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TABLE OF CONTENTS

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U.S.A.

asa@chara.gsu.edu

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Editor's Note -

This January issue of EJASA is in six parts, and is devoted to the work of Dr. Stuart A. Kingsley on the subject of SETI in the Optical Spectrum. While the concept of Optical SETI is not new, it has yet to receive the same attention as the surveys for signals from alien intelligences in the microwave spectrum. It is the desire of Dr. Kingsley, that this paper will elevate the status of the optical approach to the search for extraterrestrial intelligence.

Parts A, B and C deal with the general concepts of Optical SETI, in particular Professional Optical SETI. Part D covers Amateur Optical SETI. In that part, the basic design of an Amateur Optical SETI Observatory is described, and details given of its approximate cost. Part E contains the discussion and conclusions, and an extensive list of references. Finally, Part F contains two Appendices, the first which give the theory and specimen calculations to support the case made for both Professional and Amateur Optical SETI, and the second which gives the Post-Detection SETI Protocols.

This year will see considerable media attention given to Microwave (Conventional) SETI. On Columbus Day, October 12, NASA's Microwave Observing Project, which is otherwise known by the acronym MOP, will be activated in the Northern Hemisphere at Puerto Rico's three hundred meter diameter Arecibo telescope (Targeted Search) and NASA's thirty four meter antenna at the Deep Space Network (DSN) in Goldstone, California (All Sky Survey). Later, the seventy meter telescopes at Parkes and Tidbinbilla in Australia, and the thirty meter telescope at the Institute Argentino de Radioastronomia Villa Elisa in Argentina, will join the program for complementary observations in the Southern Hemisphere.

At this auspicious moment as we approach the five hundredth anniversary of Christopher Columbus's discovery of the Americas, Dr. Kingsley brings to the public's attention the suggestion that we may not actually be tuned to the correct frequencies, so that the chances of discovering older, more mature extraterrestrial technical civilizations will be substantially impaired.

CORRECTIONS -

While every care has been taken to ensure the theoretical correctness of this paper, inevitable mistakes will be found, particularly considering the size and complexity of this material. The author wishes it to be known that he would like to hear about these errors. The COPYRIGHT NOTIFICATION page provides information as to how he may be contacted.

The COPYRIGHT NOTIFICATION (Page iii) contains the version number for this issue of the EJASA. If later, corrected versions are released, they will have a version number greater than 1.00.

About the Author -

Dr. Stuart A. Kingsley, born in 1948, is an alien of the terrestrial kind (British), having lived most of his life in South Tottenham, London, England, where his mother still resides. Stuart is single and still harbors a long-held desire to move to Hawaii or California. Presently he is an Optoelectronics Consultant, a Senior Member of the American Institute of Electrical and Electronics Engineers (IEEE), and an Associate Member of the British Institution of Electrical Engineers (IEE). Stuart Kingsley has a Bachelor of Science (B.Sc.) Honors degree and a Doctor of Philosophy (Ph.D.) in Electrical and Electronic Engineering from The City University, London, and University College London, respectively. In 1984 he shared the prestigious British Rank Prize for Optoelectronics with his former University College London thesis advisor, Professor D. E. N. Davies, who is now Vice-Chancellor of Loughborough University, England.

Dr. Kingsley arrived in the United States in 1981 to join Battelle Columbus Division and lead their activities in fiber-optic sensing, initially as a Principal Research Scientist and later as a Senior Research Scientist. In 1987 he left Battelle and established himself as a photonics consultant. The magnet that drew him to this country was the dynamic state of American technology during the Apollo Program, which coincided with his formative teenage years. Indeed, for most of his life, Stuart has been "mad about astronomy and space", and once, in the late 1970s, volunteered to be a British Payload Specialist on the American Space Shuttle. In the 1970s, Stuart was a member of his local Haringey Astronomical Society (patron Arthur C. Clarke), which was formed after a suggestion made by Patrick Moore to Arthur's brother, Fred Clarke.

Soon after arriving in Columbus, Ohio, Stuart joined The Planetary Society (TPS) and the Space Studies Institute (SSI). The only previous time that he has ventured professionally into the space and astronomy area was in the early 1980s, when he suggested the very speculative possibility that huge fiber-optic sensors (Sagnac Interferometers) with quantum amplifiers might be used to detect gravitational waves. In this present paper, Stuart is suggesting how we might "sense" ETI, with or without optical fibers - perhaps the ultimate optoelectronic (photonic) sensing and communications project. Dr. Kingsley is presently a volunteer with the SETI Group at the Radio Observatory, Ohio State University and a member of the Columbus Astronomical Society (CAS). Stuart's greatest concern today is that the nation has forgotten how to "dream" for a better tomorrow.

As a point of information, the logo for Fiberdyne Optoelectronics normally shows a Mach-Zehnder interferometer containing a photon and a wave-packet, the latter illustrating the dual nature of light (for this text-based document, they have been replaced by "hf >> kT"). Despite the STAR TREK style caption above the logo, which is more applicable to Dr. Kingsley's usual consulting activities, the suggestion made here is that extraterrestrial artificial optical photons may have been coming in Earth's direction for a long time, only that we humans have not been sophisticated enough to notice.

CONTENTS

EJASA, Vol. 3, No. 6, January 1992

TABLES

ILLUSTRATIONS

EXECUTIVE SUMMARY

This paper shows that the rationale behind modern-day SETI (The Search For Extraterrestrial Intelligence) lore is suspect, and that our search of electromagnetic signals from extraterrestrial technical civilizations may be doomed to failure because we are "tuned to the wrong frequencies". The old idea that optical transmissions would be better for interstellar communications is revisited. That lasers might be better for interstellar communications has generally been discounted by the SETI community. Indeed, there is very little in the SETI literature about the optical approach, as its efficacy was more or less dismissed by SETI researchers some twenty years ago. This paper serves to reopen the debate.

A powerful case is made that we have inherently assumed that ETIs are technical inept, so that they lack the prowess to send very narrow laser beams into nearby star systems. This paper provides convincing theoretical proof that infrared or visible lasers would be preferred for such communication links. Indeed, the author suggests that until a thorough search for ETI signals is done in the optical spectrum, we are unlikely to be able to say anything definitive about the probability or lack of probability of intelligent life in other parts of the Milky Way galaxy, particularly if the microwave search turns out to be negative.

The author, Dr. Stuart A. Kingsley, also indicates that amateur optical astronomers should be able to construct their own Optical SETI Observatories. Details are given of the equipment required and approximate costs. He suggests that a coordinated Amateur Optical SETI activity could make a useful contribution to SETI research by conducting a low-sensitivity Targeted Search in the visible and near-infrared spectrum, in parallel with the Microwave Observing Project's Targeted Search of eight hundred selected stars. Stuart Kingsley concludes his paper, by suggesting that while it is impossible to say that ETIs would not use interstellar microwave techniques to communicate with other technical civilizations, it is a mistake to ignore the strong possibility that optical communications are preferred.

An extensive theoretical appendix is included to support the calculations for Professional and Amateur Optical SETI, and the conclusions drawn from these calculations. For those interested in the procedures to follow after detection of an ETI signal, a copy of the Post-Detection SETI Protocols is also included.

PREFACE

This paper is about the Search For Extraterrestrial Intelligence (SETI) in the Optical Spectrum. It is a revisit of suggestions which for various reasons have yet to be accepted by the majority of the SETI community. This document does not address the usual controversial aspects about SETI, such as Fermi's Paradox, i.e., "Where are they?" and the arguments of Frank Tipler. [20,39] We shall also not discuss exotic forms of radiation, such as X-rays, gamma rays, neutrinos, and gravitational waves. This paper deals primarily with the superiority of interstellar optical beamed communications over their microwave counterparts.

In general, the concept of SETI is "sold" on the basis that electromagnetic waves are the cheapest (in energy cost) and fastest way to travel through deep space, and is the next best thing to actually being there. I tend to believe that interstellar travel by humans will be quite commonplace in the centuries to come, so that for myself there is the paradox (Kingsley's Paradox) of why communicate when it is possible to travel?

It is perhaps useful to state from the start what are my basic beliefs, with the caveat that there is presently very little scientific evidence to support any of these speculative ideas.

(a) The universe is literally crawling with life, some of this extraterrestrial life being highly intelligent.

(b) In general, extraterrestrials do not stay at home, but they do not leave the exploration and colonization of the galaxy to self-replicating von Neumann probes. [20]

(c) Extraterrestrials find it easy to travel across the galaxy in near-relativistic or relativistic spaceships.

(d) On the basis of (a), (b) and (c), it is likely that at least some of the so-called sightings of Unidentified Flying Objects (UFOs) do in fact relate to visitations from other worlds, and that Earth's history and the evolution of life on this planet may have been affected by such visits.

(e) If (c) is not possible and von Neumann probes are not employed, then electromagnetic waves could be used by extraterrestrial civilizations to contact their counterparts in other stellar systems, particularly more primitive technological civilizations.

(f) If (e) is occurring, then it is more likely that the optical region of the electromagnetic spectrum would be used, in preference to the microwave region.

Note that there is of course, the possibility of radio or optical communications from von Neumann probes in our vicinity, both with us and with their home worlds. Perhaps the greatest difficulty that I have with electromagnetic SETI is my long-held belief in what has come to be known as the "Cosmic Zoo", which is related to idea (c). If we are indeed presently off-limits for "Contact" in any form, i.e., quarantined, searching for electromagnetic signals would be a waste of time, never mind the consideration as to whether there are a sufficient number of ETIs in the galaxy to make electromagnetic "Contact" probable. However, this study is restrictive in its terms of reference, as it only considers the relative efficacies of the microwave and optical approaches to electromagnetic SETI (f). For the sake of this discussion, we shall not make much of an attempt to resolve these other problems here.

I would, however, make some observations. It has been a long and somewhat difficult road for SETI researchers to establish electromagnetic SETI as a legitimate science. To some extent, for political reasons, they have had to strongly disassociate themselves from those who believe in UFOs. This somewhat artificial differentiation has been done to reduce the incidence of being labelled "crazy" by their more conservative colleagues and Members of Congress, and to maintain the rationale that electromagnetic interstellar communications is the cheapest form of travel.

In reality, there is more common-ground between scientists who believe in UFOs and those that ascribe to SETI, than the latter might care to admit. To maintain otherwise is being intellectually dishonest, for both believe in "Aliens" or what are now more affectionately referred to as "Extraterrestrials" (ETs). In the end, what one believes (as against what one knows and is scientifically proven) comes down to imagination, or the lack of. On the other hand, what one publicly admits to believing is quite another matter entirely. This involves other more down-to-earth considerations, like the fear of being ridiculed by colleagues and the scientific establishment.

One only has to remember how the "keepers of the flame" recently reacted to the Cold Fusion work of Martin Fleischmann and Stanley Pons, to realize that the scientific establishment does not take too kindly to those would dare to "rock the boat" of conventional orthodoxy. Fortunately, the theory on Optical SETI given in Appendix A is based on long-established scientific principles, so this author should fare somewhat better.

Three types of civilizations have been postulated by Kardashev for the development of "super civilizations". [4,13,25] A "Type I" civilization would be in a similar stage of development as Earth, having gained control of most of the energy sources on the planet of origin (about 4 X 10^12 W). A "Type II" civilization would have reached a level at which it controlled the energy output of its own sun (4 X 10^26 W). A "Type III" civilization would have gained control of the energy output of the entire galaxy (about 4 X 10^37 W).

This paper really addresses the type of technology and energy sources available to Type I and Type II civilizations. Freeman Dyson has described how a Type II civilization might dismantle one of the larger planets in its solar system and build a shell completely surrounding its sun. [25] A Type III civilization would hardly need to use microwave or optical technology for communications, and might consider us little more than we do ants.

During the past eighteen months, I have been associated with Dr. Robert Dixon's SETI Group at Ohio State, and have had extensive communications with the SETI Institute at NASA's Ames Research Center in Moffett Field, California. My approach in revisiting this subject has not been the conventional one of publishing a paper or papers and waiting for the "penny to drop". Rather, because several noted researchers have published papers along similar lines over the past thirty years and have largely had their ideas rejected by their colleagues, I decided to try a somewhat different strategy: To take the SETI community by storm. The reader is assured that to the best of my knowledge, no laws of physics have been violated in this study. What is true, however, is that the human imagination has been stretched.

This is not the first time, nor will it be the last, that the scientific community may have gone in the wrong direction because of mistaken assumptions. What I am doing is to seriously question present SETI lore, with due respects to Professors Philip Morrison, Frank Drake (President, SETI Institute), Carl Sagan, Dr. Bernard Oliver and the late I. Shklovskii, to name but a few. At first glance, the three decades old idea that ETI signals will be found in the quietest region of the electromagnetic spectrum seems reasonable. Thus, the 21-centimeter hydrogen (H) line and the region of the microwave spectrum between the H and lowest OH resonance lines (1.420 to 1.662 GHz), which has come to be known as the "waterhole", has become a favored "magic frequency". However, we may have been too clever by half in guessing the natural interstellar communication frequencies, and in assuming that ETIs will make it very easy for us to locate their signals. Perhaps our commitment to the search for ETI must be substantially increased before we are rewarded by success.

Over the years, many science fiction writers have involved interstellar laser communications in their story lines. Indeed, in the 1990 SETI book, FIRST CONTACT [26], edited by Ben Bova and Byron Preiss, Ben Bova wrote a story involving Optical SETI called "Answer, Please, Answer". Interestingly, a recent edition of NEW SCIENTIST [45] which had an article about SETI, also contained a review of the new paperback issue of FIRST CONTACT and criticized it, suggesting that it was inappropriate to include this science fiction material. However, there may have been more truth in that story than in much of the rest of the book. Perhaps it is time again for scientists to take note of what science fiction writers have to say!

FIRST CONTACT also contains a chapter (Chapter 9, "How to Participate in SETI", by Kent Cullers and William Alschuler) devoted to Amateur Microwave SETI, but it is not clear how many TVRO (TeleVision Receive Only) owners would wish to convert their satellite dishes for this purpose. In the microwave regime, amateurs would be competing with the "big boys", but in the optical regime they would be essentially on their own. The contribution that the amateur optical astronomy enthusiast can make in this area is described later.

What I do find slightly disturbing is that the popular literature on SETI usually says either nothing about the optical approach or dismisses it in a paragraph or two as being without merit. As far as I can recall, THE PLANETARY REPORT [17,21,37] has never discussed this approach. Even the latest PLANETARY REPORT article by Professor Paul Horowitz [37] fails again to mention the optical approach. Indeed, the Planetary Society has just launched an appeal with the help of film producer and director Steven Spielberg, to raise funds for support of the Harvard BETA (Billion-channel Extraterrestrial Assay) project. This system will eventually have six billion channels and is designed to have a channel resolution of 0.05 Hz. This trend in Microwave SETI channel resolution is directly opposite to the thrust of the Optical SETI rationale described herein, where minimum channel bandwidths of about 100 kHz are specified.

Also, there appears to be misleading information in SETI books as to the visibility of electronically detectable signals and the efficacy of using Fraunhofer lines to increase signal contrast. It is almost as if no one had bothered to "crunch" the numbers properly. The fact that Fraunhofer lines have been previously thought to have a significant bearing on transmission frequencies in the visible regime, really arises from the assumption that ETIs lack the technical prowess to send us more than a few photons per second. Once that assumption is swept away, the increased contrast ratio produced by these stellar absorption lines become less significant, particularly in relation to the use of optical heterodyne receiving systems. [71-73]

Microwave SETI researchers are looking for very weak narrow-band signals buried in noise, and require the use of signal processing algorithms like the Karhunen-Loeve Transform (KLT) presently being studied by Dr. Robert Dixon's SETI group at Ohio State [73,86]. The KLT is more effective than the Fast Fourier Transform (FFT) in extracting non-repetitive pulses from noise-like data. I assume, that Optical SETI signals will be much stronger and of substantially increased bandwidth, and may not need to be processed in this manner.

The ten-year duration, 100 million-dollar Microwave Observing Project (MOP) now just starting, dramatically extends the search space in the Microwave Cosmic Haystack. [40-45] As far as Visible Optical SETI is concerned, it would appear that scientists of the former Soviet Union have done most of the work in this area, though it represents but a tiny fraction of global modern-day SETI activities.

If we confine ourselves to Visible Optical SETI for the moment, I make the following case that the sort of visible signal intensities which would allow modest-size telescopes to produce low-noise signals in moderate bandwidths are so weak that they would be easily missed by conventional optical astronomers. One just has to remember, that for over thirty years, SETI researchers have been scanning the skies for artificial extraterrestrial microwave signals in a systematic manner. So far they have failed to detect a confirmed artificial extraterrestrial signal. What is the probability if such rare signals exist in the visible or near-infrared spectrum that optical astronomers would have accidently stumbled across them?

In early 1991, after "suggesting" that the SETI community should revisit the optical approach, I was invited to give a talk at the SETI Institute. This Optical SETI Revisited Colloquium took place in April of 1991. Prior to my NASA visit, I had concentrated my analysis on Professional Optical SETI and had given some thought to the optical equivalent of the Microwave Observing Project. Some of the signal processing ideas arising out of MOP will be transferable to the optical search. I was well-received by NASA, though there are certain members of the group who still hold to the view that the optical approach is useless, particularly at the high-frequency visible end of the spectrum. After my talk, Dr. John Billingham, Chief of NASA's SETI Office, invited me to present a paper at the Commission 51 Bioastronomy Conference of the IAU (International Astronomical Union), which is to be held in 1993, and have that paper printed in the journal ACTA ASTRONAUTICA.

In recent years, NASA has supported a limited activity in SETI at 10,600 nm. However, its main thrust has always been Microwave SETI. For about five years, NASA has been supporting Charles Townes and Albert Betz in a low-level activity at the Carbon Dioxide (CO2) laser wavelength. This work has been "piggy-backed" onto a larger program for CO2 astrophysical research. They are using an interferometric system consisting of two infrared telescopes mounted on a trailer, with two phase-locked heterodyning CO2 local-oscillator lasers, nitrogen-cooled photodetectors, and a bandwidth of a few MHz. The observations are being conducted at Mount Wilson Observatory. The SETI aspect of this work is so low-key that I found some difficulty in obtaining details about this activity.

Over the early part of the summer of 1991 while I was back home in England, I was able to convince myself that perhaps the concept of Amateur (visible and near-infrared) Optical SETI was not such an implausible idea. Over the past eighteen months, I have undertaken a substantial self-funded analysis of Professional and Amateur Optical SETI, of which this represents a brief summary. I would be interested in hearing from any major space/astronomy publication or organization that would like to approach me for an article, book, or talk, or any company which might be interested in a business relationship in this area. I have prepared a substantial illustrated viewgraph report on this subject, which the few ASCII text diagrams and graphs in this document can hardly do justice. I would be interested in producing an Optical SETI book accompanied with compiled versions of many of the spreadsheets that I have employed for these analyses. This would allow readers to do their own "what-if" analyses.

The SETI Institute and NASA have been alerted that I will be going public about Professional and Amateur Optical SETI at this time, because of my gut feeling that there will be a surge of interest in this subject seldom seen during the thirty years of modern-day SETI. NASA might like to consider coordinating world-wide Amateur Optical SETI activities to avoid excessive duplication of searches on the same target stars. This would also present the opportunity to compare data to that obtained for the same stars with the Microwave Observing Project.

After digesting this material, some readers are bound to feel that what they have read they always knew, but were intimidated by the giants of the scientific community. Perhaps there is no field of human endeavor like SETI which involves so much speculation, where the citizen with a scientific background is just as qualified to speculate as the professional SETI scientist. The controversy over this approach is bound to rage for some time. Soon after I embarked on this study in June of 1990, I came to the conclusion that if this revisit of Optical SETI was to at last be given the attention it deserved, I would have to take a very different approach to getting the material published.

It is fitting that this first publication of these ideas is being done via the electronic media, the computer networks which span the globe. It has been advantageous that it has also given me substantial space in which to delineate the full scope of my rationale in one go, without leaving too many gaps. Indeed, what started out as a small paper has turned into a mini-book. Who knows; perhaps ETIs in the future will intercept signal leakage from Earth's microwave satellite uplinks, read this document, or eavesdrop on terrestrial TV and radio transmissions, and have a chuckle (I assume that humor is more than a human trait): "Those crazy humans, if only they knew!".

During the early formative part of my life, I owned a small refracting telescope and would spend many hours studying Earth's moon and the planets. It has been a long time since I possessed another telescope. Because I believe in putting my money where my mouth is, I am now impatient to put together my own Amateur Optical SETI Observatory. This paper has yet to be peer reviewed and the author is solely responsible for its contents. Readers are encouraged to check out the relationships used and the accuracy of the calculations. The rest is then a matter of opinion and imagination.

Optical SETI investigations will probably take a lot of perseverance. In the grand tradition of American disclaimers, readers should note that I cannot accept responsibility for the lack of success in detecting ETI - ("Caveat emptor"!). Since I expect that there will be considerable reaction to this material, I therefore beg your indulgence if I do not presently reply or reply in detail to every personal message received in response, either by conventional mail, fax, or network E-mail. However, a personal response is assured through my own bulletin board system (BBS), which has been set up specifically to coordinate future world-wide Optical SETI activities.

Simultaneously with the electronic publication of this document, I have established a BBS devoted to SETI in general, and Optical SETI in particular. More modem lines may be added later as interest warrants. The telephone number is (614) 258-1710 and supports all modem speeds up to 9600 baud. The BBS is dedicated to NASA and the late Gene Roddenbery, the latter having had a substantial influence on how I view the future. Many of the spreadsheets, diagrams and graphs - and there are many - that have supported the development of my rational, will eventually be made available via the bulletin board. For further details about this computer bulletin board, see the BBS information (Page ii) at the front.

The theoretical justification for the results and conclusions drawn in this paper has been relegated to Appendix A. In this way, those readers uncomfortable with scientific theory and mathematical relationships do not have to have wade through masses of equations. It is, of course, very difficult to be everything to all people. For this reason, I have compromised in this approach by keeping the theory as simple as possible, and have avoided the use of statistical analysis and calculus. For instance, the way that the signal-to-noise ratio of a detected optical signal varies with received photon flux, bandwidth, and signal integration time is exceedingly complex when the photon flux is weak, particularly if avalanche photodetectors are employed. There will be plenty of time later for this author and others to present a more rigorous approach to Optical SETI. This can be done in a variety of learned journals, such as IEEE's LIGHTWAVE TECHNOLOGY and TRANSACTIONS ON COMMUNICATIONS, or the IEE's ELECTRONICS LETTERS.

The purpose of this document is to rekindle the debate between those who believe in the microwave approach to SETI and those who subscribe to the efficacy of the optical approach. An additional desire is to introduce my colleagues in the fiber-optics field to a rather exciting concept - an idea which dwarfs all the puny terrene "hero" long-distance demonstrations that large fiber-optics communication companies like to brag about from time to time. As actor Al Jolson used to say, "You ain't seen nothing yet!".

I would like to acknowledge discussions and encouragement from various sources: Dr. Robert Dixon (Director, SETI Program) for a very professional reaction to what I had to say, despite having devoted decades of his SETI activities to the microwave search with "Big Ear". I also acknowledge Dr. Dixon's contribution in being given access to the educational and scientific network. In addition, I would like to thank Professor Charles Townes (University of California, Berkeley) for his helpful comments when this study was first started, recent E-mail discussions with his colleague Dr. Albert Betz, Professor Philip Morrison (MIT), and correspondence with Dr. John Rather (NASA-HQ).

I would also acknowledge correspondence and discussions with Dr. Bernard Oliver, who in early November of 1990 sent me a copy of his Cyclops report, convinced that it would prove the case for the efficacy of the microwave approach. In my correspondence and discussions with Dr. Oliver, who is also known as the "grand old man" of SETI, I have not been able to shake his belief in the correctness of the microwave approach. So we have agreed to disagree over the relative merits of Microwave and Optical SETI.

Over much of the past year and a half while the ideas were developing, I have interfaced with parts of the SETI community. There is some perception that my "lobbying" for the optical approach to SETI may already have had some effect on how those within NASA and the SETI Institute now view Optical SETI. At least, I have received rather "mixed signals" over the past eighteen months as to where the consensus lies, and there appears to have been some shift towards my position, though this may be a presumption on my part.

I would particularly like to acknowledge the professional courtesy and assistance given me by Dr. Jill Tarter (NASA SETI MOP Project, SETI Institute, U.C. Berkeley) and her staff at the SETI Institute, despite the fact that I may have "come on quite strong" in revisiting Optical SETI. I also thank Dr. Kent Cullers (Signal Detection Scientist, NASA) then of the SETI Institute, for his encouragement and for checking some of my calculations relating to Professional Optical SETI. I trust he will do the same, if he can draw himself away from MOP for a few hours, for my more recent computations relating to Amateur Optical SETI.

Finally, I must acknowledge the considerable assistance of the SETI Institute's Robert Arnold (Research Assistant and Public Information) in providing me with much background information on SETI. I hope I do not give him too much of a headache when he has to deal with the surge in national and international interest in all forms of SETI which will probably result from this paper. It is highly likely that because of the Microwave Observing Project and this paper, 1992 is going to be the Year of SETI.

Dr. Stuart A. Kingsley
Columbus, Ohio
December 24, 1991

INTRODUCTION

This paper suggests that the modern Search for Extraterrestrial Intelligence (SETI) [1-45,86], which was initiated by Cocconi, Morrison [1,13], and Drake (Project Ozma) [2,3,13] is being conducted in the wrong part of the electromagnetic spectrum, i.e., that SETI receivers are presently "tuned to the wrong frequencies". This paper revisits a subject first discussed by Schwartz and Townes [46-47] thirty years ago and subsequently investigated by the late Shvartsman [48,50,54], Connes [49], Zuckerman [52], Betz [53,57] and Beskin [58]. Dr. John Rather (NASA-HQ) also considers that Optical SETI has much to commend it. [56] According to the modern broader definition of the word "optical", the wavelength region embraced covers the region between 350 nm in the ultra-violet, and far-infrared wavelengths greater than 300,000 nm (millimeter-waves start at 1 million nanometers).

Our Milky Way galaxy contains about 400 billion stars. We assume, as does most of the SETI community, that at any time there are perhaps thousands or tens of thousands of technical civilizations (the Drake Equation, Page 71, Equ. 1) [2-39] within our own galaxy. There should be at least a reasonable chance that at any time, one such civilization might be signalling in our direction from within a sphere several thousand light years in radius. The volume of space within a sphere of two thousand light years in diameter contains about ten million stars, one million of which may be capable of supporting life.

The sign of a mature technical civilization is not to waste power over empty space, but to use refined signalling techniques in preference to brute force. Although some authors have suggested that optical ETI signals would appear in the form of bright flashing points of light, this author thinks it very unlikely. The idea that such signals will be like heliographs or semaphores, sending out intense beams at Morse Code rates, is not one that should be seriously contemplated. As will be shown, there is no need to modulate the entire output of a star in order to be detected across the galaxy. [20,33]

Just as on this planet, where there are a variety of communication techniques employed, depending on distance, bandwidth, and technologies available, there is no reason to assume that there is only one universal communication frequency or spectral regime employed by Extraterrestrial Intelligences (ETIs). Different applications and environments will lead to the optimization of different technologies, so that there may be many "magic wavelengths or frequencies". For example, because of the huge distances and lower propagation losses, radio waves may be better for communication between galaxies.

If the reader does not believe that advanced extraterrestrial technical civilizations would have the wherewithal to aim tight optical beams into neighboring stars, then they need read no further. In correspondence with the author, Dr. Bernard Oliver, Deputy Director of NASA's SETI Office, has put it very strongly that ETIs would not have this capability. This viewpoint has dominated SETI rationale for several decades, and in the author's opinion, is somewhat responsible for the "bad press" that the optical approach has received.

It is the author's view that the capability to target tight optical beams is probably much easier to achieve than developing relativistic or near-relativistic spacecraft. The same large optical antenna array capability which would allow ETIs to produce narrow transmitter beams would also allow them to "view" planets orbiting nearby stars. Over millennia they will have developed catalogs for the stars in their vicinity, with full details of each star's planetary system. For them, the ballistic skills (point ahead targeting) required to land photons on a designated target, over the equivalent of twice the light time distance, will be relatively trivial. This is not to discount the possibility that ETIs may send out space probes to nearby planetary systems to gather information directly.

There is a concept inherent in the conventional SETI rationale which might best be termed "Signpost SETI". This says, that the signals we are looking for in the microwave spectrum, may only be monochromatic/semi-monochromatic beacons or acquisition carriers, and that the main transmission channels for extraterrestrials are elsewhere. If this is the case, we might find a narrow-band modulated microwave signal that tells us to tune to some place in the optical regime, and perhaps provide the "Rosetta Stone" for decoding the wideband optical channel. However, it is not clear why extraterrestrials would spectrally separate these signals into two different wavelength regimes. Both the semi-monochromatic beacon and the main wideband transmission channel could be side-by-side in the optical spectrum (see Figure 1 below). Indeed, there would be good signal processing reasons (advantages) for using what we terrenes would call a "pilot-tone technique", particularly for reception within an atmosphere (see Page 83 for a theoretical description of this technique).

```
                 Ep(t) *         Signal Modulation
                       *             Bandwidth
                       *          <------------->
                       *           ------------- Es(t)
                       *          |             |
              Beacon   *          |    Signal   |
                or     *          |    (Main    |
            Pilot-Tone *          |   Channel)  |
                       *          |             |
     ----------------------------------------------------------->
                      fp                 fs    Optical Frequency
```

Figure 1 -

Signpost SETI or pilot-tone system. The beacon or pilot-tone carrier is at frequency fp and has an electric-field amplitude Ep(t), while the information signal with amplitude Es(t) is intensity, polarization, or frequency-modulated onto a signal carrier at frequency fs. The frequency separation (fs-fp) may be several MHz to several GHz, depending upon the signal modulation bandwidth, and other factors, and fp may be above fs. The ETI beacon or pilot-tone might also contain a simple very low bandwidth intensity or polarization modulation providing the Rosetta Stone for decoding the main channel.

Such techniques can reduce the effect of transmitter and local-oscillator laser phase-noise and correct for phase-noise and wavefront distortion produced by Earth's atmosphere, allowing more efficient reception with large heterodyning telescopes, i.e., reduced signal fading and improved mean SNR. [81-82,84] The coherence cell size (ro) at visible wavelengths (Wl) is approximately 20 cm (8"), and is proportional to (Wl)^1.2. In the infrared at 10,600 nm, ro can be as large as eight meters. At the best astronomical observatories in the world, the spectral power in atmospheric turbulence is confined below 30 to 50 Hz.

Clearly, this pilot-tone technique could be used for free-space optical communications between space and Earth with some advantage. It also reduces the differential Doppler Shift and Chirp (Drift) by the ratio (fs-fp)/fs; a ratio which can be of the order of 10^-8. Note that the wideband optical signal might use spread-spectrum techniques, so that the signal energy density might be too low to be detectable. Without the "key" to unlock the pseudo-random sequence, we might mistake the main signal channel for an excess amount of random noise.

There is something quite philosophically appealing about the pilot-tone technique. It satisfies the conventional SETI rationale for the need of a "Signpost", while at the same time provides the means for more efficiently detecting the main wideband ETI channel from within a planetary atmosphere.

THE MICROWAVE OBSERVING PROJECT (MOP)

From time to time, references will be made to NASA's Microwave Observing Project, otherwise known by the acronym MOP. The objectives of this program are summarized as follows:

Project Goal: To carry out a search for microwave signals of extraterrestrial intelligent origin.

Project Objectives:

1. To use existing large radio telescopes, e.g. Arecibo, to carry out a Targeted Search of about 800 nearby solar-type stars with high spectral resolution of 1 Hz, and sensitivity in the region of 5 X 10^-27 to 1.4 X 10^-25 W/m^2, over the frequency range from 1 to 3 GHz. (Ames Research Center)

2. To use the 34-meter telescopes of NASA's Deep Space Network (DSN) to carry out a Sky Survey that will examine the whole sky at a moderate spectral resolution of 30 Hz, and sensitivity 2 X 10^-23 to 2 X 10^-22 W/m^2) over the frequency range from 1 to 10 GHz. (Jet Propulsion Laboratory - JPL)

Duration: 1990 to 1999

Cost: $12.1 million for starters, $100 million over ten years.

As will be indicated later, the author would like to add (and has recommended this to the SETI Institute) that a third objective be added to this program, to run concurrently with the previous:

3. To solicit the help of dedicated groups of amateur astronomers and coordinate their activities to conduct with their ground-based optical telescopes, a low-sensitivity Targeted Search of about 800 nearby solar-type stars with spectral resolution < 1 nm, and sensitivity 10^-16 W/m^2. For selected wavelength bands in the visible and near-infrared wavelength range (350 nm to 1,200 nm).

ASSUMPTION OF INEPTITUDE

Unfortunately, despite declarations to the contrary, many SETI activists have been very anthropocentric and have in the main assumed that ETIs are technically inept. The "Assumption of (Technical) Ineptitude" (private discussions between the author and Clive Goodall), not to be confused with the "Assumption of Mediocrity" [5-39] applied to our own emerging technical civilization, has caused a gross underestimate of the technical prowess of ETIs, e.g., their capability to aim very high-power tight beams into the life zones of nearby stars. The onus will be on them to transmit the strongest signal with their stellar or nuclear-pumped orbital lasers.

It is humbling to remind ourselves that just one century ago, very few people on this planet used electricity. We have come a long way in a short time! Yet, in the space of one hundred years, we have been able to send astronauts to the Moon, robot probes to other planets, and deploy a large space telescope in Earth orbit. Despite the very unfortunate technical problems that have plagued the 2.4-meter aperture Hubble Space Telescope (HST), we should note that being representative of state-of-the-art terrene technology, it has a designed angular resolution of 0.043" and a designed pointing accuracy of 0.012". [59-62]

In 1961, just after the invention of the laser and only two years following Cocconi and Morrison's [1] classic paper which initiated modern SETI, Schwartz and Townes [46-47] (of laser fame) suggested that in other societies, laser communications technology may have been developed before microwave communications. From looking at the development of technology during the Twentieth Century, it is probable that the development of microwave and laser technology must occur within a short time of each other. As Schwartz and Townes implied, another society, having developed laser technology first, might cultivate a SETI rationale which was based on the superiority of laser communications over its radio frequency counterpart. It may only be a historical accident that the science of SETI on this planet became so dominated by radio astronomers.

Even Townes and his colleagues [46-47,51-53] have been somewhat constrained in imagination by limiting beam divergences to be greater than about one second of arc. A uniformly illuminated diffraction limited ten-meter diameter carbon dioxide (CO2) transmitter has a FWHM beamwidth equals 0.22 arc seconds (see Table 1, Page 19, and Table 2, Line 5, Page 22), so that even this system has a beam that is slightly too narrow by their definition. Note that more recently, Betz [57] has reduced the technical limits on beam divergence to 0.1 arc seconds. When we decide what might be technically feasible in one hundred, one thousand, or ten thousand years, the only thing which should constrain our imagination are the laws of physics as we presently know them. We are reminded that mere decades ago, the idea of geosynchronous communication satellites and men walking on the Moon was considered science fiction by most people.

Although SETI is about the passive activity of listening for signals, otherwise it would be (and was) called CETI (Communications

With Extraterrestrial Intelligence), how close are we to being able to transmit strong gigawatt-type optical signals across the galaxy? The answer to this question is that we are now much closer in time to be in a position to do this than we are to the Industrial Revolution. This is practically no time at all on the Cosmic Time Scale. Perhaps SETI is one way to take those Strategic Defense Initiative (SDI) "swords" on both sides of the now defunct Iron Curtain and turn them into CETI "plowshares"!

PROFESSIONAL OPTICAL SETI

In this paper, the model employed for the Professional Optical SETI analysis is based on a very modest continuous wave (C.W.) transmitter power of 1 kilowatt (1 kW) over a range of ten light years. As a modelling convenience, it assumes symmetrical systems, i.e., that the receiver aperture is identical to that of the transmitter. This symmetrical modelling technique is one often adopted by previous comparative analyses. In reality, because by definition Extraterrestrial Intelligences (ETIs) will be older and more technically mature civilizations, if and when we do detect ETI, it will be found that the alien transmitters are huge compared to our own puny receivers.

Figure 2 is a schematic diagram showing the most important features of a heterodyning receiving system (Equs. 23, 32, and 34) suitable for Professional Optical SETI. The optical pre-detection filter is not really required for SETI activities because of the excellent background noise rejection inherent in such systems. In practice, such a receiver would at least be duplicated for the detection of two orthogonally-polarized or circularly-polarized signal components.

This optical heterodyne receiver might well use a dye local-oscillator laser that has very narrow linewidth (< 5 kHz), and which is tunable across the entire visible and near-infrared regimes. The intermediate frequency (I.F.) bandwidth of such a system might be as high as 10 GHz. The output of each photodetector might be taken to a single 10 GHz Multi-Channel Spectrum Analyzer (MCSA) which sequentially samples all 16,384 photodetectors in the 128 X 128 pixel array, or there might be one MCSA for every row or for every photodetector, leading to substantial reductions in search time.

For several practical reasons, e.g., Doppler de-chirping, it is likely that the alternative coherent detection technique called "homodyne detection" (Equ. 33), which is essentially equivalent to a heterodyne system with a zero I.F., would not be used for the frequency search, though it might be employed after acquisition of an ETI signal.

One major reason why the SETI community generally discounts the optical approach is the considerable amount of quantum noise generated by optical photons. As we increase frequency, the number of photons for a given flux intensity progressively falls, so that there is a noise component associated with the statistics of photon arrival times, which exceeds the thermal kT noise. If Bif is the electrical bandwidth, it is assumed that sufficient photons arrive in the observa-

```
                                                         I
                                               ----------<--------
                                              |
              --          Beamcombiner        |
 Signal Pr   |  |           -------           |
-----------> |  | -------> |     . | ---->> -----  PIN Photodetector
-----------> |  | -------> |   .   | ---->> /   \  (One detector in a
-----------> |  | -------> | .     | ---->> -----  128 X 128 array)
 Background  |  |           -------           |
     Pb       --            ^ ^ ^ ^           |        -----
           Optional         | | | |           |       |     |
           Optical          | | | |            --->---|     |---->
       Bandpass Filter      | | | | Po                |     |
                            | | | |                    -----
                         -------------         Intermediate Frequency
                        |             |      Electrical Bandpass Filter
                        |    Local    |                 Bif
              Po >> Pr  | Oscillator  |
                        |    Laser    |
                        |             |
                         -------------
                               |
                               |
                                -----------------<---------------
                                        Frequency Control
```

Figure 2 -

Coherent optical heterodyne receiver. The diagram shows just a single photodetector, but in a large professional heterodyning telescope, a focal-plane array of about 128 X 128 photodetectors would be used to reduced the search time. This would also ensure that if a star is centered on the array, the signal from an orbiting ETI transmitter would fall on the same pixel or on an adjacent one within the array area, depending on the distance of the star, the orbital distance and position of the transmitter, and its plane of ecliptic. For each array pixel (photodetector), the local-oscillator power Po >> the received signal Pr to ensure quantum noise limited detection. A focussed local-oscillator (L.O.) laser may be scanned across the photodetector array in synchronism with the electronic sampling of the array. This would avoid the requirement for a high power L.O., and would thus eliminate heat dissipation problems in the array.

tion or measurement time 1/Bif, for Gaussian and Poisson statistics to apply. In practice, this means that about ten photons have to be detected during each measurement interval. For the photon-starved situation at small and negative Carrier-To-Noise Ratios (CNRs), the (analog) CNR values are somewhat meaningless.

The effective noise temperature (Equ. 30) of the 656 nm system modelled in this paper is 43,900 Kelvin, considerably more than the 10 K of the microwave system. However, it is the potential high-gain transmitting capability of optical antennas (Equ. 10) which can more than make up for this 36 dB reduction in sensitivity (36 dB increase in the noise floor). As a reference performance criterion, it should be noted that a symmetrical microwave system based on the 300-meter diameter Arecibo radio telescope on the island of Puerto Rico, a 1 kW transmitter and a 10 K system temperature, would produce a CNR of about 20 dB re 1 Hz (this is illustrated in Figure 4, Page 28).

For discussions about Professional Optical SETI heterodyne receivers, we will often refer to the term Signal-To-Noise Ratio (SNR) in a generic manner as a means of denoting signal detectability. In such cases, what we really mean is CNR, as the measurement is taken at the intermediate frequency (I.F.) before electrical demodulation (detection) of the signal. In the material on Amateur Optical SETI photon-counting receivers, we will be dealing with the post-detection signal-to-noise ratio, so it is more accurately denoted by the term SNR.

Communication engineers know that it is often expedient to normalize the CNR or SNR to a 1 Hz electrical bandwidth; a bandwidth which is thought to be substantially smaller than the minimum bin bandwidth required for actual SETI observations with Professional Optical SETI receivers. This allows us to subtract 10 dB from the CNR (SNR) for each decade increase in electrical bandwidth. For instance, a CNR (SNR) of 94 dB re (with respect to) 1 Hz is equivalent to 19 dB re 30 MHz, a figure arrived at by subtracting 10.log(30 X 10^6) from 94 dB. We shall be referencing these particular numbers again later.

A bandwidth of "1 Hz" has a special significance to Microwave SETI researchers. It is often the minimum bin bandwidth employed to analyze the received signals as dispersion effects and Doppler chirp rates in the low microwave region, i.e., around 1.5 GHz, would spread the most monochromatic of signals to that order (Table 2, Line 30, Page 22) shows the maximum equatorial ground-based chirp due to Earth's rotation to be about 0.17 Hz/s). Thus, it is important to realize that for this Optical SETI analysis, the 1 Hz bandwidth is used just for the convenience of normalizing the SNR. It does not imply anything about the ideal electrical (I.F.) or post-detection bandwidth. Note that in this study, it is generally assumed that the optical predetection bandwidth is at least twice the electrical or post-detection bandwidth.

Although in Figure 2 we have indicated an optoelectronic front-end array, it is possible that future developments in photonic computer technology will allow for the employment of an all-optical receiver and signal processing array.

In terms of mean transmitter power, it is useful to normalize the different ETI transmitters to a basic unit of 1 kW. Again, this implies no preconception about the actual powers available to ETIs, which inevitably will be far in excess of this. The noise level associated with the signal is assumed to be only that due to quantum shot noise. For power-starved receiving condition, non-Poisson noise at optical frequencies may actually raise the noise floor and degrade the CNR. In the quantum (Poisson) limited detection case, for every factor of ten that we increase the power, the CNR (SNR) will increase by 10 dB. If the optical receiver is background or internally noise

```
  Relative Levels Per Pixel re 1 Hz
    |
  34 dB |___1 kW Signal                ***        1.6 X 10^-15 W______
        |                              *S*
        |                              *I* CNR = 34 dB re 1 Hz
        |                              *G*
   0 dB |___Quantum Shot Noise_________*N*________6.3 X 10^-19 W/Hz___
        |                              .A.
        |                              .L.
        |                              . .
 -32 dB |___Planckian Continuum__      . .      __4.0 X 10^-22 W/Hz___
        |                        \     . .     /
        |                         \    . .    /
 -52 dB |___Fraunhofer Dark Line_  \___._.___/  __4.0 X 10^-24 W/Hz___
        |                         <----------->
        |     H_alpha (656.2808 nm) Bandwidth = 0.402 nm = 280 GHz
 -72 dB |___Day_Sky_______________________________4.0 X 10^-26 W/Hz___
        |
        |
        |
        |
        |
-154 dB |___Night_Sky_____________________________2.5 X 10^-34 W/Hz___
        |
        |                            H_alpha
         -------------------------------------------------------------
                             Wavelength or Frequency
```

Figure 3 -

Spectral levels at a range of ten light years, per diffraction limited pixel. The normalized transmitter power is 1 kW at 656 nm, and various noise sources for a space-based or adaptive ground-based heterodyne observatory are indicated. Both the transmitter and receiver are of 10 meters aperture and are assumed perfect. Receiver quantum efficiency equals 0.5. For convenience, the quantum noise level is taken as a reference level from which the signal and other noise sources are measured. Fraunhofer dark lines are typically 10 to 20 dB below the Planckian continuum level.

limited, the CNR (SNR) will increase by 20 dB. Figure 3 is a graph of signal and relative noise spectral levels for an imagined symmetrical visible SETI system with heterodyne receiver (Equs. 32 and 34).

One of the main benefits from the optical approach is its ability to sustain wideband communications over vast distances with very high Effective Isotropic Radiated Powers (EIRPs), but using relatively small apertures (Equ. 10). The latter attribute is particularly useful for spacecraft applications. [63-66] The EIRP is the apparent power that the transmitter would have to emit for a given received signal intensity, if it was an isotropic radiator, i.e., if it radiated energy uniformly in all directions, instead of confining the energy to a narrow beam. It is given by the product of the antenna gain and transmitter power (Equ. 11). The 656 nm system has a Full Width Half Maximum (FWHM) beamwidth of 0.014 arcseconds (Page 73), so that over ten light years, the beam diameter has expanded to about 0.04 Astronomical Units (A.U.); roughly two percent of the diameter of Earth's solar orbit (Page 74)!

For many years the author had been perplexed by the fact the optical approach to SETI had been ignored. There was very much a feeling of "What did the SETI community know that he did not?". Investigations over the past eighteen months indicate that to a large extent, the answer to this paradox was that the SETI community had simply refused to believe in the possibility that ETIs could aim narrow beams, such as the 0.04 A.U. dia. beam just described, and hit their targeted planet.

PROJECT CYCLOPS

In this paper, many references are made to the Project Cyclops [5] study and the effect that it has had on SETI thinking over the past two decades. Table 1 is taken from this report, which illustrates this author's view that Cyclops has been at least partially responsible for the lack of interest in the optical approach to SETI after the early 1970's.

The first column A is the most revealing in this comparison table, in that it models an ETI transmitter at the Nd:YAG (Neodymium: Yttrium-Aluminum-Garnet) laser wavelength of 1,060 nm, that has an aperture of 22.5 cm! As can be seen, in the Cyclops analysis, the onus for detecting a strong signal has been placed at the receiver end of the system, where by definition, the technology available would be far inferior to that at the transmitter. The resulting huge multi-mirror receiving telescope system is thus incredibly expensive.

The performance of the 1.06 um (1.06 microns) and 10.6 um systems modelled in the Cyclops study have been severely compromised by restricting the transmitters and receivers to ground-based operation within terrestrial-type atmosphere, and limiting beamwidths to one second of arc. As previously mentioned, the atmospheric coherence cell size (ro) is about 20 cm (8") at Wl = 0.5 um, and is proportional to Wl^(6/5). The A infrared systems are essentially state-of-the-art for 1971. The B infrared systems are futuristic for 1971. If we assume that the 1 ns pulses have a repetition rate of one per second in the case of the first 1.06 um Nd:YAG system (Optical System A), the average power is only a modest 1 kW. One does wonder though, what a peak power of 1 Terrawatt (1,000 GW) would do to a 22.5 cm diameter transmitting mirror, or the air contained within the telescope!

SETI COMPARISONS

This paper describes two basic types of Optical SETI receiver; the Professional (coherent) heterodyne system and the Amateur (incoherent) photon-counting system. However, there is no reason why a professional receiver could not use photon-counting, and vice versa, why an amateur

Table 1 Project Cyclops comparison scenarios

	OPTICAL		INFRARED		MICROWAVE	
PARAMETER	A	B	A	B	A	B
Wavelength	1.06 um	1.06 um	10.6 um	10.6 um	3 cm	3 cm
TRANSMITTER						
Antenna Diameter	22.5 cm	22.5 cm	2.25 m	2.25 m	100 m	3 km*
No. Of Elements	1	1	1	1	1	900
Element Diameter	22.5 cm	22.5 cm	2.25 m	2.25 m	100 m	100 m
Antenna Gain	4.4x10^11	4.4x10^11	4.4x10^11	4.4x10^11	1.1x10^8	9.8x10^10
Peak or CW Power, W	10^12	10^5	10^5	10^5	10^5	10^5
Modulation	Pulse	Pulse	Pulse	PSK	PSK	PSK
Pulse, s	10^-9	1	1	1	1	1
Energy per Bit, J	10^3	10^5	10^5	10^5	10^5	10^5
EIRP, W	4.4x10^23	4.4x10^16	4.4x10^16	4.4x10^16	1.1x10^13	9.9x10^15
Beamwidth	1"	1"	1"	1"	64"	1"
RECEIVER						
Antenna Diameter	100 m	100 m	100 m	2.25 m	100 m	3 km*
No. Of Elements	400	400	1975	1	1	900
Element Diameter	5 m	5 m	2.25 m	2.25 m	100 m	100 m
Atmosphere Tran.	0.7	0.7	0.5	0.5	1	1
Quantum Effic.	0.4	0.1	0.2	0.2	0.9	0.9
Solar Background	1.2x10^-3	36	1.7x10^-3	6x10^-7	-----	-----
Noise Temp., K	13,600	13,600	1360	1360	20	20
RF Bandwidth	1 GHz	3 MHz	3 kHz	1 Hz	1 Hz	1 Hz
Detection Method	Photon	Photon	Sq. Law	Synch.	Synch.	Synch.
Range Limit (L.Y.)	26	24	22	41	500	450,000
State Of The Art?	?	No	?	No	Yes	Yes
All Weather?	No	No	No	No	Yes	Yes

* Array spread out to 6.4 km diameter to avoid vignetting.

Data taken from Table 5-3, page 50, July 1973 revised edition (CR 114445) of the Project Cyclops design study of a system for detecting extraterrestrial life. [5] This study was prepared under Stanford/NASA/Ames Research Center 1971 summer faculty fellowship program in engineering systems design. Note that at the time the Cyclops study was done, the field of "optoelectronics" (photonics) had not yet really begun. Thus, what the Cyclops study called "Optical" is really a superset of both "near-infrared", and "infrared". In this Optical SETI paper, "optical" covers the entire spectrum from ultra-violet to the far-infrared. The near-infrared 1.06 um ETI transmitter for the Optical System A is only 22.5 cm in diameter, and is modelled to be putting out 1 kW pulses of 1 ns duration, with a peak power of one trillion watts and corresponding peak EIRP of 4.4 X 10^23 W!

receiver could not use heterodyne detection. The definition adopted here is one based purely on performance and cost grounds.

We now continue with the comparisons between various type of professional heterodyning SETI systems as tabulated in Table 2 (Page 22). It should be noted that while the microwave system in this table is based on a 100-meter diameter dish, the microwave system modelled in Figure 4 (Page 28) is based on a 300-meter diameter Arecibo-type dish. The 100-meter diameter dish system of Table 2, corresponds to the Microwave System A modelled in the Cyclops study (Table 1, Page 19), each dish being one of up to nine hundred similar dishes making up the Cyclops array.

The infrared telescope system is very similar to ones previously modelled by Townes, Betz, and Zuckerman. [46-47,51-53,57] Note that by increasing the 10,600 nm infrared transmitting and receiving telescopes' diameters to twenty meters, the SNR (CNR) obtained can be increased to the same value (34 dB) indicated for the 656 nm visible system (Table 2, Line 26). Since the Carbon Dioxide (CO2) laser is very efficient, coherent, and CO2 is likely to be readily available where life becomes established, 10,600 nm may be considered a "magic optical wavelength". [46-58] This wavelength is also capable of propagating with little attenuation across substantial portions of the Milky Way galaxy. The beam divergence is such as to make the targeting of nearby stars easier. There is also an approximately sixty percent atmospheric window at this wavelength.

All these telescopes, save for the Cyclops Array (Table 1) [5], may be considered as "puny" for an Advanced Technical Civilization (ATC), but are representative of state-of-the-art terrene technology, technology available either now or within the next decade. The results are based on "perfect" space-based systems (save for the daylight background factor), so in practice, several dB may have to be taken off the calculated SNR to account for imperfections, and atmospheric absorption and turbulence, if ground-based. Because optical heterodyne receivers are proposed for the professional optical systems, Planckian starlight and daylight have no effect on ground-based system performance if the local-oscillator power per pixel (per photodetector) is a lot greater than the background power. Large ground-based optical telescopes would likely use adaptive deformable mirror and laser guide-star technology for removing the "twinkle" from the star and transmitter's image. [68-70] The performance of such telescopes should exceed the theoretical performance of the HST. [59-62] This technology may be available within five years, and will be described in more detail later.

The "pilot-tone" technique briefly described on Page 10, used in conjunction with a photodetector array, might allow the implementation of a Maximal Ratio Predetection Diversity receiver. This leads to a very simple adaptive receiver which could be operated both during the day and night. As previously indicated, a more detailed description of how this operates may be found in Appendix A (Page 83). It should be kept in mind that getting a "perfect" image of a star and/or an ETI transmitter is a more rigorous pursuit than just collecting all the photons emitted by the ETI transmitter, wherever they fall within the photodiode array area.

Table 2 (Page 22) summarizes the salient points of the comparison between different electromagnetic communications technologies as applied to SETI, using heterodyning telescopes. [71-79] A preferred wavelength, not shown in this table, might be 1,060 nm, corresponding to the Nd:YAG transitions in the near-infrared. The corresponding SNR for a 10-meter diameter 1,060 nm system is 32.1 dB.

Given a modest extension to our technology over the next century, such wideband terrene interstellar links should become feasible, though they would use digital modulation and compression techniques to reduce the required bandwidth and enhance the SNR. The apparent visual intensity of the 1 GW transmitter, the power output of a typical Twentieth Century terrene power station, would rise from an apparent magnitude of +22.7 to +7.7. This is still below unaided human eye visibility (sixth magnitude) even if not obscured by the light of its star, and amounts to only 0.62% of the star's visual intensity (not corrected for wavelength). This result demonstrates that references in the literature to the fact that such signals have never been seen by the unaided eye, or detected in low-resolution spectrographs, proves nothing about whether ETIs are transmitting in the visible spectrum. Simply put, a powerful communications signal is still weak compared to a star's (integrated over wavelength) output radiated in our direction.

Table 2, Line 11 -

The reader is left to judge whether ATCs (ETIs) would have the wherewithal to aim narrow optical beams over tens and hundreds of light years and still be sure that their signal would strike a planet orbiting within the targeted star's biosphere (zone of life). Perhaps it is this assumption alone that is the key to the efficacy of the optical approach to SETI. The option is available to defocus (decollimate) the transmitted beam when targeting nearby stars. In such a situation, the signal strength would be weakened (reduced EIRP) for nearby target systems, but would remain relatively constant when operated on more remote targets out to distances of several thousand light years. It does not make sense to cripple, which is the result of Dr. Bernard Oliver's approach, [5] the long-range performance of Extra-terrestrial Intelligence (ETI) transmitters just because the beams happen to be too narrow for nearby stars.

Clifford Singer [15] has described how superior ETI technical prowess for transmitting microwave signals at certain preferred times related to the targeted star's proper motion, can lead to an enhanced transmission efficiency, making it more likely that the recipient will be able to detect those signals. In a similar vein, Filippova and others [55] have suggested that ETIs might make use of the moment of opposition to ensure that a narrow optical beam aimed at a star would be detectable at a target planet approaching opposition. Dr. John Rather, in the August, 1991 issue of the JOURNAL OF THE BRITISH INTERPLANETARY SOCIETY (JBIS) [56], describes huge Optical ETI

Table 2 Summary of SETI performance for (symmetrical) professional heterodyne communication systems over a range of 10 light years.

	MICROWAVE SETI	OPTICAL SETI	
PARAMETER	SINGLE DISH	INFRARED	VISIBLE
1. Wavelength	0.20 m	10,600 nm	656 nm
2. Frequency, Hz	1.50 X 10^9	2.83 X 10^13	4.57 X 10^14
	TRANSMITTERS		
3. Diameter, m	100	10	10
4. Gain, dB	63.9	129.4	153.6
5. FWHM Beamwidth, arcsecs.	421	0.223	0.0138
6. Power, kW	1	1	1
7. EIRP, W	2.47 X 10^9	8.78 X 10^15	2.29 X 10^18
	RECEIVERS		
8. Diameter, m	100	10	10
9. Gain, dB	63.9	129.4	153.6
10. FWHM Beamwidth, arcsecs.	421	0.223	0.0138
11. FWHM Diameter, A.U.	1,290	0.684	0.0423
12. Intensity, W/m^2	2.19 X 10^-26	7.81 X 10^-20	2.04 X 10^-17
13. Signal, W	1.72 X 10^-22	6.13 X 10^-18	1.60 X 10^-15
14. Photon Count, s^-1	NA	163	2,640
15. Equivalent Magnitude	NA	NA	+22.7
16. Quantum Efficiency	NA	0.5	0.5
17. Effec. Noise Temp., K	10	2,719	43,900
18. Planckian, W/m^2.Hz*	8.80 X 10^-33	1.07 X 10^-25	2.74 X 10^-24
19. Star Stellar Magnitude	NA	NA	+2.2
20. Relative Brightness, %	NA	NA	6.2 X 10^-7
21. Alien Planet Magnitude	NA	NA	+24
22. SPR, dB*	64.0	55.7	65.7
23. Minimum SPR, dB*	64.0	69.5	115.7
24. Daylight, W/m^2.sr.nm	NA	2 X 10^-3	1 X 10^-1
25. SDR, dB*	NA	50.6	106.0
26. SNR, dB*	1.0	22.1	34.2
27. Radial Doppler, Hz	1.0 X 10^5	1.9 X 10^9	3.1 X 10^10
28. Orbital Doppler, Hz	1.5 X 10^5	2.8 X 10^9	4.6 X 10^10
29. Synchronous Chirp, Hz/s	1.1 X 10^0	2.1 X 10^4	3.4 X 10^5
30. Ground-Based Chirp, Hz/s	1.7 X 10^-1	3.2 X 10^3	5.1 X 10^4
31. Symbiotic Cost, $M	2	20	20
32. Ground-Based Cost, $M	200	200	200
33. Space-Based Cost, $M	100	10,000	10,000

FWHM = Full Width Half Maximum (3 dB beamwidth).
1 Astronomical Unit (A.U.) = 1.496 X 10^11 m.
1 Light Year (L.Y.) = 9.461 X 10^15 m = 63,239 A.U.
1 parsec (psc) = 3.26 L.Y.

* Signal-To-Noise (SNR) and Signal-To-Planck/Daylight (SPR and SDR) Ratios assume polarized starlight and background, with no Fraunhofer dark-line suppression (typically 10 to 20 dB).

Signal-To-Noise Ratios (SNRs) in the galactic plane fall at the rate of 20 dB per decade of range (see Equ. 38), out to approximately one thousand light years in the visible regime, where attenuation by gas and dust begins to become significant. The attenuation in the visible, of 4 dB per three thousand light years (equivalent to a one stellar magnitude reduction in brightness), drops significantly away from the galactic plane.

The following numbers refer to the line numbers given in Table 2 and give a more detailed description of the parameters:

5. Full Width Half Maximum (FWHM) far-field beamwidth (Equ. 4).

8. The Cyclops Array proposed in 1971 consisted of nine hundred 100-meter diameter dishes (of the type modelled in the table) covering an area 6.4 kilometers in diameter.

11. Full Width Half Maximum (FWHM) size of received beam (Equ. 5).

14. The rate at which photons are detected (Equ. 36).

15. Apparent visual magnitude of transmitter is not corrected for visible wavelength (Equ. 2).

20. Relative brightness of transmitter in comparison to unpolarized Planckian starlight from a G-type star (black-body at 5,800 K).

21. Apparent Stellar Magnitude of reflected Planckian starlight from a Jupiter-size extrasolar planet. Note that if we want to detect an extrasolar planet directly, it is easier to do so by detecting its emitted heat in the infrared than by detecting reflected light in the visible.

22. Signal-To-Planck Ratio (SPR) for a solar-type star at the heterodyned I.F. frequency, assuming star and transmitter are not separately resolved.

23. Minimum Signal-To-Planck Ratio (SPR) for a solar-type star at the heterodyned I.F. frequency, assuming star and transmitter are separately resolved (Equ. 9).

24. Background daylight sky radiance for ground-based visible and infrared telescopes. For the latter, the 300 K temperature of the atmosphere presents a relatively constant 24 hour/day background.

25. Signal-To-Daylight Ratio (SDR) per pixel for diffraction-limited ground-based visible and infrared telescopes.

26. For convenience, SNRs (CNRs) are normalized to a 1 Hz electrical bandwidth. The value for the microwave system is given by Equ. 29. The values for the optical systems are given by Equs. 32 and 34.

27. Typical Doppler Shift (+/-) due to line-of-sight relative motions between stars at 20 km/s (Equ. 39).

28. Maximum local Doppler Shift (+/-) due to motion of transmitter/ receiver around solar-type star (1 A.U. orbit).

29. Maximum local Doppler Drift (+/-) for transmitter/receiver in geosynchronous orbit around Earth-type planet (Equ. 40).

30. Maximum local Doppler Drift (+/-) for a ground-based equatorial transmitter/receiver on an Earth-type planet.

31. Approximate ground-based receiver cost (millions), assuming re-use or sharing of existing observatories in each hemisphere.

32. Approximate ground-based receiver cost (millions), assuming a new dedicated (adaptive) telescope in each hemisphere.

33. Approximate receiver cost (millions) for a single space-based telescope. A very conservative estimate has been used.

transmitting arrays which are of planetary size, sending out powerful Free-Electron Laser beams to an enormous number of stars simultaneously. Huge arrays can provide an extended Rayleigh (near-field) range so that the flux densities remain constant (the inverse square law does not apply) out to considerable distances (Equ. 7, Page 74).

Table 2, Line 15 -

In this table, the apparent visual magnitude and brightness of a star, planet, or transmitter, is given for comparison purposes, and is defined only for visible wavelengths, since infrared light is invisible. The apparent visual magnitude of the transmitter is essentially independent of the optical detection bandwidth as long as it is equal to or greater than the signal bandwidth, i.e., it is the same for an optical bandwidth of 1 Hz, 1 MHz, or 1 THz; these bandwidths being much less than that of the human eye.

Table 2, Line 20 -

This shows the apparent visual intensity of the transmitter with respect to the alien star (Equ. 2). If the 656 nm 1 kW transmitter power is increased by six orders of magnitude to 1 GW, the received signal will increase to 1.6 nW (2.6 X 10^9 photons detected per second), and the Carrier-To-Noise Ratio (CNR) will increase to 94 dB. In a 30 MHz bandwidth this CNR will fall to 19 dB. This is more than adequate to transmit a standard analog NTSC/PAL/SECAM F.M. video signal over 10 light years, though at a range of 100 light years the CNR would fall to an unusable -1 dB (the F.M. threshold is typically 7 to 10 dB).

Table 2, Line 23 -

The Signal-To-Planck Ratio (SPR) on this line takes into account the ability of large diffraction-limited optical telescopes to spatially separate in the focal plane, the image of the transmitted signal from the image of the aliens' star (Equs. 8 and 9). This leads to the Signal-To-Planckian Ratio (SPR) being about 10 dB greater than the Signal-To-Daylight Ratio (SDR). Clearly, even when the signal source and Planckian noise (Equ. 3) are not optically separable, the ratio of the signal to the Planckian background noise is much greater than the quantum shot noise SNR, so it is not limiting on performance.

Contrary to statements in the literature [12], there may be no need to select a laser wavelength to coincide with a Fraunhofer line if optical heterodyne reception is assumed. This is really useful only when incoherent optical detection techniques are employed (see the later material on Amateur Optical SETI) with their relatively wideband optical filters. However, it might be advisable to avoid bright emission lines that rise substantially above the continuum level.

For an advanced technical society, a laser transmitting telescope is only "slightly" more difficult to construct than a microwave transmitting dish, though Isaac Asimov appeared to think otherwise in the late 1970s. Towards the end of his 1979 book, EXTRATERRESTRIAL CIVILIZATIONS [12] (page 263), Asimov says: "With laser light we come closer to a practical signaling device than anything yet mentioned, but even a laser signal originating from some planet would, at great distances, be drowned out by the general light of the star the planet circles." He goes on to say: "One possibility that has been suggested is this: The spectra of Sun-type stars have numerous dark lines representing missing photons - photons that have been preferentially absorbed by specific atoms in the stars' atmospheres. Suppose a planetary civilization sends out a strong laser beam at the precise energy level of one of the prominent dark lines of the star's spectrum. That would brighten that dark line...." Asimov went on to imply that a laser system was complicated and that no civilization would be expected to use the harder method if a simpler (microwave) method is available.

This erroneous idea that laser transmitters have to outshine stars to be detectable has unfortunately been accepted by many in the SETI community. Dr. Jill Tarter [24] (Chapter 14, SETI: THE FARTHEST FRONTIER, Page 192) has said that "Any optical communications signal coming from a planet circling a distant star would have to outshine the star itself in order for us to detect it.". As we have seen, this is simply not true. Indeed, as we shall show later, even small incoherent receivers with optical bandwidths as large as 100 GHz can produce electronically detectable signals at intensities considerably below that of nearby stars. Note that this statement has nothing to do with the assumed technical beaming prowess of ETIs, only that a visible wavelength signal strong enough for good communications, is still weak compared to a star's visual brightness (intensity).

With optical heterodyne receivers, whose performance is essentially independent of the optical pre-mixing bandwidth (the effective optical bandwidth for background noise calculations is equal to the electrical intermediate frequency bandwidth), there does not appear to be any necessity to operate within a Fraunhofer dark absorption line in order to avail ourselves of 10 to 20 dB of Planckian continuum noise suppression. The "magic-wavelength" would thus be determined only by the availability of highly efficient and coherent laser frequencies.

Table 2, Line 25 -

The high Signal-To-Daylight (background) ratio indicates that Optical SETI is one of the few branches of optical astronomy, save for solar astronomy, which can be conducted during daylight hours under a clear, blue Earth sky. Since the background detected per diffraction limited pixel is essentially independent of aperture, this ratio (shown for 45 degrees to the zenith) is proportional to the receiving telescope's aperture area, as is the quantum SNR. The Signal-To-Nightlight ratio for ground-based observatories is some 80 dB greater.

Thus, it is suggested that Optical SETI observations with the great optical telescopes of Earth could be conducted during daylight hours while conventional astronomy is conducted at night. Also, telescopes which have been decommissioned due to light pollution effects might be brought back into service. A future symbiotic relationship (sharing of facilities) between Optical SETI and conventional astronomy, could allow Optical SETI to be conducted for one-tenth the cost indicated on Line 32 for dedicated observatories, i.e., for about twenty million dollars (United States currency).

Table 2, Line 26 -

This is the bottom line, showing the SNR (CNR) normalized to a 1 Hz bandwidth. The 34 dB CNR for the 656 nm system corresponds to a photon detection rate of 2,640 per second (Equ. 36). For practical Professional Optical SETI searches, we should be looking for signals with minimum bandwidths of about 100 kHz. As long as the Signal-To-Planck and Signal-To-Daylight ratios are larger than the quantum SNR, the former do not reduce the system performance. It should be noted that at a frequency of 1.5 GHz (wavelength = 20 cm), the full 6.4-kilometer diameter microwave Cyclops Project [5], which in 1971 would have cost about ten billion dollars, only achieves an SNR of 60 dB (see Table 1, Page 19). This is about 26 dB greater than for a 10-meter diameter symmetrical visible system.

Other than the fact that interstellar absorption at microwave frequencies for distances in excess of a few thousand light years is significantly less than in the visible spectrum, the Microwave Cyclops system has little to commend it for communications within the solar neighborhood, particularly as the cost of the receiver is about one hundred times that of a single-aperture ground-based optical counterpart. This is good grounds for thinking "small is beautiful". For some strange reason, while free-space laser communications appears to be fine for future terrene GEO (Geosynchronous Earth Orbit) to LEO (Low Earth Orbit) and deep-space communications (much of this work is being coordinated by NASA [63-66]), the SETI community appears to be convinced that ETIs would not use such technology for interstellar communications! This is illogical. A presently favored operating wavelength for terrene free-space communications systems is 530 nm (green), obtained by frequency-doubling the 1,060 nm wavelength produced by a laser-diode pumped Nd:YAG laser.

As previously mentioned, terrene SETI programs appear to have been distorted by poor assumptions in the Cyclops study (see Table 1, Page 19). [5] As we showed earlier, the efficacy of the optical approach was severely hampered by constraining the near-infrared transmitting telescope size to 22.5 cm. It boggles the mind to think that ETIs would be trying to contact us with their equivalent of a Celestron or Meade telescope. This would put the onus on us to build very large and expensive multi-aperture receiving telescopes to pick up their weak signals; surely the very opposite would be the case! The Cyclops study was unable even to predict the rise in ascendancy of the ubiquitous semiconductor chip over the following five years, and the effect it would have on SETI signal processing, even though integrated circuits were being developed in the editors' backyard!

Present-day experimental ground-based free-space communications links are already using receiving telescope apertures as large as 1.5 meters. [66] Since the overall performance of symmetrical systems is proportional to the telescope diameter raised to the sixth to eighth power (allowing for power density limitations due to heating effects at the transmitter mirror), poor estimations about transmitting and receiving telescope apertures can drastically skew a comparative systems analysis. In practice, transmitting and receiving telescopes are likely to be extremely asymmetric. If we do discover an optical ETI signal in the next few decades, it will probably be found to have been transmitted by a huge optical array, while our receiving antenna will be a relatively puny telescope.

Figure 4 shows a graph of received signal spectral density, superimposed on the Planckian spectral density curve for a (solar-type) black body radiator at a temperature of 5,778 K. The microwave system performance shown in this graph is based on the 300-meter diameter Arecibo telescope; producing a CNR some 19 dB greater than for the 100-meter radio telescope system modelled in Table 2 (Page 22).

The reader is encouraged to compare this graph to that given in FIRST CONTACT [26] (Chapter 4, Page 151, by Dr. Michael Klein). The first impressions from that graph (Figure 1 of Chapter 4) is again that optical communications are useless. This is far from the truth. Indeed, the graph is very misleading. One might be forgiven for thinking that in this model the ETIs are using Compact Disc-type laser-diodes and/or hobby model-type telescopes! The assumed

```
Spectral Density, W/m^2.Hz
  |
10^-15 |
       |                              EIRP = 2.3 X 10^18 W  23rd Mag.
       |                                                  *
       |                    EIRP = 8.7 X 10^15 W          * CNR = 34 dB
       |                                        *         *         .
10^-20 |                            CNR = 22 dB *         *.    Quantum
       |                                        *.        *      Noise
       |                              .         *         *
       |                                        *         #656 nm Beacon
       | EIRP = 2.2 X 10^10 W                   *    #   |  #(10 m Dia.)
10^-25 |       *               10,600 nm Beacon #        | |
       |       * CNR = 20 dB   (10 m Dia.)  #            |V| #
       |    . .*. . . . . . .           #                |I| 2nd Mag.
       |       * Temp. = 10 K      #    ^                |S|  #Starlight
       |       *              #         |                |I|
10^-30 |       *         #          Planckian            |B|   #
       |       *    #              Black Body            |L|
       |       # 1.5 GHz Beacon       Curve              |E|    #
       |   #     (300 m Dia.)                            | |
       |#                                                |L|     #
10^-35 |                                                 |I|
       |                                                 |G|      #
       |                                                 |H|
       |       Microwave      Millimeter      Infrared   |T| Ultra #
       |                                                 | | Violet
10^-40  ----------------------------------------------------------------
     10^8   10^9   10^10   10^11   10^12   10^13   10^14   10^15   10^16

                                Frequency, Hz
```

Figure 4 -

Spectral density and interstellar CNR for 1 kW (SETI) signals at ten light years. Quantum Efficiency at Visible and Infrared = 0.5. Microwave system is based on 300-meter diameter Arecibo-type telescopes. Optical systems are based on perfect 10-meter diameter telescopes as modelled in Table 2. The Carrier-To-Noise Ratios (CNRs) are normalized to a 1 Hz bandwidth. The EIRP of a solar-type star = 3.9 X 10^26 W, and has an apparent magnitude equal to 2.2.

optical EIRPs are much too low. Also, the graph is plotted in terms of EIRP, and therefore exaggerates the efficacy of the microwave approach for an electronic receiver (instead of an observer), because it does not show the typical 10 K noise floor of a high-quality microwave receiver, only the radio brightness of a quiet G-type star. The latter is about 54 dB beneath the 10 K systems noise floor, as shown in Figure 4, and could only be detected after considerable signal integration. At 1.5 GHz, it is generally the Cosmic Background, i.e., the 2.73 K aftermath of the theoretical Big Bang, and the electronic noise in the microwave front-end that limits signal detectability, not Planckian radio noise from the star.

LASERS

Table 3 gives a list of many of the more important laser types presently known. [79] As previously mentioned, the CO2 wavelength of 10,600 nm has been identified as an "optical magic wavelength". [46-47,51-53,57] However, there are many laser wavelengths in the visible and infrared spectrums that might be suitable for ETI transmitters and local-oscillators. We should not discount the possibility that ETIs may use efficient frequency-doubled lasers, so we might consider exploring the visible spectrum for near-infrared lasers at half the wavelengths quoted below. For example, the 532 nm wavelength corresponding to the frequency-doubled Nd:YAG 1,064 nm transition may be a suitable wavelength; one that is presently favored for terrene optical communications.

Table 3 Important laser types and wavelengths

Type	Wavelength (nm)
Free-Electron	Ultra-violet to far-infrared*
Krypton-Fluoride Excimer	249
Xenon-Chloride Excimer	308
Nitrogen Gas (N2)	337
Organic Dye (in solution)	300-1,000 (tunable)**
Krypton Ion	335-800
Helium-Cadmium	422.0
Argon Ion	450-530 (main lines 488 & 514.5)
Helium Neon	543, 632.8, 1,150
Semiconductor (GaInP)	670-680
Ruby	694
Semiconductor (GaAlAs)	750-900
Neodymium YAG	1,064
Semiconductor (InGaAsP)	1,300-1,600
Hydrogen-Fluoride Chemical	2,600-3,000
Semiconductor (Pb-salt)	3,300-27,000 (tunable)**
Deuterium Fluoride	3,600-4,000
Carbon Monoxide	5,000-6,500
Carbon Dioxide (CO2)	9,000-11,400 (main line 10,600)

* Extremely high peak powers available within the decade (> 100 GW).
** Suitable for wide-tunability receiver local-oscillators.

Carbon Dioxide and Semiconductor lasers are very efficient. In addition to the types listed above, there are a variety of chemical lasers, including: Iodine, Hydrogen Bromide, Xenon Hexafluoride, Uranium Hexafluoride, and Sulphur Hexafluoride. These chemical lasers are efficient and very powerful.

Lasers like the Helium-Cadmium and Helium-Neon can be discounted because of their very poor efficiency and low power, even though their temporal coherence is excellent. Similarly, the original Ruby laser is

Table 4 The most intense Fraunhofer lines from the Sun{1}

Wavelength, nm	Bandwidth, nm	Bandwidth, GHz	Element
410.1748	0.3133	558.7	H_delta
413.2067	0.0400	71.0	Fe I{2}
414.3878	0.0466	81.4	Fe I
416.7277	0.0200	34.5	Mg I
420.2040	0.0326	55.4	Fe I
422.6740	0.1476	247.9	Ca I
423.5949	0.0385	64.4	Fe I{2}
425.0130	0.0342	56.8	Fe I{2}
425.0797	0.0400	66.4	Fe I{2}
425.4346	0.0393	65.1	Cr I{2}
426.0486	0.0595	98.3	Fe I
427.1774	0.0756	124.3	Fe I
432.5775	0.0793	127.1	Fe I{2}
434.0475	0.2855	454.6	H_gamma
438.3557	0.1008	157.4	Fe I
440.4761	0.0898	138.9	Fe I
441.5135	0.0417	64.2	Fe I{2}
452.8627	0.0275	40.2	Fe I{2}
455.4036	0.0159	23.0	Ba II
470.3003	0.0326	44.2	Mg I
486.1342	0.3680	467.2	H_beta
489.1502	0.0312	39.1	Fe I
492.0514	0.0471	58.4	Fe I{2}
495.7613	0.0696	85.0	Fe I{2}
516.7327	0.0935	105.1	Mg I{2}
517.2698	0.1259	141.2	Mg I
518.3619	0.1584	176.9	Mg I
525.0216	0.0062	6.7	Fe I{3}
526.9550	0.0478	51.6	Fe I{2}
532.8051	0.0375	39.6	Fe I
552.8418	0.0293	28.8	Mg I
588.9973	0.0752	65.0	Na I(D2){2}
589.5940	0.0564	48.7	Na I(D1)
610.2727	0.0135	10.9	Ca I
612.2226	0.0222	17.8	Ca I
616.2180	0.0222	17.5	Ca I
630.2499	0.0083	6.3	Fe I{3}
656.2808	0.4020	280.0	H_alpha
849.8062	0.1470	61.1	Ca II
854.2144	0.3670	150.9	Ca II
866.2170	0.2600	104.0	Ca II

Table reproduced from "Astrophysical Formulae", edited by K.R. Lang, Springer-Verlag, 1978, p. 175. [90]

{1} After MOORE, MINNAERT, and HOUTGAST.
{2} Blended line.
{3} Magnetic sensitive line.

inefficient and low power. Probably, one of the more important considerations for an ETI transmitting laser is that it should be capable of being deployed in space, be able to produce extremely high C.W. or pulse powers, and be nuclear or stellar (solar) pumped.

Organic dye lasers are suitable for local-oscillators, with their wide tunability and narrow linewidth (< 5 kHz). Lead-salt semiconductor lasers are suitable for infrared local-oscillators.

FRAUNHOFER LINES

Table 4 is a list of the most intense Fraunhofer lines from the Sun and their effective bandwidths. The H_alpha Hydrogen line upon which the visible Optical SETI model is based, has a wavelength of 656.2808 nm (frequency = 4.57 X 10^14 Hz), and an effective linewidth or bandwidth of 0.402 nm (280 GHz). [88-90] The actual FWHM linewidth is somewhat less that 280 GHz.

THE OPTICAL SEARCH

An "All Sky Survey" of the type planned for the Microwave Observing Project (MOP), which pixelizes the entire celestial sphere, does not make sense in the optical regime. [40-45] The 10^16 beams (Equ. 20) for a diffraction limited 10-meter diameter visible-wavelength telescope are mainly wasted looking out into empty (local) space. For a celestial sphere one thousand light years in radius, containing one million solar-type stars, the average angular separation between stars is 0.23 degrees (see Figure 10). A 34-meter diameter radio telescope at 1.5 GHz has a typical field-of-view (FOV) of 0.41 X 0.41 degrees, and thus, on average, its FOV encompasses several stars. It is efficient when conducting a radio "All Sky Survey" to continuously scan the celestial sphere in consecutive or adjacent strips or sectors.

The 10-meter diameter Professional 656 nm Optical SETI Telescope would have a typical FOV = 0.33 X 0.33 degrees and a 128 X 128 photodetector array FOV = 2.1" X 2.1". Since the average separation between stars is 0.23 degrees, the average number of stars in the optical array FOV is 6.4 X 10^-6. Thus, the narrow diffraction-limited field-of-view means that for most of the time the optical detector(s) would be viewing empty space. A similar situation prevails for the smaller, single detector amateur optical telescopes to be discussed later. The argument has been advanced by Dr. Bernard Oliver, in correspondence with the author and at the author's SETI Institute talk, that because an "All Sky Survey" would be out of the question at optical frequencies, this implies that ETIs would not use these frequencies.

The author's response to this is that there is nothing "holy" about the "All Sky Survey" approach. What we may wish to do is to have a Targeted Search of tens of thousands of stars, instead of a mere eight hundred as presently planned for MOP (see Page 11). However, each time we wish to scan another star in the frequency domain, we will move the telescope to an adjacent sector of the sky that contains the desired object.

While there is the possibility that ETI transmitters exist in the interstellar voids, far from their home stars, the author thinks that this scenario is unlikely (except perhaps within our own solar system, i.e., von Neumann-type probes), if for no other reason than it would place the energy-intensive transmitters far from a "cheap" and plentiful energy source.

One of the many objections made to the optical approach to SETI is that there are just too many frequencies to search. As Figure 5 illustrates, under the author's rationale, this is more a perception than a reality because of the wider signal bandwidths assumed.

```
  21-cm Water-Hole                                Channel or Bin
     |                                                  |
   ------------------------------------------------------------------
  |  *                                                  #            |
  |  *                      MICROWAVE HAYSTACK          #            |
  |  *                                                  #            |
   ------------------------------------------------------------------
  |                                  |               --> <--         |
1 GHz                              10 GHz              1 Hz      100 GHz

    Number of 1 Hz frequency channels or bins between
    1 GHz and 10 GHz = 9 Billion.


            10,600 nm                                 656 nm
               |                                         |
   ------------------------------------------------------------------
  |            *                                   #     *           |
  |            *             OPTICAL HAYSTACK      #     *           |
  |            *                                   #     *           |
   ------------------------------------------------------------------
  |                                  |          --> <--              |
10 THz                            100 THz       100 kHz        1,000 THz

    Number of 100 kHz frequency channels or bins between
    20 THz and 920 THz = 9 Billion.
```

Figure 5 -

The Microwave and Optical Cosmic Haystack frequency domains. This demonstrates that the number of frequencies to search in the microwave and optical haystacks are of similar magnitude.

Wide bandwidth means that laser linewidths, Doppler shifts, and chirps (drifts) are less significant, and the number of frequencies to search in the optical spectrum is more manageable. Just because visible frequencies are over five orders of magnitude higher than microwave frequencies does not mean that there are over 10^5 more frequencies to search in the optical frequency domain. The modulation bandwidth of proposed optical ETI signals as a percentage of the carrier frequency may be as large or larger than the percentage modulation bandwidth of proposed microwave ETI signals. In fact, assuming minimum bin bandwidths of 100 kHz, the number of frequencies to search in the entire optical spectrum may not be much greater than the number of 1 Hz frequencies between 1 and 10 GHz, i.e., nine billion! This is illustrated diagrammatically in Figure 5. This clearly has important ramifications in terms of the search time.

The reader should note that for a drifting carrier signal, i.e., one subjected to Doppler Chirp, the optimum detection bandwidth is equal to the square root of the frequency drift rate. [5,8] This assumes that the local-oscillator laser is not de-chirped. Thus, the optimum bandwidth for a monochromatic 1.5 GHz signal drifting at a local Doppler Chirp rate of 0.17 Hz/s (see Table 2, Line 30, Page 22) is about 0.4 Hz, while for a monochromatic 656 nm signal drifting at 51 kHz/s, the optimum bandwidth is 226 Hz. If the bin bandwidth is excessive, too much system noise is detected, and the CNR is degraded. On the other hand, if the bin bandwidth is too small, the response time of the filter (approximately 1/Bif) is insufficient to respond to all the energy in the signal as it sweeps by, again leading to a reduction in CNR and detectability.

It is an interesting exercise to estimate the time that would be required at visible wavelengths for both an All Sky Survey and a Targeted Search. We will assume the use of a 10-meter diameter receiving telescope, a 128 X 128 photodetector array (16,384 pixels), and initially, a single 10 GHz bandwidth Multi-Channel Spectrum Analyzer (MCSA) that sequentially samples all 16,384 photodetectors. These MCSAs could have final bin bandwidths of about 100 kHz. At this time, 10 GHz MCSAs do not exist, and the state-of-the-art for single-chip devices employed in Microwave SETI is about 10 MHz. However, it is only a question of time before these more powerful 10 GHz devices are developed.

For the purposes of this brief analysis we shall not concern ourselves with the huge amount of data storage that must be provided, or the data reduction time overhead required. Equ. 20 (Page 81) shows that the number of received beams for such a telescope is about 10^16. Since the minimum sampling time per pixel for a 10 GHz bandwidth is 100 ps, the time to sample the entire array of 16,384 instantaneous beams is 1.64 microseconds. The number of array sets of beams in the celestial sphere consisting of 10^16 beams is 6.1 X 10^11. Thus, the time just to "look" at one 10 GHz wide band of the visible spectrum, assuming that a continuous scan of the sky could be made with no dead time or overlap, is 10^6 s, i.e., 11.6 days! This is a substantial amount of time for a single band just 10 GHz wide.

Since there are 42,857 bands of 10 GHz bandwidth between 350 nm and 700 nm, the time required to search the entire sky and all visible frequencies, is at a minimum, 1,360 years! Even if we had 128 parallel MCSAs (don't even consider having 16,384 - 10 GHz MCSAs!), the time to search even a 10 GHz band is long, notwithstanding the "slight" data storage problem. Clearly, we can forget about this form of optical All Sky Survey, since it is a grossly inefficient way of scanning or pixelizing the sky. Almost all the data bins will be empty bins, having been derived from beams pointing to empty (near) space. The situation for an Optical All Sky Survey is actually much worse than just implied, due to the additional time that each pixel must be sampled to ensure a high probability of detecting the fewer, but more energetic optical photons - more about this in a moment.

On the other hand, if we only consider a Targeted Search, the time required is much shorter and allows for the search to be done across the entire optical spectrum, not just at selected laser frequencies or Fraunhofer lines. As we have just seen, if the photon arrival rate is sufficiently high, the time with a single 10 GHz MCSA for a single scan of the entire array is 1.64 microseconds. To scan for one star over the entire 350 nm to 700 nm band would take 0.070 seconds (assuming suitable L.O. lasers). This is a trivial amount of time, and the amount of data that has to be collected and stored is relatively insignificant. Indeed, it is the time to do the FFTs and move the telescope to a new position that will be the most significant overheads here.

The above times are highly optimistic because the basic flux sensitivity of any kind of receiver, be it microwave or optical, depends on the sampling or integration time. Hence, before we can estimate the realistic length of time for a given search, we must decide what are the minimum detectable flux levels that we wish to detect. This, in turn, will determine the minimum sampling time for each pixel. Usually, SETI minimum detectable flux estimates are based on integrating a very weak signal for a period of time, and not for providing sufficient SNR to allow actual demodulation. We must also decide if we want to model a system based on short pulses or on continuous wave (C.W.) signals.

Of course, it is extremely unlikely that the signal flux would be sufficiently high to allow for a high probability of detecting the photons in a sampling bandwidth of 10 GHz. In reality, our minimum MCSA bin bandwidths would be about 100 kHz, and the sampling (integration) time is at least a factor of 10^5 longer. For the purposes of this further analysis, we shall assume a C.W. signal and a 100 kHz minimum bin bandwidth, so that the pixel sampling time is now 10 us. For our 10-meter diameter 656 nm symmetrical heterodyning telescope system, we can estimate the minimum detectable signal flux density by calculating the flux required to reduce the CNR to 0 dB.

We have already shown (Table 2, Line 12, Page 22), that a flux intensity of 2.04 X 10-^17 W/m^2 will produce a CNR = 34 dB re 1 Hz. Therefore, in a 100 kHz bandwidth, the CNR will be -16 dB. To increase the CNR to 0 dB means that the intensity must be increased by 16 dB to 8.12 X 10^-16 W/m^2. Thus, the minimum detectable signal flux for this bandwidth and sampling rate is 8.1 X 10^-16 W/m^2. This is equivalent to saying that during the 10 microsecond sampling time, if an ETI signal is present on one pixel, we would have a reasonable probability of detecting one photon (Equ. 36). This signal flux would be produced by a ten meter diameter transmitter at a range of ten light years, with a power of 16 dB re 1 kW, i.e., 40 kW. This is a trivial amount of power for an ETI.

On the basis that the author thinks that ETI transmitter powers will be in excess of 100 MW and perhaps even substantially in excess of 1 GW, we could decide to lower the detection sensitivity and go for a faster sampling rate, thus speeding up the search. For the purposes of this analysis we will stick to the 100 kHz pixel sampling rate. As previously stated, we will assume that we are doing our single star signal processing in real time, with 100 kHz minimum bin bandwidths. This means that the entire array would take 0.164 s to scan. If we assume no scan dead time, then to scan the entire visible band between 350 nm and 700 nm at a sensitivity level of about -150 dBW/m^2 (10^-15 W/m^2), would take about two hours (Equ. 21, Page 82). An All Sky Survey of this type would take at least 136 million years! If a survey of this type could have been started when the dinosaurs roamed Earth, we would be just about reaching the end of the first scan! (Don't anyone accuse the author of lacking a sense of humor).

On the other hand, for a sensitivity of -150 dBW/m^2, a Targeted Search scan of a single star over the 280 GHz effective bandwidth of the 656 nm Fraunhofer line (Table 4, Page 30) with a 10 GHz MCSA, with on-line data storage, and a 10 microsecond pixel sampling time, would take 4.6 seconds. This is a very reasonable time, so that a slower scan at selected laser and Fraunhofer lines could be performed to reduce the minimum detectable flux levels.

PROFESSIONAL CO2 SETI

Just as this paper was being completed, the author received a copy of Albert Betz's (University of California, Space Sciences Laboratory, Berkeley, CA 94720) latest paper on Optical CO2 SETI. [57] For the sake of completeness, because there is currently so little Optical SETI literature available, and because Betz's paper is a very up-to-date account of the only observational Optical SETI work presently being done in the United States, a short description is now given. The work of Townes and Betz is supported by a NASA grant NAGW-681. As mentioned on Page 5, this low-profile SETI work is being done on Mount Wilson, and is piggy-backed onto a much larger NASA program to investigate astrophysical phenomena at the galactic center, e.g., a possible black hole.

To start with, here now is a complete quote of the abstract from Dr. Betz's paper, which was presented in August of 1991 at the Santa Cruz, California USA-USSR SETI Meeting:

"In an effort complementary to NASA's search for microwave signals from an extraterrestrial intelligence, we are searching for possible laser signals of a similar origin. We are surveying approximately 300 nearby stars in a multi-year effort to detect narrowband laser signals in the 10 um wavelength region. For this directed search, we are using an available 1.7 m telescope and a heterodyne receiver tuned to discrete CO2 laser frequencies between 26-30 THz. The bandwidth of the heterodyne allows us to analyze a Doppler velocity range up to

+/-60 km/s around selected laser lines, and thus accommodate the velocity dispersions of hypothesized laser sources orbiting nearby stars. The resolution of the spectrometer is currently 2.4 MHz (24 m/s), with 10^3 spectral channels available. Although this resolution is somewhat coarse, any indication of a signal could be subsequently analyzed at much higher resolution with the type of signal processor (MCSA) now being developed for the microwave survey."

Betz uses a slightly different transmission throughput relationship to that employed by this author (Pages 77-78). For his parameters: Pt = 1 kW, D = 10 m, R = 10 L.Y. (9.461 X 10^16 m), and Wl = 10.6 um (see Appendix A for parameter definitions):

$$Pr = 9.9 \times 10^{-18} W$$

This figure for received power is about 2.1 dB greater than given in Table 2, Line 13 on Page 22 (6.1 X 10^-18 W). The reason for the slight discrepancy is that Betz uses an approximation by omitting a PI^2/16 factor (see Equs. 13 and 14 on Pages 77 & 78 for more details).

Earlier it was stated that the minimum beam divergence thought possible by Townes and others was about one second of arc. However, this recent paper by Betz indicates a new, more optimistic limitation of about 0.1 second of arc. This is only a factor of 7.25 greater than the 0.0138" diffraction limited beamwidth for the visible system (as shown in Table 2, Line 5 on Page 22, and on Page 73). By assuming that the nearest stars to be targeted are around 50 parsecs (163 L.Y.) away, a beam divergence of 0.1 arcsecond is compatible with the expected zones of life. Because of this increase in beam directivity, Betz gets an infrared SNR improvement over the 300-meter diameter Arecibo system of about 3 dB (a factor of 2). Figure 4 on Page 28 shows that the microwave system has a CNR of 20 dB, while the infrared system has a CNR of 22 dB; a 2 dB difference in favor of the infrared system. Thus, taking into account the slightly different assumptions made in this analysis, i.e., the transmission relationship, the microwave front-end temperature and quantum efficiency, the theoretical results for the CO2 system in this paper are in very close agreement with that of Betz's paper.

The Townes and Betz CO2 telescope is computer driven, with the ability to point blind to approximately one arcsecond, both during the day and night. As indicated on Page 23, CO2 SETI is just as effective during the day as at night, since, whatever the limitations of the sky background, it is essentially constant over the 24 hour day.

The reader should note that the 128 X 128 pixel array specified for the Professional Visible SETI system has a field of view of about 2.1 X 2.1 arcsec (Figure 10, Page 81), and thus is semi-compatible with the pointing accuracy of Betz's system. Note that a medium size visible wavelength telescope with a single incoherent photodetector system, may have to be steered and pointed during daylight hours with point blind accuracy better than 1 arcsec. If the pixel size and FOV are increased to accommodate steering inaccuracies and atmospheric turbulence, the daylight background would increase and degrade the SNR.

INCOHERENT OPTICAL SETI AT 10,600 nm

In a later section, we will describe an incoherent Optical SETI receiver for visible and near-infrared wavelengths, with Amateur Optical SETI application. For the sake of completeness, Figure 6 has been included here to demonstrate the relatively poor response of a small incoherent (photon-counting) CO2 receiving system. This should be compared to Figure 8 (Page 44), given for the case of incoherent Optical SETI at visible wavelengths. Identical signal flux levels and telescope apertures have been employed in both graphs. These graphs have been located at the top of their respective pages to allow the pages to be flicked back and forth for easier comparison.

In the incoherent CO2 system, where the signal-to-noise ratio (SNR) is quantum noise limited, the SNR it is greater than in the visible spectrum because "hf" is smaller. However, where the SNR is background noise limited, the SNR is severely degraded. For a high signal intensity of 10^-14 W/m^2, as produced by a transmitter at a distance of ten light years with an EIRP of about 10^21 W, the SNR for a 30 cm-diameter CO2 receiving telescope begins to degrade for optical bandwidths greater than about 1 MHz.

The infrared telescope's photodetector must be subject to considerable cooling, e.g., using liquid nitrogen, to avoid high dark-current, and it must be provided with a cold-shield to restrict its field-of-view (FOV) to background thermal radiation. Note that the performance of an amateur CO2 system could well be much worse than shown in Figure 6, because CO2 transmitter gains and EIRPs are likely to be much less than available at visible wavelengths. Unfortunately, high-Q optical filters centered on the CO2 wavelength are not available with wide tuning characteristics, although a small degree of tuning may be obtainable by tilting the filters. Fixed optical filters with 100 GHz bandwidths at 10,600 nm are available for several hundred dollars. The cost of a extremely high-Q 10 GHz (0.035 percent bandwidth) interference filter may run into several thousand dollars. Even then, the thermal background detected is excessive, and the filter itself must be cooled.

As has been pointed out repeatedly and demonstrated by Equ. 32 (Page 88), the optical heterodyne receiver has the great advantage over its direct detection counterpart (Equ. 31), in that the effective optical bandwidth through which background radiation is received is determined by the small electrical I.F. bandwidth. Also, because of the excessive dark-current characteristics of 10,600 nm photodetectors, there is considerable merit in using a local-oscillator laser to swamp out these noise sources, though coherent detection would not necessarily obviate the necessity to employ some cryogenic cooling. Thus, there is much truth in the observation that as far as ground-based CO2 SETI receivers are concerned, only coherent receivers are practical, such as the interferometer system presently being employed by Townes and Betz on Mount Wilson, and described on the previous two pages. [57]

```
Postdetection Normalized SNR, dB re 1 Hz
   |
   |
  80 | Ir = 10^-10 W/m^2             EIRP = 1.1 X 10^25 W
     |* * * * * * * * * * * * * * * * * * * * * * * * * *
     |                                                       *
  60 | Ir = 10^-12 W/m^2             EIRP = 1.1 X 10^23 W         *
     |* * * * * * * * * * * * * * * * * * * *
     |                                           *
  40 | Ir = 10^-14 W/m^2             EIRP = 1.1 X 10^21 W
     |* * * * * * * * * * * * * * *                     *
     |                                *                     *
  20 | Ir = 10^-16 W/m^2                  *                     *
     |* * * * * * * * * * *                  *
     |                        *                  *
   0 |.Ir = 10^-18 W/m^2.........*...................*..............
     |* * * * * *                   *                   *
     |               *                  *                   *
 -20 | Ir = 10^-20 W/m^2 *                 *                    *
     |*                     *                 *
     |     *                   *                 *
 -40 |         *                  *                 *
     |            *                  *                 *
     |               *                  *                 *
 -60 |                  *                  *                 *
     |                     *                  *                 *
     |                        *                  *
 -80 |        Day & Night        *                  *
     |                              *                  *
     |                                 *                  *
-100  --------------------------------------------------------------
   10^0      10^2      10^4      10^6      10^8      10^10  ^  10^12
                                                            |
                         Optical Bandwidth, Hz              |
                                                   100 GHz (37.5 nm)
```

Figure 6 -

Signal-to-noise ratio versus optical bandwidth for (perfect) photon-counting CO2 receivers. Range = 10 light years, wavelength = 10,600 nm, diameter = 30 cm, antenna efficiency = 0.7, spectrometer efficiency = 0.5, quantum efficiency = 0.5. Dark current is assumed to be negligible, though in practice it will impact the above sensitivity curves at lower flux levels, even more than the sky background.

Needless to say, the construction cost of a heterodyning CO2 SETI telescope/receiver is likely to be excessive for the amateur enthusiast. For this reason, CO2 SETI is not being proposed for the amateur. This activity is best left to NASA and the professional observer.

ADAPTIVE TELESCOPE TECHNOLOGY

Perhaps one of the most exciting developments in modern optical astronomy is the subject of adaptive telescope technology. The author believes that this not only has profound implications for conventional optical astronomy but also for Optical SETI. In particular, for what we call Symbiotic Optical SETI. What follows is a description of the technique obtained from the tutorial introduction to reference 69.

"Earth-based telescopic adaptive-optics systems need a reference (guide) star which is near objects of interest and bright enough to provide information on the wavefront distortion. But natural guide stars for a usable portion of the visible spectrum are few and far between, allowing glimpses of just 0.003 percent of the night sky. Rather than cursing the darkness, astronomers and engineers are lighting some celestial candles of their own.

To create the artificial guide stars, a laser is beamed into the sky, which answers back inflamed. The laser energy creates Rayleigh backscattering in the stratosphere (10 - 40 km up) and resonance-fluorescence backscattering in the mesospheric sodium layer (80 - 100 km). No radically new technology is required for the lasers, although the breadth of capabilities is large for a single laser. For zenith viewing of a 20-cm atmospheric patch using the Rayleigh approach, the laser must put out 82 watts; for the sodium-backscattering approach the required exciting power is 14 watts. At the sodium layer, which results from meteor ablation, the beam must be 0.5 meter in diameter, with a pulse rate of 100-200 pps and 100 millijoules per pulse.

The laser guide-star concept was first put into practice by Chester Gardner and Laird Thompson, who in 1987 created, photographed, and measured their own glowing beacon, shot like some giant flare above the Mauna Kea Observatory in Hawaii. [69]

The basic system requirement is that the distortion of the guide star must be measured and the adaptive mirror adjusted in the time it takes for a star to twinkle, or, depending on how you look at it, the time between twinkles. This window of visibility known as twinkle time (also called scintillation coherence time) is open for a scant 10 milliseconds."

The requirements to produce a diffraction limited image over the entire focal image plane are rigorous. It could be that the criteria for Optical SETI are rather less demanding. The requirement here is for imaging the ETI signal onto a two-dimensional photodetector array, where the primary purpose (neglecting Planckian suppression needs) of the array is to detect ETI photons, not to produce a super high-quality extended image. As described on Pages 10 and 83, it is shown how efficient detection of an ETI signal might be obtained with a simple passive technique, if ETIs cooperate by transmitting a signal accompanied by a pilot-tone beacon. Such a technique automatically makes any telescope adaptive, without the need for deformable mirrors and laser guide stars.

THE COLUMBUS TELESCOPE PROJECT

As this paper was nearing completion, the author learned that a decision had been made to terminate Ohio State University's participation in The Columbus Project, the construction of a twin 8-meter diameter interferometric telescope to be built on Mount Graham in southeastern Arizona. The instrument, which is supposed to see "first light" in 1994, will have the light gathering power of a single 11.3-meter (448-inch) mirror and the resolving power of a 22-meter (866-inch) telescope.

The project was a joint venture between OSU, the University of Arizona, and Italy's Arcetri Astrophysical Observatory. The reason given for OSU's pulling out of the project was a lack of privately donated funds. Within these pages, this author has suggested the possibility of a future symbiotic relationship between Professional Optical Astronomy and Professional Optical SETI. During the early part of this study, an idea was formulated that plans for The Columbus Telescope might be changed, so that both scientific activities could be undertaken at that site; Professional Optical Astronomy being done at night, and Professional Coherent Optical SETI mainly during the day.

On Columbus Day, October 12, the Microwave Observing Project will commence its search of the sky. As we in Columbus, Ohio, approach the quincentennial of Columbus' discovery of the Americas, what more fitting way could there be to celebrate the first encounter with the New World than if OSU's participation in The Columbus Project was resumed and the telescope's purpose modified to include the search for extraterrestrial intelligence. The New World would be looking for other, perhaps older worlds, with more mature technical civilizations.

OSU is already home to the "Big Ear" Radio Observatory, which under the guidance of Professor John D. Kraus (Director) and Dr. Robert Dixon (Assistant Director), has been undertaking conventional microwave SETI for many years. On the same site in Delaware (a little north of Columbus), and close to "Big Ear", is the Perkins Optical Observatory. At the moment, the author is working on ideas to upgrade the Perkins Observatory for Semi-Professional Incoherent Optical SETI. This observatory presently contains a 81-cm (32-inch) Cassegrain.

OPTICAL SETI RATIONALE

SETI would not seem so mysterious to the average person if it was recognized that this is yet another communications problem, albeit complicated by the fact that we do not know where or when to look, the transmission frequency, the bandwidth, or the modulation format. In many ways it is just another aspect to our manned and unmanned space program, but one that has received relatively little funding. It took many years before SETI was recognized as a legitimate science and not pseudoscience. The technology described here for Optical SETI is more than just a means of contacting emerging technical civilizations. If intelligent life is not uncommon in the galaxy, and if electromagnetic waves are still the primary means of interstellar communications, the ability of optical relays to form a galactic network might obviate the necessity to use low-loss microwaves or the far-infrared in order to propagate across the entire galaxy in one go. After all, it is very difficult to have a snappy conversation when communicating over one hundred thousand light years!

Earlier, we showed that our "perfect" 10-meter diameter symmetrical 656 nm heterodyning system was capable of yielding over a range of 10 light years, a CNR of about 34 dB re 1 kW re 1 Hz, for a diffraction limited EIRP of 2.3 X 10^18 W (see Table 2 and Figure 4). Since a solar-type star has an EIRP of 3.9 X 10^26 W, we pose the question: What is the communication capability of such a communications link when the mean EIRP of a large transmitter array is 2.5 times that of the star, i.e., when the mean EIRP is about 10^27 W? This condition corresponds to the transmitter appearing as a 1st magnitude object; a situation which would produce a noticeable (2.5 times) brightening of the ETI's star. Since the ratio of EIRPs {10^27/(2.3 X 10^18)} is 4.4 X 10^8, the CNR will be improved by 86 dB, resulting in a CNR of about 120 dB re 1 Hz, and a photon detection rate of about 10^12 s^-1 (Equ. 36). If the bandwidth is increased to 10 GHz, the CNR falls to about 20 dB. Thus, this just naked-eye noticeable transmitter would be just about capable of sending a 10 Gbit/s data stream across 10 light years with low bit-error-rate {BER} (Equ. 37). This would allow a hypothetical Encyclopedia Galactica to be uploaded or downloaded rather efficiently!

This might give new meaning to Arthur C. Clarke's "Extra-Terrestrial Relays", which in the October, 1945 issue of WIRELESS WORLD described the basic idea for the present terrene geostationary (the Clarke Belt) satellite system. [67] Clarke had originally given his article the title "The Future of World Communications". Perhaps this paper should be titled "The Future of Interstellar Communications"?

In many ways, Arthur C. Clarke and "Extra-Terrestrial Relays" has done more to shape what we now call the "Global Village" than any other single factor on our planet. Indeed, the spreading of the ideas of democracy, and freedom, and the breakup of the Soviet Empire have more to do with former Soviet President Mikhail Gorbachev, Russian President Boris Yeltsin, and author Clarke than any other factor. The latter is perhaps the unsung hero here. The failure of the August 1991 Soviet Coup was facilitated by the ease with which it is now possible to communicate. Those readers who own TVROs (TeleVision Receive Only) satellite receivers will especially appreciate the power of this technology. We can be sure that the reception, demodulation, and decoding of the first ETI signal - be it microwave, millimeter-wave, or optical - will have an immense effect upon our civilization. Just the act of detecting a carrier signal will forever change our view of the Universe and humanity.

The following section deals with the amateur approach to Optical SETI, showing how an amateur observatory can be constructed. This is based on the more controversial assumption that optical ETI signals may be present in the visible spectrum, and of sufficient intensity, to yield detectable signals with relatively small receiving telescopes.

AMATEUR OPTICAL SETI

Working on the assumption that highly advanced ETI technology could appear to late Twentieth Century humanity like "magic", it is imagined that ETIs will be using much larger transmitting telescopes or arrays and transmitter powers far greater than 1 kW. [56] In practice, the signal is likely to be pulsed, and, depending on the duty cycle, even less detectable by normal integrating detectors, i.e., the unaided eye, photographic plates, or standard CCDs. Optical SETI is a branch of science to which the enthusiastic amateur astronomer may be able to make a useful contribution. In so doing, this may increase public and scientific interest in all forms of SETI so that this field of scientific endeavor will at last get the financial support and effort it richly deserves.

```
                         Optional                     I
                        Intensifier         ----------<---------
              --          ------           |
 Signal Pr   |  |        |      |          |
-----------> |  | -----> |      | -----> -----   PIN Photodetector,
-----------> |  | -----> |      | -----> /   \ APD or Photomultiplier
-----------> |  | -----> |      | -----> -----
 Background  |  |        |      |          |        -----
     Pb       --          ------           |       |     |
         Narrow-Band                        --->---|     |----->
   Optical Bandpass Filter                         |     |
    (or Monochromator) Bo                           -----
                                         Low-Pass Electrical Filter
                                                      Be
```

Figure 7 -

Incoherent (direct) detection optical receiver. The image or photon intensifier is only required if a zero-gain PIN photodetector is employed. The narrow-band optical filter (Bo < 0.1 nm) is ideally a tunable device like a scanning grating monochromator. The photodetector current I is proportional to the received signal Pr.

Figure 7 is a basic schematic of an incoherent photon-counting receiver for an Amateur Optical SETI Observatory. The high cost and technical difficulties of optical heterodyne detection in the visible and near-infrared spectrum means that the amateur's receiver will most likely have to use photon-counting, a little cooling, and a monochromator. Unlike coherent receivers, incoherent receivers do not have the ability to reject Planckian starlight and daylight background noise if the signal is weak.

Figure 8 results use slightly more conservative assumptions than employed to derive Table 2 (Equ. 15, Page 78). It is assumed that the amateur telescope has a diameter of thirty centimeters (twelve inches), uses a low-resolution scanning grating monochromator bandwidth of 100 GHz (0.143 nm) at 656 nm, and employs a receiver consisting of a single perfect photon-counter. For a received flux density of 10^-12 W/m^2, the SNR is about 39 dB re 1 Hz (Equ. 31, Page 87). In the region of the graph where the SNR is reduced due to Planckian starlight, daylight background further reduces the SNR by a few dB.

In the Microwave Cosmic Haystack, the flux densities of interest lie in the range of 10^-27 to 10^-20 W/m^2. It is suggested that the corresponding flux levels in the Optical Cosmic Haystack would be in the range of 10^-20 to 10^-10 W/m^2. As indicated in Figure 8, an EIRP = 10^23 W at a range of ten light years produces a received signal intensity Ir = 10^-12 W/m^2, with an apparent visual magnitude of eleven. This would not be visible to the unaided eye even if it was not completely outshone by the second magnitude star.

This 39 dB Signal-To-Noise Ratio represents an SNR penalty compared to the performance of a 10-meter heterodyning array receiving telescope of about 34 dB. This 34 dB SNR penalty figure should not be confused with the 34 dB CNR that was established in Table 2 (Page 22) for a 1 kW transmitter. Starlight and daylight sky backgrounds only slightly affect the SNR for this range, intensity, and optical bandwidth. The effect of the 10 to 20 dB Fraunhofer Planckian suppression factor has not been included in the graph of Figure 8; allowance for which would improve the night sky performance for weaker signals and/or larger optical bandwidths.

If a powerful ETI signal is detected, given an adequate SNR, it might even be possible for an amateur observer to demodulate a signal of moderate bandwidth, not just detect the presence of an excess number of photons arriving in a given time! A photodetector bandwidth of about 1 MHz would probably be desirable, and well as a spectrum analyzer covering a similar frequency range.

As can be seen from Figure 8, the SNR is degraded by Planckian starlight at low signal intensities and larger optical bandwidths. In this regime, if the signal flux drops by 20 dB, the SNR falls by 40 dB because the receiver is no longer signal quantum noise limited. Clearly, if ETIs want their signals to be detected by relatively small incoherent receivers, it pays to use pulses with low duty-cycle in preference to C.W. signals. High peak EIRPs can override all external and internal noise sources and thus make their signals as detectable as possible for a given mean EIRP.

In Table 2 we showed that the 1 kW signal at a range of ten light years produces a received intensity of 2.04 X 10^-17 W/m^2. If this was received by a one-meter diameter incoherent adaptive ground-based telescope, the normalized SNR in a 100 GHz (0.143 nm) optical bandwidth (not allowing for Planckian dark line continuum suppression) would be about -42 dB re 1 Hz. In this situation it would indeed help to operate the transmitter within a Fraunhofer line. The SNR would be increased to -32 dB re 1 Hz for a 10 dB Fraunhofer line contrast factor. Either way, the presence of the signal would not be detectable without considerable integration. However, if the ETI transmitter mean power was increased to 1 GW, leading to a received intensity of 2.04 X 10^-11 W/m^2, the SNR would increase dramatically to about

```
Postdetection Normalized SNR, dB re 1 Hz
   |
   |
  80 |
     |
     | Ir = 10^-10 W/m^2      EIRP = 1.1 X 10^25 W (6th Magnitude)
  60 |* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
     |
     | Ir = 10^-12 W/m^2      EIRP = 1.1 X 10^23 W (11th Magnitude)
  40 |* * * * * * * * * * * * * * * * * * * * * * * * * * * *
     |                                                           *
     | Ir = 10^-14 W/m^2      EIRP = 1.1 X 10^21 W (16th Magnitude)
  20 |* * * * * * * * * * * * * * * * * * * * * *
     |                                               *
     | Ir = 10^-16 W/m^2                                  *
   0 |.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*....................*.....
     |                                       *                    *
     | Ir = 10^-18 W/m^2                         *
 -20 |* * * * * * * * * * * * *                      *
     |                            *                      *
     | Ir = 10^-20 W/m^2              *                      *
 -40 |* * * * * * *                       *                      *
     |                *                       *
     |                    *                       *
 -60 |                        *                       *
     |                            *                       *
     |                                *                       *
 -80 |         Night Sky                  *                       *
     |                                        *
     |                                            *
-100  --------------------------------------------------------------
   10^0      10^2      10^4      10^6      10^8      10^10  ^  10^12
                                                            |
                         Optical Bandwidth, Hz              |
                                                 100 GHz (0.143 nm)
```

Figure 8 -

Signal-to-noise ratio versus optical bandwidth for (perfect) Photon-counting 656 nm receivers. Range = 10 light years, diameter = 30 cm, antenna efficiency = 0.7, spectrometer efficiency = 0.5, quantum efficiency = 0.5, excess avalanche gain noise factor = 0, dark current = 0. EIRP of a solar-type star = 3.9 X 10^26 W. A diffraction limited 10-meter diameter 1 GW transmitter produces an EIRP = 2.3 X 10^24 W, and appears to be 0.6 percent of the brightness of a second magnitude solar-type star.

63 dB re 1 Hz; essentially independent of Planckian background. This signal would stick out like a proverbial sore thumb. In the case of Professional Heterodyning Optical SETI, we were dealing with stronger detected signals and a local-oscillator produced shot noise floor. Because we are dealing here with smaller, incoherent receivers that use an avalanche photodetector, the precise analysis for the CNR or BER is

extremely complex when the received signal power is very small and/or larger post-detection bandwidths are employed. The reader is cautioned, that the above results may be somewhat optimistic.

Figure 8 forces us to consider whether such easily detectable signals could have been missed by professional optical astronomers? Perhaps, because there are so many stars and frequencies to search, and with the limitations of conventional spectrographic equipment, we can hope that these signals have been missed or overlooked. Again, if the signals have low duty-cycle, the mean signal powers detected by integrating detectors would be considerably less.

Scanning grating monochromators/spectrometers are available with ten times the resolution previously quoted, i.e., 10 GHz (0.0143 nm) optical bandwidths. High-Q Fabry-Perot spectrometers with bandwidths as small as 1 MHz are perhaps less useful here because of their free-spectral range and multiple response characteristics, requiring additional broadband filtering. However, the tandem combination of a scanning grating monochromator and a Fabry-Perot would form a very powerful optical filtering and spectral analysis system, comparable in many respects to what could be achieved with a heterodyne system.

For the thirty-centimeter diameter telescope system, ETI signal detectability will not be substantially degraded for peak signal strengths higher than about 10^-14 W/m^2 (sixteenth magnitude) if the spectral resolution < 0.01 nm. If the EIRP was about 10^25 W, the received signal flux would be at the threshold of unaided eye visibility of about 10^-10 W/m^2, and yield an SNR of 60 dB re 1 Hz. This would give an SNR = 30 dB in a 1 kHz post-detection bandwidth, or a just detectable 0 dB in a 1 MHz bandwidth.

It would appear that as long as we can construct efficient photon-counting receivers, that the sensitivity of small incoherent receiving telescopes will not be unduly affected by the relatively large optical bandwidths of such receivers, though their sensitivity will be degraded if operated in daylight.

There was no particular reason in choosing the 656.2808 nm (457.1214 THz) H_alpha line for the purposes of modelling the visible system. While it could be considered a "magic wavelength", it does not coincide with a known laser transition. It has an effective bandwidth of about 280 GHz, though its half-power bandwidth is somewhat smaller (Table 4, Page 30). A less expensive way of undertaking Amateur Optical SETI observations at this single wavelength, instead of using the more flexible scanning grating monochromator, would be to employ a standard narrow-band H_alpha solar filter. To further reduce costs, a photomultiplier could be used in place of the state-of-the-art cooled avalanche (geiger-mode) photodetector.

It may be possible for amateur astronomy groups to "steal a march" on NASA as far as the low-sensitivity search for ETI in the visible and near-infrared spectrum is concerned. For Amateur Optical SETI to be a sensible pursuit for the astronomical and space enthusiast requires the belief that ETI technology would appear to emerging technical civilizations comparable to ourselves to be like "magic". The demands placed on assumed ETI technical prowess are even greater than when considering the practicality of Professional Optical SETI. The onus would be on ETIs to make their signals easily detectable.

Since peak EIRPs > 10^23 W are thought possible, which lead to peak intensities at a range of ten light years greater than 10^-12 W/m^2 (eleventh magnitude), the detectability of such signals with amateur equipment is imaginable. Telescopes with apertures greater than about one meter diameter are only slightly affected by daylight when observing nearby stars, indicating that Daylight Professional/Semi-Professional Optical SETI may be feasible for larger telescopes with incoherent receivers. It should be realized that even during the day, the sky is essentially black when viewed with artificial narrow bandwidth eyes!

It is not yet clear whether the 81-cm (32-inch) Perkins Telescope in Delaware, could be upgraded with a precision-drive system that would allow for satisfactory image-tracking during the night and day. Image-tracking difficulties at night might be mitigated by using a photon-counting array or image intensifier (or microchannel plate) instead of a single photodetector. There are also some concerns, regarding the effects on conventional astronomical nighttime observations, of thermal currents caused by the observatory dome being open during the day.

Because optical bandwidths of these incoherent Amateur Optical SETI receivers will be much wider than the effective optical bandwidths in coherent Professional Optical SETI receivers, there is no concern for anticipating or removing local line-of-sight Doppler chirps (drifts). These chirps can be as high as 50 kHz/s (Table 2 and Equ. 40). Such drifts are insignificant for optical bandwidths of the order of 100 GHz in any reasonable amount of observation (dwell) time. Allowance should be made for Doppler shifts of the ETI transmitter and Fraunhofer lines when making a detailed search of specific frequencies, since these shifts can be comparable to the width of a Fraunhofer line (Table 2 and Equ. 39). For specific laser frequencies not coinciding with Fraunhofer lines, this requires knowledge of our line-of-sight velocity relative to the star being observed. However, for transmissions and observations within Fraunhofer lines, the receiver could simply be tuned for minimum Planckian starlight noise. As before, it is assumed that ETIs will remove their local line-of-sight transmitter Doppler shift (and chirp) with respect to their star.

It should be noted for the record that thermoelectrically-cooled CCD (Charged Coupled Device) cameras are now available to the amateur which allow the sixteenth magnitude to be reached in under one minute of integration, with negligible threshold effects. Even the fastest photographic film has such low quantum efficiency that only a few percent of the photons are converted to exposed film grains. The dark current count for the photon-counter should ideally be kept below about five hundred counts per second if the SNR of a potential ETI signal is not to be excessively degraded. It may be reasonable to suggest that eliciting the help of thousands of enthusiastic amateur optical astronomers might considerably aid the low-sensitivity Targeted Search of the entire Northern and Southern Hemisphere skies.

HOW TO BUILD YOUR OWN AMATEUR OPTICAL SETI OBSERVATORY

How easy and cheap will it be for amateur astronomy organizations to combine the efforts and resources of their members to participate in this activity? The answer to this is that there is no hard figure. It depends very much on how sophisticated and sensitive one is prepared to be. There will always be tradeoffs between sensitivity and cost. Figure 9 shows a basic Amateur Optical SETI system based on the use of twenty-centimeter (eight-inch) or larger telescopes. While smaller telescopes (reflectors or refractors) may be used, the potential detectability of ETI signals will be degraded.

However much the reader may be excited by the statements made herein, the reality of the situation is that SETI, be it conducted in the microwave or optical spectrums, can become a rather monotonous endeavor. It is an activity well-suited for automation. Hence, the system to be described makes extensive use of computer-driven hardware. The same computer can be used to analyze the spectral (optical and electrical) data obtained with various signal processing algorithms to see if there is a weak ETI signal hidden within the noise.

Particularly for an optical receiver with a wide tuning range, i.e., one that uses a grating monochromator, the mass of the additional equipment required to be attached would be excessive for a small telescope. Hence, the preferred way to couple the SETI receiver to the telescope would be via several meters of a single strand of low-loss multimode optical fiber. The output face of the fiber-optic umbilical replaces the slit normally found in a monochromator/ spectrograph. This approach is additionally useful if cryogenic cooling techniques have to be employed at the optical front-end.

The optical fiber is positioned to be centrally placed in the focal plane and the fiber input arranged by suitable imaging, i.e., SELFOC lens (GRIN rod), to match to the telescope's diffraction limited spot size (Airy disk). In practice, if daylight SETI is not attempted, the optical fiber's aperture and FOV may be increased to accommodate image wander caused by typical atmospheric turbulence conditions. The diagram shows a beamsplitter sharing the image with the CCD, though the CCD might make use of off-axis guiding to avoid light loss, i.e., for locking onto a guide star. The graded-index lens also serves to convert the focal ratio of the telescope to one that matches the fiber for maximum throughput, this operation being equivalent to matching numerical apertures. Some mode scrambling may be required to ensure that the output numerical aperture (N.A.) of the fiber is fully illuminated at all times, whatever the light launching conditions. This ensures that amplitude fluctuations do not occur in the slitless monochromator or spectrometer as the image of the star and transmitter dances around the entrance (input end) of the fiber.

Multimode optical fiber essentially depolarizes light, so that any polarization analysis equipment must be situated at the input, focal plane end of the fiber. There will be an inherent throughput loss of about 50 percent in the monochromator because high resolution diffraction gratings have a tendency to polarize light.

```
 --------------------   Beamsplitter/Off-Axis Guiding CCD Imaging/
|      8" - 14"      |-- _  Tracking Camera-------------->-------------
|                    |  |_|->-                                         |
| Schmidt-Cassegrain |--      | Optional Polarizing Optics & Multimode |
 --------------------         | Fiber-Optic Umbilical in Focal Plane   |
              |  |            |                                        |
              |  |            |    -----------------     -----         |
           ---------          |   |    Scanning     | | APD |        |
          |  Drive  |<>-       ->>|    Grating      |->-| or  |->-     |
           ---------    |         |  Monochromator  |   | PM  |   |    |
                        |          -----------------     -----    |    |
                        |                 ^                       |    |
                        |                 |                    -----   |
                        |                 |                   | Amp |  |
                        |                 |                   |     |  |
                        |                 |                    -----   |
                        |                 |                       |    |
   -----------          |                 |    -------------      |    |
  |           |         |                 |   |   Optional  |     |    |
  |    VDT    |         |                 |   |   Spectrum  |<----|    |
  |           |         |                 |   |   Analyzer  |     |    |
   -----------          |                 |    -------------      |    |
      |   |             | RS-232/IEEE-488 |                       |    |
  ------------- <>------------<>----------    Baseband Signal     |    |
 |     PC      |<-------------<----------------------<------------|    |
  ------------- <-----                            -------          |    |
    Optional          | CCD Video                | Low   |        |    |
  FFT Spectrum        |                Audio <---| Pass  |<-------|    |
  Analyzer Card       |                          | Filter|        |    |
                      |                           -------          |    |
                      |          -----------                       |    |
                      |         |   Video   |<--------------------     |
                      |         |  Monitor  |<-------------------------|
                      |         |   Or TV   | CCD Video                |
                      |          -----------                           |
                      |                                                |
                       ------------------------------------------------
```

Figure 9 -

Basic Amateur Optical SETI or Poor Man's Optical SETI. Only a single photodetector is used, which can be either an avalanche photodiode (APD) or a photomultiplier (PM). The optical filter can be a computer-controlled scanning monochromator or a relatively inexpensive fixed interference filter. Additional focal-plane optical fibers and photo-detectors may be employed for maintaining star-lock. An electronic mixer and filter may be included between the photon-counting receiver and the display/audio devices to beat down the detected spectrum to lower frequencies. This electrical local-oscillator would likely be driven by the PC. The TV (video) monitor can be used both to display the star field via the CCD imaging/tracking camera and the detected signal, or these could be displayed on the PC. Later, several telescopes could be slaved together to increase light gathering power, sensitivity, and SNR of a would-be ETI signal.

The output of the fiber is expanded and collimated in the usual way. However, if a single photodetector is employed, as indicated in Figure 9, some form of cylindrical output lens will be required to match the aspect ratio of the beam from the diffraction grating(s) to the photodetector. For this reason, some investigators may prefer to use a photomultiplier with a large cathode to collect all the photons.

As this document was nearing completion, the author's attention was drawn to a recent report by Douglas et al [93] on an astronomical heterodyned spectrometer. The title of the report is somewhat misleading as this author feels that the word "homodyned" would have been more applicable. Unless fringes actually move across a photodetector at an interference beat rate, a system cannot be said to really employ heterodyne techniques. However, the report does describe a high resolution spectrometer using a fiber-optic umbilical, and in that respect is relevant to the discussion here.

In Figure 9, the purpose of the conventional CCD is just to display the star field on a television (TV) or personal computer (PC) monitor and for precision star tracking. In this preferred design, it does not detect the ETI signal; that job is performed by a relatively fast single solid-state Avalanche photodetector (APD) or photomultiplier (PM). APDs have the advantage of high quantum efficiency but the disadvantage of higher dark current; the converse being the case for photomultipliers. With state-of-the-art solid-state photodetectors like the RCA SPCM-100-PQ Single Photon-Counting Module, the cooling to reduce dark current noise is applied via Peltier (thermoelectric) coolers, and their mass is relatively insignificant. Though the imaging CCD can itself be used as the ETI detector, this approach might compromise detection sensitivity and bandwidth. It would also require a very high-quality and expensive CCD array. This would be incompatible with the use of the device for star field imaging and fine guidance because of the narrow-band optical filtering requirements of the SETI receiver. The input end of the fiber-optic umbilical might be dithered in the focal plane to aid guidance, and to ensure fine dynamic-tracking on a star's image. Indeed, four additional optical fibers with unfiltered photodetectors might surround the ETI-detecting fiber and be used for this purpose.

Note that the audio monitor in the schematic is for listening to the hiss of stellar noise and perhaps audibly detecting the presence of a strong artificial signal. The Planckian background in a 100 GHz optical bandwidth for a 2nd Magnitude star, produces a photon-count rate of about 18,000 s^{-1}, which should be compared to the dark-current count rate for a high-quality cooled photodetector or photomultiplier of less than several hundred counts per second. An essential component will be a variable threshold detector connected to an alarm system. The TV or PC monitor could also serve to display a noisy raster and the presence of any coherent signals. It is unlikely though, that an ETI TV picture will pop up (in any TV standard), considering the deficiencies in SNR and bandwidth with amateur receivers! However, if high SNR and bandwidth can be supported by ETI transmitters and terrene professional receivers over interstellar distances, a sequentially scanned TV [36] picture would be the most effective bridge between our two cultures.

Even as this is being written, substantial developments are being made in terrestrial video compression techniques for High Definition TeleVision (HDTV). Compression ratios as high as 100:1 have been achieved with only a small reported impairment in perceived video quality. [87] A 100:1 compression ratio would reduced bandwidth required by the digitized video signal by a factor of 100. If it was applied to an ETI interstellar communication system, the effective CNR could be increased by 20 dB. Of course, we cannot yet comment on whether ETIs would use such techniques, or what their level of sophistication is. What we can say, however, is that optical communications technology, along with video compression techniques, would make it much easier to transmit high-quality "real-time" video signals over thousands of light years. What was previously thought possible with old-fashioned analog TV signals and a 1 GW transmitter over ten light years now becomes possible over one hundred light years.

ETI signals may be linearly or circularly polarization-modulated, so that as previously mentioned, some means of analyzing the light would be required to detect the modulation. This polarization analyzing system could include a polarizer and a Soleil-Babinet compensator or quarter/half-wave retardation plates. The latter might be spun to cause sampling of all polarization states. If the signals are frequency (or phase) modulated with relatively small deviations, then only the professional heterodyne receiver will be able to recover the modulation envelop, whatever the signal strength.

Shopping List -

1. 8"-14" (20-36 cm) or larger Schmidt-Cassegrain with periodic error correction drive and RS-232 or IEEE-488 interface.

   Low $2,000 High $12,000

2. CCD imaging and tracking system with RS-232 or IEEE-488 interface.

   Low $1,100 High $3,200

3. Polarizaton analyzer.

   Low $100 High $2,000

4. Fiber-optic umbilical and connectors (ten meters).

   Low $150 High $150

5. Triple grating monochromator (resolution 0.1 to 0.01 nm) with RS-232 or IEEE-488 interface.

   Low $1,000 High $6,500

6. APD photon-counter or photomultiplier front-end.

   Low $200 High $3,000

7. Front-end cooling system.

Low $200 High $1,000

8. PC with fixed (hard) disk and RS-232/IEEE-488 interfaces.

Low $1,000 High $3,000

9. Spectrum analyzer PC card or stand-alone 0-10 MHz spectrum analyzer.

Low $1,000 High $4,400

10. Video and audio monitors (PC may double-up for this purpose).

Low $200 High $200

11. Miscellaneous

Low $1,000 High $2,000

12. Labor - Free

Total cost: Low $8,000; High $38,000

Thus, the low-end cost is approximately $8,000; less if telescope and computer system are already available. This is an affordable activity for many clubs and societies. Some of the equipment above is optional and may be replaced by less sophisticated devices, e.g., the automatic scanning monochromator could be replaced by a manual monochromator or a series of discrete high-Q bandpass filters, such as a 656 nm H_alpha filter. By omitting the electrical spectrum analyzer and using a fixed optical bandpass filter, instead of a scanning monochromator, the cost of a rudimentary system adaptation to an existing telescope would fall to about $3,000. This figure will be affordable for some individual enthusiasts.

Instead of a scanning grating monochromator, a scanning grating spectrometer might be used, where a linear CCD array is employed to produce an essentially instantaneous display of optical spectra (over a limited band) on a video display terminal (VDT). However, this does not allow for the flexibility of employing a single photodetector optimized for bandwidth and photon-counting sensitivity, and thus this approach will be more expensive and/or less sensitive. Often, monochromators use triple gratings in order to obtain spectral resolutions of 0.01 nm or better. As previously mentioned, a set of four optical fibers surrounding the signal fiber and corresponding low-bandwidth photodetectors might be used in the system for fine guidance purposes.

Within this account of Amateur Optical SETI is the ambitious desire to detect the modulation envelop. Hopefully, the ETI signals will be intensity or polarization-modulated so that the modulation can be detected by an incoherent receiver. For weak signals, we may only be able to detect the presence of an optical carrier or beacon (perhaps Signpost SETI) and then only after some signal integration. However, this would be a significant achievement by itself, allowing for more powerful professional receivers to be built later for detecting the modulation envelope.

As a spin-off from the MOP, electronic Multi-Channel Spectrum Analyzers (MCSAs) could be developed for the Amateur Optical SETI market, eventually making Amateur Optical SETI an even more affordable activity for optical astronomy clubs and societies. Perhaps ETIs do not expect their signals to be detected until the targeted civilizations make a collective, cooperative, and systematic search of their home skies!

THE MICROWAVE AND OPTICAL OBSERVING PROJECT (MOOP)

The following is the author's tentative list of objectives for the optical extension to MOP. It is called the Microwave and Optical Observing Project, otherwise known by the acronym MOOP.

Project Goal: To continue the search for microwave (and millimeter wave) signals of extraterrestrial intelligent origin and to extend the search into the infrared and visible spectrums.

Project Objectives:

1. To use existing large ground-based optical telescopes to carry out a Targeted Search of about 800 nearby solar-type stars with spectral resolution of 1 kHz and sensitivity 10^-16 W/m^2. For selected laser wavelength bands corresponding to atmospheric windows in the visible and infrared wavelength range (350 nm to 12,000 nm).

2. To use existing large ground-based optical telescopes to carry out a Targeted Search of about 1 million nearby solar-type stars with spectral resolution of 100 kHz and sensitivity 10^-10 W/m^2. For selected laser wavelength bands corresponding to atmospheric windows in the visible and infrared wavelength range (350 nm to 12,000 nm).

3. To use dedicated groups of amateur astronomers and coordinate their activities to conduct with their ground-based optical telescopes a low-sensitivity Targeted Search of about 800 nearby solar-type stars with spectral resolution < 1 nm, and sensitivity 10^-16 W/m^2. For selected wavelength bands in the visible and near-infrared wavelength range (350 nm to 1,200 nm).

Duration: 2001 - 2010

Cost: $20M for starters. Assumes use of existing large ground-based professional telescopes and the cost of modifying the telescopes for adaptive reception and Optical SETI.

Table 5 Nearest stars favored for MOP's 800 star Targeted Search

RGO Number	RH H M S	DEC D M	Relative Vel. km/s	Distance L.Y.	Apparent Magnitude	Spectral Type
559A	14 36 11	-60 37.8	-22.2	4.39	-0.01	G2 eye, SB
559B	14 36 11	-60 37.8	-0.0	4.39	1.33	K0 eye
144	3 30 34	-9 37.6	+15.4	10.79	3.73	K2 eye
820A	21 4 40	38 30.0	-64.3	11.01	5.22	K5 eye, AB
820B	21 4 40	38 30.0	-63.5	11.01	6.03	K7 eye
845	21 59 33	-56 59.6	-40.4	11.20	4.69	K4 eye
71	1 41 45	-16 12.0	-16.2	11.77	3.50	G8 eye
380	10 8 19	49 42.5	-26.0	14.68	6.59	K7
166A	4 12 58	-7 43.8	-42.4	15.90	4.43	K1 eye
702A	18 2 56	2 30.6	-7.2	16.72	4.03	K0 eye, UD
702B	18 2 56	2 30.6	-10.0	16.72	6.00	K5 eye, SB
663A	17 12 16	-26 31.8	-0.7	17.25	4.32	K0 eye
663B	17 12 16	-26 31.9	-0.2	17.25	5.10	K1 eye
570A	14 54 32	-21 11.5	+19.5	18.11	5.78	K5 eye
664	17 13 9	-26 28.6	-1.3	18.31	6.34	K5
783A	20 7 55	-36 13.7	-130.3	18.42	5.31	K3 eye
764	19 32 28	69 34.6	+26.7	18.52	4.69	K0 eye
34A	0 46 3	57 33.1	+9.4	18.94	3.44	G0 eye
139	3 17 56	-43 15.6	+86.8	20.25	4.26	G5 eye
66A	1 37 54	-56 26.9	+22.5	21.32	5.07	K0 eye
66B	1 37 54	-56 26.9	+19.4	21.32	5.90	K0 eye
566A	14 49 5	19 18.4	+3.9	22.03	4.54	G8 eye
566B	14 49 5	19 18.4	+5.4	22.03	6.91	K5
892	23 10 52	56 53.5	-17.8	22.18	5.57	K3 eye
33	0 45 45	5 1.4	-12.6	22.62	5.75	K2 eye
105A	2 33 20	6 39.0	+23.4	22.64	5.82	K3 eye, UD
667A	17 15 33	-34 56.2	+1.2	23.29	5.91	K3 eye
667B	17 15 33	-34 56.2	-0.0	23.29	7.20	K5
17	0 17 29	-65 10.1	+8.8	23.44	4.23	G0 eye
68	1 39 47	20 1.6	-33.7	24.32	5.24	K1 eye
178	4 47 7	6 52.5	+24.3	24.70	3.19	F6 eye
673	17 23 16	2 10.2	-28.3	24.70	7.53	K7
666A	17 15 15	-46 35.1	+23.6	24.89	5.48	G8 eye
713	18 21 58	72 42.7	+32.5	25.27	3.58	F7 eye, SB AB
879	22 53 37	-31 49.8	+9.0	25.47	6.49	K5
117	2 50 7	-12 58.3	+18.8	25.67	6.05	K0
23A	11 15 31	31 48.6	-15.5	25.67	3.79	G0 eye, SB AB
423B	11 15 31	31 48.6	-15.9	25.67	4.80	G0 eye, SB
216B	5 42 21	-22 26.2	-10.1	26.50	6.15	K2
216A	5 42 23	-22 27.8	-9.7	26.50	3.60	F6 eye
502	13 9 32	28 7.9	+6.1	27.17	4.26	G0 eye
785	20 12 10	-27 11.0	-54.2	27.17	5.73	K0 eye, SB
506	13 15 47	-18 2.0	-8.5	27.39	4.74	G6 eye
827	21 22 20	-65 35.6	-29.5	28.10	4.22	F6 eye
231	6 11 44	-74 44.2	+34.9	28.35	5.08	G5 eye
75	1 44 6	63 36.4	+1.8	28.59	5.63	K0 eye

Table 5 is an extract from the list (provided by the SETI Institute) of the closest stars that form the group of 800 stars which are subject to MOP's "Targeted Search". [40-45] Presently, the list covers stars in the range of 4.39 to 81.5 light years from Earth, but is subject to review.

UD = White Dwarf
EB = Eclipsing Binary
AB = Astrometric Binary
SB = Spectral Binary
eye = Visible to the unaided eye under good conditions (apparent visual magnitude less than 6.0 - about 224 stars).

559A = Alpha Centauri A
144 = Epsilon Eridani
71 = Tau Ceti

The Amateur Optical SETI system just described is quite capable of being upgraded in sensitivity by slaving "n" similar telescopes together, and combining the photons from the "n" optical fibers through a single monochromator and photon-counter. In this way, ten telescopes of 25-cm (10") aperture would have approximately the same sensitivity as a single 81-cm (32") telescope, but in a more cost-effective manner. Of course, ten small telescopes would not have the same ability as a 32" (81 cm) telescope to reject the effects of daylight, should daylight Optical SETI be desired. The approach could be adopted, as with the original Cyclops Study, to gradually increase the number of telescopes as the need arises and availability of funding, assuming that ETI signals are not detected soon after system activation.

A large, single barrel, telescope could be constructed using several smaller mirrors, each with its own focus and optical fiber. In this way, only one drive system would be required. A much simpler construction is possible because we do not need to image a star field, just collect as many photons as possible from the region around a single star (light-bucket mode of operation). This could be somewhat like the Multi-Telescope Telescope (MTT) that has been designed by Georgia State University's (GSU) Center for High Angular Resolution Astronomy (CHARA). [92]

LIST OF PREVIOUS AND PRESENT OPTICAL SETI ACTIVITIES

The following material has been extracted from a comprehensive list on all modern-day SETI activities so far, and was prepared in October of 1991 by Dr. Jill Tarter of the SETI Institute.

Dr. Tarter lists sixty three different SETI observing programs, starting with Project Ozma in 1960 at the Green Bank National Radio Observatory in West Virginia, to Harvard University's microwave search of Messier M31 and M33 from the Oak Ridge Observatory. This list also includes the 1983-1984 Amateur Microwave SETI program organized by Dr. Kent Cullers, which used Silicon Valley Hams with their satellite TV dishes (TVROs).

Of this list of sixty three observing programs, only three were or are concerned with Optical SETI, and these optical programs are listed below. Optical SETI observing programs currently amount to less than 5 percent of all SETI programs to date. In actuality, the ratio is nearer 3 percent because Shvartsman's two programs can be considered as one. This supports the author's contention that Optical SETI has suffered benign neglect.

Date: 1973 - 1974
Observer(s): Shvartsman et al. "MANIA"
Site: Special Astrophysical Observatory (former Soviet Union)
Instrument Size (m): 0.6
Search Wavelength (nm): 550
Frequency Resolution (Hz): df = 100 kHz (dWl = 10^-7 nm)
Objects: 21 Peculiar Objects
Reference: 48
Comments: Optical search for short pulses of length 3 X 10^-7 to 300 seconds, and narrow laser lines. Prototype for later system on 6 m telescope.

Date: 1978 to Present
Observer(s): Shvartsman et al. "MANIA"
Site: Special Astrophysical Observatory (former Soviet Union)
Instrument Size (m): 6
Search Wavelength (nm): 550
Frequency Resolution (Hz): df = 100 kHz (dWl = 10^-7 nm)
Objects: 93 Objects
Flux Limits: < 3 X 10^-4 of the optical flux is variable in any object observed.
Total Hours: 250
Reference: 54 and 58
Comments: Have searched 30 Radio Objects with Continuous Optical Spectra to date, looking for optical pulses from potential Kardashev type II or III civilizations.

Date: 1990 to Present
Observer(s): Betz
Site: Mt. Wilson
Instrument Size (m): 1.65 m element of Townes IR Interferometer
Search Wavelength (um): 10.6
Frequency Resolution (Hz): 3.5 MHz (35 m/s)
Objects: 100 nearby solar-type stars
Flux Limits: 1 MW transmitter out to 20 psc
Total Hours: Continuing
Reference: 57
Comments: Search for IR beacons at CO2 laser frequency using narrowband acousto-optical spectrometer.

DISCUSSION

The thirty-year-old rationale which would have us believe that the low frequency end of the microwave regime is the place to search for ETI signals is seriously suspect. If the underlying assumption of present-day SETI lore that the best ETIs could do would be to send us very weak low bandwidth signals is swept away, then almost all the so-called problems that are usually advanced to dismiss the optical approach become insignificant. This is even more so if the use of optical heterodyne reception is assumed. The increased immunity of such systems to background noise means that the signal detectability constraints set by Planckian starlight are essentially removed. In addition, with dechirping of the local-oscillator to remove local Doppler drift along the line-of-sight, problems from local Doppler drift are eliminated.

Because of the very narrow field-of-view of a photodetector array, Doppler drift compensation can be made simultaneously to all pixels in the array to a very high degree. The larger bandwidths mean that the effects of finite laser linewidths, Doppler shift and residual drift are minimized, and the number of frequencies to search in the entire optical spectrum is in reality no more than in the microwave spectrum.

Up to now, the SETI community has taken some comfort in the fact that the obvious explanation as to why we have not detected ETI signals is simply that they are too weak and that we need sophisticated hardware and signal processing algorithms to extract this information. An even simpler explanation for the lack of success so far is that there are strong signals but they are elsewhere in the electromagnetic spectrum. Of course, Tipler [39] has an even more simpler explanation.

It is the author's prediction that in years to come, it will be hard to understand how anyone in the late Twentieth Century, e.g., people like Frank Tipler, could think it possible that humanity was all alone - that Earth is atypical in that we are the "first civilization". If anything, it is far more likely that the answer to "Where are they?" is that we live in a "Cosmic Zoo". Tipler believes that ETI technologies only slightly superior to our own, if they exist, would have produced self-replicating von Neumann machines (probes) that would have rapidly populated the galaxy. Therefore, since we have not detected these machines or they have not contacted us, ETIs do not exist.

The "Cosmic Zoo" rationale is probably the only viable alternative explanation as to why ETIs do not appear to have colonized the entire galaxy. We could just as easily be a typical or atypical civilization, developing in a sector of the galaxy that is off limits for physical contact, i.e, the Prime Directive so much loved by STAR TREK fans. As was stated in the Preface, if the author has any doubts about the efficacy of the Optical SETI, it surely has to do with the Kingsley Paradox of "why communicate when one can just as easily travel?". Nevertheless, the author is sufficiently convinced about the plausibility of this Optical SETI rationale to believe it worthwhile to construct his own Optical SETI Observatory and mount his own search. He intends to start this project as soon as possible.

The author has taken some pains to try and understand why he believes Tipler is wrong. The author finds it very difficult to accept that only once in the ten billion year history of our galaxy has intelligent life arisen. Secondly, since the dawn of the Space Age, i.e., since about 1957, he has thought that life was common throughout the galaxy, and as a STAR TREK and science fiction fan, he has believed that the future for mankind was in space. Thus, the idea that there would be no one to meet out there is an anathema.

It is the author's intuitive feeling, that soon we will learn that life appears relatively rapidly, given the right environmental conditions. Life, rather than being the exception to the rule, is the inevitable consequence of the mixture of certain elements, temperatures, cosmic catastrophes, and time. In the roughly fifteen billion year existence of the Universe, there will have been no shortage of the latter. At the moment, we still have a very sketchy picture of how life arose on this planet - that possibly, lines of evolution were erased and new lines initiated several times during Earth's history, due to bombardment by meteors, planetoids and comets.

If ETIs are operating in the visible spectrum we should not expect to see flashing lights in the sky, for the power required to do this and outshine their stars is much greater than required to establish a decent communications channel. Free space optical communications will be a mature technology for any spacefaring civilization. It seems reasonable to assume that they will spinoff this technology for SETI transmitters should they wish to contact emerging technical civilizations. The fact that optical magic frequencies are hard to identify at this time, save for 10,600 nm, is not an argument that such frequencies do not exist.

Perhaps the only reasons for ETIs to build very large microwave arrays would be to eavesdrop on radio frequency leakage from primitive technical civilizations (like us), to beam microwave power, for astrophysical research, or to communicate with other galaxies. Even this author has some problems in believing that the civilizations of extraterrestrials would be so altruistic and long-lived to attempt electromagnetic communications across the intergalactic voids. The interstellar eavesdropping scenario is also problematic, as it is likely that a developing technical civilization only produces substantial radio frequency leakage for a short period in its history. In time, other technologies like fiber optics will replace high-power radio and TV transmitters, and military radar systems will be decommissioned. For this reason, if we attempt eavesdropping with large radio frequency antennas ourselves, failure to detect such signals may not imply very much about the existence or lack thereof of ETIs. Thus, if the MOP does not detect ETI in the next decade, we should not jump to the conclusion that we are alone in the Milky Way galaxy.

On the other hand, some civilizations may be continually threatened by cosmic catastrophes in the form of bombardment by planetoids. These races may have instigated powerful radar early warning systems for planetary defense purposes. These comments are good examples of how difficult it is to predict the future. Even Arthur C. Clarke and

Stanley Kubrick appear to have been caught out by Pan Am going bankrupt before it had a chance to ply the heavens between Earth and the Moon (2001: A SPACE ODYSSEY, to the strains of the "Blue Danube"), or that there would be no Soviet Union in 1992, let alone in 2001 or 2010! We can only hope (and pray) that there will be a dynamic American Space Program in 2001. We should not be too hard on Arthur Clarke, for without his idea concerning "Extra-Terrestrial Relays" (Page 41), when the word "Extraterrestrial" meant something completely different, the Soviet Union might still be in existence. One notes in passing, that the spaceship DISCOVERY, which was central to Arthur Clarke's 2001 and its sequel 2010, used microwave dishes for its communication's link with Earth. [94-96] Surely, the main (high-gain) link should have been a laser-based system, notwithstanding the bright Earth background, and the high solar background that might on occasion be viewed by the DISCOVERY looking back towards Earth! A heterodyning telescope of several meters diameter on the DISCOVERY, and a similar system on or near Earth, could easily sustain a 1-10 Gbit/s data rate out to Jupiter and beyond.

We cannot even be sure that ETIs would want their signals to be detected within an atmosphere or otherwise too easily. These are prevalent assumptions among most SETI proponents. There might be logical reasons for ETIs to think that only when a technical civilization begins to "emerge" from its planet would it be truly mature enough, and in a culturally receptive frame of mind, to receive signals from ETIs. Thus, the recipients' atmosphere itself might be used as an automatic protective blanket to avoid cultural shock. In a way, the electromagnetic search for ETI is one of the greatest hunts and detective stories ever. Unfortunately, there are still so few clues.

CONCLUSIONS

The author feels that it is still an open question as to what are the optimum electromagnetic frequencies for interstellar communications. As he concluded in his talk last year to the SETI Institute: "The jury is still out as to whether ETIs are signalling with low-energy microwave photons, or with high-energy optical photons". What the author will say is that he feels a strong case has been made in this paper for the SETI community and NASA to review their present attitude towards the optical approach. This does not mean that the Microwave Observing Project (MOP) should be abandoned or severely modified, since clearly we need to do a exhaustive search in the microwave spectrum. Some of the signal processing techniques developed for MOP will also be applicable to the optical search.

In many ways the Cyclops Report may have become the cornerstone upon which much of present-day SETI lore rests. While the report itself was a very comprehensive study of Microwave SETI, and of high technical quality, certain very conservative assumptions in that study lead this author to consider the report flawed. Just like for NASA's studies of the efficacy and cost of Microwave PowerSat technology back in the 1970's, if we ask the wrong questions we are likely to get incorrect answers. Attempting to lift all the material for PowerSats from the deep gravitational well of Earth is sure to make the technology uneconomic and damaging to the environment. Sweep away the inherent anthropocentric Assumption of Ineptitude of present SETI lore and the problems associated with the optical approach disappear.

There appear to be some indications of group-think within the SETI community, where it is easier to agree with the consensus than disagree. The U.S. Space Shuttle CHALLENGER tragedy of 1986 is a classic example of how group-think and the desire to conform can have immense ramifications. The issues may not be so acute here: Nevertheless, they represent an impediment to the acceptance of new (or revisited) ideas.

Planning for an extensive optical search should be started now, so that if by the year 2000 the results of the MOP are negative, we can immediately initiate Professional Optical SETI activities. This would be a natural extension to MOP so that the program could eventually be renamed MOOP, the Microwave and Optical Observing Project. In the meantime, amateur astronomers could be conducting a low-level (low-sensitivity) optical search, helping to establish some ground rules for a later high-sensitivity professional optical search.

It is believed that Professional Optical SETI with large heterodyning telescopes is compatible with Professional Optical Astronomy in that they can share most of the hardware, yet be undertaken at different times so as not to interfere with each other's observations. There is theoretical and experimental evidence to suggest that the new adaptive telescope technology using Rayleigh or Sodium Resonance Fluorescence laser guide stars [69] can be made to work during daylight hours. This clearly has important ramifications for the concept of Symbiotic (Serendip) Optical SETI. The idea of modifying Earth's Great Optical Telescopes for Symbiotic (Serendip) Professional Optical SETI has many attractions; where the scientific endeavors of conventional and SETI astronomy could be of mutual benefit to each other.

There is probably a case here for an automated retrospective historical study of stellar spectrographic plates to see if ETI signals actually exist and are on record. It is quite possible that anomalous spectral lines will be found in the record, signifying laser transmissions, but which had previously been overlooked, fogged the film, saturated the recording media, been mistaken for natural bright emission lines, or put down to "technical problems with the spectrographic equipment". It would not be the first time that a major scientific discovery had been missed for lack of attention and curiosity. There does appear to be some doubt as to whether C.W. ETI signals, if present, would have been accidently detected during conventional optical astronomy and recognized for what they were. This is the crux of the matter as far as the efficacy of Amateur Optical SETI is concerned.

It is left as an exercise for others to determine the probability of missing an ETI signal at any particular flux level. It is the very concept that ETIs are supposed to be rare which makes it plausible to suggest that the historic accidental discovery of ETI by optical astronomers would be unlikely.

Initially, to reduce the optical search time, we would concentrate on efficient laser transition frequencies presently known to humanity, and Fraunhofer dark lines. It is suggested that we must keep an open mind here. For thirty years we have been digging relatively deep trenches in a very small corner of our electromagnetic backyard. Was it prudent to do this without at least turning over the topsoil in the rest of the electromagnetic garden, particularly in that part of the spectrum where solar output peaks, and which tells us and ETIs most about our Universe?

The study also seems to indicate that the amateur SETI enthusiast could make a useful contribution to the search using medium-size amateur optical telescopes with photon-counting receivers. It is certainly more debatable whether Optical ETI signals are present at sufficient flux intensities to be detectable by small incoherent telescopes. However, although the theoretical SNRs described for small photon-counting (direct-detection) receiving telescopes are not particularly impressive, even if very high mean EIRPs are assumed, it must be remembered that ETI signals are likely to be pulsed and far more detectable than the C.W. signals assumed here for the simplified analyses. This would be particularly true for detection systems with optical bandwidths greater than 100 GHz.

Today, the technology is available to construct efficient, highly-sensitive photon-counting receivers for the visible and near-infrared regimes. For several thousand dollars, top-of-the-line amateur optical telescopes could be equipped with the instrumentation to make unattended frequency searches of selected targeted stars. If this new scientific endeavor really takes off, market growth will lead to considerable reductions in hardware and software costs, making this activity more affordable.

Not only would it be possible to slave many amateur telescopes together at one site, to produce the equivalent of a larger telescope, but it may also be possible to slave telescopes at different sites and average the data. This would, of course, require accurate time synchronization between the telescopes, though this should not be much of a problem. However, the requirement to match the wavelength accuracy of the optical filter or monochromator to within 100 GHz is probably a more severe obstacle. In the case of co-site slaving, where pre-detection combining of photons would occur, the SNR would increase at a rate proportional to the number of identical telescopes. For remote site slaving, where only post-detection electrical signal combining could be employed, the SNR would increase at a rate proportional to the square root of the number of identical telescopes.

While it is the author's view that Professional Optical SETI ought not to required the use of more sophisticated signal processing algorithms like KLTs [73,86] for extracting very weak pulsed signals from noise, Amateur Optical SETI may well benefit from its use.

Perhaps one of the interesting aspects of the Amateur Optical SETI concept using incoherent detection is that not only may there be a useful contribution made by the enthusiast, but that such activities may occur before Professional (Visible) Optical SETI and its coherent detection systems get established. A low-level search by amateurs might help set some of the criteria for later professional searches, even if the results are negative. Amateur optical SETI has the potential to bring SETI to the masses, something that has not really been possible at microwave frequencies, except in a limited way for a few enthusiastic radio hams with modified satellite receivers (AMSETI). [26] It also has the power to cause a renaissance in public interest for astronomy and the night sky. It is an activity in which amateur optical astronomers who live in big cities can participate, unincumbered by light pollution, the bane of conventional amateur astronomers. This could be the opportunity to dust off those old telescopes and put them to use again.

It is clear, [27-29] that today there is an enormous interest in SETI amongst the population. Professional SETI scientists could tap into that interest to receive increased SETI funding and the cooperation of enthusiastic amateurs.

It does not appear that Amateur Optical SETI at the infrared Carbon Dioxide (CO2) wavelength of 10,600 nm would be very sensible because of the limitations set by the essentially 24-hour day, 300 K temperature background of the atmosphere, particularly for small apertures. As we have seen, Professional Optical SETI in the visible and near-infrared can use coherent or incoherent optical receivers. The coherent approach is generally more sensitive but far more complex and expensive. However, based on performance considerations, both ground-based Professional and Amateur Optical SETI in the infrared would have to be restricted to coherent receivers. This represents a complexity and cost problem for the amateur. Of course, there could be very powerful CO2 ETI transmitters present, as powerful as conjectured for Visible SETI that have so far escaped detection, for we may not been looking in the right direction at the right moment, with suitable detection equipment. The CO2 observational work now being undertaken by Dr. Albert Betz and Professor Charles Townes [57] is addressing this issue.

Presently, Dr. Jill Tarter and Deborah Schwartz-Koyler of the SETI Institute are involved with a NASA project (NASA NCC 2-407) titled: "Supporting Research and Technology Activities in the Preparation of a Three-Dimensional Map of the Infrared Sky". The goal of this project is to construct a detailed three dimensional model of the infrared sky, which will enable us to reconsider the question of the "best" frequency at which to conduct a search for electromagnetic radiation, which is indicative of the existence of an extraterrestrial technological civilization. Thus, despite the general consensus that Microwave SETI has the greatest likelihood for success, others are even now beginning to probe deeper into the infrared part of the optical spectrum.

Since the start of modern-day SETI thirty two years ago, a strong Microwave SETI constituency has developed. It will be understandable if this author's views are attacked by that community, for many SETI researchers have much at stake - decades of work invested in the microwave regime and professional reputations. I would council the following thought: The public, and by that I mean the taxpayer, and Members of Congress, should clearly be informed that it is quite possible that the search for ETI in the microwave spectrum will be unsuccessful - not because such signals are not present, but because we are presently tuned to the wrong frequencies. It may well be necessary to extend the search into the optical regime before we can be sure whether electromagnetic ETI signals do or do not exist. It will not look good for the SETI community if, in ten years time, they have to go back to Congress, cap in hand, and ask for more funding to extend the search into the optical regime after decades of maintaining that the optical approach was useless. Note that these sentiments have previously been expressed privately to both the SETI Institute and NASA. It is the author's contention that SETI has been "hijacked" by radio astronomers. It should now be clear to the reader that for humanity to have devoted less than 5 percent of its SETI observation programs to the optical regime, and an even smaller percentage to basic Optical SETI research, was probably unwise. The author hopes that readers will urge the SETI Institute, NASA, and Congress to rectify this omission.

NASA should be able to put an end to recent problems in deploying large high-gain microwave antennas in space, e.g., on the Galileo probe, by moving to fixed high-gain optical antennas as soon as possible. During the next few decades, other lights (visible and near-infrared) will appear in the sky of terrene origin: they will be the advanced laser communication systems of GEO and LEO satellites, along with signals coming back to Earth from NASA's next generation of deep space probes. [63-66] Sometime next century, humans will be seen walking on the planet Mars. These HDTV television signals are likely to traverse most of the distance between Mars and Earth via laser, be relayed around the globe via laser-based geosynchronous satellites, and arrive in people's home via optical fiber. When humanity sends out (non-relativistic) interstellar probes to investigate nearby star systems, the data and pictures of those encounters (hopefully with other planetary systems) will come back to Earth via laser. The computer technology of the day will also be substantially dependent on photonics. See the January 13, 1992 issue of NEWSWEEK (pp. 56-57) for the article on "The Highway to the Future", describing a fiber-optic multi-gigabit data highway system being proposed for the United States. Also see the January 9, 1992 issue of ELECTRONIC DESIGN (pp. 73-80) for the article on "The World of Communications is Moving to Fiber Optics". The author has seen the future, and it is photonic.

Truly, the superior communications and computing technology of the future will be photonic, a technology that is likely to be around for a while. Indeed, in the future, one of the main uses for low-gain microwave space communications might well be the "acquisition" of the party at the other end of the link, so that the high-gain laser communications system can be locked on! The amateur SETI enthusiast, with the right photonic receiving equipment, will be able to tune in on these Earth-bound optical transmissions. How ironic, that next century the complaint will surely arise, that terrene optical transmissions are interfering with our ability to carry out Optical SETI free of false alarms! Now where have we heard that before?

We end as we began. If we look at the basic beliefs that differentiate the proponents of the Microwave and Optical SETI rationales, or the belief in Unidentified Flying Objects (UFOs), an area that has been even more controversial than SETI, we find that the respective convictions hinge on our assumptions about the technical abilities of ETIs. In the case of Microwave SETI, the proponents believe that while intelligent life within in galaxy is not rare, that ETIs do not have the technical wherewithal to get the full benefits of the superior optical technology for interstellar communications. If the reader subscribes to the Optical SETI rationale, they will additionally believe that ETIs have the technical prowess to use the superior laser technology in an effective manner. Advocates of UFOs essentially accept that ETI technology is so superior to our own that rapid interstellar travel is easy for them, and if these ETIs actually wanted to make contact, they would make physical contact. In the end, the reader's belief will be limited only by their own vision.

The theoretical results quoted in this paper are based on standard text book relationships, familiar to students of electrical engineering, physics, and astronomy. Please refer to Appendix A for a list of most of these formulas and specimen calculations. Perhaps the main reason for the difference between the conclusions of this analysis and many previous comparative SETI analyses, is that the author has shown a bit more imagination.

A few additional closing statements. It may appear from the author's comments throughout this document that he does not hold high regards for the efforts over the past thirty two years of many noted (microwave) SETI scientists. This would be far from the truth. It is the nature of science that for every two steps forward, it may often take a step back in the light of new discoveries or new ideas. It is very easy with hindsight to criticize those who have gone before, but without their predecessors' work and developments in other scientific fields and technologies, it is unlikely that the new discovery or idea would ever have seen the light of day. Each generation of scientists and engineers builds on the foundations laid by earlier generations.

Readers are reminded that there is little which is innovative about the contents of this document which have not previously been described by Charles Townes [46-47,80] and others - the author has just been a bit more forceful. Innovative ideas, like good wines, take time to mature. The author hopes that the effort he has expended in this revisiting of the optical approach to the search for extraterrestrial intelligence will at last cause Optical SETI to be seriously considered by the scientific community as warranting closer study.

This paper could be the start of an exciting new chapter in both SETI and professional/amateur optical astronomy. One thing which can be said for certain is that should a professional or amateur astronomer discover electromagnetic (radio or optical) signals from ETIs, neither they nor humanity will ever be the same. There is no doubt that a Nobel Prize will await the discoverer. Perhaps now is the time to get familiar with those Post-Detection SETI Protocols! [25] See Appendix B for a description of these protocols.

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APPENDIX A

THEORY AND SPECIMEN CALCULATIONS

The Drake Equation:

Fundamental to all SETI approaches is the belief that there are a reasonable number of technological civilizations out there who might be trying to communicate with us.

The following formula for the number of technological civilizations in the galaxy is a modified form of the one devised in 1961 by Frank Drake [2-3] of Cornell (also President of the SETI Institute) and is known as the famous "Drake Equation": [13,25]

N = R*.fp.ne.fl.fi.fc.L (1)

where R* = number of stars in the Milky Way galaxy (400 X 10^9),
fp = fraction of stars that have planetary systems (0.1),
ne = average number of planets in such star systems that can support life (1),
fl = fraction of planets on which life actually occurs (0.1),
fi = fraction of such planets which intelligent life arises (0.01),
fc = fraction of intelligent beings knowing how to communicate with other civilizations (0.1),
L = average lifetime (fraction of the age of its star) of such technical civilizations (0.001).

Substituting what some might say are conservative values given in parentheses for the entire Milky Way galaxy:

N = 4,000

Thus, there could be a minimum 4,000 worlds for us to detect in our galaxy. If there were only 4,000 technical civilizations within a galaxy that is 100,000 light years in diameter, then the probability of detecting ETI signals is likely to be small. However, many SETI scientists and exobiologists give more optimistic values for these parameters, and thus yield higher values for N. If fp, fl, fi, fc, and L are significantly higher, our galaxy would be teeming with intelligent technical civilizations. If we assume that the average lifetime of a star is 10 billion years, then a value of L = 0.001 implies that civilizations can last 10 million years. Clearly, there is a substantial degree of uncertainty in the value of L.

Within 1,000 light years of Sol there are 10 million stars, of which 1 million are solar-type. Thus, taking a more optimistic value for "N", the SETI community reasons that there is a significant chance of detecting an ETI signal if we "look" out to 1,000 light years, assuming of course, that we are tuned to the correct frequencies. The issue of the correct frequencies to search is at the heart of this paper.

Apparent Stellar and Signal Magnitudes:

The relationship between Apparent Stellar Magnitude (m) [88-90] and the brightness or intensity of a solar-type star (or a laser operating at or near the peak of the photopic response) may be expressed in the form:

$$m = -[19 + (2.5).\log(Ir)] \tag{2}$$

where Ir = received intensity (W/m^2).

The threshold for unaided eye visibility (dark sky) is $m = +6$. As mentioned above, this expression may also be used to estimate the approximate visibility of a laser, i.e., the apparent signal magnitude, if its wavelength is not too far removed from the peak of the low-intensity visual response at 500 nm. Here are several intensities and corresponding magnitudes as a function of range R. We note that the Sun's total output (EIRP) = 3.90×10^{26} watts:

At R = 1 A.U. (1.496×10^{11} m):

$Ir = 1.39\ \text{kW/m}^2$
$m = -26.8$

Thus the solar flux density at normal incidence just outside Earth's atmosphere is $1.39\ \text{kW/m}^2$.

At R = 10 L.Y. (9.461×10^{16} m):

$Ir = 3.48 \times 10^{-9}\ \text{W/m}^2$
$m = +2.2$

At R = 100 L.Y. (9.461×10^{17} m):

$Ir = 3.48 \times 10^{-11}\ \text{W/m}^2$
$m = +7.2$*

At R = 1,000 L.Y. (9.461×10^{18} m):

$Ir = 3.48 \times 10^{-13}\ \text{W/m}^2$
$m = +12.2$*

* Not visible to the unaided eye.

In Table 2 (Page 22), Apparent Magnitudes are quoted for stars, extrasolar planets, and ETI transmitters on the basis of the visual brightness or intensity of each object acting alone. Because the reason for quoting the Apparent Magnitudes is to demonstrate that relatively strong laser transmitters are still "visually" weak, the Apparent Magnitudes are only given for the visible wavelength.

Planckian Starlight Background:

For observations at night, the background Nb may be taken as the Planckian (black body) starlight continuum level (Npl). [88-90] With no allowance for the Fraunhofer dark line absorption or bright line emission, the non-polarized spectral energy density is given by:

$$Npl = \frac{2.\pi.h.f^3r^2}{c^2[e^{(h.f/k.T)} - 1]R^2} \quad W/m^2.Hz \qquad (3)$$

where h = Planck's constant (6.63×10^{-34} J.s),
c = velocity of light (3×10^8 m/s),
Wl = wavelength (656 nm),
f = frequency (c/Wl = 4.57×10^{14} Hz),
k = Boltzmann's constant (1.38×10^{-23} J/K),
T = temperature (5778 K),
r = radius of star (6.96×10^8 m),
R = distance of receiver (10 L.Y. = 9.461×10^{16} m).

At R= 1 A.U.:

$$Npl = 2.19 \times 10^{-12}\ W/m^2.Hz$$

At R = 10 L.Y.:

$$Npl = 5.47 \times 10^{-24}\ W/m^2.Hz$$

Full Width Half Maximum (FWHM) Angular Beamwidth:

For the purposes of this part of the analysis, we have assumed a fully (uniformly) illuminated circular aperture and not a beam with a Gaussian intensity profile, as might be obtained from a laser with a single transverse TEMoo mode. The diffraction limited half-power (-3dB) beamwidth is given by: [66,85]

$$\text{FWHM Beamwidth} = \frac{(58.5).Wl}{d} \quad \text{degrees} \qquad (4)$$

where Wl = wavelength,
d = diameter (aperture) of telescope.

For d = 10 m (professional telescope) and Wl = 656 nm:

FWHM Beamwidth = 0.0138 arc seconds

For d = 0.30 m (amateur telescope) and Wl = 656 nm:

FWHM Beamwidth = 0.461 arc seconds

Full Width Half Maximum (FWHM) Diameter:

The diffraction limited far-field half-power (-3 dB) beam diameter is given by:

$$\text{FWHM Diameter} = \frac{(1.02).Wl.R}{d} \text{ meters} \qquad (5)$$

At R = 10 L.Y.:

FWHM Diameter = 6.33 X 10^9 m = 0.0423 A.U.

Gaussian Beamwidth:

If a laser is used to illuminate a transmitting telescope, and if the aperture is greater than 4wo, theory gives the far-field 1/e^2 beam diffraction angle as:

$$\text{Gaussian Beamwidth} = \frac{(115).Wl}{PI.wo} \text{ degrees} \qquad (6)$$

where wo = the TEMoo mode waist radius of the Gaussian beam.

For a compromise aperture diameter d = 2wo, where a little diffraction will occur and produce some sidelobe energy, the (1/e^2) diffraction angle of the main lobe of a 10-meter telescope is given by:

Gaussian Beamwidth = 0.0172 arc seconds

The corresponding (1/e^2) Gaussian beam diameter at the target is:

Gaussian Diameter = 0.0527 A.U.

This is not that different to the previous case for a fully-illuminated aperture (no amplitude taper apodization).

Rayleigh Range:

For a Gaussian beam, the Rayleigh or near-field range of a diffraction limited single or multi-aperture (array) telescope is given by:

$$\text{Ray} = \frac{PI.wo^2}{Wl} \qquad (7)$$

At the Rayleigh range Ray, the beam diameter has expanded by a factor of 1.414. As the distance increases beyond the Rayleigh range, the beam diameter becomes proportional to distance, and the inverse square law applies to the beam intensity.

Considering our 10-meter diameter transmitting telescope with a Gaussian beam, and a compromise aperture diameter d = 2wo.

For wo = 5 m and Wl = 656 nm:

Ray = 1.2 X 10^8 m

= 0.0008 A.U.

Now consider an array that has a width of 10 km.

For wo = 5 km and Wl = 656 nm:

Ray = 1.2 X 10^14 m

= 800 A.U.

Finally, consider a Mercury-size planetary phased-array as conjectured by Dr. John Rather. [56]

For a wo = 2,439 km and Wl = 656 nm:

Ray = 2.8 X 10^19 m

= 3,000 L.Y.

With such a huge array, the inverse square law does not apply over considerable distances. The Rayleigh range can stretch out over 3,000 light years, so that the flux density is essentially undiminished by distance, accept for any interstellar absorption effects. Of course, the implication that a pencil beam (celestial searchlight) some 3,500 km in diameter, i.e, of planetary diameter, could be landed on a desired planet 10 lights years away, let alone 3,000 light years, somewhat stretches even this author's imagination!

Polar Response:

The Polar Response (PR) or Directivity of a transmitting or receiving telescope with a single fully illuminated circular aperture, with no amplitude taper (apodization), is given by: [85]

$$PR = \frac{[2.J1\{(PI.d/Wl).\sin(PHI)\}]^2}{[(PI.d/Wl).\sin(PHI)]^2} \qquad (8)$$

where $J1$ = Bessel Function of the first kind,
d = diameter (aperture) of telescope,
Wl = wavelength,
PHI = angular separation.

For the 10-meter diameter telescope at 656 nm, the first sidelobe is located at 0.022 arc seconds from the main lobe, and the response is 17.6 dB down. The second sidelobe occurs at 0.036 arc seconds from the main lobe, and response is 23.8 dB down.

In a diffraction limited space-based telescope system, where the angle PHI between the image of the transmitter and star is >= FWHM/2 (-3 dB half width half maximum), the Planckian suppression, ignoring scattering within the telescope, is given by:

$$\text{Suppression Factor} \geq 10.\text{Log}\left[\frac{8}{PI.\{(PI.d/Wl).\sin(PHI)\}^3}\right] \text{ dB} \qquad (9)$$

Equ. 9 essentially shows that the suppression factor is inversely proportional to the telescope's aperture raised to the third power. For a transmitter at 10 light years, located 1 A.U. from its star, and centered on the main lobe of the receiver, the maximum angular separation of the star is 0.275 arcseconds. Using the parameters for the 10-meter diameter 656 nm telescope which has a FWHM beamwidth of 0.0138 arc seconds, we find that the condition PHI >= FWHM/2 is more than satisfied, and the minimum suppression factor for the Planckian starlight continuum is:

Suppression = 50 dB

This value is added to the Signal-To-Planckian Ratio (SPR) to arrive at the effective SPR when a large telescope is diffraction limited, and viewing a nearby star system at right angles to the star's plane of ecliptic (Table 2, Line 23, Page 22). The suppression factor can be larger than predicted by Equ. 9 (up to a limit set by scattering and secondary mirror diffraction) if the star's image happens to be situated in a response null. However, scattering effects and non-ideal optics will set a limit to this suppression factor to between 40 and 50 dB.

Antenna Gain:

The gain of a uniformly illuminated antenna is given by: [5,71,85]

$$G = \frac{4.PI.At}{Wl^2} \qquad (10)$$

where At = area of transmitting telescope mirror (78.5 m^2).

For a 10-meter diameter telescope at 656 nm:

$$G = 2.3 \times 10^{15}$$

$$= 153.6 \text{ dB}$$

Effective Isotropic Radiated Power (EIRP):

The Effective Isotropic Radiated Power [5,8,85] is given by:

$$EIRP = G \cdot Pt \quad \text{Watts} \tag{11}$$

where Pt = transmitter power (W).

For Pt = 1 GW:

$$EIRP = 2.29 \times 10^{24} \text{ W}$$

Received Signal Intensity:

The received signal intensity just outside Earth's atmosphere is:

$$Ir = \frac{EIRP}{4 \cdot \pi \cdot R^2} \tag{12}$$

where EIRP = effective isotropic radiated power (W),
R = range (10 L.Y. = 9.461×10^{16} m).

At a range of ten light years, a 1 GW transmitter EIRP = 2.29×10^{24} W produces an intensity (Ir) just outside our atmosphere of 2.04×10^{-11} W/m^2. For a perfect space-based 10-meter diameter telescope, the received signal power (Pr) is 1.6 nW.

Received Signal Power:

From Equs. 10, 11, and 12, and because the receiving aperture area At = PI.D^2/4, we may write the "perfect" received signal for the symmetrical telescope system in the simple form:

$$Pr = Pt \cdot \frac{\pi^2 \cdot D^4}{16 \cdot R^2 \cdot Wl^2} \tag{13}$$

It can be clearly seen from the above, that the received power is proportional to D^4 and inversely proportional to Wl^2. Thus, beamed optical links, particularly those operating in the visible spectrum, have the potential for tremendous throughputs.

A slightly simpler form of this expression has been used by Albert Betz in his recent CO2 paper. [57] To a close approximation, Equ. 13 may be further simplified to:

$$Pr = Pt.\frac{D^4}{R^2.Wl^2} \qquad (14)$$

A more conservative analysis for ground-based observatories, would take into account atmospheric transmission losses, aperture blocking, and spectrometer efficiency in the case of an incoherent receiver. For a a ground-based telescope, the optical power reaching the photodetector is given by:

$$Pr = Ir.Tr.Ae.Ar.SE \qquad (15)$$

where Ir = intensity just outside atmosphere (2.04×10^{-11} W/m^2),
Tr = atmospheric transmission (0.4 for visible, 0.6 for CO2),
Ae = antenna efficiency (0.7),
Ar = antenna aperture area (0.0707 m^2),
SE = spectrometer efficiency (0.5).

For a 30-cm diameter (12-inch) visible telescope, and the above parameter values (1 GW, 10 m transmitter, EIRP = 2.29×10^{24} W, $Ir = 2.04 \times 10^{-11}$ W/m^2), the received visible signal:

$$Prv = 2 \times 10^{-13} \text{ W } (-127 \text{ dBW})$$

For a 30-cm diameter (12-inch) CO2 telescope, and the above parameter values (1 GW, 10 m transmitter, EIRP = 8.78×10^{21} W, $Ir = 7.81 \times 10^{-14}$ W/m^2), the received infrared signal:

$$Pri = 1.2 \times 10^{-15} \text{ W } (-149 \text{ dBW})$$

Daylight Background:

The sky background radiation power detected per pixel, is given by:

$$Pb = (PI.THETA^2.Ae.Ar.SE/4).Bo.N(Wl) \text{ W} \qquad (16)$$

where $THETA$ = diffraction limited beamwidth (5.34×10^{-6} radians),
Bo = optical bandpass (0.143 nm),
$N(Wl)$ = spectral radiance (W/m^2.sr.nm).

For the incoherent optical systems, the pixel has a diffraction limited field-of-view (FOV) corresponding to the Airy disk, i.e., (2.44)Wl/d radians, where Wl = wavelength, and d is the aperture diameter. For coherent systems, a smaller FOV is employed; that corresponding to the FWHM response, i.e., (1.02)Wl/d radians. The latter pixel size is smaller because of the requirement to reduce the amount of local-oscillator power that does not beat with the signal but only induces excess quantum shot-noise.

At visible wavelengths:

N(Wl) = 0.01 W/cm^2.sr.micron [71]
      = 0.1 W/m^2.sr.nm
N(f) = 1.43 X 10^-13 W/m^2.sr.Hz

The daytime sky background for a 12" (30 cm) telescope at 656 nm (not allowing for atmospheric distortion effects) with an optical bandpass filter bandwidth Bo = 100 GHz (0.143 nm):

Pbv = 7.9 X 10^-15 W (-141 dBW)

The background is about 14 dB (Prv - Pbv) below the signal from the 1 GW transmitter which produces an EIRP = 2.29 X 10^24 W, and a flux of 2.04 X 10^-11 W/m^2 at a range of 10 light years. Thus, in this small photon-counting receiver, the fluctuation noise from the daylight background is 14 dB below that of the quantum shot-noise generated by the signal. This has little effect on signal detectability. If a polarizer is employed, Pb can be reduced by a further 3 dB. For a perfect space-based 10 meter diameter visible telescope, the daylight spectral density is about 4 X 10^-26 W/Hz (Figure 3, Page 17).

For infrared systems, the 300 K temperature of the atmosphere produces a black body peak at approximately 10,600 nm, with a spectral radiance given by:

N(Wl) = 0.0002 W/cm^2.sr.micron [71]
      = 0.002 W/m^2.sr.nm
N(f) = 7.5 X 10^-13 W/m^2.sr.Hz

The sky background for a cooled 12" (30 cm) telescope at 10,600 nm (not allowing for atmospheric distortion effects) with a cooled 0.35 percent optical bandpass filter bandwidth Bo = 100 GHz (37.5 nm):

Pbi = 1.1 X 10^-11 W (-110 dBW)

For an EIRP = 8.78 X 10^21 W and Ir = 7.81 X 10^-14 W/m^2, the potential CO2 SNR is degraded by about 39 dB (Figure 6, Page 38) because the background noise is 39 dB -(Pri - Pbi) above the quantum shot noise. The infrared graph of Figure 6 is plotted to the same scales as that of the Figure 8 (Page 44) visible graph, to make comparisons easier, and the pages may be flicked back and forth to show the differences more dramatically. We can clearly see that the effective optical bandwidth must be substantially reduced if ETI signal detectability at 10.6 microns is not to be impaired. Thus, only heterodyning receivers, with effective optical bandwidths measured in MHz and not GHz, are suitable for CO2 SETI within the atmosphere.

Field Of View (FOV):

The relationship between the solid angle occupied by each star and the area of the celestial sphere "occupied" by a typical star is:

$$\mathrm{OMEGAs} = \frac{A}{R^2}\ \mathrm{sr} \qquad (17)$$

where A = area of the celestial sphere, i.e., 4.PI.R^2/N; N being the number of stars being considered (10^6).

$$\mathrm{OMEGAs} = \frac{4\pi}{N}\ \mathrm{sr} \qquad (18)$$

Let us assume that sky survey is done out to a distance of 1,000 light years. This means that we are searching the entire celestial sphere around the Sun with a radius of 1,000 light years. This sphere of 4.PI steradians (sr), contains about 10 million stars of which approximately 1 million are solar-type. Assuming that for a sphere of this size, these 1 million stars are distributed fairly uniformly:

$$\mathrm{OMEGAs} = 1.26 \times 10^{-5}\ \mathrm{steradian}$$

For small angles, the solid angle FOV OMEGAs and the linear angle FOV THETAs, are related by:

$$\mathrm{OMEGAs} = \frac{\pi \cdot \mathrm{THETAs}^2}{4}\ \mathrm{sr} \qquad (19)$$

$$\mathrm{THETAs} = 0.23\ \mathrm{degrees}$$

Array Field Of View:

Figure 10 shows the typical field-of-view (FOV) for a 10 meter diameter telescope. It has a usable Telescope Field-Of-View of about 0.33 X 0.33 degrees. At 656 nm, the diffraction limited FOV for each pixel, and based on the Rayleigh criterion (1.22)Wl/d radians, is 8 X 10^-8 radians (0.0165"). For a 128 X 128 diffraction limited two-dimensional array, the array has a linear field-of-view = 1.02 X 10^-5 radians (2.1"). The corresponding array FOV is:

FOV = 2.1" X 2.1"

Thus, at any instant of time, the average number of stars in the 2.1" X 2.1" array field-of-view is approximately:

$$6.4 \times 10^{-6}$$

```
 ------------------------------
|                              |
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|                              |
|     *                        |
|                              |
|                              |
|        2.1 arc seconds       |
|            -->o<--           |
|           Array FOV          |
|                              |
|                              |
|                              |
|                              |
|     *   0.23 degrees   *     |
|     <------------------>     |
 ------------------------------

  Telescope FOV = 0.33 degrees
<------------------------------>
```

Figure 10 -

Typical FOVs for a large optical telescope. The diagram (not to scale) illustrates the fact that the optical telescope's array field-of-view generally observes empty space; the array itself occupying just a small fraction of the telescope's usable (focal plane) field-of-view.

Number Of Received Beams:

The number of directions resolved by a telescope (with a maximum off-axis loss of 1 dB) is stated in the Cyclops report [5] as being given approximately by:

$$Nd = 4.G \qquad (20)$$

where G = gain.

For a 10 meter diameter telescope at 656 nm, $G = 2.3 \times 10^{15}$. Thus:

$$Nd = 9.2 \times 10^{15} \text{ beams}$$

An alternative expression has been given [8] where Nd = G. In this paper, for the purposes of roughly estimating the search time for an All Sky Survey, Equ. 20 has been used. Nd has been taken as being 10^{16} beams or directions.

The Search Time

For the Targeted Search, the time to scan a single star with the heterodyning array, is given by:

$$Ts = \frac{Inor.Npix.(fu-fl).Td}{Imin.Nmsca.Bmsca.Bbin} \quad s \qquad (21)$$

where Inor = normalized flux (8.12 X 10^-16 W/m^2),
Imin = minimum detectable flux (8.12 X 10^-16 W/m^2),
Npix = number of pixels (16,384 photodetectors),
Nmsca = number of parallel multi-channel spectrum analyzers (MCSAs), {<= Npix} (1),
Bmsca = total bandwidth of MCSA (10 GHz),
Bbin = minimum MCSA bin bandwidth (100 kHz),
fu = upper optical frequency (8.57 X 10^14 Hz),
fl = lower optical frequency (4.29 X 10^14 Hz),
Td = dead time overhead factor per array scan (1.0).

The dead time overhead factor is >= 1, and for this estimate, has been taken to be unity, i.e., implying zero overhead. The normalized flux is defined as that flux level that causes the normalized CNR (SNR) (dB re 1 Hz) to fall to 0 dB. Note that if the pilot-tone maximal ratio predetection combining system described later is employed, the number of pixels (Npix) is effectively reduced to unity. Also, the number of receiver beams Nd is assumed relatively constant over the band fu-fl. If we substitute the values given in parentheses into Equ. (21), for the visible optical bandwidth between 350 nm and 700 nm, and a minimum detectable flux level of about -150 dBW/m^2, we find that:

Ts = 2 hours

The time to do an All Sky Survey of this type is increased by a factor (10^16/16,384), so that Ts = 136 million years! If we wanted to store all the data collected, the number of bits would be, to say the least, astronomical. Clearly, we would need to be very selective in the wavelengths scanned. i.e., fu-fl would have to be very small, so that a guess of the magic optical frequencies would be mandatory.

This rough optimistic search time estimate, shows that it would be ridiculous to consider a Visible SETI All Sky Survey modelled on the one being employed for the Microwave Observing Project (MOP). [40-45]

Optical Heterodyne Detection:

In an optical heterodyne receiver (Figure 2, Page 15), the signal current I is proportional to the product of the signal electric field and the local-oscillator electric field, and a difference or Intermediate Frequency (I.F.) is produced because the photodetector is a square-law device. [71-78,81-82] Let us see how this heterodyne beat signal is created. Consider two optical beams mixing on a photodiode (square-law detector). Let the beams be given by:

Received signal beam electric-field component = Er.cos(wrt+phi),
Local-oscillator beam electric-field component = Eo.coswot.

The photodetector current is given by:

I = k(Er+Eo)^2 (22)

where k = a constant of proportionality relating the current responsivity of the photodetector (Ri) to the electric-field.

I = k[Er.cos(wrt+phi)+Eo.coswot]^2

I = kEr^2.cos2(wrt+phi)+2kEr.Eo.cos(wrt+phi).coswot+kEo^2.cos2wot

I = 0.5kEr^2[1+cos2(wrt+phi)]
+ kEr.Eo[cos{(wr-wo)t+phi}]+kEr.Eo[cos{(wr+wo)t+phi)}]
+ 0.5kEo^2[1+cos2wot]

Rejecting all but the difference frequency term,

I = kEr.Eo[cos{(wr-wo)t+phi}] (23)

where (wr-wo)/(2.PI) = fr-fo = Bif, is the difference, beat or intermediate frequency.

Thus, the signal detected is proportional to the product of the received signal and local-oscillator electric-fields. In an optical homodyne receiver, wo = wr, and the intermediate frequency is zero. The optical mixing efficiency factor H, which is not indicated here (Equ. 32 & 33) and accounts for wavefront distortion and beam misalignment, is typically somewhat less than 50%.

Pilot-Tone Maximal Ratio Predetection Combining:

The pilot-tone technique has been previously applied to radio frequency diversity receivers to overcome deep fades. [84] It has also been employed by the author on multimode fiber homodyne and heterodyne systems with a 4-quadrant photodetector acting as an optical space diversity receiver. [81,82] The spatial incoherence of the radiation pattern from a multimode optical fiber is very similar to that of a free-space optical beam received by a large telescope within an atmosphere.

The theory behind the terrene pilot-tone method is as follows, and makes no specific assumption about modulation techniques employed by ETIs, i.e., whether intensity, polarization, frequency or phase modulation, analog or digital. With reference to Figure 1 (Page 10):

Let the pilot-tone carrier at fp be given by:

Ep(t).sin[wpt+dphi] (24)

and the modulated information signal at fs be given by:

Es(t).sin[wst+phi(t)+dphi] (25)

```
where  dphi   = phase disturbance caused by the transmitter laser
                (jitter) or Earth's atmosphere,
       phi(t) = represents possible phase or frequency modulation.
```

The phase disturbances dphi, are essentially common to both the signal and the pilot-tone, as they are almost identical optical frequencies and travel the same optical path. However, dphi generally differs at each photodetector.

```
                         -------
sin[(ws-wo)t+phi(t)+dphi]|       |    -----    cos[(ws-wp)t+phi(t)]
------------------------>| Mixer |-->| LPF |-------------------------->
    1st I.F (1.1 GHz)    |       |    -----      2nd I.F (100 MHz)
                         -------
                            ^                        To Summer ------>
                            |
    sin[(wp-wo)t+dphi]      |
-----------------------------
     2nd L.O. (1 GHz)
```

Figure 11 -

Maximal Ratio Precombining. The bandpass-filtered signal from each photodetector provides two separately-filtered 1st I.F and 2nd L.O. signals to an electronic mixer. The 2nd I.F. produced after the low-pass filter (LPF), has all the laser local-oscillator and atmospheric-induced phase noise dphi eliminated.

The frequencies given in brackets in Figure 11 are arbitrary, and used to help clarify the technique. Each pixel of the 128 X 128 array has one of these circuits, whose in-phase outputs are simply added (in a summer) and taken to a single MCSA.

If we heterodyne a local-oscillator laser operating at frequency wo with both these signals, we obtain the difference frequency signals or 1st I.F. from the photodetector proportional to:

Ep(t).Eo.sin[(wp-wo)t+dphi] (26)

Es(t).Eo.sin[(ws-wo)t+phi(t)+dphi] (27)

where dphi now also includes the effects of local-oscillator jitter.

The pilot-tone signal as stated by Equ. (26), may be passed through a narrow-band filter and amplifier, to produce what is effectively a strong electrical second local oscillator (2nd L.O.) signal for an electrical mixer. It may also be used to lock a narrow-band Phase Locked Loop (PLL) whose Voltage Controlled Oscillator (VCO) is used as the strong, amplitude-stable and clean 2nd local oscillator. The information signal as stated by Equ. (27), may be passed through a wideband filter and applied to the other port of this electrical mixer. The 2nd I.F. output of the electrical mixer is proportional to:

$$Ep(t).Es(t).Eo(t)^2.cos[(ws-wp)t+phi(t)] \qquad (28)$$

The phase disturbances dphi introduced by the atmospheric turbulence and laser jitters have been eliminated by the process of electrical mixing. Thus, if the image of the transmitter is instantaneously or sequentially smeared out over many pixels, all the second I.F. contributions are in phase, and may be simply summed to provide predetection diversity combining and a substantial reduction in amplitude instability (scintillation).

It also provides the best type of predetection summation in the form of Maximal-Ratio Combining. Although the system appears to implement Equal-Gain Combining, the effect of the electronic mixer is to cause the weakest signals to be automatically weighted downwards, and hence cause Maximal Ratio Combining of the photodetector signals. Those pixels producing the weakest signal also produce the lowest quantum, Planckian or background noise contributions to the input of the electrical mixer, so that the summed electrical signal power is not degraded by noise from pixels with little or no optical signal. This occurs because when no optical signal is present, the noise output of each electronic mixer is essentially that due to a noise^2 term, and hence is very small. Only a single MCSA would be required, which would be effectively continuously "looking" at the combined outputs of all 16,384 pixels. We would have only one MCSA, but 16,384 electronic front-end systems for predetection combining of the photodetector outputs, based on the mixing technique illustrated in Figure 11.

A predetection combining system with a single MCSA would not detect directly any Planckian starlight noise from a star in the array field-of-view alone, only that which overlapped and mixed (downconverted) with an ETI signal on one or more pixels. However, for nearby stars where the transmitter and star are separately resolved, we would lose any Planckian suppression effect of a (single pixel) diffraction limited telescope. Also, if there are significant interstellar or atmospheric group-delay dispersion effects between the signal and pilot-tone, the technique would not work. This consideration may affect the choice for the value of (fs-fp) and may itself limit modulation bandwidth to be less than a few GHz, notwithstanding SNR considerations. Of course, to use this technique will require the cooperation of the ETI.

Would they be so obliging? It would be difficult to justify building such a receiving signal processing system without foreknowledge that

ETIs employ this technique - this could be said to be putting the cart before the horse! Anyway, before implementing such a system, assuming ETIs would use such a modulation format, we would have had to previously detect this modulation format to know what electrical filters to use!

Radio Frequency Signal-To-Noise Ratio:

The Carrier-To-Noise Ratio (CNR) in the Microwave Heterodyne [5,8,85] 100-meter diameter, 1 kW dish system operating at 1.5 GHz over a range of 10 light years:

$$CNR = \frac{Pr}{kTBe} \qquad (29)$$

where Pr = received power (1.72×10^{-22} W),
T = effective system temperature (10 K),
Be = electrical intermediate frequency bandwidth (1 Hz).

$$CNR = 1 \text{ dB}$$

A symmetrical Cyclops array system [5] with 900 such dishes at both the transmitter and receiver would have a CNR = 60 dB.

Optical Signal-To-Noise Ratio:

The dimensions of all signal and noise components the following optical expressions are in units of amperes^2, and by multiplying by the photodetector load impedance, may be turned into units of power. The numerators are representative of the electrical signal power in the photodetector load, while the denominators represents the electrical noise power in the photodetector load. [71-78]

For coherent receivers, dual-balanced photodetection is assumed so that all the received signal power is utilized, and the noise floor is not raised by excess intensity noise on the local-oscillator laser. It is further assumed that the linewidths of the received signal and local-oscillator laser are sufficiently small compared to the modulation bandwidths, as to not raise the noise floor.

The effective system noise temperature of an optical receiver may be expressed in the form:

$$Teff = \frac{h.f}{eta.k} \text{ K} \qquad (30)$$

where h = Planck's constant (6.63×10^{-34} J.s),
f = frequency (4.57×10^{14} Hz).

$$Teff = 43{,}900 \text{ K}$$

Incoherent Signal-To-Noise Ratio:

Direct Detection and Photon-Counting

$$SNR = \frac{Pr^{2}(MRi)^{2}}{[2e\{Ri(Pr+NbBo)+Ib\}M^{(2+x)}+2eIs+2Nb\{Pr+NbBo\}(MRi)^{2}+4kTF/RL]Be} \qquad (31)$$

where Pr = received optical power (W),
Po = local oscillator power (W),
M = avalanche gain,
eta = photodetector quantum efficiency (0.5),
Ri = unity gain responsivity (W/A),
e = electronic charge (1.6 X 10^-19 C),
Nb = background radiation spectral density (W/Hz),
Ib = bulk dark current at unity gain (A),
Is = surface dark current (A),
x = excess noise factor,
k = Boltzmann's constant (1.38 X 10^-23 J/K),
T = front-end amplifier temperature (K),
F = front-end amplifier noise figure,
RL = front-end load (Ohms),
Bo = optical pre-detection bandwidth (Hz),
Be = noise equivalent electrical bandwidth, which for a single-pole filter = PI/2 x maximum modulation frequency (Hz).

The electrical signal power is proportional to Pr^2, and the noise components proportional:

1. To the quantum noise produced by the signal photons.

2. To the fluctuation noise produced by the background radiation Pb (NbBo). Notice that this noise is proportional to the optical bandwidth, and the ratio of this noise to the quantum noise component is inversely proportional to the received optical power.

3. To the shot noise produced by the bulk dark current in the photodetector.

4. To the shot noise produced by the surface leakage dark current.

5. To the background radiation beating with the signal, which is independent of optical bandwidth. The noise spectral density is the important factor here.

6. To the noise beating with noise, which is proportional to both the noise spectral density squared and the optical bandwidth. The latter two noise components are insignificant and may be safely omitted for this application where the background is very small.

7. To the thermal kT noise in the photodetector load and front-end amplifier, and may be neglected for shot noise limited direct detection receivers, and ideal photon-counting receivers.

The total noise produced is proportional to the electrical post-detection bandwidth Be. To an approximation at high avalanche gain, the surface dark current component Is, which is not subject to gain, is sometimes ignored, and Ib is called Id.

Coherent Signal-To-Noise Ratio:

Heterodyne Detection (Reception)

$$\mathrm{CNR} = \frac{HPrPo(MRi)^2}{[e\{Ri(Pr+Po+NbBo)+Ib\}M^{(2+x)}+eIs+2Nb\{HPo+NbBo\}(MRi)^2+2kTF/RL]Be} \tag{32}$$

Homodyne Detection

$$\mathrm{CNR} = \frac{2HPrPo(MRi)^2}{[e\{Ri(Pr+Po+NbBo)+Ib\}M^{(2+x)}+eIs+2Nb\{HPo+NbBo\}(MRi)^2+2kTF/RL]Be} \tag{33}$$

The electrical signal power is proportional to Pr and the optical mixing efficiency H, and the noise components proportional:

1. To the quantum noise produced by the signal photons.

2. To the shot noise produced by the local oscillator.

3. To the fluctuation noise produced by the background radiation Pb (NbBo). This noise is also proportional to the optical bandwidth and its ratio to the quantum shot noise is effectively inversely proportional to the local oscillator power Po.

4. To the shot noise produced by the bulk dark current in the photo-detector.

5. To the shot noise produced by the surface leakage dark current.

6. To the background radiation beating with the local oscillator, which is very small, the noise being proportional to the noise spectral density and independent of optical bandwidth.

7. To the background noise spectral density squared, which is again very small, the noise being proportional to the optical bandwidth.

8. To the thermal kT noise of the optical front-end, which like the case for all other noise components except that due to the local-oscillator quantum shot-noise, is negligible for sufficient local-oscillator power.

The local-oscillator (L.O.) is assumed to have negligible excess intensity noise or it is balanced out, so that the Relative Intensity Noise (RIN) is at the theoretical quantum noise level.

Note, the excess noise due to a non-Poisson distribution of arriving photons in a power-starved situation, is not included in this expression. Poisson statistics imply that sufficient photons arrive during the observation time to take the probability of the arrival of a photon as being given by a binomial distribution. [83] In situations where the optical receiver is power-starved, i.e., when there are relatively few photons arriving during the signal integration time so that Bose-Einstein [73] statistics apply, the non-white noise associated with statistics of the photon arrival times will lower the effective CNR.

The total noise produced is again proportional to the electrical post-optical detection bandwidth Be. Usually Po >> Pr and Pb, and thus other multiplicative noise components relating to Pr and Pb are not included in these expressions, since they are negligible. For this application the nearest star is several light years away, Po is much larger the background Pb, and the latter component is also negligible for all optical bandwidths, unlike the case for incoherent detection. This is also generally true for large diffraction limited telescopes operating in daylight. For SETI to be practical, the EIRP needs to be extremely high, but since the star is distant, the background Nb is very small. However, for communications within the solar system, these background noise components (from the Sun or reflected light from Earth or another planet) can be significant. [94-95]

For the Amateur Optical SETI analysis, a more conservative approach for assessing the performance of various receiving systems has been employed. Account has been made for the efficiencies of atmospheric transmission, telescope aperture, monochromator (incoherent systems only) and in the case of coherent receivers, an allowance for the optical (heterodyne or homodyne) mixing efficiency.

Expression (31) relates to incoherent detection, while (32) and (33) relate to coherent detection. The ideal shot-noise limited direct detection receiver approaches the performance of the photon-counting receiver at higher received powers. For substantially cooled photon-counting receivers, the dark currents Is and Ib may be taken as zero, and thermal noise is insignificant. In the quantum noise limit, the CNR of the homodyne system is 3 dB more than the heterodyne, which is itself 3 dB more than the direct detection or photon-counting receiver.

Quantum-Noise Limited Signal-To-Noise Ratio:

The Carrier-To-Noise Ratio in a perfect quantum noise limited (656 nm) optical heterodyne system where the L.O. has negligible intensity and phase noise, and where the shot noise from the L.O. swamps all other sources of noise, is given by:

$$CNR = \frac{\eta P_r}{h f B_{if}} \qquad (34)$$

where Pr = received optical power (1.6 nW),
Bif = Intermediate Frequency bandwidth (30 MHz).

One of the major advantages of using the normalized CNR approach is that we can express the CNR for the perfect diffraction-limited ten meter diameter symmetrical heterodyne system, for any transmitter power, range and electrical bandwidth, in the form:

$$\boxed{CNR = 54 + 10.\log(Pt) - 20.\log(R) - 10.\log(Be)\ \text{dB}} \tag{35}$$

where Pt = transmitter power (kW),
R = range (L.Y.),
Be = I.F. bandwidth (Hz).

For Pt = 1 GW, R = 10 L.Y., and Be = Bif = 30 MHz:

$$CNR = 19\ \text{dB}$$

Again, it should be remembered that this relationship (Equ. 35) only holds out to distances where interstellar attenuation is insignificant, and will over-estimate the CNR at very low received optical powers (Pr) and/or higher bandwidths (Be). For a huge transmitting array, the Rayleigh near-field range may be so large (Equ. 7), that the 20.log(R) term disappears from the above expression, and the 54 dB constant has a higher value.

We see that one advantage of coherent detection for this application is that the effective bandwidth determining the relative level of detected background noise is the electrical bandwidth Be, not the optical bandwidth Bo. Since Be can be much less than Bo, coherent receivers have a considerable sensitivity advantage over incoherent receivers in the presence of weak signals and/or significant background radiation, besides being able to allow for the demodulation of phase or frequency-modulated signals. In the case of the heterodyne receiver, Be corresponds to the I.F. bandwidth, and the signal has still to be demodulated. A further stage of "detection", either square-law or synchronous, must be applied to demodulate the intelligence on the signal. For this reason, the signal-to-noise ratio for the radio frequency heterodyne and optical heterodyne systems is denoted as CNR and not SNR.

Signal Integration:

In practically all SETI systems, what is being looked for is an ETI beacon. In such systems, the sensitivity of the receiver is enhanced by post-detection signal integration, perhaps over many seconds. This increases the detected signal level, and reduces the noise level; both at the expense of increasing the search time. This can only be done for detecting the presence of a signal beacon, not for the demodulation of a continuously and rapidly changing non-repetitive signal.

In the case of a microwave or optical receiver with square law detection and an input SNR less than unity, the Signal-To-Noise Ratio can be increased by (post-detection) integration of a number of detected pulses over a period of time. In such a situation, the SNR is proportional to the square-root of (Nc), where Nc is the total pulse count during the observation integration time. [83,88] The same relationship applies to the post-detection counting of individual photons, but not to pre-detection. That is why the quantum limited CNRs (SNRs) for both incoherent and coherent optical detection systems are proportional to the photon count rate. See Equ. 36 below.

Photon-Count Rate:

The equivalent photon-count rate for the heterodyne receiver is given by:

$$N_{ph} = \frac{\eta . P_r}{hf} \ s^{-1} \qquad (36)$$

Alternatively, this can be expressed as CNR.(Bif). For the 1 GW transmitter that results in a CNR = 19 dB re 30 MHz:

$$N_{ph} = 2.64 \times 10^{9} \ s^{-1}$$

This count rate is more than adequate for the photon arrival (and detection) statistics to be taken as Gaussian (Poisson), and hence the CNR expressions should give an accurate figure for the Carrier-To-Noise Ratio. This is reasonably true even for the 1 kW transmitter, where on average, only 5,280 photons arrive per second, of which on average, 2,640 photons are detected every second. However, the method of expressing CNRs in this analysis, even in the power-starved case, allows for a simple linear extrapolation for CNR at any received optical power (Equ. 35).

Bit Error Rate (BER):

This analysis has concentrated on optical signal detectability in terms of SNR not Bit Error Rate (BER), as would be applicable for a digital system. For the sake of completeness, the following expression may be used to predict the photon-count rate for a required BER: [78]

$$m = \frac{-\ln(2.BER)}{\log_2 N} \qquad (37)$$

where m = average number of photons per bit required by an ideal N-PPM (pulse position modulation) system to achieve a given BER.

The photon-count rate is simply the product of m and the bit rate. For an ideal coherent system with on-off keying (OOK) or 1-PPM, $BER = 10^{-9}$, and very small extinction (light off/light on) ratio, $m = 10$ photons/bit. However, a more realistic value is nearer to 20 photons/bit. Thus, for a 1 GHz (approx. 1 GBit/s) channel:

$$\text{Minimum Photon-Count Rate} = 2 \times 10^{10}\ s^{-1}$$

The modelled 1 GW system is a little deficient in being able to achieve this goal, since this required count rate is an order of magnitude greater than the calculated value of Nph. With digital compression techniques, the 1 GW transmitter is capable of supporting a late Twentieth Century digital HDTV signal, compressed into a 10 MHz bandwidth. [87]

Range Equation:

Instead of expressing the CNR as a function of transmitter power, range and bandwidth, we can express the quality of the optical communications link in terms of its maximum range. As before, if we ignore interstellar absorption, the range (in light years) required to reduce the quantum limited CNR to 0 dB for the "perfect" 10-meter diameter 656 nm symmetrical Professional Optical SETI system defined by Equ. 35, can be express in the form:

$$R_{max} = 10^{[\{54 + 10.\log(P_t) - 10.\log(B_e)\}/20]} \qquad (38)$$

where P_t = transmitter power (kW),
B_e = I.F. bandwidth (Hz).

For P_t = 1 GW (EIRP = 2.29×10^{24} W) and B_e = 1 MHz:

$$R_{max} = 500\ \text{L.Y.}$$

Doppler Shift:

The maximum Doppler Shift is given by:

$$df = \frac{v}{c}.f\ \ \text{Hz} \qquad (39)$$

where v = maximum line-of-sight velocity (29.8 km/s),
c = velocity of light (3×10^8 m/s),
f = frequency (4.57×10^{14} Hz).

For a ground-based receiving telescope, the maximum local Doppler Shift at 656 nm due to the orbit of Earth around the Sun:

$$df = \pm 45.5 \text{ GHz}$$

Doppler Drift:

The maximum Doppler Drift (Chirp) is given by:

$$df' = \frac{w^2 . r}{c} . f \text{ Hz/s} \tag{40}$$

where w = angular velocity (7.27×10^{-5} rad/s),
r = radius of planet or orbit (6,378 km).

For a receiving telescope on the equator, the maximum local Doppler Drift at 656 nm due to Earth's rotation is:

$$df' = \pm 51 \text{ kHz/s}$$

Fortunately, for Amateur Optical SETI observations, the Doppler Drift during reasonable observations times is insignificant with respect to the bandpass of the incoherent optical filter (approximately 100 GHz).

APPENDIX B

THE SETI PROTOCOLS

The following information was provided by Robert Arnold of the SETI Institute.

November 20, 1991

Dear Colleague,

It is my pleasure to send you a copy of a document entitled "Declaration of Principles Concerning Activities Following the Detection of Extraterrestrial Intelligence."

The Declaration was developed over a period of several years by the SETI Committee of the International Academy of Astronautics, with the assistance of many experts interested in this question. In April of 1989 it was approved by the Board of Trustees of the Academy, and also by the Board of Directors of the International Institute of Space Law. Over the last two years it has been endorsed by the Committee on Space Research, by Commission 51 of the International Astronomical Union, by the members of Commission J of the Union Radio Scientifique Internationale, and by the International Astronautical Federation.

The document is intended as a series of guidelines for individuals or organizations, national or international, engaged in carrying out radio searches for extraterrestrial intelligence. In the near future it will be sent by the Academy to all such individuals and organizations with a request that they give consideration to endorsing it.

In the meantime, the SETI Committee of the International Academy of Astronautics will continue to review the principles and procedures of the Declaration, and will assemble a special post-detection committee, as indicated in Principle 9 of the document. The Committee is also working on a second declaration, designed to expand the wording of Principle 8 into a process for obtaining international agreement on questions about a reply from Earth after the detection of a signal.

Sincerely,

John Billingham
Chief, SETI Office

Enclosure:

Declaration of Principles Concerning Activities Following the Detection of Extraterrestrial Intelligence -

We, the institutions and individuals participating in the search for extraterrestrial intelligence,

Recognizing that the search for extraterrestrial intelligence is an integral part of space exploration and is being undertaken for peaceful purposes and for the common interest of all mankind,

Inspired by the profound significance for mankind of detecting evidence of extraterrestrial intelligence, even though the probability of detection may be low,

Recalling the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, which commits States Parties to that Treaty "to inform the Secretary General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of the, nature, conduct, locations and results" of their space exploration activities (Article XI),

Recognizing that any initial detection may be incomplete or ambiguous and thus require careful examination as well as confirmation, and that it is essential to maintain the highest standards of scientific responsibility and credibility,

Agree to observe the following principles for disseminating information about the detection of extraterrestrial intelligence:

1. Any individual, public or private research institution, or governmental agency that believes it has detected a signal from or other evidence of extraterrestrial intelligence (the discoverer) should seek to verify that the most plausible explanation for the evidence is the existence of extraterrestrial intelligence rather than some other natural phenomenon or anthropogenic phenomenon before making any public announcement. If the evidence cannot be confirmed as indicating the existence of extraterrestrial intelligence, the discoverer may disseminate the information as appropriate to the discovery of any unknown phenomenon.

2. Prior to making a public announcement that evidence of extraterrestrial intelligence has been detected, the discoverer should promptly inform all other observers or research organizations that are parties to this declaration, so that those other parties may seek to confirm the discovery by independent observations at other sites and so that a network can be established to enable continuous monitoring of the signal or phenomenon. Parties to this declaration should not make any public announcement of this information until it is determined whether this information is or is not credible evidence of the existence of extraterrestrial intelligence. The discoverer should inform his/her or its relevant national authorities.

3. After concluding that the discovery appears to be credible evidence of extraterrestrial intelligence, and after informing other parties to this declaration, the discoverer should inform observers throughout the world through the Central Bureau for Astronomical Telegrams of the International Astronomical Union, and should inform the Secretary General of the United Nations in accordance with Article XI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Bodies. Because of their demonstrated interest in and expertise concerning the question of the existence of extraterrestrial intelligence, the discoverer should simultaneously inform the following international institutions of the discovery and should provide them with all pertinent data and recorded information concerning the evidence: the International Telecommunication Union, the Committee on Space Research, of the International Council of Scientific Unions, the International Astronautical Federation, the International Academy of Astronautics, the International Institute of Space Law, Commission 51 of the International Astronomical Union and Commission J of the International Radio Science Union.

4. A confirmed detection of extraterrestrial intelligence should be disseminated promptly, openly, and widely through scientific channels and public media, observing the procedures in this declaration. The discoverer should have the privilege of making the first public announcement.

5. All data necessary for confirmation of detection should be made available to the international scientific community through publications, meetings, conferences, and other appropriate means.

6. The discovery should be confirmed and monitored and any data bearing on the evidence of extraterrestrial intelligence should be recorded and stored permanently to the greatest extent feasible and practicable, in a form that will make it available for further analysis and interpretation. These recordings should be made available to the international institutions listed above and to members of the scientific community for further objective analysis and interpretation.

7. If the evidence of detection is in the form of electromagnetic signals, the parties to this declaration should seek international agreement to protect the appropriate frequencies by exercising procedures available through the International Telecommunication Union. Immediate notice should be sent to the Secretary General of the ITU in Geneva, who may include a request to minimize transmissions on the relevant frequencies in the Weekly Circular. The Secretariat, in conjunction with advice of the Union's Administrative Council, should explore the feasibility and utility of convening an Extraordinary Administrative Radio Conference to deal with the matter, subject to the opinions of the member Administrations of the ITU.

8. No response to a signal or other evidence of extraterrestrial intelligence should be sent until appropriate international consultations have taken place. The procedures for such consultations will be the subject of a separate agreement, declaration or arrangement.

9. The SETI Committee of the International Academy of Astronautics, in coordination with Commission 51 of the International Astronomical Union, will conduct a continuing review of procedures for the detection of extraterrestrial intelligence and the subsequent handling of the data. Should credible evidence of extraterrestrial intelligence be discovered, an international committee of scientists and other experts should be established to serve as a focal point for continuing analysis of all observational evidence collected in the aftermath of the discovery, and also to provide advice on the release of information to the public. This committee should be constituted from representatives of each of the international institutions listed above and such other members as the committee may deem necessary. To facilitate the convocation of such a committee at some unknown time in the future, the SETI Committee of the International Academy of Astronautics should initiate and maintain a current list of willing representatives from each of the international institutions listed above, as well as other individuals with relevant skills, and should make that list continuously available through the Secretariat of the International Academy of Astronautics. The International Academy of Astronautics will act as the Depository for this declaration and will annually provide a current list of parties to all the parties to this declaration.

INDEX