

**SEARCHING FOR INTELLIGENT LIFE IN THE UNIVERSE:  
NASA'S HIGH RESOLUTION MICROWAVE SURVEY**

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## 1. INTRODUCTION

The nature of the universe, the place of humans in it, and the question of life elsewhere have captured the interest and stimulated the imaginations of men and women since *Homo sapiens* first contemplated the cosmos. Today, the question of whether life, even intelligent life, exists beyond Earth remains one of the most intriguing questions confronting humankind. While ours is not the first generation to contemplate life beyond Earth, we *are* the first to develop and apply the technical means required to conduct a scientific investigation of the question. The search for an answer to this ages-old question, for millennia the private domain of philosophers and theologians, has sparked the High Resolution Microwave Survey (HRMS), one of the most scientifically unique and technically challenging programs ever undertaken by the National Aeronautics and Space Administration.

On Columbus Day, October 12, 1992, after a 15-year research and development effort by the NASA Ames Research Center and the Jet Propulsion Laboratory, NASA inaugurated a 10-year program to search the sky for radio signals of intelligent extraterrestrial origin. Initial observations of NASA's HRMS utilized the National Science Foundation's 305-meter radioastronomy telescope at Arecibo Observatory in Puerto Rico (operated for the NSF by Cornell University's National Astronomy and Ionospheric Center), and the 34-meter telecommunications research antenna located at NASA's Deep Space Communications Complex, Goldstone, California.

This paper discusses the historical development of NASA's Search for Extraterrestrial Intelligence (SETI) and HRMS programs, their implementation and historical relationship to the field of exobiology. It then describes the scientific rationale, goals and objectives, search strategies, technology, current status, and future activities of the HRMS. Recognizing that the terms and concepts associated with radioastronomy and astrophysics may not be common parlance to most biomedical researchers, the authors have written in an informative rather than technical style. Those who wish a more rigorous treatment are encouraged to refer to the references cited.

## II. THE PLURALITY OF WORLDS

Today, as in ancient times, the desire to know whether we are alone in the universe remains a defining characteristic of the human condition. After centuries of philosophical and theological debate, ours is the first generation capable of pursuing the answer in a scientifically and technologically credible manner. Historically, attempts to define humanity's place in the universe were theoretical exercises that did not produce enduring answers but provided the underlying basis for the mythological and scientific cosmologies that gave rise to many modern philosophies and religions as well as modern science. NASA's HRMS is the modern successor of a body of science that has its roots in the geocentric and anthropocentric cosmologies that dominated "natural philosophy" for two millennia after Aristotle.

Belief in the existence of inhabited worlds beyond Earth was widespread during the Greek and Roman periods. The atomist cosmology advocated by many Greek philosophers in the 4th and 5th century BC is exemplified by the musings of Epicurus's disciple Metrodorus of Chios: "It would be strange if a single ear of corn grew in a large plain or were there only one world in the infinite."<sup>1</sup> Similarly, Lucretius (ca. 70 BC) asserted that, "...there is such a huge supply of atoms that all eternity would not be enough time to count them; there is the force which drives the atoms into various places just as they would have been driven together in this world. So we must realize that there are other worlds in other parts of the universe, with races of different men and different animals."<sup>2</sup> The philosophical paradigms principally developed by atomists such as Lucretius and Epicurus, which hold that Earth and humanity do not occupy a privileged position in the universe and that extraterrestrial bodies are similar in formation and composition to Earth, provide the historical and philosophical basis for the modern science of exobiology,

In sharp contrast to the atomists, Aristotle's cosmological world view placed Earth at the center of motion of concentric spheres containing the moon, planets, and stars. Aristotelian cosmology was accepted until the sixteenth and seventeenth centuries when it was superseded by the Copernican view that the Sun is central in our system of planets.

The Copernican revolution overthrew Aristotle's geocentric cosmology and supported the argument that if the Earth is a planet that operates under natural laws, then other planets operating under the same laws may also be "earths"; if the Earth is not central, then neither is man.<sup>3</sup>

Armed with the scientific observations of Galileo and Kepler, sixteenth and seventeenth century Copernicans believed inhabited planets existed around other stars. They reasoned that, if the moon and the stars exist for the benefit of humankind, then other moons and stars must exist for the benefit of extraterrestrial civilizations. In the mid-seventeenth century, Descartes resurrected Greek atomism, combined it with Copernicanism and proposed the first new cosmological world view since Aristotle.

According to Cartesian cosmology, solar systems could and would be formed as a natural consequence of vortices acting on the atoms in the universe. Although the vortex concept was soon eclipsed by Newton's universal principles of gravity, the concept that planetary systems form around stars as a common and natural consequence of cosmic evolution remains an area of intense scientific investigation.

Like Descartes', Newton's cosmology was predominantly mechanical but did not require that the formation of stars necessarily be accompanied by the formation of a retinue of planets. Newton was cautiously noncommittal on the issue of the plurality of worlds, suggesting that if it were the Creator's will that other worlds be formed, then they would be subject to His dominion.

Following the Copernican revolution and supported by Newtonian cosmology, the essentially atomist position concerning the "plurality of worlds" and the natural generation of life became an important part of natural theology. The concept of a plurality of inhabited worlds was accepted as consistent with the attributes of an all wise, all loving and all powerful Creator. Nonetheless; "If in the Newtonian system the plurality of worlds concept was reconciled with theism through natural theology, this was not equivalent to a reconciliation with Christianity. Demonstrating the difference between Christian apologetics and the idea of a plurality of worlds, both Albertus Magnus and St. Thomas Aquinas asserted that God could have made other worlds, but in fact had not.

The official position of the Holy Roman Church supported the primacy of the Earth and Man as the pinnacle of God's creative works. Those who disagreed did so at great risk. For example, on February 17, 1600, Giordano Bruno was declared a heretic by the Inquisition and burned at the stake after having been found guilty of a variety of crimes against the Church including publicly claiming that Earth is but one of a multitude of inhabited worlds. Nonetheless, a general agreement that a universe teeming with life was defensible and consistent with Western concepts of Christianity emerged over the next two centuries. One notable exception, Thomas Paine, held that the concept of plurality of worlds caused Christianity to become "little and ridiculous, and scatters it in the mind like feathers in the air."<sup>4</sup> The plurality of worlds concept entered the twentieth century a clear winner, but balanced precariously on philosophical rather than scientific arguments,

Although the plausibility of extraterrestrial life improved with the exposition of the Darwin-Wallace theory of evolution by natural selection, not all scientific evidence supported the concept of extraterrestrial life. Pasteur's disproof of spontaneous generation and the replacement of the Kant-Laplace Nebular Hypothesis (which suggested that planets regularly form out of the spinning nebulae of dust and gas accompanying star formation) by the "planetesimal hypothesis" of solar system formation (which required the unlikely and infrequent near collision of stars) suggested that planets were unlikely to form and life difficult to develop elsewhere.

During the nineteenth and twentieth centuries, several interesting scientific and nonscientific endeavors supported the concept of a plurality of worlds. In 1820, German mathematician Karl Friedrich Gauss proposed a unique method for signaling telescope-wielding inhabitants of the moon or other planets. Gauss's plan was to plant a huge right triangle of wheat in the middle of Siberia. Large square stands of pine trees would bound each of the sides of the triangle and the square area adjoining the hypotenuse would equal the sum of the areas of the other two. Earthlings were supposed to signal the heavens that they had advanced far enough intellectually to understand the Pythagorean theorems. Twenty years later, astronomer Joseph von Littrow proposed digging huge geometrically shaped trenches in the Sahara Desert, filling them with kerosene and lighting them on fire, thus creating interplanetary beacons.

In 1894, Percival Lowell founded an observatory for the purpose of searching for life on Mars. In 1877, Italian astronomer Giovanni Schiaparelli had described observations of *canali*; incorrectly translated to literally mean structures built to transport water. Lowell published maps of these purported waterways and fueled a "Mars fever" that did not subside until after the Mars "close approach" in 1924, when "Martians" failed to contact Earth, as had been predicted.<sup>5</sup> Energized by Lowell's claims of life on Mars, radio pioneers Nikola Tesla and Guglielmo Marconi attempted to intercept radio signals emanating from the Red Planet, and even reported success. Scientists speculate that these findings represent the first documented reports of 'whistlers,' a well-known magnetospheric phenomenon,

The concept that Earth and its solar system were unique suffered a further blow in 1918, when astronomer Harlow Shapley demonstrated that the solar system lies at the outskirts of the Milky Way and occupies an insignificant place with respect to the 200-400 billion stars in the Galaxy. Advances in astronomical spectroscopy provided empirical evidence that the same elements present on Earth are present throughout the universe. Terrestrial physical processes could be expected to occur beyond Earth.

In the mid-1940's, the nebular hypothesis was reinstated and the pioneering work of Miller and Urey<sup>7</sup> demonstrated that many of the organic chemical components of living systems could be synthesized abiotically.

By the mid-20th century, biological and physical (planetary) evolution were joined in the broad concept of "cosmic evolution," which gave rise, in the 1960's, to the science of exobiology (see below).

Comprehensive historical analyses of the ongoing philosophical and theological debates surrounding the concept of the existence of extraterrestrial life and advanced civilizations have been written by Crowe<sup>8</sup>, Dick<sup>9</sup>, and Guthke<sup>10</sup>, among others.

### III. LIFE IN THE UNIVERSE

As astronomers came to understand that the Sun, Earth and Galaxy are physically unremarkable, a biological corollary was developing. If Earth were not physically central, were its inhabitants, biologically central or unique? Physical laws appeared to operate in the same manner throughout the universe. Therefore, might not the circumstances that gave rise to life and intelligence on Earth develop elsewhere? Determining the unique conditions that spawned life on Earth and searching for life off of Earth are important activities of the science of exobiology.

#### A. Exobiology

Exobiology is defined as the study of the origin, evolution and distribution of life in the universe. Since the term was coined by Nobelist Joshua Lederberg, the scope of exobiology has expanded considerably.<sup>11</sup> Exobiologists seek to explain how the process of star and solar system formation led to the existence of the Sun and Earth and how those processes yielded conditions suitable for life. They also study how life may have originated on Earth and factors that influence planetary and biological evolution. This leads to the question of where else life may be found in the universe and how best to determine its existence. Exobiology focuses on tracing the pathways taken by the biogenic elements from the origin of the universe through major evolutionary epochs of living systems and their precursors, including; 1) the cosmic evolution of biogenic compounds, 2) prebiotic evolution, 3) the early evolution of life, and 4) the evolution of advanced life.<sup>12</sup>

The principal goal of research in the cosmic evolution of the biogenic compounds is to determine the history of the biogenic elements (C, H, N, O, P, & S) from their birth in stars to their incorporation into planetary bodies. The six stages in this history that have been defined for study are supported by numerous interdisciplinary studies in cosmo-chemistry, astronomy, laboratory astrophysics and by solar system exploration missions.

Research in prebiotic evolution seeks to understand the processes leading from the origin of a planet to the origin of life.

The strategy is to investigate the processes that established the physical and chemical conditions within which living systems arose by determining: 1) constraints on prebiotic evolution imposed by physical and chemical histories of planets, 2) forms in which prebiotic organic matter have been preserved in planetary materials, 3) chemical systems that served as precursors to metabolizing and replicating systems on Earth and elsewhere, and 4) developing models of active boundary regions in which chemical evolution could have occurred,

The goal of research into the early evolution of life is to determine the nature of the most primitive organisms, the environment in which they evolved and the way in which they influenced that environment.

Two natural repositories of Earth's evolutionary history are being studied, the molecular record in living organisms and the geological record in rocks. These paired records are used to determine: 1 ) when and where life first appeared, 2) characteristics of the first living organisms, 3) phylogeny and physiology of microorganisms that inhabit hydrothermal vents or other primitive environments, 4) the original nature of biotic energy transduction, membrane function and information processing, and 5) key physical, chemical, and biotic forces affecting microbial evolution.

The study of the evolution of advanced life seeks to determine the extrinsic factors influencing the development and distribution of **advanced** life. This research includes evaluating extraterrestrial influences on the appearance and evolution of multicellular life by: 1 ) tracing the effects of major changes in Earth's environment on the evolution of complex life, especially during mass extinction events, 2) determining the effects of events originating in space on the production of environmental changes affecting the evolution of advanced life, and 3) searching for evidence of advanced life elsewhere in the Galaxy. Paleontology and some areas of molecular evolutionary biology are contributing significantly to this area of study, but the search for extraterrestrial intelligence is perhaps the most immediate and exciting opportunity to expand human understanding of life in the universe. Exobiology studies support the hypothesis that planets and life are natural consequences of cosmic evolution. The existence of the Earth as a model for biogenesis demonstrates that once established, living systems can naturally evolve toward complexity and intelligence. **No** claim of uniqueness for this solar system is justified by current models.

Unfortunately, the direct physical search for life elsewhere is an extremely complicated and time-consuming undertaking. Despite the almost flawless performance of the Viking mission hardware, searching for simple forms of life on Mars proved difficult and no unequivocal signs of extant or extinct life were found.<sup>17,18</sup> Due to time and energy limitations associated with interstellar travel<sup>19</sup>, humans are constrained, for now, to look for indirect evidence of life beyond our solar system. Because it can reveal itself through its technology, intelligence may be the characteristic of life on a planet that is currently most amenable to detection.

## B. Recommendations of the National Academy of Sciences

The National Academy of Sciences Space Studies Board recently recommended a program to search for life beyond our solar system.<sup>20</sup> The Board delineated four objectives for this search:

**Objective 1:** To determine the frequency and morphology of nearby planetary systems.

“For the purposes of exobiological understanding, a significant planetary census will be required. Only this can provide a meaningful estimate of the frequency of occurrence of terrestrial-mass planets at orbital distances from the primary star that are suitable for the maintenance of surface temperatures amenable to life.”

**Objective 2:** To determine the frequency of occurrence of conditions suitable to the origin of life.

“The actual surface temperature of any particular planet will depend upon the abundances and chemical nature of its atmospheric constituents as well as its distance from the host star.”

**Objective 3:** To search for presumptive evidence of life in other planetary systems,

“Any potentially suitable terrestrial-type planets must be studied in detail to search for signs of **nonequilibrium** chemical constituents, possibly signifying the action of some form of active biological system.”

**Objective 4:** To search for evidence of extraterrestrial technology.

“Because the instrumentation for detecting evidence of extraterrestrial technology is far more mature than the instrumentation necessary for examining distant planets minutely, another technology (and, by inference, another biology exhibiting intelligence) may be detected before any other evidence is found for extraterrestrial life.”

The rationale supporting the fourth objective (above) is the impetus for SETI (Search for Extraterrestrial Intelligence) efforts undertaken by NASA and other organizations around the world. By detecting **evidence** of extraterrestrial technology, these efforts would reveal the presence of life elsewhere and revolutionize the science of exobiology. Accordingly, SETI investigations are among the most far-reaching efforts underway in exobiology today.

## IV. THE HISTORICAL DEVELOPMENT OF NASA'S SETI PROGRAM

### A. Project Ozma

Modern SETI investigations began in Green Bank, West Virginia, early on April 8, 1960, at the National Radio Astronomy Observatory's (NRAO) newly constructed Howard Tatel 85-foot diameter radio telescope.

Frank Drake, a 29-year old Harvard postdoctoral student and resident astronomer, tuned a one-channel receiver to 1420 MHz (21 cm), the resonant frequency of neutral hydrogen, and pointed the telescope toward the star Tau Ceti. When Tau Ceti set in the west, he redirected the telescope toward Epsilon Eridani. Both are solar-type stars 11.9 and 10.7 light years, respectively, from Earth. On that day, Frank Drake conducted the first recorded search of a portion of the microwave radio spectrum for signals emanating from an extraterrestrial civilization. Drake named this first search "Ozma," after L. Frank Baum's story about "a land far away, peopled by strange and exotic beings." 5

The concepts embodied in Project Ozma and other modern SETI searches were first voiced in the science community in September 1959, when physicists Giuseppe Cocconi and Philip Morrison published a paper in *Nature* entitled, "Searching for Interstellar Communications." 21 Cocconi and Morrison, who formulated their hypothesis independently of Drake, pointed out that radio waves were the most efficient method of transmitting messages across interstellar distances and that modern radio telescopes were sufficiently sensitive to receive them.

#### B. The Green Bank Conference and Beyond (1961-1970)

Ozma and the Cocconi-Morrison paper generated significant interest in the concept of searching for technologically advanced life beyond Earth using modern radio astronomy techniques. On October 31, 1961, the Space Science Board of the National Academy of Sciences convened a special meeting of eminent scientists and engineers at NRAO's Green Bank Observatory. The meeting, organized by J. Peter Pearson, was chaired by Drake. Other participants included electronics pioneer Dana Atchley, neuroscientist John C. Lilly, Philip Morrison, Bernard (Barney) Oliver (then vice president for research of the Hewlett-Packard Corporation), astrophysicists Carl Sagan and S. S. Huang, chemist Melvin Calvin, and then director of the Green Bank Observatory Otto Struve. It was at this Green Bank SETI Conference that Professor Calvin learned he had been awarded the Nobel Prize in chemistry. Although invited, Cocconi could not attend.

In 1962, Soviet SETI pioneer I. S. Shklovskii published his book *Universe, Life, Intelligence*.<sup>22</sup> Interest in the scientific and technical challenges associated with searching for intelligent life beyond Earth encouraged other respected scientists to publish. In 1963, these early works were summarized and extended in A.G.W. Cameron's scientific anthology *Interstellar Communication: the Search for Extraterrestrial Life*.<sup>23</sup>

Interest in SETI expanded with the proliferation of publications including the proceedings of a symposium held at Byurakan, Soviet Armenia, sponsored by the Armenian Academy of Sciences<sup>24</sup> and books written by Sullivan<sup>25</sup>, Sagan and Shklovskii<sup>26</sup>, and Drake<sup>27</sup>, to name a few.

### C. A Decade of Study and Preparation (1971-1980)

In 1971, the first joint Soviet-American conference on SETI was convened at the Byurakan Astrophysical Observatory in (then) Soviet Armenia. The conference was jointly sponsored by the Academies of Sciences of the US and the USSR. Although no official transcripts were made, Carl Sagan later published an abbreviated account of the proceedings.<sup>28</sup> Also, the English translation of Academician Kaplan's compendium of SETI-related essays by Soviet scientists was published.<sup>29</sup>

Coincidentally, 1971 was also the year when NASA sponsored a study to recommend search strategies and identify technologies, system designs, manpower and costs required to conduct a scientifically and technically valid SETI search. Termed "Project Cyclops," the study was organized by John Billingham, then Director of the Biotechnology Division at the NASA Ames Research Center (ARC). The effort was conducted jointly by Stanford University and ARC under the sponsorship of the NASA-American Society of Engineering Education (ASEE) Summer Faculty Fellowship Program in Engineering Systems Design. To lead the project, Billingham chose an acknowledged world leader in electronics who had attended the 1961 Green Bank SETI conference- Barney Oliver.

The Cyclops report was published in 1972<sup>30</sup>, a year which provided another important milestone in the history of the NASA SETI effort. The National Academy of Sciences decadal report on astronomy and astrophysics supported the concept of a concerted SETI effort, stating that, "a project with the goal of detection of intelligent life elsewhere may, in the long run, be one of science's most important and most profound contributions to mankind and to civilization."<sup>31</sup>

In 1975 and 1976, Philip Morrison chaired a series of science workshops convened to evaluate the validity of fundamental criteria supporting a program to detect extraterrestrial intelligent life. His charter also included identifying areas of research in astronomy and other fields that would improve the confidence levels of current probabilistic estimates vis-a-vis the Drake Equation (see below), explore alternative search methods, recommend an appropriate funding level and assess the social and scientific impact of success or failure. These important deliberations were later summarized and published.<sup>32</sup> It was during this review process that the term "SETI" was officially adopted as the acronym for NASA's "Search for Extraterrestrial Intelligence" program.

Stimulated by their participation in these workshops, scientists and engineers at the Jet Propulsion Laboratory (JPL) joined the SETI effort. Bruce Murray, the laboratory's director at the time, noted that NASA's Deep Space Network of large antennas and highly sensitive receiving systems could play an important role in a microwave search. Murray, Samuel Gulkis and Robert Edleson<sup>33</sup> laid the groundwork for JPL's role in the program. From that time on SETI benefited from the contribution and support of two NASA centers

In 1979, an international community of scientists representing several Commissions of the International Astronomical Union (IAU) met in Montreal, Canada. Building on the discoveries of ground- and space-based astronomy; the group laid the groundwork for a new branch of astronomy (bioastronomy) which is dedicated to the study of life in the universe and the search for extraterrestrial life.<sup>34</sup>

#### D. SETI Comes of Age (1980-1992)

By 1980, more than 3 dozen SETI searches had been conducted at radio astronomy observatories in eight different countries. Although no investigators reported the successful detection of a radio signal from a verifiable extraterrestrial source, most early SETI studies utilized innovative modifications to systems principally designed for radio astronomy. Efforts were often limited in scope or method by assumptions about the characteristics and origin of incoming signals imposed by the capabilities of the systems employed. To carry out a SETI search in a thorough and scientifically credible manner would require a system designed from the ground up to be used for SETI observations.

In 1980, NASA appointed a 13-member SETI Science Working Group (SSWG) composed of scientists and engineers from NASA, JPL, other Federal agencies, universities and private industry. The SSWG determined the feasibility and scope of a formal SETI program within NASA and ensured that crucial scientific objectives were identified, appropriate organizational structure was developed, and system requirements, costs and schedules were reasonable.

Their report<sup>35</sup> also suggested ways in which SETI activities and hardware could contribute to radio astronomy and other disciplines and examined ways in which the US and international scientific communities could participate jointly in a SETI program.

In 1981, the second decadal US-USSR SETI conference was held in Estonia. In 1982, astronomer George Field chaired another National Research Council decadal survey of astronomy and astrophysics. In their report<sup>36</sup>, the "Field Committee" recommended support for seven emerging programs, including, "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." Also in 1982, the 51st IAU Commission, **Bioastronomy**, was officially established. Two years later, in Boston, MA, the IAU sponsored the first of a series of international symposia devoted to bioastronomy.<sup>37</sup> Subsequent international meetings were held at Lake Balaton, Hungary<sup>38</sup> and Val Cenis, France.<sup>39</sup>

In April 1987, a Program Plan<sup>40</sup> proposing complementary search strategies was submitted to NASA Headquarters by ARC and JPL. These field centers jointly proposed to develop and operate automated observing systems utilizing high speed signal processing equipment usable at existing ground-based radio astronomy and deep space communications facilities,

JPL proposed to conduct a moderate resolution Sky Survey of the "terrestrial microwave window" (see below). A complementary search strategy employing a high resolution Targeted Search of the approximately 1000 solar-type stars within 80 light years of Earth at frequencies between 1 and 3 GHz would be the responsibility of ARC, which would also act as the lead management center.

At NASA Headquarters, the program would be managed by the Life Sciences Division within the Office of Space Science and Applications (OSSA) with important technical and financial support from the Office of Space Communications (OSC). The following year, an internal Non-Advocate Cost Review panel declared NASA's SETI-Microwave Observing Project (MOP) technically and programmatically ready for full project status.

In the fall of 1987, (Fiscal Year 1988), NASA's SETI-Microwave Observing Project (SETI-MOP) reached full project status after ARC and JPL provided a Project Initiation Agreement (PIA) detailing plans for implementation. The SETI-MOP was approved by the Office of Management and Budget (OMB) for funding in Fiscal Year 1989, but Congress did not appropriate funds. The project was resubmitted as part of NASA's Fiscal Year 1990 budget request and was funded. After years of intensive study, hard work and thin budgets, the SETI-MOP was approved and funded.

In 1991, the third decadal joint US-USSR SETI conference was held at the University of California at Santa Cruz. The Soviet team headed home just days prior to the events leading to the disintegration of the USSR and the establishment of the Commonwealth of Independent States.

## V. TOWARD OTHER PLANETARY SYSTEMS (TOPS)

The acronym "SETI" correctly identified the NASA program as well as the area of space science it represented until October 1, 1992. Then, NASA's SETI-related activities were redesignated the High Resolution Microwave Survey (HRMS), an activity of the Toward Other Planetary Systems (TOPS) program managed at NASA headquarters by the Solar System Exploration Division. SETI remains a recognized area of scientific investigation within NASA and around the world but no longer exists within NASA as a program separate from TOPS,

The scientific goal of TOPS is to develop and apply advanced ground- and space-based techniques to detect and characterize extrasolar planets and **protoplanetary** systems. The "Drake Equation" is often used as a conceptual framework for considering factors thought to determine the existence of other planets, the development of extraterrestrial life and intelligence and the number of other "good Earths" in the Milky Way Galaxy. It provides a unifying theme for the strategies incorporated in the TOPS program, including the HRMS.

## A. The Drake Equation

While preparing to chair the 1961 meeting at the National Radio Astronomy Observatory, Frank Drake developed an approach to bounding values of key factors that would logically determine the number of technologically advanced civilizations that may exist in the Milky Way.

Although many of the factors it contains are little more than probabilistic estimates, this “equation without an answer” is now familiar to the scientific community as a unifying concept under which to focus on these interrelated factors. The Drake equation is usually written:

$$N = R_{\star} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_{cc} \cdot L$$

Where,

$N$  = The number of civilizations in the Milky Way whose electromagnetic emissions are detectable

$R_{\star}$  = The rate of formation of stars suitable for the development of intelligent life

$f_p$  = The fraction of those stars that have formed planetary systems

$n_e$  = The number of planets, per solar system, with a physical-chemical environment suitable for life to develop

$f_l$  = The fraction of suitable planets upon which life actually appears

$f_i$  = The fraction of life bearing planets on which intelligent life develops

$f_c$  = The fractions of intelligent civilizations that develop a communications technology releasing detectable signs of their existence into space

$L$  = The length of time such civilizations continue to exist and release signals into space

Uncertainties in the values of the factors increase proceeding from left to right. Differing assumptions and estimates made for each factor lead to values for  $N$  ranging from  $N=1$  (“We are alone”) to values of  $N$  in the hundreds of thousands. Current estimates of the factors in the Drake Equation have been published recently by Billingham and Tarter.<sup>41</sup>

The speculative nature of the Drake Equation is indicative of our ignorance of the subject. There are at least two possible ways to move beyond speculation: 1 ) explore other worlds *in situ*, or 2) use remote (indirect) sensing techniques.

## B. Interstellar Travel and Other Flights of Fancy

The value of exploring nearby worlds by “going there” has been aptly demonstrated by the spectacular successes of NASA's planetary and solar system exploration programs. Over the past three decades, the robotic and piloted missions to the Moon and the planets have produced an impressive list of scientific accomplishments and a wealth of new and often unexpected information about our solar system.

Based on these successes, some may consider it plausible to send piloted probes to “nearby” stars. Our closest solar neighbors, members of the Alpha Centauri triple star system, are “only” 4.2 light years away (approximately 25 trillion miles). The primary star of the system is similar to our Sun. This system might seem an inviting place to visit, but the time required to get there is far longer than one might anticipate. The *Voyager* spacecraft is one of the fastest moving payloads ever launched from Earth. In 1989, as *Voyager* crossed the orbit of Neptune, it effectively left the solar system and was speeding away at more than 50,000 miles per hour. If it were targeted for the Alpha Centauri system (which it is not) the journey would take an additional 40,000 years. Even the closest stars are incredibly far away.

The trip might be completed much faster using a highly futuristic “photon rocket” technology. By accelerating a spacecraft the size of a *Saturn V* rocket (the rocket used to launch *Apollo* astronauts to the Moon) to 20% of the speed of light, a round-trip voyage to the Alpha Centauri system could be accomplished in approximately 44 years. The major challenge would be to obtain the energy required to alternatively accelerate and then decelerate the spacecraft. Oliver has calculated that the energy required would equal the entire world energy consumption for three hundred years, leading him to describe piloted interstellar missions as “flights of fancy.”<sup>42</sup> In comparison, interstellar communication using electromagnetic waves that travel at the speed of light requires only 20th century technology, is inexpensive, and can explore many very distant stars or planetary systems at modest cost.

## C. NASA'S TOPS Program

In the context of the Drake Equation, scientists are interested in measuring the rate of star formation, developing improved models of the evolution of stars, and deriving better estimates of  $f_p$  (the fraction of stars that are orbited by planets) and  $n_e$  (the number of planets per solar system with an environment conducive to life). The main thrust of TOPS is to search for and characterize extrasolar planets and protoplanetary systems, including the detection of non-equilibrium concentrations of chemicals indicative of life. The current theory is that all stars, including those that are similar in age and luminosity to our Sun, form by the collapse of interstellar clouds of gas and dust. The aggregated material remaining in orbit around such stars is believed to form planetesimals which further coalesce to form planets. It is only within the last year that the first planet orbiting a star other than our Sun was reported<sup>43</sup>.

To accomplish the goals of the TOPS program, scientists will develop and utilize both direct and indirect measurement techniques to focus on four central questions: 1) Do planets exist around other stars? 2) If so, how common is their formation? 3) What is the process by which they form? 4) If other planets exist, has life and intelligence evolved on any of them?

TOPS will utilize a phased approach, beginning with ground-based (TOPS-O) studies employing the 10-meter optical telescope at the Keck Observatory on Mauna Kea, Hawaii. When the second Keck telescope is completed, Keck I and Keck II may be used as an optical/infrared interferometer. TOPS-O will also utilize a variety of other ground-based observational techniques, including astrometry, radial velocity measurements, infrared imaging and interferometrically-coupled telescopes.

TOPS-1 incorporates the space-based components of the TOPS program. Options under study include placing instruments in low-Earth, Sun-synchronous, or high Earth orbit and at the Earth-Sun Lagrange position L<sub>1</sub>. The final stage (TOPS-2) will utilize more ambitious Earth orbiting or lunar-based facilities. The TOPS astronomy goals, objectives and proposed methods have been summarized recently by the NASA Solar System Exploration Division and the TOPS Science Working Group<sup>44</sup>.

The TOPS program did not originally include plans to search for evidence of intelligent life in other planetary systems. Scientists recognized, however, that intensive studies of nearby stars at visible and infrared wavelengths could lead to unexpected detections of extraterrestrial technologies. For example, Dyson<sup>45</sup> and Kardashev<sup>46</sup> suggest that advanced civilizations might build vast structures in space which would absorb heat and light from their sun and radiate thermal energy at infrared wavelengths. It was proposed that these putative technological civilizations could be discovered by scientists studying the infrared emission of stars.

With the inclusion of the HRMS, the TOPS program now has an element that purposefully searches for radio signals from other planetary systems. High sensitivity radio searches for evidence of extraterrestrial technology may provide important insights relevant to Drake equation factors  $f_i$ ,  $f_c$  and  $L$  and otherwise contribute to astronomy and astrophysics. Most importantly, the verified detection of a signal of extraterrestrial origin would demonstrate, for the first time, that  $N$  is greater than 1 and that we are not alone.

## VI. THE HIGH RESOLUTION MICROWAVE SURVEY (HRMS)

Communication using photons (electromagnetic radiation) is commonplace in our society. Typical examples include: 1) transmissions at UHF and VHF frequencies used for TV and radio transmissions, 2) microwaves used for satellite communications and 3) lasers that carry telephone traffic over fiber optic cables.

On Earth, manipulation of the electromagnetic spectrum provides several efficient methods of communication. What might be the best medium for effective high speed communication across the vast distances between the stars? The laws of physics suggest that, here too, photons (which are massless) are the preferred choice.

### A. The Microwave Window

Although the speed of light and the consequences of General Relativity are significant barriers to interstellar travel, light itself (electromagnetic radiation) remains an effective medium to search for and characterize other planetary systems. Photons travel at the speed of light and are the easiest to generate, focus, and capture. Accelerating particles with mass (e.g. electrons) requires incredible amounts of energy compared to the photon. The kinetic energy of one electron traveling at half the speed of light is 12 billion times the total energy of a microwave photon traveling twice as fast!

Which frequencies in the electromagnetic spectrum are best for interstellar communication? Optical and infrared lasers offer some advantages but must exceed the output of the "parent" star in order to be detected. At interstellar distances, the angular separation of a planet (or an orbiting transmitter) and the central star is so small that light from the planet may well be lost in the glare. The SETI Working Group<sup>30</sup> concluded that the frequencies in the electromagnetic spectrum between 1 and 60 GHz are the most suitable for interstellar communication.

This portion of the spectrum, known as the "free space microwave window," was chosen largely because it includes the frequencies where the energy of a photon is low and the Galaxy is the quietest. Stars are incredibly bright in the visible spectrum but, at frequencies used by Earth's radio and radar transmitters, the Sun is faint and the products of human technology outshine it by billions of times. Civilizations on planets orbiting stars within fifty light years could detect microwaves emitted from Earth-based transmitters using technology no more advanced than ours.

In Figure 1, the background noise (equivalent to static on AM radio bands) is plotted on the vertical axis versus frequency on the horizontal axis. The free space portion of the window is bounded by the darker shaded area. At frequencies below 1,000 MHz (1 GHz), "synchrotron" radiation from electrons interacting with magnetic fields in the Galaxy causes the background noise to rise dramatically.

On the right of the window, "quantum noise" dominates as the increased energy of high frequency photons creates added noise in the receiver. Between these two walls of noise lies the relatively quiet free space microwave window where the "floor" is the (2.76 degree K) noise caused by the "Big Bang."

### FIGURE 1 about here

The upper curve in Figure 1 shows the effect of Earth's atmosphere on the free space microwave window. Atmospheric oxygen and water absorb and re-emit energy, thus adding to the background noise, especially above 10 GHz. The "terrestrial microwave window" is not as wide as the free space window but defines the quietest region to listen for microwave transmissions from Earth's surface. The region from 1-10 GHz, is where the energy per photon and absorption by interstellar gas and dust are minimized. The frequencies comprising the microwave window would be a quiet region of the electromagnetic spectrum on any planet, including those with water and oxygen in their atmosphere.

The terrestrial microwave window also contains the band of frequencies bounded by the natural emission lines of hydrogen (H) at 1.420 GHz and the hydroxyl radical (OH), which radiates at four discrete frequencies between 1.665 and 1.720 GHz. This portion of the microwave window is known as the "water hole" and might be significant to any species with a water-based biochemistry. Any civilization with an understanding of the physical nature of the universe might consider these particular frequencies to have "universal" significance. The boundaries of the water hole frequencies are marked by the short vertical lines in Figure 1.

### B. Signal Characteristics

HRMS searches the terrestrial microwave window for signals with characteristics that distinguish them from those produced by natural astrophysical sources. For instance, signals commonly produced by telecommunications technologies are often highly compressed in time and frequency. In contrast, natural radio sources emit energy over a wide range of frequencies. Even the sharpest natural signals, those given off by interstellar masers, have line widths of a few hundred Hertz. Signals with bandwidths significantly less than a hundred Hertz would either be non-natural or a newly discovered astronomical radio source.

The ratio of the bandwidth to the transmitted frequency of signals used in communication can be as small as one part in several billion. Although a signal may have a very narrow bandwidth and have been transmitted at a constant frequency, there may have been relative acceleration between the transmitter and Earth before it was received. Causes of relative acceleration include the diurnal rotation and orbital motion of a planet with a transmitter on its surface or the orbital motion of a space-based transmitter.

Such acceleration would cause variable (Doppler) shifts in the frequency of the signal received on Earth. HRMS systems rapidly search for pulsed signals that drift in frequency.

A narrowband pulse produced by a radio analog of a lighthouse beacon would be easily distinguishable as non-natural. By effectively storing energy and emitting it instantaneously, pulsed emissions provide an efficient way of transmitting a detectable signal. Although pulsars are natural sources of pulses, the physics of the emission process spreads the signal over many megahertz and makes it broadband,

Technologically generated microwave signals are strongly polarized, i.e., vibrate in a particular direction or the plane of the vibration rotates uniformly with time. Natural radio sources seldom exhibit strong polarization. For instance, radio waves from quasars generally vibrate in random directions. In order to optimize chances of detecting narrowband signals, HRMS electronics select extremely narrow frequency slices from the wide range of frequencies that are collected and amplified in two orthogonal polarizations. Searching for narrowband signals in the frequency range between 1 and 10 GHz may require examining tens of billions of channels. To search this many channels rapidly, many millions of channels must be processed each second.

### C. Signal Processing Systems

The goal of any signal processing system is to detect weak signals in the presence of noise. Noise (or "static") imparts random fluctuations to the output of any receiver system and reduces sensitivity. External sources of noise include the interstellar plasma, Earth's atmosphere, and the residual noise from the Big Bang (see Figure 1). Internal noise is primarily due to the random thermal motion of electrons in the receiver. Because of the direct relationship between thermal motion and noise power in a system, the amount of noise is expressed as a temperature. The best radio astronomy receiver systems have equivalent noise temperatures in the range from 15K to 25K. The lower the system temperature, the more sensitive the receiver,

Any signal arriving at Earth from a distance would be relatively weak and spread out over a very large area. To be detected, as much of the signal power as possible must be collected and fed into the antenna's receiver system. The larger the collecting area of the antenna, the more signal power it can gather and focus. Ultimately, the detectability of a signal depends on the amount of power as compared to the noise in the signal (the signal-to-noise ratio, or **SNR**). The power in a signal is contained within a range of frequencies called the signal bandwidth. Noise power also exists over the entire bandwidth of the receiver system. Filters can be used to isolate a channel or smaller range of frequencies within the receiver bandwidth. If the channel contains a signal, the optimum SNR is achieved when the bandwidth of the channel exactly matches the signal bandwidth.

If the channel is wider than the signal, excess noise is added to the channel and the SNR decreases. If the channel is too narrow, some signal power is excluded and the SNR also decreases. A signal processing system designed for SETI observations must receive and analyze channels that closely match the bandwidth of the signal.

The length of the observation also has an important effect on the SNR. If a signal is on continuously for an extended period, the power received in the signal channel will be accumulated. The noise in the channel fluctuates around an average value but the signal always adds power to the channel and the SNR steadily increases.

Having identified a range of likely frequencies and some characteristics of interstellar signals, there remains the question of where to look. One possibility would be to search in the vicinity of nearby (within 100 light years) stars that are similar to the Sun with respect to temperature, mass, and age. Using the Sun as a model, these stars would be good candidates to contain solar systems and, life-bearing planets. However, communicating civilizations may be distributed in space such that the most detectable ones are not the closest ones. If true, every direction of the sky would be equally likely to contain a signal from a distant civilization.

#### D. Complementary Search Strategies

HRMS has two complementary search strategies that are designed to minimize the number of assumptions concerning the location(s) of technologically advanced civilizations. One strategy, termed a Targeted Search, is based on the possibility that Earth-like planets with technological civilizations may be relatively common around Sun-like stars. Approximately 800 candidate stars located within 100 light years of Earth have been identified.

The second strategy, the Sky Survey, is based on the possibility that powerful radio transmitters are transmitting from planetary systems around stars or other sources beyond the limits of our current knowledge. In this case, an effective search should not be limited to preselected points, but should include the entire celestial sphere.

The Targeted Search stresses sensitivity and has developed systems to detect either pulsed or continuous signals over the 1-3 GHz frequency range. The Sky Survey trades lower sensitivity for the ability to survey the 99 percent of the sky that is not covered by the Targeted Search and to span a larger frequency range, from 1-10 GHz.

Both search teams have developed and built special-purpose digital signal processing equipment that automates most of the data accumulation and processing activities. Because it is impossible to predict the polarization, strength, or type of signal(s) emitted by other civilizations, the search strategies are sensitive to a variety of signal types in two orthogonal (right and left circular) polarizations.

As discussed above, important factors determining the sensitivity of a search include: the size of the antenna, the noise temperature of the receiver system, the length of time spent observing, the temporal characteristics of the signal, and the fraction of the receiver bandwidth occupied by the signal. A primary objective of HRMS is to balance these factors in order to optimize sensitivity and conduct a rapid but thorough search for a reasonable cost.

## VII THE HRMS TARGETED SEARCH AND SKY SURVEY SYSTEMS

Insert Figure 2 about here

A generic diagram of HRMS Targeted Search and Sky Survey systems is shown in Figure 2. State-of-the-art microwave technology is used to optimize the sensitivity of the radio frequency receiving subsystem. High speed digital technology is used in the spectrum analyzer and signal processor modules to process the data streaming from the receiver. These processors, performing 100 billion digital operations per second, divide data into approximately 30 million frequency bins and automatically search for channels that contain power levels greater than those produced by background noise. The function of the processors is to automatically sift through tens of millions of individual frequencies each second and identify channels with characteristics associated with "intelligence." The most promising candidates are screened further and saved for subsequent analysis.

### A. The Targeted Search

The Targeted Search is the higher sensitivity element of HRMS. The objective is to test the hypothesis that extraterrestrial civilizations are transmitting at microwave frequencies and that, appropriately equipped, Earth's largest radio telescopes can detect these signals. The combined effects of background noise, receiver characteristics, and the behavior of signals from moving transmitters favor the low frequency (1 to 3 GHz) portion of the microwave window as the search region with the best sensitivity and probability of success.

The design of the Targeted Search System (TSS) is determined by the search strategy. It would be ideal to process the entire 2 GHz of spectrum at one time, thereby enabling the TSS to completely search each star during one observation period,

The limitations of modern digital electronics and the requirement for a small mobile system dictate a TSS that can process only 20 MHz of bandwidth at a time. Each star must be observed 100 times to cover the entire 2 GHz frequency band. Because large radio telescopes are shared by many astronomers, observing time is a precious commodity and the observation time for each 20 MHz band is generally limited to 300 seconds.

Observations may be extended up to 1000 seconds for special targets such as stars within 20 light years. In 1995, the 42-meter radio telescope at the National Radio Astronomy Observatory in Green Bank, WV is scheduled to be dedicated to HRMS and longer observations will be possible.

Signal processing in the TSS occurs in stages. A multichannel spectrum analyzer (MCSA) first divides the 20 MHz bandwidth into narrow channels, which are produced across the entire spectrum simultaneously. Signal detection computers temporarily store the output during the observation period and analyze it for the presence of signals during the subsequent observation period (0.7 seconds). Any signals found by the detection computers are reevaluated by a control computer. A signal that has the appropriate characteristics and whose source cannot be identified undergoes further tests.

The Targeted Search MCSA produces 28.74 million 1 Hz channels over 20 MHz. Each channel is 1 Hz wide and slightly overlapped with the adjacent channels to provide nearly uniform sensitivity across the entire 20 MHz. In order to maintain sensitivity to pulsed signals, each spectrum is overlapped by 50% in time with the preceding and subsequent spectra. Multiple simultaneous resolutions are required in order to be sensitive to a range of pulsed signals. For pulses with durations between 0.025 and 1.5 seconds the MCSA produces resolutions of 1, 2, 4, 7, 14, and 28 Hz,

### **Insert Figure 3 about here**

The output of the MCSA is sent to two signal detection computers. Both detectors store data during an observation and process it during the subsequent observation. The Continuous Wave Detector (CWD) receives the power measurements from all channels at either the 1 Hz or 2 Hz resolution and searches for continuous signals by summing the power along all possible signal paths in the frequency-time data array. At the same time, a Pulse Detector (PD) receives data on the few thousand channels in each resolution with the highest power for each spectrum and looks through the data array for sets of three regularly spaced pulses. Both detectors process data in less time than the duration of the subsequent observation (i.e., "near real-time").

The detectors report the properties of any detected signals to a control computer called the System Control Subsystem (SCS) which compares the reported signals with a database of previously detected RFI. Any signal that cannot be identified as interference is immediately subjected to further tests. If a signal becomes a candidate extraterrestrial signal, other observatories will be contacted to confirm its existence and source. During the next 8 years, the TSS will deploy to radio telescopes in the U.S. (Puerto Rico and West Virginia), Australia, and possibly France. The system is fully transportable and electromagnetically shielded to prevent its electronics from contaminating the host radio telescope.

## B. The Sky Survey

The HRMS Sky Survey uses the 34-meter diameter antennas located at Goldstone, CA and Tidbinbilla Australia, operated by NASA's Deep Space Network (DSN). Similarly-sized antennas at radio astronomy observatories may also be used. In order to complete the survey of the entire sky in less than 7 years, the Sky Survey System equipment will first be deployed to antennas in the Northern hemisphere and later to Australia.

**Insert Figure 4 about here**

As depicted in Figure 4, Sky Survey observations are made by pointing the survey antenna along a controlled pattern so that small areas of the sky (sky frames) are individually surveyed and later assembled to form a mosaic. Approximately 25,000 sky frames are required to cover all the directions in the sky and all frequencies between 1 and 10 GHz. Each sky frame takes from 1 to 2 hours to complete.

**Insert Figure 5 about here**

A schematic scan pattern for a representative sky frame is shown in Figure 5. As the antenna beam sweeps left and right across the frame the spectrum analyzer accumulates and passes data to the processor at regular time intervals (represented by the dots in the figure). The oval-shaped "race track" pattern is designed so intermediate results from each beam area along a scan are compared with the corresponding beam areas from the adjacent tracks. The scans are synchronized to allow the sky to rotate a few degrees between adjacent tracks. This interscan comparison is needed to identify some types of RFI.

The spacing of the scan tracks affects the spatial uniformity of the survey sensitivity. The nominal separation has been selected to be equal to one half-power beam width (HPBW). This value represents a compromise between smaller separations, which would enhance search sensitivity, and larger separations, which would reduce the time to complete the survey.

The detection process for the Sky Survey begins in the digital signal processing hardware. The system calculates the noise power baseline, sets a threshold, and records frequency, power, and bandwidth information that identifies those frequency bins that exceed threshold. These reports are temporarily stored so that comparisons can be made with reports from adjacent scan lines. "Singlet" detections are strong signals that are detected only on a single scan line. "Doublet" detections are signals that are detected along adjacent scan lines after compensation is made for Earth's rotation,

Doublet detections with poorly matching positions are classified as RFI. The initial detection reports are subjected to additional tests to sort out and save radio astronomy data and to discard RFI that has eluded the first screening process. A limited number of the remaining reports are selected and stored for future analysis. Upon completion of the sky frame, the HRMS Sky Survey computer selects a few of the strongest "singlet" and "doublet" reports from the event file and the position of the source is reobserved. The confirmation process involving reobservation by the Sky Survey system is critically important to HRMS scientists and will be continuously refined.

A prototype was developed to provide a proof of concept model for the operational Sky Survey system. The heart of the prototype system is the special purpose 2-million channel digital wide-band spectrum analyzer (WBSA) and a signal processor system, designed and built at JPL<sup>47</sup>.

The WBSA features a pipelined Fast Fourier Transform (FFT) architecture that transforms 40 MHz of input bandwidth into 20 Hz bins in the frequency domain. To accommodate the wide bandwidth in real time, the WBSA performs 4.5 billion operations per second. The spectrum analyzer accommodates two input channels to simultaneously search for right and left circularly polarized signals. The output data from the WBSA is passed to a signal detection module that performs baseline estimation, filtering and thresholding functions. The WBSA and signal detection hardware for the operational Sky Survey system are currently being built. In the new system, bandwidth will be expanded from 20 MHz to 320 MHz. This expansion is necessary to accomplish the survey within the seven-year observational phase of the HRMS. It would take 100 years to complete the survey using only the 20 MHz prototype system. Experience gained from the current use of the prototype system will be used to improve the design of the operational system, which is scheduled for completion in 1996.

## VIII. INITIAL OBSERVATIONS: OCTOBER 12, 1992

The observational phase of the HRMS was inaugurated at 1900 hours Universal Time on October 12, 1992 at the NASA Goldstone Deep Space Communications Complex in California and the Arecibo Observatory in Puerto Rico. In a coordinated program, the Arecibo antenna pointed at the star GL61 5.1 and the Goldstone antenna began to survey the first sky frame that was selected to include the position of the Targeted Search's first star. (see Figure 6)

Insert Figure 6 about here

Columbus Day 1992, was chosen, in part, to celebrate the spirit of exploration. HRMS clearly reflects humanity's insatiable desire to know more about our world (and other worlds) tomorrow than we know about them today. The theme of exploration and discovery was highlighted in keynote addresses given by SETI pioneers Philip Morrison (at Arecibo), and Carl Sagan (at Goldstone). The beginning of the search generated world-wide media interest and attracted a combined attendance in excess of **750** people.

#### A. Targeted Search

The Targeted Search System (TSS) used the 305-meter (the world's largest) antenna at the Arecibo Observatory, in Puerto Rico, (see Figure 7) for its initial observations. The system processed a 10 MHz bandwidth into more than 14 million channels and simultaneously produced multiple resolutions from 1 Hz to 28 Hz. Data were analyzed in near real-time for the presence of continuous wave and pulsed signals. The observations focused on a list of 25 stars within 100 light years of Earth. Receivers provided by the observatory allowed observations in four frequency bands covering a total of about 300 MHz within the range from 1.3 to 2.4 GHz.

Each "observation" of a star in a particular frequency band consisted of three steps: the antenna was first pointed at the star, then away from the star and then back at the star. Only signals that were present both times the telescope was pointed at the star and disappeared when the telescope was pointed away were considered valid candidate signals and were subjected to further examination. Other signals were considered RFI. Many signals were detected and cataloged during the 200 hours of assigned telescope time. Only fifteen signals required additional verification tests, and all of them proved to be intermittent RFI.

**Insert Figure 7 about here**

#### B. Sky Survey

The Sky Survey observations began with the new 34-meter research antenna (See Figure 8) at the Venus Development Station at NASA's Goldstone Deep Space Communications Complex. The initial surveys were conducted near 8.5 GHz. Currently, the Sky Survey prototype system is being used to continue the development of the operational system and to improve the efficiency of the signal processing algorithms that reduce RFI. A set of three sky frames covering parts of the plane of our Milky Way Galaxy are being observed repeatedly in the frequency bands 1.6-1.75 GHz and 1.38-1.43 GHz. These observations, using a 26-meter antenna, optimize radio astronomy data and improve RFI excision strategies.

**Insert Figure 8 about here**

### C. Results of Initial Observations

As stated, no signals from beyond our Solar System were detected during initial observations with Targeted Search and Sky Survey systems. A few signals, subsequently identified and cataloged as RFI, were detected but none passed the required reobservation and verification tests.

Currently, the Targeted Search and Sky Survey teams are applying the lessons learned from these initial observations to upgrade and improve hardware, software and observational techniques. The combination of these two search modes represents a million-fold improvement in the capability to search for a variety of signal types in the multidimensional search space characterized by parameters such as frequency, bandwidth, direction and time. With experience and the arrival of the operational systems, HRMS efficiency will continue to improve.

## IX. **OTHER IMPORTANT CONTRIBUTIONS**

Besides providing an answer to one of humanity's most enduring questions, HRMS contributes to many areas of science, technology, and education and its science rationale draws from numerous technical and non-technical disciplines. Advances in HRMS science and technology may provide important contributions to astronomy, biology, chemistry, physics, computer science and other areas.

Searching for faint signals from distant technologies has already pushed the state-of-the-art in signal processing technology and provided instruments with numerous potential applications outside SETI. HRMS educational outreach activities have demonstrated potential to significantly improve science and mathematics curricula in elementary and middle schools throughout the US.

### A. Astronomy

The Sky Survey and the Targeted Search will search the sky at frequencies and sensitivities never before achieved. The Sky Survey will catalog information on more than 50,000 radio sources at frequencies below 5 GHz and will greatly extend existing surveys. The cataloged results of higher frequency scans will be especially important in finding compact radio sources with inverted spectra. Astronomers will be provided with continuum and spectral line maps of the entire sky.

High resolution spectral line maps over such a broad frequency band will include both known and new molecular maser emission lines. (The recently discovered methanol maser emission at 6 GHz<sup>48</sup> would easily have been found by the Sky Survey.) Modifications to the observing strategy under consideration will provide sensitivity to flare stars, pulsars, and unusual objects like Cygnus X-3.

In order to select approximately 1000 sun-like stars for the Targeted Search observation list, several thousand nearby stars must be studied in detail. This research will result in more complete knowledge of a large sample of nearby stars including their temperature, age, motion, and whether they have significant stellar or planetary companions.

## B. Multiple-Use Technologies

The electronic systems developed for the HRMS are basically special-purpose supercomputers that detect very weak signals in the presence of noise. The electronics, from integrated circuits to circuit boards, to subsystems, can be modified and applied in a variety of non-SETI areas.

The DSP Engine chip developed for the Targeted Search performs Fourier Transforms faster and more accurately than any other commercially available chip. The Fourier Transform has many applications including medical diagnostic imaging and geophysical resource exploration, among others. The HRMS signal processors must maintain a high degree of signal purity. The broadband, high sensitivity feed antennas and receivers under development for the HRMS could be used in many communications applications, especially spread spectrum communications. The combination of bandwidth (320 MHz), low noise temperature, and compact size challenge the state-of-the-art,

Analog to digital converters (ADC's) have many communications and signal processing applications. The ADC developed for the initial Targeted Search observations is unusually compact, accurate, and has a very high SNR. One ADC circuit board in the signal detection system is currently being evaluated for potential commercial applications.

## C. Educational Opportunities

The interdisciplinary nature of HRMS and the tremendous interest the topic of extraterrestrial life generates in men, women and children of all ages, abilities, ethnicities, social and economic backgrounds is evident.

Judging from the popularity of books, movies and television productions, the search for intelligent life in the universe is a topic that increasingly commands the interest of students, educators and the general public. The HRMS enjoys similarly widespread public appeal and support. Hundreds of SETI-related college-level science courses are taught each year and no modern astronomy text is written without mentioning SETI. Major newspapers and magazines frequently print articles on the progress of HRMS. Public lectures are always popular and well-attended.

Through the **very** positive responses to numerous classroom visits and lectures by HRMS scientists and engineers, it became clear that **the** topic of searching for intelligent extraterrestrial life could be developed into an exciting and effective vehicle to attract and retain young children to science and engineering-related subjects. Searching for, finding and, perhaps communicating with other inhabitants of the Milky Way serves as a naturally interesting theme under which scientific and other science-related topics can be taught.

The SETI Institute (a non-profit science and education corporation) encouraged David Milne, Jill Tarter and Kathleen O'Sullivan and a cadre of professional educators to design and develop a multidisciplinary science curriculum termed "Life in the Universe--An Exciting Vehicle for Teaching Integrated Science. Using life in the universe as an overarching theme, a proposal was submitted for a grant to develop science curricula for grades 3-9 that will meet California State Board of Education guidelines for "Science Curriculum Framework and Criteria," recommendations from the American Association for the Advancement of Science's (AAAS) Project 2061 and the National Science Teacher's Association's (NSTA) "Scope, Sequence and Coordination" guidelines for interdisciplinary science instruction. The proposal was funded by the the National Science Foundation (NSF) Division of Materials Development, Research and Informal Scientific Education (70%) and the HRMS program office (30%).

Curriculum materials centering on: 1) exploring the universe, 2) life on Earth and 3) life in the universe contain significant interdisciplinary science while being of great interest to children. The accompanying teacher's guides are self-contained and self-explanatory. Supporting classroom materials, when not furnished with the curriculum guides, are inexpensive and easy to obtain. Team members are currently developing and evaluating 6 teacher's guides, each containing 6 to 10 science lessons, for use in elementary and middle schools. The guides emphasize critical thinking skills, "science as a way of knowing" and mathematics as the language of science and are presented in a concept and process-oriented manner.

The teaching strategy is to present interrelated science topics using a variety of instructional vehicles, including short lecture, demonstration, game format, individual and group research, and other formats that maximize student involvement, hands-on and cooperative learning. The teacher acts as a facilitator and lessons are written so that teachers who may not be at ease teaching science topics are comfortable with the materials.

The classroom teachers who design the lessons during the summer test the lessons in their own classrooms during the ensuing fall. Participating teachers are assisted by experienced curriculum designers, artists, educational writers, and NASA and JPL researchers. Classroom trials are observed and assessed by experienced classroom evaluators. After revision, guides are tested nationwide by teachers who did not originally participate in the development of the materials.

To date, teacher's guides under development have been tested by 1100 elementary and middle school students in 14 states and the Commonwealth of Puerto Rico. Responses by students, teachers and administrators have been extremely positive.

The guides have been reported effective in motivating girls as well as boys, students with special learning needs as well as gifted students, students for whom English is not a principal language and students from diverse ethnic and economic backgrounds. All curriculum materials are scheduled to be completed and ready for unlimited distribution by summer, 1994. Plans include having the guides translated into Spanish and other languages.

#### D. Cultural Aspects of SETI

The topic of sentient life beyond Earth penetrates the depths of the human condition and the potential psychological, sociological, political, theological and philosophical aspects of an effort of this type must also be considered. Public reaction to the SETI effort, whether it leads to a verifiable detection or to a prolonged search with no detections, is being studied by a select group of scholars from many academic disciplines and institutions. The topic has been designated "Cultural Aspects of SETI" and the results will be published late in 1993.

### **X. A CHALLENGE TO THE PRESENT: A LEGACY FOR THE FUTURE**

HRMS, the NASA-sponsored effort to determine the existence of other ecosystems in the Galaxy represents one of the most compelling scientific sagas of all time. Scientists and engineers involved in searching for extrasolar planets and the living organisms some of them they may contain face considerable challenges. By viewing those challenges as opportunities and implementing projects like the HRMS, humankind reaffirms its commitment to the scientific quest for knowledge and its desire to explore. If interstellar radio transmissions are ever detected, humans will gain insight into the nature and accomplishments of other intelligent beings. In the absence of any such signals, we may gain unexpected insights into our priorities as a species. As the eminent philosopher Lewis White Beck concluded, if advanced extraterrestrial civilizations are discovered, "...there is no limit to what in coming centuries we might learn about other creatures and, more portentously, about ourselves. Compared to such advances in knowledge, the Copernican and Darwinian Revolutions and the discovery of the New World would have been but minor preludes."<sup>4</sup>

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of Steven Dick, Linda Billings, George Schulz, Bob Arnold and Lydia Razran Stone to the completion of this article. SETI historian Steven Dick, of the US Naval Observatory, contributed material and critically evaluated sections pertaining to SETI history and the concept of plurality of worlds. BDM Corporation author and journalist Linda Billings' suggestions for improvements to organization and technical style greatly improved readability of the manuscript. George Shultz, of the Jet Propulsion Laboratory, provided the figures and drawings and Bob Arnold, of the SETI Institute, provided quick and thorough access to the Institute's technical publications and references archives, Michelle Murray of the SETI Institute provided help with manuscript preparation. Lydia Razran Hook, of Lockheed Engineering and Sciences Co., provided invaluable assistance in insuring the accuracy of referenced works, MJK's contribution to this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration,

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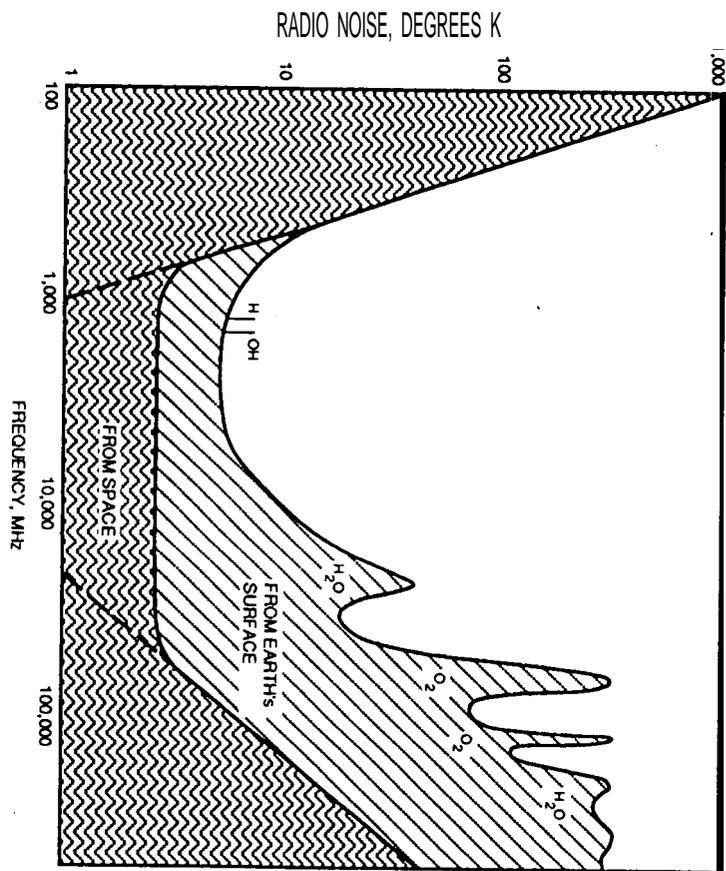
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SEARCHING FOR INTELLIGENT LIFE IN THE UNIVERSE: NASA'S HIGH  
RESOLUTION MICROWAVE SURVEY

COULTER,G., et al.

FIGURE CAPTIONS

- Figure 1: The microwave window from Earth's surface and from space.
- Figure 2: A diagram of the major components of the HRMS Targeted Search and Sky Survey systems.
- Figure 3: HRMS prototype MCSA detects signal from Pioneer 10 spacecraft, radiating a signal with a power of about 1 Watt at a distance of 5.3 billion km (3.3 billion miles), produced the above trace on the SETI MCSA display. Each line of dots represents the power in 200 frequency channels, each 1/2 Hertz wide, during a two-second observation. The size of the dot represents the power. The Earth's rotation causes the apparent frequency of the signal to change with time,
- Figure 4: Representation of a typical sky frame that will form mosaic maps for the HRMS Sky Survey. Approximately 25,000 sky frames will be required to survey the sky at all frequencies between 1 GHz and 10 GHz.
- Figure 5: A schematic representation of the scan pattern for one sky frame.
- Figure 6: View of the Eastern sky as seen from Goldstone at noon (1900 UT), October 12,1992. The shaded areas define the boundaries of the first two sky frames of the HRMS Sky Survey. The location of the first star observed by the Targeted Search team at Arecibo is shown in sky frame Number 1,
- Figure 7: The 34-meter diameter microwave antenna at the Venus Research and Development station, Goldstone California,
- Figure 8: Aerial view of the world's largest (305 M) radio telescope at Arecibo, Puerto Rico; operated by NAIC (National Astronomy & Ionosphere Center) at Cornell under contract to the National Science Foundation.



XX. The Microwave and from Space

Fig. 1

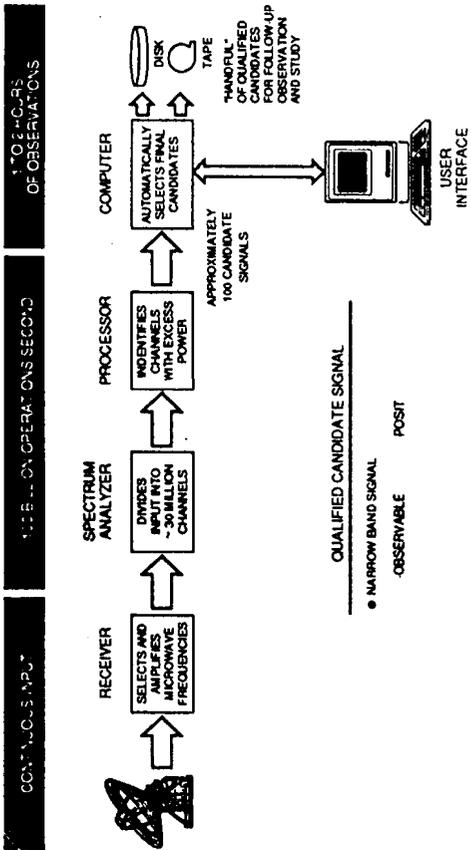
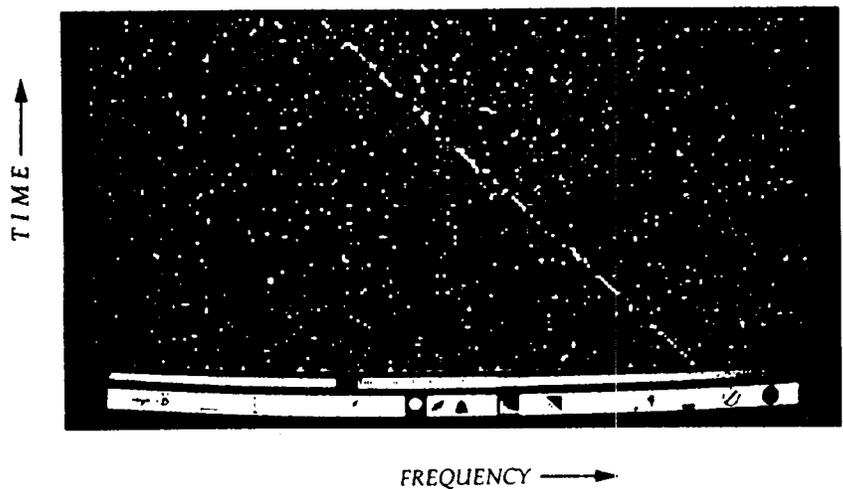


Figure 2

### A Spectrum Analysis Display

This display shows the output of a 74,000-channel prototype of a 10-million channel spectrum analyzer developed for the SETI Program at Stanford University. Each horizontal line of dots represents one time sample of about 200 adjacent frequency channels. The brightness of each dot is proportional to the amount of power in that channel. One hundred successive time samples of the spectrum are shown.

The bright diagonal line is produced by the center frequency of the Pioneer 10 spacecraft. The upward drift to the left is due to a gradual shift in the frequency, primarily caused by Earth rotation. The signal is not particularly apparent in any one time sample (horizontal line) but stands out in the total collection of 100 samples. The spectrum analyzer will be connected to detectors that will automatically search for sloping lines or trains of regular pulses.



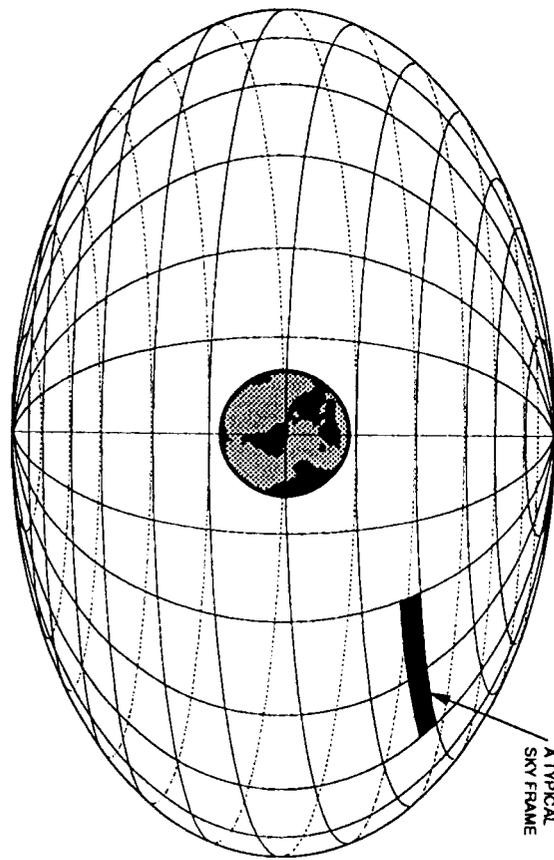


Figure .5

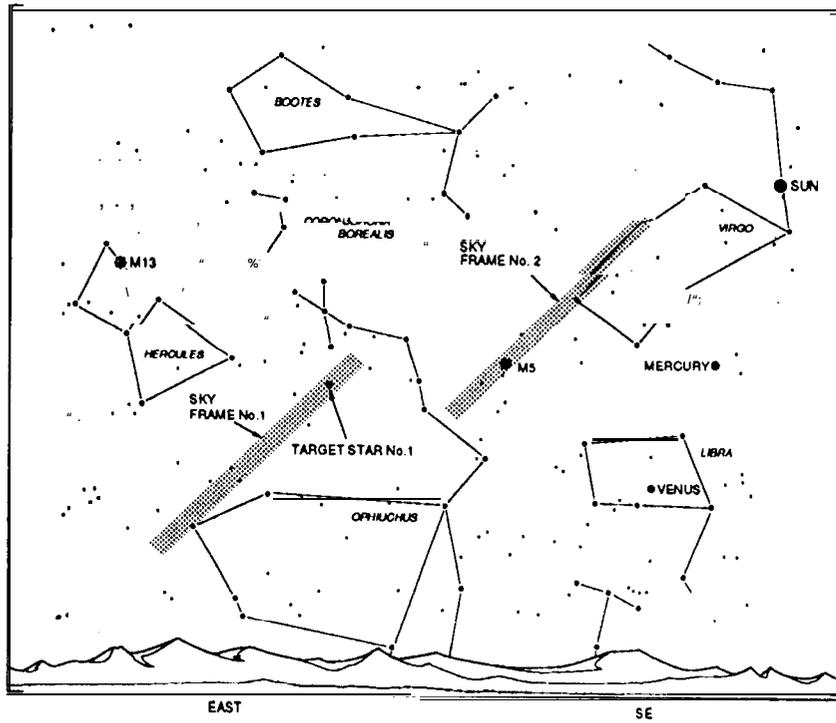


Figure XX. View of Eastern Sky as Seen from Goldstone at Noon, October 12, 1992

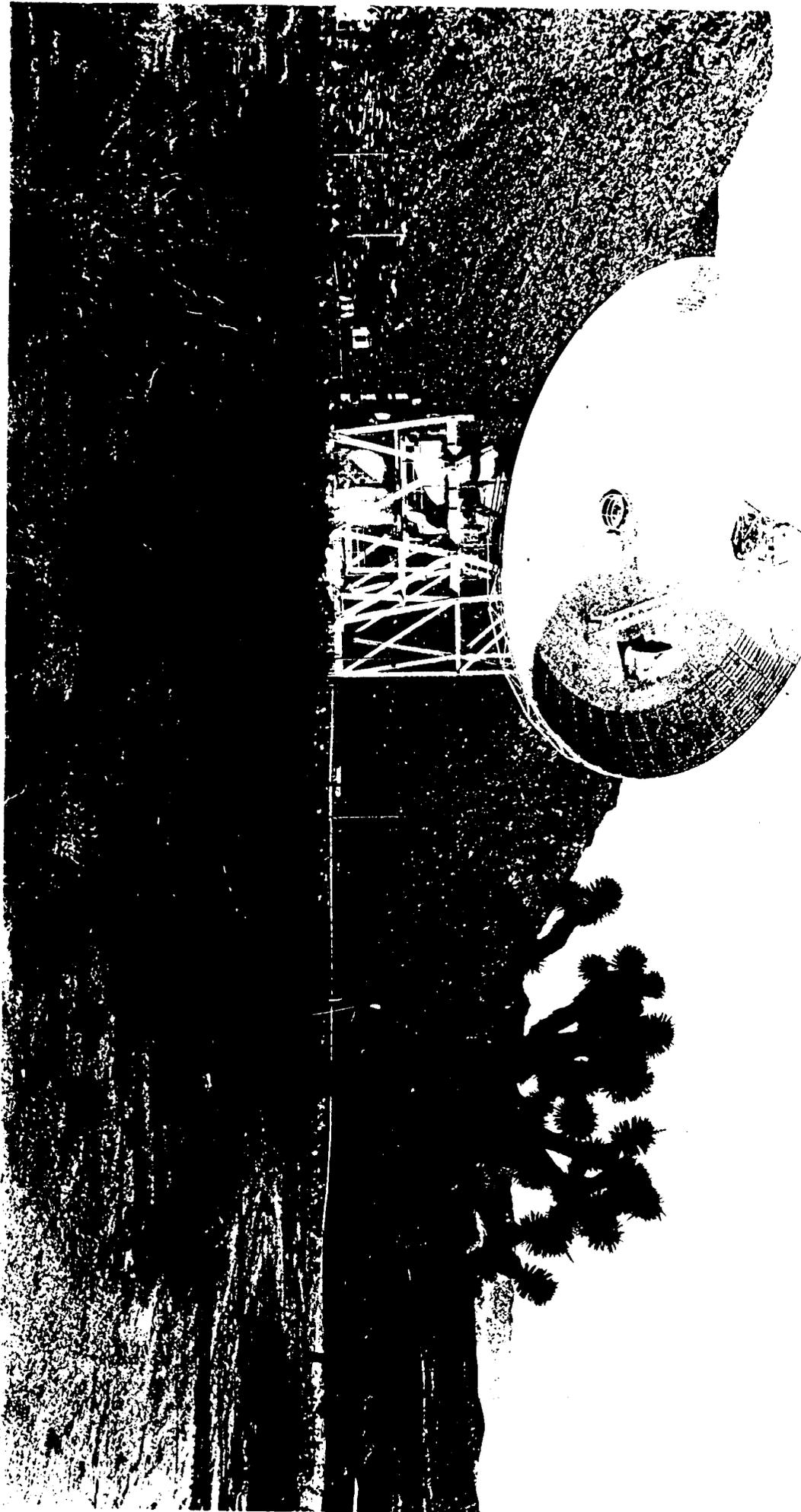


Fig. 7



Fig. 8