 5 & 5 \\ 0 & 4 & 4 & . & 3 & 1 & 1 \end{pmatrix}$$

The transform  $CZT$  is composed of three identical groups of  $3 \times 3$  matrices, and an additional group that is in fact identical to the others except for the addition of the constant 3. All the elements are the products  $nk^2$  modulo 6, where, for example,  $3 + 4 = 1$ , modulo 6. The addition of 3 in the exponent is equivalent to multiplying each of the elements in the lower right group by  $\exp[2\pi i(3/6)]$ , or  $-1$ .

The shuffled transform is therefore equal to the "product" of two smaller matrices,  $CZT_2$  and  $CZT_3$ , that are themselves small CZT transforms of dimension 2 and 3.

$$CZT_6 = CZT_2 \otimes CZT_3$$

where

$$CZT_2 = \begin{pmatrix} 0 & 0 \\ 0 & -1 \end{pmatrix}$$

where again the -1 is the actual coefficient, not the value of the exponent, and

$$CZT_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 2 & 2 \end{pmatrix}$$

The product  $CZT_2 \otimes CZT_3$  is computed by the rules for the outer product of two matrixes. The much larger CZTs are factored in a similar manner. Their size is chosen to have many mutually prime factors, and then the shuffle prescription is obtained via the Chinese Remainder Theorem.

The factoring that has been demonstrated here for the CZT provides the basis for a chirp detector under the assumption that the frequency offset  $f_0$  defined above is

zero; i.e., that the pulse is drifting across the dc or baseband channel at time zero. Arbitrary frequency offsets must be accommodated for a realistic detector. One means of including frequency offsets is to reduce the bandwidth into small regions. Then short-length CZTs can be computed for each of these regions simultaneously. The short-length CZTs are highly efficient, so that many short CZTs can be computed in a time comparable to compute one large CZT.

The decimation of the frequency band then reduces the range of possible frequency offsets. It is expected that a sequence of short CZTs, each with a different frequency offset, can be arranged in such a manner as to provide an efficient means of computing the sequence in a time comparable with one large transform.

The algorithms for the CZTs organized in this manner can be programmed into the processors in the MCSA. Together with a swept LO, the MCSA becomes a high-temporal-resolution spectrometer which will be able to detect individual pulsar pulses with extraordinary sensitivity. The MCSA therefore appears to be well suited for high-sensitivity observations of both galactic and extragalactic pulsars.

## APPENDIX K

### SETI AND SERENDIPITY

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#### Abstract

*The SETI instrumentation that has been proposed will view the Universe through a set of observational filters which have never before been systematically employed by astronomers. In this section, a particular model of what constitutes a truly new and unique astrophysical phenomenon is used to predict the likelihood of an astrophysically serendipitous discovery during the course of the proposed SETI observational program.*

The serendipitous detection of an ETI signal during the course of regularly scheduled radio astronomical observations has been an intriguing possibility for the past two decades. For some, this has been enough. For others, unsatisfied with such a passive approach, it has been enough to attempt detection through unconventional applications of radio astronomical instrumentation. Had detections occurred during such searches, they too would have been serendipitous to the development of the field of RA. For still others, use of equipment intended for the detection of weak, noise-like signals from astrophysical sources has not been enough. SETI-specific instrumentation having unique capabilities for the efficient detection of a moderately broad range of artificial signals has been designed and partially constructed. As a result, it is now possible to consider what serendipitous discoveries of an astrophysical nature might result from the use of this equipment in regularly scheduled SETI observations.

The SETI instrumentation (see chapters 4 and 5 and appendixes B and J) is not the ideal equipment with which to conduct canonical radio astronomical observations, nor was it intended to be. Nevertheless it does provide access to a wide range of cells within the multiparameter phase space (frequency, direction, bandwidth, time, and polarization) that characterizes the observable Universe. Some of these cells overlap the observational regime already under investigation by radio astronomers. Suggestions for exploring these previously sampled cells to extend our understanding of known phenomena, have already been presented in other sections (see chapter 6). The concern of this appendix is the potential for serendipitous discoveries arising from sampling those cells of observable phase space which are

uniquely accessible with SETI instruments. Specifically, are there likely to be any such discoveries?

Historically, astronomers have repeatedly been pleasantly surprised by new phenomena uncovered with the inauguration of a new instrument sensitive to unexplored phase space. Therefore astronomers as a class may be overly optimistic with respect to anticipating new discoveries. At some time it would seem that all major astrophysical phenomena will have been identified. Detailed understanding of all these phenomena might be lacking, but no fundamentally different class of sources will remain to be discovered. Is it possible that astronomy has reached that epoch? SETI will scan new cells, but it may do so in vain if these cells contain no new natural or artificial phenomena. There are some simple statistical arguments that indicate this is *not* the current situation. But it must be admitted that these arguments have been presented by an astronomer. Furthermore, no such arguments can determine whether the new cells to be sampled by the instrumentation are the “right” cells for making a discovery. The statistics predict only that the set of unexplored but occupied cells is not a null set. From this a small but significant probability of serendipitous discovery of new astrophysical phenomena can be calculated directly from the number of new cells to be opened by SETI.

Harwit (1975, 1981) has estimated that there exist some  $2 \times 10^5$  five-dimensional cells within the phase space characterizing the Universe observable through electromagnetic radiation. Four dimensions (frequency coverage plus spatial, spectral, and temporal resolutions) are measured logarithmically with each unit corresponding to one decade. The fifth dimension is polarization which has four possible states: circular, linear, elliptical, and unpolarized. The total number

of cells calculated by Harwit is the product of 24 decades of frequency coverage, 8 decades of spectral resolution, 23 decades of temporal resolution, 18 decades of angular resolution, and 4 polarization states, minus certain subsets of cells excluded on the basis of two-dimensional uncertainty principles and by the physical sizes of measurement baselines.

Of these  $2 \times 10^5$  cells, some  $10^4$  have been sampled, with  $4 \times 10^3$  having been well explored. To date, astronomical exploration has resulted in the identification of 43 distinct, natural Class A phenomena,<sup>1</sup> according to Harwit. The number of Class A phenomena detected to date in more than one observable parameter is  $\sim 100$ ; the total number of such phenomena detectable in only a single observable parameter, including those not yet discovered, may be as high as 400. These figures result from a bold application of Poisson statistics which may not be completely correct in detail, but should serve to place a lower bound on the numbers (Harwit, 1975, 1981). Given that phenomena remain to be discovered, is it likely that SETI instrumentation will detect one or more? The answer depends upon the precise number of new phase space cells to be explored by SETI.

The projected instrument will observe orthogonal circular polarizations simultaneously and, therefore, should be about equally sensitive to all polarizations. The instrument will operate over 4 decades of angular resolution ( $2 \times 10^4$  arcmin for the isotropic coverage of the sky survey, to 2 arcmin at 3 GHz with the Arecibo dish for the targeted search), over 6 decades of temporal resolution (4-kHz pulses to 1000-sec integration time on target), and over a single decade of continuous frequency coverage (1-10 GHz). These ranges are not unique to SETI and fall within the domain of previously sampled phase space dimensions. What is new and unique to SETI is the increased spectral resolution afforded at radio frequencies. Starting with the resolution achieved in typical spectral line observations of  $\nu/\Delta\nu \sim 10^6$ , SETI will operate over 3 decades of spectral resolution up  $\nu/\Delta\nu \sim 10^9$ . Not all temporal and spectral resolutions are jointly possible, since  $\Delta t$  must be greater than  $1/\Delta\nu$  if the instrument is to have time to fully respond to a signal. When this is properly accounted for, the number of new cells to be explored by SETI is  $\sim 200$ , or about  $1 \times 10^{-3}$  of the estimated number of previously unsampled cells in the Universe. Even if the "applicable" frequency resolution is restricted to  $\leq \nu/\Delta\nu \sim 10^8$  as Harwit has done (assuming that no more strongly coherent radiation phenomena can be observed in the astronomical Universe), the number of newly opened cells is still an impressive  $\sim 100$ , or  $\sim 6 \times 10^{-4}$  of the previously unexplored volume. In fact, SETI instrumentation

and the observational programs being proposed will search, within the next decade, through a new volume of multi-dimensional phase space which is equal in size to 1% of the volume explored to date by all other types of astronomical observations.

Harwit estimates there are between 100 and 500 Class A phenomena observable by one or more parameters. On this basis one predicts that this search can be expected to discover between  $1.1 \times 10^{-3} \times (100 \text{ to } 500)$  or 0.11 to 0.55 such phenomena! Success is not inevitable, even in terms of these formal calculations, yet the numbers are encouraging and lend support to the concept of SETI and serendipity.

Apart from undetected Class A phenomena, it is possible to contemplate in a far less speculative manner what new classes of previously known phenomena might be uncovered with the aid of SETI instrumentation. In this application, the value of the instrument lies in its ability to more thoroughly explore previously sampled phase space cells. Compared with current radio astronomical capabilities, the planned instrumentation affords not only uniquely high spectral resolution, but also complete and continuous frequency coverage over 1 decade of the spectrum, combined with complete coverage of the sky and prolonged views over a large number of particularly interesting directions, including nearby stars, molecular clouds, and the galactic center. It is therefore predictable that if the SETI instrumentation is used to observe long enough in each of a large number of interesting directions, it will detect previously unknown line radiation from either frequencies or directions not sufficiently well sampled to date. Further, the instrumentation may be capable of detecting continuum radiation from nearby target stars and catalogue those strong enough for astrometric studies. Since the MCSA is almost completely under the control of down-loaded microcode,<sup>2</sup> the normal (SETI) digital Fourier transforms (DFTs) may be replaced by a range of other transforms and functions. In particular, one may code in CZTs and then the instrument may well prove to be a nearly ideal pulsar detector. (See appendix J for further possibilities in pulsar research.) Finally, since all observations will be conducted in two orthogonal polarizations, properly retrieved data on the Faraday rotation of any linearly polarized radiation component may reveal structure in the spatial distribution of electrons and magnetic field in both our own and other galaxies. While none

<sup>1</sup>Each Class A phenomenon differs from others by a factor of at least 1000 in one of the observable parameters.

<sup>2</sup>The MCSA is under microcode software control with the exception of two elements in its first (74-kHz) filter section. These are the eight-point FFT, hard-wired for speed and economy, and the weighting function in a plug-in ROM which is used to set just the *shape* of the filter function. The MCSA is also equipped with a powerful microcode/timing debug capability. (Microcode, made up of strings of 144-bit words, is developed on a computer with the aid of an MCSA compiler. There is also an efficient compiler for the DFT processors. See appendix B for further discussion of the MCSA design.)

of these considerations constitutes the discovery of a Class A phenomenon, each would extend our knowledge of the astrophysical Universe and reward any planning efforts required to enhance the probability of serendipity in SETI.

### References

Harwit, Martin: The Number of Class A Phenomena Characterizing the Universe. *Q. J. Astron. Soc.*, vol. 16, 1975, pp. 378-409; also in *Cosmic Discovery: The Search, Scope, and Heritage of Astronomy*, Basic Books (New York), 1981, pp. 39-42, 219-224, and 291-297.



## APPENDIX L

### THE ADVANTAGES OF COHERENT TELESCOPE ARRAYS FOR SETI

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#### Abstract

*By combining the simultaneous output of several antennas oriented in the same direction, SETI is offered important advantages. An array pattern has narrow principal maxima. Because the ETI signal is expected from a single direction, an array is a better match to the source. Other possible advantages are (1) strong RFI rejection if signal processing is by multiplication; (2) signals from any direction within the diffraction beam of the largest antenna will be detected and the array provides directive information on a scale of  $\lambda/D$ , where  $D$  is the largest telescope separation distance; (3) multiplying systems, especially, provide good baseline stability, improving weak signal detection; (4) presence of interference fringe phase offers an unbiased estimator for weak signals; (5) strong RFI rejection implies minimum time wasted on false alarms; and (6) adding more collecting area increases sensitivity.*

#### General Principles

Because ETI signals will appear as point sources on the sky, they are better matched to antenna arrays than to single dishes. Hence the linking together of several antennas for SETI observations offers a number of advantages, including increased sensitivity and flexibility, relative freedom from RFI, and some direction-finding capability. The strategy for the use of arrayed antennas is slightly different for the targeted search mode as compared with the sky survey mode.

For the targeted search, the direction to the star is known. The array is phased and the direction-finding capability of the extended antenna is not used. If the signals from all antennas are added, the overall sensitivity increases with the added collecting area. Phasing may be accomplished through the use of delay lines and "fringe rotators." If RFI is encountered in the observations, the multiple antenna system permits a mode of operation strongly discriminating against it. Half the combined output signal from a pair of antennas is in the cross term that must be phased, and the interference is considerably reduced. If only this output term is used, system sensitivity is halved (i.e., equal to that of a single antenna), assuming signals from equal antennas, but freedom from RFI is considerable. In a Very Large Array study by Thompson (1982), the conclusion was that in the tight array the reduction in local monochromatic RFI sensitivity relative to a single antenna was 22–28 dB, and

30–36 dB in the most extended configuration. Such discrimination could spell the difference between success and failure in a SETI observation. One benefit of operating in the multiplying rather than in the straight additive mode is the reduction in false-alarm rate, a particularly important matter when examining the data. A scheme for implementing this mode is discussed below. A final point here is that for wide antenna separations, as in very-long-baseline interferometry, local interference such as was present in Thompson's study vanishes, and RFI/wanted-signal discrimination is fixed by the quality of the multipliers. Site-dependent interference is expected with all antennas used for SETI.

For the sky survey there is another advantage in using the multiplying mode because the direction of a source within the primary beam of the individual antennas is unknown. In the spectral output of the multiplying system, both phases and amplitudes of the cross terms are recorded, and the phase of the signal provides refined information about the source direction. For a brief detection of a transient signal, the positional ambiguity is reduced from being the size of the primary beam to lying on the set of instantaneous fringe lines for a single pair of antennas. If there are three or (better) more antennas in use, the source position must be somewhere on the intersection of the fringe patterns. Thus the direction-finding capability of a widely extended array is realized.

The hardware cost to achieve the antenna phasing proposed here is not large and the technique is well known. As an example, note the very large array at Socorro, New Mexico (built and operated by NRAO). The advantages in sensitivity, freedom from RFI (including the reduction in false alarm rate), and the value of accurate direction-finding for transient signals are considerable.

### An Interferometer System for SETI

ETI signals will be coming from one or a few directions in the sky, rather than from a continuum of directions, and the antenna system which best matches such signals is the array rather than the filled aperture antenna. The simplest array is the two-element interferometer. Consider how two DSN antennas might be used as an interferometer with the present multichannel back-end designed for SETI. A little additional hardware is required, and it must be possible to divide the spectrometer into two halves.

The plan is conventional. An ETI signal arriving at both antennas from direction  $\vec{n}$  suffers a differential delay which changes with time due to the rotation of the Earth (fig. L-1). A little signal processing of a single polarization output from the antennas removes  $\tau(t)$ . The outputs are then separately added and subtracted, and the sum and difference signals are passed through the two halves of the spectrometer. The complex output of each channel is squared and differences are formed from the squared outputs from corresponding spectral channels. These differences represent the power spectrum of the ETI signal, and the operation is equivalent to a multiplication which strongly discriminates against unwanted interference if sufficiently long time averages are used (fig. L-1).

Here are some details. The ETI signal is  $f(t)$  and occupies some of the band that, after translation to baseband, can be

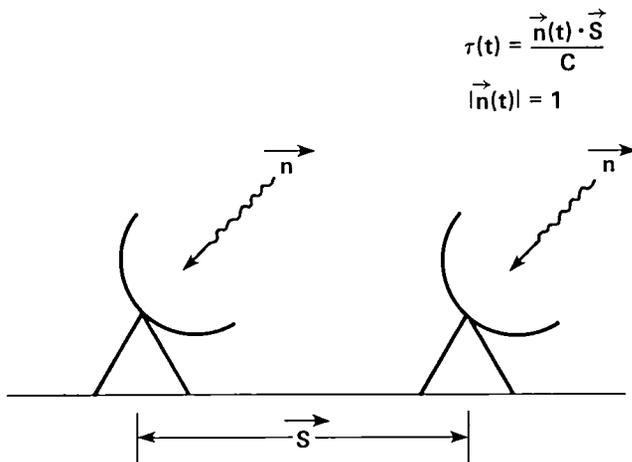
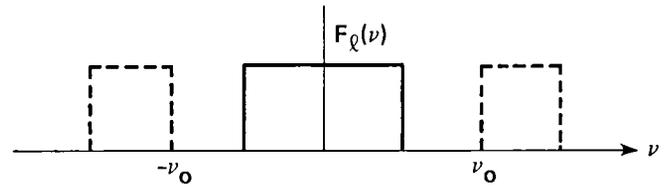


Figure L-1.— An ETI signal arriving at separate antennas suffers a differential delay which changes with time because of the rotation of the Earth.



$$F(\nu) = \Psi[f(t)] \text{ AND } \Psi[f_Q(t)] = F_Q(\nu)$$

( $\Psi$  IS THE FOURIER TRANSFORM OPERATOR)

Figure L-2.— Translation of signal to baseband.

analyzed by the spectrometer. The baseband spectrum is  $F_Q(\nu)$ , and its time function is  $f_Q(t)$ . The shift uses an oscillator at  $\nu_0$  and a low pass filter (fig. L-2). The connection between  $f_Q(t)$  and  $f(t)$  is

$$f(t) = f_Q(t)\cos(2\pi\nu_0 t) - \hat{f}_Q(t)\sin(2\pi\nu_0 t)$$

where

$$\hat{f}_Q(t) \equiv (1/\pi) \int_{-a}^a [f_Q(u)/(t-u)] du$$

To work out the necessary processing for the ETI signal, we first suppose that it alone is present.  $f(t)$  is received at one antenna, and  $f(t - \tau)$  is received at the other. The baseband conversions for the two signals are shown in figure L-3, where

$$\phi(t) = \phi(0) + \int_0^t 2\pi\nu_1(t')dt' ; \quad \nu_1(t) \text{ is close to } \nu_0$$

Evidently,  $O_1(t) = (1/2)f_Q(t - \tau)$ . The other output is

$$O_2(t) = \text{Low Pass}[(1/2)f_Q(t - \tau)\cos 2\pi\nu_0(t - \tau)\cos \phi(t) - (1/2)\hat{f}_Q(t - \tau)\sin 2\pi\nu_0(t - \tau)\cos \phi(t)]$$

or,

$$O_2(t) = (1/2)f_Q(t - \tau)\cos[2\pi\nu_0(t - \tau) - \phi(t)] - (1/2)\hat{f}_Q(t - \tau)\sin[2\pi\nu_0(t - \tau) - \phi(t)]$$

Then,  $O_2 = (1/2)f_Q(t - \tau)$  if we make  $2\pi\nu_0(t - \tau) - \phi(t) = 0$ , and this is guaranteed if  $\nu_1(t)$  is given by

$$\nu_1(t) = \nu_0(1 - \dot{\tau}) \quad \text{and} \quad \phi(0) = -2\pi\nu_0\tau(0)$$

Now,  $O_1(t) = O_2(t) = (1/2)f_Q(t - \tau)$  and the effect of the delay has been removed.

In general, other signals will be present, including both noise and unwanted interference

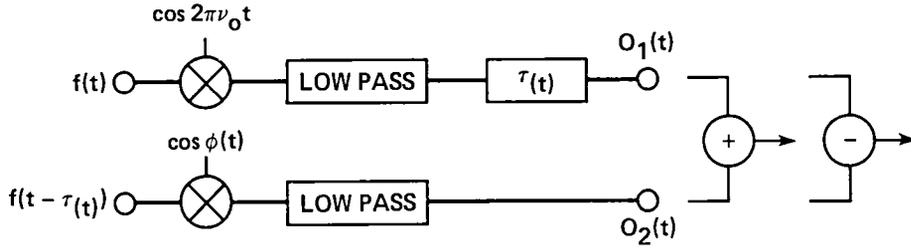


Figure L-3.— Functional block diagram of the circuit required to translate a signal baseband.

$$O_1(t) = (1/2)f_{\varrho}(t - \tau) + X(t)$$

$$O_2(t) = (1/2)f_{\varrho}(t - \tau) + Y(t)$$

Suppose we form the sum and difference, pass these through the two halves of the spectrometer, and then subtract the squared outputs from corresponding channels. For the  $n$ th channel the result is

$$\begin{aligned} \langle O_n \rangle &= \langle [(O_1 + O_2)_n^2 - (O_1 - O_2)_n^2] \rangle \\ &= 4 \left[ (1/4) \langle f_{\varrho}^2(t - \tau) \rangle + (1/2) \langle f_{\varrho}(t - \tau) X_n(t) \rangle \right. \\ &\quad \left. + (1/2) \langle f_{\varrho}(t - \tau) Y_n(t) \rangle + \langle X_n(t) Y_n(t) \rangle \right] \end{aligned}$$

The terms  $\langle X_n^2(t) \rangle$  and  $\langle Y_n^2(t) \rangle$  are eliminated in the difference. In the accumulated power spectrum, the second and third terms vanish on the average because the ETI signal and any other signal or noise will be uncorrelated. The fourth term may contain interference.

If an interfering signal gets into only one antenna,  $\langle X_n(t) Y_n(t) \rangle = 0$ . This term may have a nonzero value if the interference gets into both. There are many possible forms of interference. We consider only a couple of cases to illustrate the interference elimination capability of the interferometer.

Assume an identical signal gets into both antennas

$$X_o(t) = X_{\varrho}(t) \cos 2\pi\nu_0 t - \hat{X}_{\varrho}(t) \sin 2\pi\nu_0 t$$

Then

$$O_{1x}(t) = (1/2)X_{\varrho}(t - \tau)$$

and

$$\begin{aligned} O_{2x}(t) &= (1/2)X_{\varrho}(t) \cos[2\pi\nu_0 t - \phi(t)] \\ &\quad - (1/2)\hat{X}_{\varrho}(t) \sin[2\pi\nu_0 t - \phi(t)] \end{aligned}$$

when  $\phi(t) = 2\pi\nu_0(t - \tau)$

$$O_{2x}(t) = (1/2)X_{\varrho}(t) \cos 2\pi\nu_0 \tau - (1/2)\hat{X}_{\varrho}(t) \sin 2\pi\nu_0 \tau$$

The output interference term is

$$I_n = \langle [X_{\varrho_n}(t - \tau)(X_{\varrho_n}(t) \cos 2\pi\nu_0 \tau - \hat{X}_{\varrho_n} \sin 2\pi\nu_0 \tau)] \rangle$$

Probably the worst case is the presence of a CW signal

$$X_{\varrho_n}(t) = \cos \omega_1 t \quad \text{and} \quad \hat{X}_{\varrho_n}(t) = \sin \omega_1 t$$

$$\begin{aligned} I_n &= \langle [\cos \omega_1(t - \tau)(\cos \omega_1 t \cos \omega_0 \tau - \sin \omega_1 t \sin \omega_0 \tau)] \rangle \\ &= (1/2) \langle \cos(\omega_1 + \omega_0)\tau \rangle \cong (1/2) \langle \cos 2\omega_0 \tau \rangle \\ &\cong (1/2) (\sin 2\omega_0 \tau T) / (2\omega_0 \tau T) \end{aligned}$$

where  $T$  = integration time.

Now the natural fringe rate is

$$\nu \dot{\tau} = (\dot{h} \nu / c) |\vec{S}| \cos(h - h') \cos \delta$$

where

$h'$  = baseline hour angle

$\delta$  = antenna declination

$\nu \dot{\tau} = 0.24 \cos(h - h') \cos \delta$  Hz, for  $\nu = 1$  GHz and  $|\vec{S}| = 1$  km.  
Then for  $T = 10$  sec

$$(4\pi\nu \dot{\tau} T)^{-1} = (4\pi \times 0.24 \times 10)^{-1} \cong 1/30$$

Because the interfering signal is shifted by 0.24 Hz at one antenna output, its average value in the output tends to zero, being down to less than 3% of its initial value after only a 10-sec integration time.

Another case would be a pulsar or otherwise modulated signal getting into both antennas. Then

$$\langle X_{\varrho_n}(t - \tau) [X_{\varrho_n}(t) \cos 2\pi\nu_0 \tau - \hat{X}_{\varrho_n}(t) \sin 2\pi\nu_0 \tau] \rangle$$

is somewhat more complicated. However, the coherence time,  $t_c$ , for a single frequency component of any signal is

approximately equal to or greater than  $1/B$ , where  $B$  is the individual filter bandwidth. Since  $B = 30$  Hz,  $T_c \geq 30$  msec, which is longer than any expected geometrical delay time.  $\tau = (1/c)\vec{n} \cdot \vec{s}$ , the estimate above applies quite generally.

The required hardware consists of (1) a programmable oscillator for  $\nu_1 = \nu_0(1 - \dot{\tau})$ , and (2) a variable delay line which can be set with a precision of  $1/B_0$ , where  $B_0$  is the whole spectrometer bandwidth.

## Reference

Thompson, Richard A.: The Response of a Radio-Astronomy Synthesis Array to Interfering Signals. IEEE Transactions on Antennas and Propagation, vol. AP-30, no. 3, 1982, pp. 450-456.

## APPENDIX M

### ON THE OPTIMUM FREQUENCY FOR INTERSTELLAR COMMUNICATIONS: CENTIMETER VERSUS MILLIMETER VERSUS INFRARED WAVELENGTHS

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#### Abstract

*If the broadcasting society is not concerned with directionality and transmits into a fairly large solid angle, then long wavelengths around 20 cm are favored. If that society wants to transmit only a very narrow beacon, then it is not now possible, given our current lack of knowledge of advanced space technology, to predict reliably whether short or long wavelengths are to be preferred.*

We approach this question from the vantage point of the *transmitting* society, presumably a society more advanced than we are. The motivation for this is that, as a newly emergent technological civilization, we are now special. The average transmitting society is likely to be well in advance of us and will be transmitting mainly for the benefit of others like itself. At the end of this discussion we will briefly consider how to best accommodate the fact that we are special.

The basic assumption that we will make is that the transmitting antenna is located in space and the transmitting society assumes that the receiving society also has giant space antennas. This seems to be a safe assumption which, however, introduces a large uncertainty into our final result.

Some assumptions that we make, such as “the equal power assumption,” are probably the best we can do, but, in fact, *may* be very wrong. That is, we assume that the transmitting society is capable of broadcasting a given amount of power independent of wavelength.

There are many factors that could influence a choice of frequency. We will not list them all here, but will discuss only three important ones, namely,

1. Is there a “magic” frequency obviously best in some universal sense?
2. How directional is the transmitted signal? That is, are we searching for a narrowly beamed transmission or one that is broadcast over a large solid angle? An example of the latter possibility might be a civilization in the Andromeda galaxy that illuminates either the entire Milky Way, or, perhaps, a section of a spiral arm.
3. How does the maximum size of a giant space telescope that could be constructed by an advanced civilization vary as a function of wavelength?

Concerning the first question, there have been many magic frequencies or frequency ranges suggested in the literature, including for example, the Waterhole; the 6-cm transition of H<sub>2</sub>CO; natural lengths constructed from the Bohr radius, the fine structure constant, and possibly  $2\pi$ ; the 22-GHz transition of H<sub>2</sub>O; and the centroid of the 2.7 K cosmic background radiation. So there does not seem to be any obvious single universal frequency to search.

Concerning the second and third questions, we assume that the areas of both the transmitting and receiving antennas,  $A_T(\lambda)$  and  $A_R(\lambda)$ , increase with wavelength,  $\lambda$ . The power received is

$$P_R = (P_T A_R / 4\pi R^2)(4\pi / \Omega_B) = (P_T A_R)(R^2 \Omega_B)$$

where  $P_T$  is the transmitted power,  $R$  is the distance between the Earth and the transmitter, and  $\Omega_B$  is the broadcast solid angle. For the “equal-power assumption” case and the situation where  $\Omega_B$  is independent of frequency, the received power is much greater in the radio than in the infrared for reasonable choices of  $A_R(\lambda)$ . A comparison of detector, photon, and background noise sources (e.g., Townes, 1981) indicates that RF noise is not so much larger than infrared noise to offset the difference in received power. So, for this case, long wavelengths offer the best prospect for detection in the sense of optimizing the S/N. The upper limit to the optimum wavelength is set by the increase in background noise beyond  $\sim 20$  cm.

If the transmitter is beamed so that  $\Omega_B$  is determined by the diffraction limit of the transmitting antenna, then the wavelength for optimum S/N is much harder to determine. If  $A_R$  and  $A_T$  follow the same power law, so that  $A \propto \lambda^n$ ,

then  $P_R \propto \lambda^{2n-2}$ . With present terrestrial telescopes,  $n \sim 1$ . If the same value applies to space structures, then  $P_R$  is independent of  $\lambda$ .

However, we do not now know enough about building giant space antennas to predict  $A_T(\lambda)$  with any reliability. It seems conceivable that, in space,  $1/2 \leq n \leq 2$ . Since the ratio of  $\lambda_{\text{radio}}$  to  $\lambda_{\text{infrared}}$  may be larger than  $10^4$ , this introduces an *enormous* uncertainty into the final result. So it is not now possible to predict reliably at what wavelength the extraterrestrials are likely to transmit, based on considerations of this type.

Since we do not possess an advanced space technology, we can now do better in the microwave domain than in the infrared. If we ask whether the cm or mm domain is to be preferred for nonbeamed signals, then long cm wavelengths

are preferable, as discussed above. For beamed transmissions there is little to choose between cm and mm wavelengths, given the sensitivities of newly developed silicon-insulator-silicon mm-wavelength mixers. The Earth's atmosphere does introduce some extra noise at mm-wavelengths, but, considering all the uncertainties in this field, this seems to be an insufficient reason to choose cm over mm wavelengths if one is searching for a narrowly beamed transmission.

#### Reference

Townes, C. H.: At What Wavelength Should We Search for Signals from Extraterrestrial Intelligence? Proc. Nat. Acad. of Sci., vol. 80, no. 4, 1981, pp. 1147-1151.

## SELECTED SETI REFERENCES AND READING LIST

with Commentary by

Charles L. Seeger

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The Astronomy Survey Committee (G. B. Field, Chairman): *Astronomy and Astrophysics for the 1980's*. Vol. 1. The National Academy of Sciences, National Research Council. National Academy Press, Washington, D.C., 1982.

"The Assembly of Mathematical and Physical Sciences accepts this report as the consensus of the U.S. astronomical community and believes that it will be ranked quickly with the Whitford and Greenstein reports as an indispensable blueprint for the future of astronomy and astrophysics during their respective decades." Among seven Moderate New Programs recommended for the eighties is "An astronomical Search for Extraterrestrial Intelligence (SETI), supported at a modest level, undertaken as a long-term effort rather than a short-term project, and open to the participation of the general scientific community." Supporting arguments are given at length.

The Astronomy Survey Committee (J. L. Greenstein, Chairman): *Astronomy and Astrophysics for the 1970's*. Vol. 1. The National Academy of Sciences, National Research Council. National Academy Press, Washington, D.C., 1972.

"One of the most striking conclusions of the report is the high probability it assigns to the existence of intelligent life elsewhere in the universe." (From the letter of transmittal by Harvey Brooks, for the Committee on Science and Public Policy (COSPOP).)

ASTROSEARCH: Bimonthly SETI newsletter sponsored by DELTA-VEE, Inc.; ASTROSEARCH, P.O. Box 3294, Saratoga, CA 95070.

Combines Cosmic Search (see below) and CQ-ET, an amateur (radio) SETI [AMSET] newsletter; also combines chief editorial personnel. It covers Space, the Search for Extrasolar Planets, and SETI. There is nothing amateurish about many of the AMSET "hams." They are professionals.

Barnes, Right Rev. E. W., F.R.S., Bishop of Birmingham, at the British Association symposium on *The Evolution of the Universe*; reported in *Nature Supplement*, vol. 128, no. 3234, 1931, pp. 719-722.

"If only an instrument could be invented which should enable us to determine whether stars, within, say, a hundred light-years' distance, have planetary systems attached to them! We should then know whether any of the few thousand stars near the sun have planets on which life may conceivably exist. If even one such system were found, the present theory of planetary origins would collapse. Failing any such invention of a super-telescope, there remains the possibility of wireless communication." [Oldest nonfiction reference to the idea of SETI?]

Billingham, J., ed.: *Life in the Universe*. NASA CP-2156, 1981; also, MIT Press, Boston, Mass., 1981.

Proceedings of the Life in the Universe Conference held at NASA Ames Research Center, June 19 and 20, 1979: "A meeting to explore prospects for research into the nature and distribution of life in the Universe." Thirty-three contributions by specialists from almost as many disciplines block out much of what is surmised and the little that seems surely known about the history of the Universe, from the Big Bang to the presence of intelligent, technological life on Earth. Major uncertainties and promising research directions are highlighted in this unique volume.

Billingham, J.; Oliver, B. M.; and Wolfe, J. H.: *A Review of the Theory of Interstellar Communication*. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 47-57.

Summarizes a (by now) classic approach to estimating the likely number of transmitting civilizations in the galaxy.

- Billingham, J.; and Pešák, R., eds.: *Communication with Extraterrestrial Intelligence*. *Acta Astronautica*, vol. 6, no. 1-2, 1979.
- Contains 18 papers covering a wide range of topics, which were presented originally at the 1975-6-7 CETI Review Sessions of the International Academy of Astronautics.
- Black, D. C.: *In Search of Other Planetary Systems*. *Space Sci. Rev.*, vol. 25, 1980, pp. 35-81.
- A thorough review of the history of and modern approaches to the problem of detecting planets in nearby star systems.
- Black, D. C.: *On the Detection of Other Planetary Systems: Detection of Intrinsic Thermal Radiation*. *Icarus*, vol. 43, 1980, pp. 293-301.
- Examines specific aspects of techniques for the detection of planets in the infrared regime where the brightness contrast with the central star is less than in the optical range by a large factor.
- Black, D. C.; and Scargle, J. D.: *On the Detection of Other Planetary Systems by Astrometric Techniques*. *Astrophys. J.*, vol. 263, 1983, pp. 854-869.
- Compact introduction to the problem of detecting periodic signals in astrometric data, with examples. Stresses intrinsic sources of error and develops a measure of planetary detection efficiency. Compares the capabilities of a good ground-based system with those of a comparable space-based system. Stresses the value of periodogram analytic techniques.
- Bowyer, S.; Zeitlin, G.; Tarter, J.; Lampton, M.; and Welch, W. J.: *The Berkeley Parasitic SETI Program*. *Icarus*, vol. 53, 1983, pp. 147-155.
- "Parasitic programs for . . . (SETI), carried out concurrently with conventional radio astronomical observing programs, can be an attractive and cost-effective means of exploring multidimensional search space intrinsic to this effort. We describe a microprocessor-based automated SETI acquisition system which searches for and records spectra of narrowband signals in the [intermediate frequency] band of an observatory receiver." In 35 days at the UCB Hat Creek Observatory, 4000 narrowband signals were recorded while taking  $10^5$  spectra. Over 3900 were probably due to local RFI. The remainder are being studied.
- Bracewell, R. N.: *An Extended Drake's Equation, the Longevity-Separation Relation, Equilibrium, Inhomogeneities, and Chain Formation*. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 67-69.
- The author argues the need to refine Drake's schematic equation for the number of coexisting, transmitting civilizations.
- Bracewell, R. N.: *The Galactic Club: Intelligent Life in Outer Space*. W. H. Freeman and Company, 1974.
- Highly readable synopsis of major unanswered questions about the nature and distribution of intelligent life, including suggestions for contact by interstellar probes.
- Buyakas, V. I.; and 22 other authors (listed alphabetically): *An Infinitely Expandable Space Radiotelescope*, *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 175-201.
- Summarizes a preliminary design study for 1- to 10-km-diam space radio telescopes. Modules built on Earth are assembled in orbit. Points out the enormous value of a system of large space antennas in exploration of the Cosmos. Precise three-dimensional, interferometrically synthesized views of our Universe to far beyond the Local Group of galaxies should be possible.
- Cameron, A. G. W., ed.: *Interstellar Communication*. W. A. Benjamin, Inc., New York, 1963.
- The first collection of original essays on interstellar communication, with stimulating papers by Morrison, Oliver, Bracewell, Cameron, Shklovskii, Towns, Huang, Calvin, Golary, Purcell, and von Hoerner. Also included are two papers by Frank Drake, one of which describes the first definitive attempt to detect ETI radio signals — Project Ozma.
- Cocconi, G.; and Morrison, P.: *Searching for Interstellar Communications*. *Nature*, vol. 184, no. 4690, 1959, pp. 844-846.
- The seminal paper proposing that humans could and should search for radio signals of extraterrestrial origin at frequencies *near* the interstellar 21-cm atomic hydrogen line band.
- Cosmic Search: "A magazine about Space, the Future and the Search for Intelligent Life beyond the Earth, presented in a popular, responsible manner." Published by Cosmic Quest, Inc., Box 293, Delaware, OH 43015. Ceased publication with Vol. 4, No. 1, Serial No. 13, and combined with CQ-ET under the new title ASTRO-SEARCH, P. O. Box 3294, Saratoga, CA 94070.

Cousins, N.: in *Why Man Explores*. NASA EP-125, Washington, D.C., 1976, pp. 3-5.

"It is almost unscientific to think that life does not exist elsewhere in the universe. Nature shuns one of a kind." "It is almost ironic that we should have to ask this question [why explore the universe?] because it is almost as though we have to apologize for our highest attributes, almost as though we have to remind ourselves we are, by nature, creatures of exploration." ". . . conventional wisdom has never been good enough to run a civilization."

Cullers, D. K.; and Rathjen, S.: *The Ultimate QSO*. QST, Dec. 1982, p. 60.

"Is [galactic] communications the next frontier for amateur radio? It could be, if more SETI-inclined hams tune their rigs to the stars." Argues that by combining home computers with amateur radio technologies, hams can join the exploration for ETI signals at ultra-high frequency with sensitivities for very-narrowband, slowly modulated signals roughly comparable to that planned for the NASA all-sky survey. Frequency coverage with any one instrument would be enormously less than in the NASA plan. With a bit of luck, however. . . .

Dixon, R. S.; and Cole, D. M.: *A Modest All-Sky Search for Narrowband Radio Radiation Near the 21-cm Hydrogen Line*. *Icarus*, vol. 30, 1977, pp. 267-273.

Modest but devoted search running since 1973 at OSURO in a 380-kHz band centered on the HI-line corrected to Galactic Center of Rest. So far, no confirmed ETI signal has been detected above  $1.5 \times 10^{-21}$  W/m<sup>2</sup> in declination range 14-48 degrees North. Uses beam switching.

Drake, F. D.: *Project Ozma*. *Phys. Today*, vol. 14, Apr. 1961, pp. 40-46. Also *Interstellar Communications*. A. G. W. Cameron, ed., W. A. Benjamin, Inc., New York, 1963, pp. 176-177 and *McGraw-Hill Yearbook of Science and Technology*, New York, 1962.

First printed account of Project Ozma. Nontechnical, but contains block diagram of Ozma electronic system. Concentrates on arguments for search.

Drake, F. D.: *The Radio Search for Intelligent Extraterrestrial Life*. Ch. IX. *Current Aspects of Exobiology*. G. Mamikunian and M. H. Briggs, eds., Pergamon Press, New York, 1965, pp. 323-345.

Early discussion of the logic of a radio search for the existence of extraterrestrial life and an account of Project Ozma, the first post-World War II radio exploration for intelligent signals from two of the nearest Sun-like stars.

Drake, F. D.: *Will the Real SETI Please Stand Up?* *Phys. Today*, vol. 35, no. 6, June 1982.

"The plan for SETI derives from the best and most effective of scientific traditions and procedures. In essence, only a single and the most minimal assumption is the basis of the program: that what has happened in our solar system has occurred elsewhere." An update on the state of the NASA study and a gentle reproof of those who argue that, by using what they choose to believe we know now, they can "prove" that we are alone in the universe, or, surely, very nearly so. And that, therefore, there is no need to search for physical evidence bearing on the matter. [Shades of Aristotle!]

Edelson, R. E.: *An Experiment Protocol for a Search for Radio Signals of Extraterrestrial Intelligent Origin in the Presence of Man-made Radio Frequency Sources*. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 145-162.

This paper describes the ETI signal-detection problem in the face of stochastic noise and human-caused interference, and suggests a protocol for their rapid elimination on-line.

Gindilis, L. M.; Kardashev, N. S.; Soglasnov, V. A.; Spangenberg, E. E.; and Etkin, V. S.: *Search for Signals from Extraterrestrial Civilizations by the Method of Synchronous Dispersion Reception*. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 95-104.

A search for very-broadband extraterrestrial pulses, using a widely spaced (up to 3000 km) diversity-receiving system employing small antennas, and correcting for interstellar dispersion in order to screen out local sources of noise and human-caused interference.

Goldsmith, D., ed.: *The Quest for Extraterrestrial Life: a Book of Readings*. University Science Books, Mill Valley, Calif., 1980.

Collection of articles dealing with many aspects of SETI and exobiology; spans the centuries from 70 B.C. to the present. The arrangement and the notes by the editor clearly demonstrate what is well understood and what remains controversial or unknowable about these subjects.

Goldsmith, D.; and Owen, T.: *The Search for Life in the Universe*. The Benjamin-Cummings Publishing Co., Inc., Menlo Park, Calif., 1980.

A very readable introductory textbook which presents the subject of astronomy from the point of view of what it may tell us about the prospects for finding life elsewhere in the Universe. Extremely entertaining and accurate, it includes more biology and critical humor than is the norm for this type of book. A successful contemporary update to Shklovskii and Sagan (see below).

Gould, Stephen Jay: *The Wisdom of Casey Stengel*. Discover, vol. 4, no. 3, 1983, pp. 62-65.

“... opinions about the form and frequency of non-earthly beings record the hopes and fears of speculating scientists more than the constraints of evidence.” Thoroughly demolishes Tipler’s evolutionary arguments favoring the uniqueness of human intelligence, which Tipler incorrectly attributes to “... all the great contemporary experts in the theory of evolution — ...” Gould supports SETI because “... we can’t know until we try.” And because, “Curiosity impels, and makes us human.”

Gulkis, S.; Olsen, E. T.; and Tarter, J.: *A Bimodal Search Strategy for SETI*. *Strategies for the Search for Life in the Universe*. M. D. Papagiannis, ed., D. Reidel Publishing Company, Dordrecht, Holland, 1980, pp. 93-105.

The targeted-star observing mode and the sky-survey mode. A moderately technical report on the status of the NASA SETI R&D program development being carried out jointly at the NASA Ames Research Center and the Jet Propulsion Laboratory of the California Institute of Technology.

Haldane, J. B. S.: *The Origins of Life*. *New Biology*, no. 16, Penguin, London, 1954, p. 12.

Original early essays on the origin of life and chemical evolution, written before the critical experiments of Miller and Urey.

Harrington, R. S.: *Planetary Orbits in Binary Stars*. *Astronom. J.*, vol. 82, 1977, pp. 753-756.

Study of those binary systems whose separations appear to allow a stable planetary orbit within the habitability zone around the solar-type star often present in such systems.

Hart, M. H.: *N is Very Small*. *Strategies for the Search for Life in the Universe*. M. D. Papagiannis, ed., D. Reidel Publishing Company, Dordrecht, Holland, 1980, pp. 19-25.

Summarizes 8 yr of developing his arguments that we are alone not only in the galaxy, but probably in the local group of galaxies as well. The antithesis of Sagan’s views.

Hart, M. H.; and Zuckerman, B.: *Extraterrestrials: Where Are They?* Pergamon Press, 1982.

A collection of short papers and edited discussions from “Where Are They? A Symposium on the Implications of Our Failure to Observe Extraterrestrials,” held at University of Maryland, November 1979, to provide a public arena for a wide variety of views not commonly espoused by the “classic” SETI proponents, such as Drake and Sagan. The paucity of our astrophysical, biological, and terrestrial historic knowledge relevant to questions about the prevalence of life in the universe is well illustrated, as are the often strongly held, intuitive stances of researchers in this field which spans the sciences from astrophysics to zoology.

Horowitz, P.: *A Search for Ultra-Narrowband Signals of Extraterrestrial Origin*. *Science*, vol. 201, 1978, pp. 733-735.

A total of 185 Sun-like stars were observed in 80 hr on frequencies near 1.4 GHz with 0.015-Hz bandwidth at NAIC, Arecibo, P.R. Found no signals above  $4 \times 10^{-27}$  Wm<sup>2</sup> within 500 Hz of the hydrogen rest frequency relative to the Solar System barycenter.

*Icarus*, International Journal of Solar System Studies. Academic Press, Inc., 111 Fifth Avenue, New York, N.Y. 10003.

Publishes refereed papers monthly on a wide range of topics, many of which are related to or are on SETI, or CETI.

*Journal of the British Interplanetary Society*. The British Interplanetary Society, 27/29 South Lambeth Road, London, SW8 1SZ, England.

Internationally famous journal. Editorial matter ranges from nontechnical to moderately technical. Besides special issues, “Each issue is now devoted to one of five main subject areas, viz. Space Technology, Space Applications, Astronautics History, Space & Education, and Interstellar Studies.” Papers in SETI area are frequent. (Published since 1934.)

Journal of the British Interplanetary Society, vol. 28, no. 11, Nov. 1975.

Entire issue devoted to "Development of Intelligence and Civilization in the Universe." Contains papers by S. von Hoerner, K. A. Ehricke, David Viewing, Bob Parkinson, and a translation of USSR Research Programme on the Problems of Communication with Extraterrestrial Civilizations adopted by the Scientific Council on the Problem Area of Radio Astronomy (Academy of Sciences of the USSR).

Kaplan, S. D., ed.: Extraterrestrial Civilizations: Problems of Interstellar Communication. NASA TTF-631, 1971.

Interesting collection of Soviet papers from previous years which cover many aspects of interstellar communication.

Kardashev, N. S.: Strategy for the Search for Extraterrestrial Intelligence. Acta Astronautica, vol. 6, no. 1-2, 1979, pp. 33-46.

The author argues the importance of the search to humankind, to its self-understanding and its survival. He points out the value of the 10-km space radio telescopes now being studied.

Kraus, J. D.: Big Ear. Cygnus-Quasar Books, Powell, Ohio, 1976.

"Big Ear is a personal, behind the scenes account of astronomers, engineers, inventors – humans all – their successes and failures. It is a story about the steel and aluminum structures we have raised to probe the cosmos and of our attempt to answer the question, 'Are we alone?'" (From the Foreword)

Kreifeldt, J. G.: A Formulation for the Number of Communicative Civilizations in the Galaxy. Icarus, vol. 14, 1971, pp. 419-430.

Extends the Drake equation through a linear system formulation allowing for different star generation rates and for different civilization-lifetime and development-time distributions. An expression is given for the variance of the estimate of the number of communicative civilizations in the galaxy.

Kuiper, T. B. H.; and Morris, M.: Searching for Extraterrestrial Civilizations. Science, vol. 196, 1977, pp. 616-621.

"The search for extraterrestrial intelligence should begin by assuming that the galaxy has been colonized." Discusses a range of reasons why a microwave search might

fail; the "zoo" hypothesis; "magic" frequencies for interstellar beacons; and the likelihood that we or some species like us will colonize the galaxy.

Lederberg, J.: Exobiology: Approaches to Life Beyond the Earth. Science, vol. 132, 1960, pp. 393-400.

A distinguished geneticist explores aspects of life outside the Earth, or exobiology. Includes suggestions for searching for life in the Solar System.

Machol, R. E.: Two Systems Analyses of SETI. Acta Astronautica, vol. 6, no. 1-2, 1979, pp. 163-173.

A systems analysis of hyperdimensional search space demonstrates that for the next few years the greatest benefit/cost ratios will arise from development of better spectrum analyzers (up to  $10^9$  channels) and better data processors.

Mallove, E. F.; Connors, M. M.; Forward, R. L.; and Paprotny, Z.: A Bibliography on the Search for Extraterrestrial Intelligence. NASA RP-1021, 1978.

Extensive bibliography of interstellar communication and related matters; 1488 entries; largely complete through February 1977. Major divisions are

1. Life-supporting extrasolar environments
2. Origin and evolution of extrasolar life
3. Methods of searching for ETI
4. Decoding signals from ETI
5. Philosophical, psychological, and sociological aspects of the search for ETI
6. Miscellaneous

Mallove, E. F.; and Forward, R. L.: Bibliography of Interstellar Travel and Communication. J. British Interplan. Soc., vol. 33, no. 6, 1980, pp. 201-248.

Extensive bibliography of interstellar communication and interstellar travel. Contains 2699 references sorted into 13 major categories and their subdivisions, and by author(s). Continued development of this bibliography is now in the care of Dr. R. S. Dixon, The OSU Radio Observatory, 2015 Neil Avenue, Columbus, OH 43210.

Martin, A. R., ed.: The Arecibo Observatory. J. Brit. Interplan. Soc., vol. 32, 1979, pp. 228-236.

A felicitous and thorough account of the history and capabilities of the world's largest radio telescope and support facilities at NAIC, Puerto Rico. Describes its use for radio and radar astronomy and for ionospheric

and cislunar free-electron studies. Outstanding achievements are summarized. Altogether exemplary reportage. Thanks Mr. [sic] Amahl Shakhshiri for compiling the material.

Maxim, Hiram Percy: WHAT IS IT ALL ABOUT? Sci. Amer., vol. 146, 1932, pp. 199-203.

*IT* is life, the Universe, and everything. "If humility is good for our souls, then we should have extraordinary souls, for as we look out from our little speck of cosmic dust and realize the facts, we cannot but become superlatively humble." (Might this yet come to pass! See some of the references herein.) Scientist/engineer, famous inventor, founder of national and international amateur radio societies, "The Old Man," as he signed off in QST, was raised warmly in the Age of Reason. Lacking only supportive data acquired in the last half-century, he presents the fundamental case for a radio exploration for "others" from today's point of view. He also wrote "Life's Place in the Cosmos," published in 1933.

Miller, S. L.; and Orgel, L. E.: The Origins of Life on Earth. Prentice-Hall, Englewood Cliffs, N.J., 1974.

Summary of 20 yr of laboratory and fieldwork in chemical evolution; written by two of the leading investigators in this field.

Morrison, P.: Why Man Explores. NASA EP-125, 1976, pp. 7-10.

"If you ask, 'Why do human beings explore?' I would answer, as I think the Greeks would answer, 'Because it is our nature.' For me, exploration is filling in the blank margins of that inner model [of external reality], that no human can escape making. It is the speed, which is our way to change, that eventually marks us. Democratus said, 'I would rather find one cause than be emperor of Persia.' That is a statement which a physicist can beautifully adhere to; were we to lose that feeling, it would be a heavy loss. Finally, for me, human beings explore because in the long run, time after time, when we wish to adapt to the world as our inner nature has evolved, both by genetics and by culture, we can do nothing else."

Morrison, P.; Billingham, J.; and Wolfe, J., eds.: The Search for Extraterrestrial Intelligence: SETI. NASA SP-419, 1977. (Reprinted, with trivial deletions, by Dover Publications, New York, 1979.)

Report of a 2-yr series of science workshops on interstellar communication, chaired by Philip Morrison.

Discussed are the philosophy, technology, strategy, and timeliness of carrying out an exploration for ETI now. After Project Cyclops, the next major discussion leading to the realization of a great exploration.

Morrison, P.; Billingham, J.; and Wolfe, J.: The Search for Extraterrestrial Intelligence – SETI. Acta Astronautica, vol. 6, no. 1-2, 1979, pp. 11-31.

After an introduction, this article presents the index, preface, and major section on "CONSENSUS" from NASA SP-419 by the same editors.

Murray, B.; Gulkis, S.; and Edelson, R. E.: Extraterrestrial Intelligence: An Observational Approach. Science, vol. 199, 1978, pp. 485-492.

Gives arguments for exploring the whole sky for ETI signals in the entire frequency band of the terrestrial microwave window, and suggests a procedure to do it in about 5 yr to flux levels of about 200 dBW/m<sup>2</sup> at a resolution of 300 Hz.

Oliver, B. M.: Thermal and Quantum Noise. Proc. IEEE, vol. 53, no. 5, 1965.

Tutorial paper; develops theory of black body radiation, and thermal and quantum noises from basic physical principles, and shows how to apply the results to signal collectors and receivers throughout the electromagnetic spectrum.

Oliver, B. M.; and Billingham, J., eds.: Project Cyclops: A Design Study of a System for Detecting Extraterrestrial Intelligent Life. NASA CR-114445, 1972 (Revised edition, 1973).

The remarkable (also first) detailed conceptual design study of a system for detecting signals from ET civilizations. Proposes an Earth-based system, expandable as required, consisting of phased antennas with a sophisticated data processing system (now out of date because of progress in integrated solid-state digital electronics). A rich source of basic signal-plus-noise detection theory.

Oliver, B. M.: State of the Art in the Detection of Extraterrestrial Intelligent Signals. Acta Astronautica, vol. 18, 1973, pp. 431-439.

A summary of possible engineering systems for the detection of signals from ETI life; includes the main features of the Project Cyclops design.

Oliver, B. M.: Proximity of Galactic Civilizations. *Icarus*, vol. 25, 1975, pp. 360-367.

Examines the number of times in galactic history that two civilizations might have emerged independently and close to each other and, as a result, perhaps stimulated each to search for yet other civilizations.

Oliver, B. M.: Rationale for the Water Hole. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 71-79.

Physical and psychological basis for thesis that (in the absence of any more cogent reason to prefer another frequency band) the Waterhole should be considered the primary, preferred frequency band for initial interstellar search efforts.

Oparin, A. I.: *Life: Its Nature, Origin and Development*. Oliver and Boyd, London, 1961.

Summary of the writings of the distinguished biochemist; includes some of earliest theories about chemical evolution, particularly as first proposed by the author in the 1920s and later.

Owen, T.; Cess, R. D.; and Ramanathan, V.: Enhanced CO<sub>2</sub> Greenhouse to Compensate for Reduced Solar Luminosity on Early Earth. *Nature*, vol. 277, 1979, pp. 640-641.

A faint young Sun is one of the most unavoidable consequences of stellar structure theory. Given here is a promising atmospheric scenario which keeps the Earth's temperature adequately constant over geologic time. Geophysical data are needed in order to verify it.

Papagiannis, M. D., ed.: *Strategies for the Search for Life in the Universe*. D. Reidel Publishing Company, Dordrecht, Holland, 1980.

Proceedings of the joint sessions of IAU Commissions 16, 40, and 44, held August 15 and 16 in Montreal, Canada, during the 1979 IAU General Assembly: 23 papers, many concerned with the pros and cons of the popular question, "Where are they?"

Pesěk, R.: Activities of the IAA CETI Committee from 1965-1976 and CETI Outlook. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 3-9.

The Chairman reviews a decade of activity by this committee of the International Academy of Astronautics. He concludes that the committee has done valuable work and should continue to provide IAA support to CETI (SETI in the U.S.).

Peterson, A. M.; Narasimha, M.; and Narayan, S.: System Design for a Million-Channel Digital Spectrum Analyzer (MCSA). *Proc. IEEE, 13th Annual Asilomar Conference on Circuits, Systems, and Computers*, IEEE Catalog No. 79-CH1468-8C, 1980, pp. 14-17.

First published account of architectural approach and off-the-shelf hardware used in the design of digital megachannel spectrum analyzers for the NASA SETI receiving system. A progress report, in effect, since implementation was delayed, thus leaving time for still greater sophistication.

Ponnamperuma, C.; and Cameron, A. G. W., eds.: *Interstellar Communication: Scientific Perspectives*. Houghton Mifflin, New York, 1974.

Collection of essays on interstellar communication presented in a lecture series at NASA Ames Research Center in 1971. A successor to Cameron's original collection.

Ridpath, Ian: *Messages from the Stars: Communication and Contact with Extraterrestrial Life*. Harper Colophon Books, Harper & Row, New York, 1978.

Well presented popular account of search for life beyond the Earth, on other planets in the Solar System, and in the galaxy beyond.

Sagan, C., ed.: *Communication with Extraterrestrial Intelligence*. M.I.T. Press, Cambridge, Mass., 1973.

Detailed and exciting account of the first international meeting on communication with ETI, held in 1971 at Byurakan, Armenia, under the joint auspices of the United States and the Soviet Academies of Science.

Sagan, C.; and Drake, F.: The Search for Extraterrestrial Intelligence. *Sci. Amer.*, vol. 232, no. 5, 1975, pp. 80-89.

Condensed account of activities in interstellar communications to date, including description of attempts already made to "listen" for signals.

Sagan, C.: Life. *The Encyclopaedia Britannica*, vol. 10, 1979, pp. 893-911.

Starts with various definitions of life, describes it as we know or hypothesize it (pre-Viking Mars Lander experiments), and concludes with a brief discussion of life as we do not know it – extraterrestrial life.

Sagan, C.; and 70 cosigners: Extraterrestrial Intelligence: An International Petition. *Science*, vol. 218, no. 4571, 1982, p. 426.

“No *a priori* arguments on this subject can be compelling or should be used as a substitute for an observational program. We urge the organization of a coordinated, worldwide, and systematic search for extraterrestrial intelligence.”

Schneider, S. H.; and Thompson, S. L.: Cosmic Conclusions from Climatic Models: Can They be Justified? *Icarus*, vol. 41, 1980, pp. 456-469.

“None of this is meant to discourage further ingenious – or even speculative – use of climatic models on cosmic questions. But we conclude that cosmic conclusions from climatic models should be accompanied by clear admission of the vast uncertainties in the climatic component of the argument, let alone other parts of the problem.”

Seeger, C. L.: Strategic Considerations in SETI, and a Microwave Approach. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 105-127.

Thorough account of search strategy and equipment designs at Ames circa mid-1979. First description of a million-channel spectrum analyzer design developed by the SETI team and A. M. Peterson (Stanford University), and of the consequent data-manipulation problem.

Seeger, C. L.: The Recognition of Extraterrestrial Artificial Signals. *Proc. IEEE*, 13th Annual Asilomar Conference on Circuits, Systems, and Computers, Nov. 5-7, 1979; IEEE Catalog No. 79CH1468-8C, 1980, pp. 18-22.

Two basic concerns in designing an efficient SETI receiving system are (1) on-line detection of artificial signals at low S/N and (2) determining if a signal is “natural,” or a human artifact, or a sign of ETI. One is looking for a “steel needle” in a “cosmic scrap iron pile.”

Shklovskii, I. S.; and Sagan, C.: *Intelligent Life in the Universe*. Holden-Day, New York, 1966.

First substantive book on many aspects of theories about the prevalence of life in the Universe. An enthusiastic and imaginative joint venture over great distance by two distinguished astrophysicists arguing in favor of multiple life sites in the Universe. A classic, now somewhat dated.

Siebrand, W. J.: Radiospectroscopic Study of Astrophysical Photon Source Flares and the SETI. *J. British Interplan. Soc.*, vol. 35, 1982, pp. 135-141.

Proposes cooperative time-domain contact strategy. When an ETI observes a sudden brightening event, it transmits for some weeks a directive, instructive beacon signal directed 180° from the event, in the expectation that astronomers farther down the unusual photon stream will be particularly studying the event and may discover the beacon. Suggests SETI maintain a daily all-sky survey for these notable events and concentrate their searches in these directions, thus doing their cooperative share.

Simpson, G. G.: *The Nonprevalence of Humanoids. This View of Life: the World of an Evolutionist*. Harcourt, Brace & World, Inc., New York, 1964, pp. 253-271 and 299-301.

Chapter 13 in this graceful and stimulating book by a master evolutionary biologist and systematist presents a vigorous argument in support of his estimate that humans are likely to be the only intelligent “humanoid” species in our galaxy, but not necessarily the only intelligent species rampant.

SPACEFLIGHT. The British Interplanetary Society, 27/29 South Lambeth Road, London, SW8 1SZ, England.

“. . . provides essential reading not to be found in any other publication. Present events and future plans are dealt with in news items and major articles. Extensive participation by readers is developed through correspondence, book reviews, personal accounts, and histories . . . part of a communications network connecting all who have interests in space.” (Published monthly since 1956.)

Stull, M. A.; and Alexander, G.: *Passive Use of the Radio Spectrum for Scientific Purposes and the Frequency Allocation Process*. *J. Air Law and Commerce*. The Southern Methodist University School of Law, Dallas, Tex., vol. 43, 1977, pp. 459-534.

“Our principal conclusion is that the requirement that frequency allocation be governed by ‘public interest, convenience, or necessity’ mandates that both federal science policy and the special character of the passive services be considered by the FCC in all frequency allocation decisions which may affect the passive services. The frequency management powers of the OTP and the State Department, however, may make it difficult or impossible for the FCC to act as Congress

intended it should; this situation threatens harm to all spectrum users, but may be especially serious for economically weak groups such as the passive services. . . ." This study of U.S. communication law provides information and suggestions of value to radio astronomers and to the prosecution of SETI.

Subotowicz, M.: *Interstellar Communication by Neutrino Beams*. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 213-220.

Neutrino properties are described, and the reactions that produce and detect them are given. Thoughts of neutrino SETI are (still) "premature" because of extraordinarily difficult technical problems.

Sullivan, Walter: *We Are Not Alone: The Search for Intelligent Life on Other Worlds*. McGraw-Hill Book Company, New York, 1966.

Gifted and fascinating discussion of the possibility of life throughout the Universe, by an outstanding science writer.

Sullivan, W. T., III; Brown, S.; and Wetherill, C.: *Eavesdropping: The Radio Signature of the Earth*. *Science*, vol. 199, no. 4327, 1978, pp. 377-388.

Besides looking for "beacons," SETI observers should try to eavesdrop. An extensive examination of Earth's UHF and microwave signature. Our UHF-TV carriers and powerful aircraft surveillance radars and planetary radars have made us highly "visible" and information to other species who may exist in the galaxy outside the Solar System if they have even our level of radio technology — and the interest to look for us. We could detect ourselves with our present technology if we were at the distance of the nearer stars.

Tarter, J.; Cuzzi, J.; Black, D.; and Clark, T.: *A High-Sensitivity Search for Extraterrestrial Intelligence at 18 cm*. *Icarus*, vol. 42, 1980, pp. 136-144.

Observed 201 nearby stars for 4-40 sec with NRAO 91-m telescope and very long baseline interferometry Mark I mag-tape recording terminal. Data reduced with CDC 7600 computer system at Ames to give ~5-Hz frequency resolution over ~1.4 MHz at  $12\sigma$  sensitivity of  $1.1 \times 10^{-23}$  W/m<sup>2</sup>. Most sensitive, high-resolution, broadband search to date; first search at 18-cm wavelength; efficient use of telescope time, but onerous in reduction. Located "new" false alarm sources at the site and demonstrated great advantages of on-line data reduction.

Tarter, Jill: *Searching for THEM: Interstellar Communications*. *Astronomy*, vol. 10, no. 10, 1982, pp. 6-22.

Attractive summary of history and philosophy of SETI written for the general public. This issue's featured article, it is illustrated with many beautiful and colorful astronomical photographs.

Tarter, J. C.; and Israel, F. P.: *A Symbiotic Approach to SETI Observations: Use of Maps from the Westerbork Synthesis Radio Telescope*. *Acta Astronautica*, vol. 9, no. 6-7, 1982, pp. 415-419.

This preliminary study [at frequencies near the 21-cm HI line] has shown that data taken by radio astronomers using large synthesis arrays can profitably be analyzed for SETI signals (in a noninterfering manner) provided only that the data are available in the form of a more or less standard two-dimensional map format. Found no "radio stars" or ETI signals at 542 stellar positions studied with sensitivities ranging from  $7.7 \times 10^{-22}$  to  $6.4 \times 10^{-24}$  W/m<sup>2</sup>.

Tarter, J. C.: *SETI Program*. *Science, Letters*, vol. 220, no. 4595, 1983, p. 359.

A signer of the Sagan et al. "International Petition" (see above) objects to Tipler's comments (*Science*, p. 110, 14 January 1983). "Success is not guaranteed in SETI. 'We represent a wide variety of opinion on the abundance of extraterrestrials . . . [but] we are unanimous in our conviction that the only significant test of the existence of extraterrestrial intelligence is an experimental one' . . . SETI is now, and has been for decades, a scientific endeavor." Though almost exclusively in unrefereed media, be it noted, Tipler's convictions have been well exposed to the scientific community and to the general public. There, perhaps, the matter should be allowed to rest. For ". . . no one should be surprised that profound and sweeping conclusions require significant experimental effort." And, with wide scientific support, the quest for hard data is under way.

*The Planetary Report: The Planetary Society*, 110 South Euclid, Pasadena, CA 91101.

The Planetary Society is "a non-profit organization devoted to encouraging, supporting, participating in and perhaps even helping to underwrite the greatest adventure the human species may ever know — the exploration of the solar system, the search for planets around other stars, and the quest for extraterrestrial life." The March/April 1983 issue of *The Planetary Report* (vol. 3, no. 2) is largely devoted to SETI news.

Tipler, F. J.: Extraterrestrial Intelligent Beings Do Not Exist. *Quart. J. Roy. Astron. Soc.*, vol. 21, no. 3, 1980, pp. 267-281.

“Although this argument has been expressed before, its force does not seem to have been appreciated. I shall try to rectify this situation by showing that an intelligent species with the technology for interstellar communication would necessarily develop the technology for interstellar travel, and this would automatically lead to the exploration and/or colonization of the Galaxy in less than 300 million years.” Quite the most extensive discussion yet in favor of this particular imaginable extremum. More than 81 references. This archetypical paper and its references should be studied in introductory science courses intent on teaching the philosophy and methodologies of science.

Troitskii, V. S.; Starodubtsev, A. M.; and Bondar, L. N.: Search for Radio Emissions from Extraterrestrial Civilizations. *Acta Astronautica*, vol. 6, no. 1-2, 1979, pp. 81-94.

Extensive account of widely separated synchronous observations since 1970 in centi- and decimeter bands, using dipoles and simple horn antennas. Found evidence for global, sporadic radiation apparently originating in the Earth's magnetosphere.

United Nations, Ralph Chipman, ed.: THE WORLD IN SPACE: A Survey of Space Activities and Issues. UNISPACE 82, published in cooperation with the United Nations by Prentice Hall, Inc., New York, 1982, pp. 178-185.

Summary of two-decade-old, “classic” rationale and approach to SETI. Concludes with a cursory section on the possible impact on humankind of the discovery of an extraterrestrial civilization. In this connection, the views expressed are surely those of a small fraction (perhaps just a few individual members) of western civilization. Representatives at the United Nations have suggested that the question of impact was, in their view, worth serious study.

Wolfe, J. H.; Edelson, R. E.; Billingham, J.; Crow, R. B.; Gulkis, S.; Olsen, E. T.; Oliver, B. M.; Peterson, A. M.; Seeger, C. L.; and Tarter, J. C.: SETI – The Search for Extraterrestrial Intelligence: Plans and Rationale. *Life in the Universe*. NASA CP-2156, 1981. Also MIT Press, Boston, Mass., 1981.

Reflects 1979-80 NASA bimodal approach [still valid] to SETI planning. Proposes exploration of a well-defined volume of multidimensional microwave search space using advanced ground-based technologies to achieve exceptional sensitivities and unusually wide instantaneous frequency coverage. When carried out, such an approach will improve our exploration of search space by a factor of many millions. With an 8- or 16-MHz bandwidth, Mode One would examine all Sun-like stars within 80 ly in the 1.2- to 3.0-GHz band, using dual polarization and frequency resolutions of 1, 32, 1024, and 74,000 Hz and dwell times per direction and frequency band up to 1000 sec. Mode Two would scan the whole sky over the 1.2- to 10-GHz range with a dual-polarized bandwidth of 256 MHz and 0.3- to 3.0-sec “look” times in any direction and frequency band, but with a best resolution of 32 Hz.



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| 16. Abstract<br><br>This report covers the initial activities and deliberations of a continuing working group asked to assist the SETI Program Office at NASA. Seven chapters present the group's consensus on objectives, strategies, and plans for instrumental R&D and for a microwave search for extraterrestrial intelligence (SETI) projected for the end of this decade. Thirteen appendixes reflect the views of their individual authors. Included are discussions of the 8-million-channel spectrum analyzer architecture and the proof-of-concept device under development; signal detection, recognition, and identification on-line in the presence of noise and radio interference; the 1-10 GHz sky survey and the 1-3 GHz targeted search envisaged; and the mutual interests of SETI and radio astronomy. The report ends with a selective, annotated SETI reading list of pro and contra SETI publications. |  |   |                   |
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If Undeliverable (Section 158  
Postal Manual) Do Not Return