THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) IN THE OPTICAL SPECTRUM

INTRODUCTION: This two-page summary paper suggests that the Search For Extraterrestrial Intelligence (SETI) is being conducted in an erroneous region of the electromagnetic spectrum, i.e., that SETI receivers are "tuned to the wrong frequencies". Table 1 summarizes the salient points of the comparison between different electromagnetic communications technologies as applied to SETI, using heterodyning telescopes to detect continuous wave (cw) beacons. This paper revisits a subject first discussed by Schwartz and Townes[1] 32 years ago, and subsequently investigated by Ross[2], Shvartsman[3], Connes[4], Zuckerman[5] Betz[6], Sherwood[7] and Rather[8]. Note that according to the modern definition of the word "optical", the wavelength region embraced covers the region between 10 nm (ultra-violet) and 1 mm (far-infrared).

PROFESSIONAL OPTICAL SETI: The tabled calculations are based on a very modest cw transmitted power of 1 kW, over a range of 10 light years. As a modelling convenience they assume symmetrical systems, i.e., that the receiver aperture is identical to that of the transmitter. A microwave system based on the 300 meter diameter Arecibo dish would produce a Signal-to-Noise (SNR) ratio of about 20 dB. It is expedient to normalize the bandwidth to 1 Hz; a bandwidth which is thought to be substantially smaller than the minimum bin bandwidth required for actual SETI observations with Professional Optical SETI receivers. The performance of systems operating at wavelengths towards each end of the visible spectrum, i.e., 656 nm and 488 nm, are very similar. A preferred wavelength, not shown in the table, might be 1,060 nm, corresponding to the Nd:YAG transitions in the near-infrared. The corresponding SNR for a 1,060 nm system is 32 dB. Note that by increasing the 10,600 nm infrared transmitting and receiving telescopes diameters to 20 meters, the SNR obtained can be increased to the same value (34 dB) indicated for the 656 nm visible system. Since the Carbon Dioxide (CO_2) laser is very efficient, coherent, and CO_2 is likely to be readily available where life becomes established, 10,600 nm may be considered a "magic optical wavelength". This wavelength is also capable of propagating with little attenuation across substantial portions of the Milky Way Galaxy, and the beam divergence is such as to make the targeting of nearby stars easier. There is also an atmospheric window at this wavelength.

All these telescopes, save for the Cyclops Array[9], 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, so in practice, several dB may have to be taken off the calculated SNR to account for imperfections, and ground-based atmospheric absorption. Because optical heterodyne receivers are proposed for the professional optical systems, Planckian starlight and daylight have no effect on system performance. 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.[10] This technology should be available within five years.

LINE 11: The reader is left to judge whether ATCs 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 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 the long-range performance of Extraterrestrial Intelligence (ETI) transmitters just because the beams happen to be too narrow for nearby stars. Strelnitskij et al[11] has suggested that ETIs might make use of the moment of opposition to ensure that a narrow beam aimed at a star would be detectable at a target planet approaching opposition.

LINE 20: This shows the apparent visual intensity of the transmitter with respect to the alien star. If the 656 nm 1 kW transmitter power is increased by six orders of magnitude, the received signal will increase to 1.6 nW, 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 F.M. video signal over 10 light years. 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 techniques. The apparent visual intensity of the 1 GW transmitter would rise from an apparent magnitude of +22.7 to +7.7, still below naked eye visibility (6th magnitude) even if not obscured by the light of its star. This is only 0.62% of the star's visual intensity. This result demonstrates that references in the literature to the fact that such signals have never been seen by the naked 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 output radiated in our direction.

LINE 23: The Signal-to-Planck Ratio 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. This leads to the Signal-to-Daylight ratio being about the same as the Signal-to-Planckian ratio. Clearly, even when the signal source and Planckian noise are not optically separable, the ratio of the signal to the Planckian background noise is much greater than the quantum shot noise SNR. Contrary to statements in the literature, there may be no need to select a laser wavelength to coincide with a Fraunhofer line. This is only really useful when incoherent optical detection techniques (see the section on Amateur Optical SETI) with their relatively wideband optical filters are employed for detecting cw beacons. With optical heterodyne receivers, whose performance is essentially independent of optical 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 only be determined by the availability of highly efficient and coherent laser frequencies. The Fraunhofer line suppression benefits are also not required for high-power pulsed beacons and incoherent receivers.

LINE 25: The high Signal-to-Daylight (background) ratio indicates that **Optical SETI is the one branch of visible astronomy, save for solar astronomy, that can be conducted during daylight hours, under a clear blue sky**. Since the background detected per pixel is independent of aperture, this ratio (shown for 45° to the zenith) is proportional to the receiving telescope's aperture area, as is the quantum Signal-to-Noise ratio. The Signal-to-Nightlight ratio for ground-based observatories is some 80 dB greater. Optical SETI observations with the great optical telescopes of the world could be conducted during daylight hours while conventional astronomy is conducted at night. Also, telescopes that have been decommissioned due to light pollution effects might be brought back into service. A future symbiotic relationship 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 $20 million.

LINE 26: This is the bottom-line, showing the SNR normalized to a 1 Hz bandwidth. Minimum Intermediate Frequency (I.F.) bin bandwidths for practical Professional Optical Heterodyne SETI searches should be about 100 kHz. As long as the Signal-to-Planck and Signal-to-Daylight ratios are larger than the SNR, the former do not reduce the system performance. It should be noted that at a frequency of 1.5 GHz ($\lambda = 20$ cm), the full 6.4 km diameter microwave Cyclops Project, which in 1971 would have cost about $10 billion, only achieves an SNR 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 few thousand light years is significantly less than in the visible spectrum, the Microwave Cyclops system has little to commend it, particularly as the cost of the receiver is about 250 times that of a single aperture 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 to LEO and deep-space communications, and much of this work is being coordinated by NASA[12], the SETI community appears to be convinced that ETIs would not use such technology for interstellar communications! This is illogical. Terrene SETI programs appear to have been distorted by poor assumptions in the Cyclops study. In that study, only ground-based transmitters and receivers were considered, and the largest transmitting telescope ATCs (ETIs) would use at 1,060 nm was limited to a diameter of 22.5 cm! Present-day experimental ground-based free-space communications links are already using receiving telescope apertures as large as 1.5 m, and the author's Amateur Optical SETI (AMOSETI) receiver is slightly larger than 22.5 cm! Since the overall performance of symmetrical systems is proportional to the telescope diameter raised to the sixth to eighth power, poor estimations about transmitting and receiving telescope apertures can drastically skew a comparative systems analysis. SETI would not seem so mysterious to the lay person if it was recognized that this is just another communications problem, albeit complicated by the fact that we don't know where to look, when to look, the transmission frequency or modulation format.

Unfortunately, despite declarations to the contrary, many SETI activists have been very anthropocentric, and have in the main assumed that ETIs are technically inept. This has caused a gross underestimate of the technical prowess of ETIs, e.g., their capability to aim very high-power tight beams into the zones of life of nearby stars. The onus will be on them to transmit the strongest signal (with stellar or nuclear-pumped orbital lasers). It is humbling to remind ourselves, that a century ago, very few people on this planet used electricity - we have come a long way in a short time!

AMATEUR OPTICAL SETI: On the assumption that ETI technology would appear to late 20th Century man to be like "magic", it is imagined that ETIs will be using much larger transmitting telescopes or arrays, and transmitter powers far in excess of 1 kW[8]. In practice, the signal is likely to be pulsed [2]; and thus less detectable by normal integrating detectors, i.e., the naked 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 so increase public and scientific interest in all forms of SETI, that this field of scientific endeavor will at last get the financial support it richly deserves. The high cost and technical difficulties of optical heterodyne detection in the visible and near-infrared spectrum, means that the amateur's receiver and early professional receivers will most likely have to use photon-counting, a little cooling and a monochromator or selection of optical bandpass filters. Unlike coherent receivers, incoherent receivers do not have the ability to reject Planckian starlight and daylight background noise if the signal is weak. However, if extremely high-power pulse signals are assumed, then even small photon-counting receivers can yield detectable signals.

An Effective Isotropic Radiated Power (EIRP) = 10^{23} W at a range of 10 light years produces a signal intensity of 10^{-12} W/m^2, with an apparent magnitude of 11, and thus would not be visible (Sun's EIRP = 3.9×10^{26} W). Using slightly more conservative assumptions than employed to derive Table 1, if we assume an amateur telescope of about 30 cm diameter (12"), a scanning grating monochromator bandwidth of 100 GHz (0.143 nm) at 656 nm, a receiver with a single perfect photon-counter, and a received flux density of 10^{-12} W/m^2, the SNR is about 39 dB re 1 Hz for a cw beacon. This is an SNR penalty compared to the performance of a 10 meter heterodyning array receiving telescope of about 34 dB. Starlight and daylight sky backgrounds only slightly affect the SNR for this range and optical bandwidth, and the 10 to 20 dB Fraunhofer Planckian suppression factor has not been included; allowance for which would improve the performance for weaker signals. If an ETI signal is detected, given an adequate SNR, it might even be possible for an amateur observer to demodulate a signal of moderate bandwidth. An amateur Optical SETI observer could most profitably search for strong pulsed signals of about 1 ns duration, rather than weak cw beacons, with only modest optical filtering, since such signals might actually briefly outshine the ETIs' star! The author is presently designing and building what is believed to be the world's first Amateur Optical SETI Observatory, based around the 10" (25.4 cm) Meade LX200 Schmidt-Cassegrain telescope. It will initially use an ultra-fast photomultiplier in an attempt to detect fast ETI pulses.

It may not be ridiculous to suggest that eliciting the help of thousands of enthusiastic amateur astronomers might considerable aid the low-sensitivity Targeted Search of the entire sky. An All Sky Survey of the type planned for the High Resolution Microwave Survey (HRMS), which pixelizes the entire celestial sphere, does not make sense in the optical regime. There, the narrow diffraction-limited field-of-view, means that for most of the time the optical detector(s) would be viewing empty space. It is estimated that a basic amateur system (with a single photodetector) could be constructed for about $8,000, though sophisticated systems would cost considerably more. Who knows, perhaps ETIs don't expect their signals to be detected until the targeted civilizations make a collective, cooperative and systematic search of their home skies!

FIRST INTERNATIONAL CONFERENCE ON OPTICAL SETI: On January 21-22, SPIE will be holding a historic conference on Optical SETI (Conference 1867) which is being organized and chaired by the author. Among the 16 papers scheduled: Dr. Peter Backus who is the Active Deputy Project Scientist for the Targeted Search portion of NASA's HRMS, will give the keynote paper on NASA's search for evidence of extraterrestrial technologies. Drs. David Latham and David Soderblom will discuss the strategies for the SETI star targeting survey and Drs. Michael Klein and Samuel Gulkis from JPL will describe the high-resolution all-sky survey. The "Grand Old Man" of SETI, Dr. Bernard M. Oliver, who is extremely critical of the optical approach, will demonstrate for the first time to the laser communications community why ETIs would not use lasers for (SETI) interstellar communications. Professor Frank Tipler, a strong critic of SETI, will explain why both Microwave and Optical SETI is a waste of time, since he thinks that we are the first civilization in this galaxy.

Philosopher Clive Goodall will rebut Frank Tipler's arguments, and noted philosopher Professor Neil Tennant will present his view of why there could be major problems in actually decoding the message on an ETI signal. This may be the first time that philosophers have presented papers at a technical meeting organized by SPIE. Dr. Guillermo Lemarchand will describe both Radio and Optical SETI activities in Argentina, and give an account of the MANIA Optical SETI project devised by the late Professor Shvartsman of the former Soviet Union. Drs. John Rather and Monte Ross (conference co-chairman) will give accounts of their approaches to interstellar laser communications. Dr. Ross believes the M-ary Pulse Position Modulation (PPM) would be most effective for interstellar communications. This author will present a review paper and describe the amateur approach to Optical SETI. There will be a workshop at the end of the conference, moderated by Professor Charles Townes (1964 Nobel laureate - lasers/masers), who earlier will talk about his CO_2 Optical SETI laser work, and the CO_2 Optical SETI observations being conducted by Dr. Albert Betz on Mt. Wilson.[13-17]

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Table 1 Summary of SETI cw beacon system performance for (symmetrical) professional heterodyne receivers at a range of 10 Light Years.

PARAMETER	MICROWAVE SETI		OPTICAL SETI		
	CYCLOPS ARRAY	SINGLE DISH	INFRARED	VISIBLE	
1. Wavelength	0.20 m	0.20 m	10.6 µm	656 nm (red)	488 nm (green)
2. Frequency, Hz	1.50 X 10^{9}	1.50 X 10^{9}	2.83 X 10^{13}	4.57 X 10^{14}	6.15 X 10^{14}
TRANSMITTERS					
3. Diameter, m	6,400	100	10	10	10
4. Gain, dB	93.5	63.9	129.4	153.6	156.2
5. FWHM Beamwidth, arcseconds	6.57	421	0.223	0.0138	0.0103
6. Power, kW	1	1	1	1	1
7. EIRP, W	2.22 X 10^{12}	2.47 X 10^{9}	8.78 X 10^{15}	2.29 X 10^{18}	4.14 X 10^{18}
RECEIVERS					
8. [a] Diameter, m	6,400	100	10	10	10
9. Gain, dB	93.5	63.9	129.4	153.6	156.2
10. FWHM Beamwidth, arcseconds	6.57	421	0.223	0.0138	0.0103
11. FWHM Received Beam Diameter, A.U.	20.2	1290	0.684	0.0423	0.0315
12. Received Intensity, W/m^2	1.97 X 10^{-23}	2.19 X 10^{-26}	7.81 X 10^{-20}	2.04 X 10^{-17}	3.68 X 10^{-17}
13. Received Signal, W	1.40 X 10^{-16}	1.72 X 10^{-22}	6.13 X 10^{-18}	1.60 X 10^{-15}	2.89 X 10^{-15}
14. Photon Count Rate, s^{-1}	NA	NA	163	2,640	3,544
15. [b] Equivalent Stellar Magnitude	NA	NA	NA	+22.7	+22.1
16. Quantum Efficiency	NA	NA	0.5	0.5	0.5
17. Effective Noise Temperature, K	10	10	2,719	43,900	59,070
18. Planckian Starlight, W/m^2.Hz*	8.80 X 10^{-33}	8.80 X 10^{-33}	1.07 X 10^{-25}	2.74 X 10^{-24}	1.77 X 10^{-24}
19. Star Stellar Magnitude	NA	NA	NA	+2.2	+2.2
20. [c] Relative Brightness, %	NA	NA	NA	6.2 X 10^{-7}	1.1 X 10^{-6}
21. [d] Alien Planet Magnitude	NA	NA	NA	+24	+24
22. [e] Signal-To-Planck Ratio, dB*	90.5	64.0	55.7	65.7	70.2
23. [f] Signal-To-Planck Ratio, dB*	90.5	64.0	69.5	115.7	124.2
24. [g] Daylight/Sky Background, W/m^2.sr.nm	NA	NA	2 X 10^{-3}	1 X 10^{-1}	1 X 10^{-1}
25. [h] Signal-To-Daylight Ratio, dB*	NA	NA	50.6	106.0	113.7
26. [i] Signal-To-Noise Ratio, dB*	60.1	1.0	22.1	34.2	35.5
27. [j] Radial Doppler Shift, Hz	±1.0 X 10^{5}	±1.0 X 10^{5}	±1.9 X 10^{9}	±3.1 X 10^{10}	±4.1 X 10^{10}
28. [k] Orbital Doppler Shift, Hz	±1.5 X 10^{5}	±1.5 X 10^{5}	±2.8 X 10^{9}	±4.6 X 10^{10}	±6.2 X 10^{10}
29. [l] Synchronous Doppler Chirp, Hz/s	±1.1 X 10^{0}	±1.1 X 10^{0}	±2.1 X 10^{4}	±3.4 X 10^{5}	±4.6 X 10^{5}
30. [m] Ground-Based Doppler Chirp, Hz/s	±1.7 X 10^{-1}	±1.7 X 10^{-1}	±3.2 X 10^{3}	±5.1 X 10^{4}	±6.9 X 10^{4}
31. [n] Symbiotic Ground-Based Receiver Cost, $M	NA	5	50	50	50
32. [o] Ground-Based Receiver Cost, $M	50,000	200	200	200	200
33. [p] Space-Based Receiver Cost, $M	?	100	10,000	10,000	10,000

In the galactic plane, Signal-To-Noise Ratios in the visible regime fall at the rate of 20 dB per decade of range, out to approximately several thousand light years, when attenuation then starts to become significant.
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-Planck/Daylight Ratios assume polarized starlight and background, and no Fraunhofer dark-line suppression (typically 10 to 20 dB).

[a] The Cyclops Array proposed in 1971, consisted of 900, 100 meter diameter dishes covering an area 6.4 km in diameter.
[b] Apparent magnitude of transmitter is not corrected for visible wavelength.
[c] Relative brightness of transmitter in comparison to unpolarized Planckian starlight (black-body emitter at 5,800 K).
[d] Apparent Stellar Magnitude of reflected Planckian starlight from a Jupiter-size alien (extra-solar) planet.
[e] Signal-To-Planck Ratio at the heterodyned I.F. frequency, assuming star and transmitter are not separately resolved.
[f] Signal-To-Planck Ratio at the heterodyned I.F. frequency, assuming star and transmitter are separately resolved.
[g] Background daylight sky radiance for ground-based visible telescopes and infrared telescopes (24 hr/day, 300 K atmosphere).
[h] Signal-To-Daylight Ratio (per pixel) for diffraction-limited ground-based visible telescopes and infrared telescopes.
[i] For convenience, Signal-To-Noise Ratios are normalized to a 1 Hz electrical bandwidth.
[j] Typical Doppler shift due to line-of-sight relative motions between stars at 20 km/s.
[k] Maximum local Doppler shift due to motion of transmitter/receiver around solar-type star (1 A.U. orbit).
[l] Maximum local Doppler drift (chirp) for transmitter/receiver in geosynchronous orbit around Earth-type planet.
[m] Maximum local Doppler drift (chirp) for a ground-based transmitter/receiver on an Earth-type planet.
[n] Approximate ground-based receiver cost (1993 millions), assuming re-use or sharing of existing observatories in each hemisphere.
[o] Approximate ground-based receiver cost (1993 millions), assuming a new dedicated (adaptive optical) telescope in each hemisphere.
[p] Approximate receiver cost (1993 millions) for a single space-based telescope.

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