Optical SETI for Academics and Amateurs

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ABSTRACT

A high-intensity pulsed laser, teamed with a moderate sized transmitting telescope, forms an efficient interstellar beacon. To a distant observer in the direction of its slender beam, such a laser transmitter, built with "Earth 2000" technology only, would appear (during its brief pulse) five thousand times brighter than our sun in broadband visible light in the direction of its slender beam; even at ranges of 1000 light years a single nanosecond laser pulse would deliver roughly a thousand photons to a 10-meter receiving telescope. The Harvard SETI group has developed a targeted search experiment that has examined 5000+ stars for short optical pulses during the past 2 years. A second, nearly identical observatory in Princeton, New Jersey will be coming online in a matter of months. These experiments will observe the same targets simultaneously, with a relative timing precision of 0.1 microseconds, allowing for unambiguous identification of short optical pulses. In the Harvard SETI group, we are also developing an all-sky survey that will search the entire Northern sky for extraterrestrial laser flashes. In this paper, I will introduce optical SETI, compare it with radio SETI, discuss our current targeted search, and offer suggestions for low-cost amateur optical SETI experiments.

Subject headings: interstellar communication; SETI

1. Introduction

Historically the Coccini and Morrison suggestion (1959) that SETI be carried out at the 21 cm wavelength of neutral hydrogen came at a time in our technological development when no other astronomical lines were known in the microwave, and there were no lasers. The rapid development of laser technology since that time – a Moore's Law doubling of capability roughly every year – along with the discovery of many microwave lines of astronomical interest, have lessened somewhat the allure of hydrogen-line SETI. Indeed, on Earth the exploitation of photonics has revolutionized communications technology, with high-capacity fibers replacing both the historical copper cables and the long-haul microwave repeater chains. Additionally, the elucidation of the consequences to SETI of interstellar dispersion (first seen in pulsar observations) has broadened thinking about optimum wavelengths. Even operating under the prevailing criterion of minimum energy per bit transmitted, one is driven upward to millimetric wavelengths.

Moreover, there are other considerations that might well encourage the use of shorter wavelengths still. A transmitting civilization might wish to minimize transmitter size or weight, or use a system capable of great bandwidth, or perhaps design a beacon that is very easy to detect.

In comparing the relative merits of radio vs optical, it has sometimes been incorrectly assumed that one would always prefer coherent (heterodyne) detection, and that the noise background is given by an effective temperature $T_n = h\nu/k$. For high resolution spectroscopy one must use such a system, mixing the optical frequency down to microwave frequencies where radio techniques can be used; but if one is interested instead in the detection of short pulses it is far better to use photon-counting detectors (e.g., photomultipliers). That is because the process of heterodyning and linear detection is *intrinsically* noisy, for fundamental reasons: because heterodyne detection allows a measurement of phase, there must be uncertainty in the amplitude. The added noise is immaterial in the radio region, where there are many photons per mode; but it is serious in the optical, where the photon field is dilute.

Townes (1961, 1983) has made a comparison of received SNR vs wavelength, making reasonable assumptions about antenna apertures and accuracies, detection methods, transmitter power, and so on. The bottom line is that optical methods are comparable, or perhaps slightly preferred, *in the single figure of merit of delivered SNR for a given transmitter power.* Other factors are obviously important – for example penetration of an atmosphere (which favors microwave) or the advantages of pulsing and high data rates (which favors optical) – and could easily tip the balance. The conclusion is that the SETI community's historical bias toward microwaves should surely be reconsidered.

Laser technology is in a phase of rapid catchup relative to the mature technology at radio frequencies. Recently lasers with a megawatt of continuous optical output have been built, and picosecond pulses of a petawatt (10^{15}W) have been produced. Progress in solid-state lasers has been impressive, and there are laser designs on the drawing board that would produce repetitively pulsed megajoule nanosecond pulses. As we will show below, optical pulsed beacons formed with that sort of technology permit detection with very simple apparatus – just a telescope with a pair of white-light photomultipliers in coincidence.

2. Feasibility with Present Technology

It is a useful exercise to calculate the features of an optical SETI transmitter and detector using only "Earth 2000" technology. This section is not intended to be a blueprint for a future transmission scheme; rather, it is a sanity check that pulsed optical beacons are a sensible way to make interstellar contact.

2.1. Transmitters and Detectors

Let us consider a civilization, at least as technologically advanced as our own, that wishes to establish contact with its galactic neighbors. Its task would be to irradiate the planetary zones of the nearest N stars within some range $R_{\max}$[1] with a beacon distinguishable from astrophysical phenomena and from noise.

We assume that the transmitting civilization has a catalog of target stars, their positions, proper motions and ranges with sufficient accuracy to permit aiming to an error no greater than ~ 10 AU when the beam reaches the target. At a range of 1000 ly, this corresponds to a proper motion uncertainty of 33 μas/year and a positional accuracy of 33 mas. This is certainly within the grasp of an advanced civilization since the *Earthly* field of astrometry will achieve μas precision early in the next century.

To send a pulse to $N = 10^6$ stars with a single laser system, the sender would probably use an assembly of fast beam steering mirrors of relatively small size and weight, in combination with a large objective that is steered slowly. Assuming that the sending apparatus could settle to diffraction limited pointing in ~ 0.01 sec (feasible by today's engineering standards), the recipient would observe an optical pulse coming from a nearby star repeated every 10^4 seconds. (This period could be dramatically reduced by transmitting only to an intelligent subset of the targets and/or by using multiple transmitters.) As will be shown below, each pulse would contain a substantial number of photons and would be substantially above all known terrestrial and astrophysical backgrounds (assuming reasonable apertures, pulse energies, etc.).

These pulses could be detected with a reflecting telescope of modest aperture followed by a beamsplitter and a pair of photodetectors of nanosecond or better speed. (We choose nanosecond because it is roughly the speed of PMT's, and all known backgrounds disappear at this time scale). The electronics could be a pair of pulse height discriminators driving a coincidence circuit. The telescope would track the star by the photodetector's "singles" rate while waiting for the unique coincidence signature of some hundred photons arriving in each detector within the resolving time of a nanosecond. As we will see, this signature is easily detected even in broadband visible light; i.e. no spectral filters are required.

2.2. A Transmission Scheme

To give a sense of the difficulty (or relative ease) of interstellar communication by optical pulses, we calculate several useful quantities for one specific

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[1] $R_{\max}$ is comparable to the average separation between intelligent civilizations; $N = 10^3$ for $R_{\max} = 100$ ly and $N = 10^6$ for $R_{\max} = 1000$ ly

transmission scheme: a "Helios" laser [2] beamed 1000 ly between two 10-meter Keck telescopes, each orbiting a Sun-like star. We should note that this "Earth 2000" scheme is surely modest in technological sophistication and scale for a truly advanced civilization.

The transmitted beam is slender as it emerges from transmitting telescope, $\theta_b \approx \lambda_H/D_K = 20$ mas (6 AU at 1000 ly). Its short (3 ns) and energetic ($E_p = 4.7$ MJ) pulses arrive at the receiving telescope as

$$\begin{aligned} N_R &= \frac{\pi^2 D_K^2 D_K^2 E_p 10^{-4R/5R_E}}{16\lambda_H R^2 hc} \\ &= 1200 \text{ photons} \end{aligned} \tag{1}$$

unbroadened in time. If the beam is broadened to irradiate a 10 AU disk, then the number of received photons drops to ~ 500 per pulse. Here D_K is the telescope diameter, $10^{-4R/5R_E} = 0.78$ is the extinction factor ($R_E \approx 1.15$ kpc is the distance over which the intensity of a 1 μm pulse will decrease by 2 magnitudes; note that R_E is a rapidly increasing function of wavelength), $\lambda_H = 1.047\ \mu$m is the wavelength of the transmitted photons and $R = 1000$ ly is the distance between the telescopes. The stellar background is quite small, $\sim 3 \times 10^{-2}$ photons/ns for a G2V star.

The interstellar medium both scatters and absorbs these optical pulses. The effects of scattering over large distances can be quite severe. It tends to reduce the "prompt" pulse height while simultaneously producing two exponential tails, one due to forward scattering (which lasts a few seconds), as well as a much longer tail due to diffuse scattering. The prompt pulse ("ballistic" photons) is unscattered (therefore unbroadened in time) and reduced in amplitude. Absorption also reduces the prompt pulse height so that the total surviving fraction is $e^{-\tau}$, where $\tau = \frac{4}{5}\frac{R}{R_E}\log_e 10$ is the total optical depth, as mentioned above. Note that the $\sim$20% extinction is modest for the range considered above (1000 ly), but becomes unmanageable for distances substantially greater than R_E.

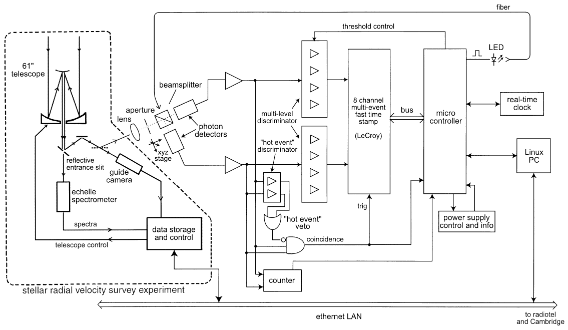

Fig. 1.— Block diagram of the targeted search at Agassiz Station.

Thus in this example the broadband and scattered laser outshines its parent star by a factor of 5000! But we must not forget that advanced civilizations are supposed to be more *advanced* than we are! "Earth 2000" technology should be a lower bound on the technical sophistication of extraterrestrial civilizations. With a modest extrapolation of another 2-3 orders of magnitude in delivered flux, which can hardly be considered daring given the Moore's law pace of the optical laser industry, we conclude that a moderately advanced civilization should have no trouble outshining its parent star by six or more orders of magnitude.

3. Targeted Optical SETI at Harvard

3.1. The Experiment

Our targeted search program runs piggyback on a stellar radial-velocity survey at the 1.5 m telescope at Agassiz Station in Harvard, Massachusetts. These experiments use an echelle spectrograph to measure the periodic Doppler shifts of stellar spectra indicating unseen companions. Our experiment takes about one third of the light from the relatively narrow field of view (a 15 arcsec circular patch) of the telescope, unused by the primary spectrograph, as shown in Fig. 1.

This light is re-imaged and passes through a beamsplitter into two hybrid avalanche photodiodes (Hamamatsu R7110U-07), whose outputs feed a pair of multi-level discriminators with levels corresponding to roughly 3, 6, 12, and 24 photoelectrons. By time stamping level crossings with a LeCroy MTD-135, we obtain approximate "waveforms" of incoming pulses.[3] Coincident pulses

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[2] "Helios" is a diode-pumped Yb:S-FAP laser in development at LLNL for inertial confinement fusion that is potentially capable of 3 ns, 3.7 MJ pulses (10^{15} W) at 349 nm (or 4.7 MJ at the native 1.047 μm wavelength) at $\sim$10 Hz reprates (Slusher 1999).

[3] Actually, the microcontroller records the *last* rise and fall

seen in both channels trigger the microcontroller to record the waveform profiles and arrival times of both channels. A "hot event" veto filters out a class of large amplitude, bipolarity signals which appear to be produced by breakdown events in the photodetectors. Counters, and various controls and monitors allow us to test the apparatus and monitor its long term fitness. Fiber-coupled LEDs test the detectors and coincidence electronics before every observation.

The diagnostic data, along with coincident pulse data, are sent to a PC and recorded in a log file. After each night of observations, the log files are automatically transferred to computers at Harvard University where they are incorporated into a web-enabled database to facilitate analysis. We track the data through automated daily emails which summarize the previous night's observations. Additionally, the web-enabled database allows us to easily view the data in many forms: chronological summaries, ordered searches by various criteria, observational summaries for individual objects, diagnostic data for particular observations, etc.

Our target list is composed of objects being surveyed both for SETI and for other astrophysical interests. Dave Latham and colleagues have recently begun characterizing 11,000 F, G, and K dwarfs for possible observations by next generation targeted SETI searches. Specifically, they're looking for evidence of stellar companions that would interfere with planets in the habitable zone. A sample of G dwarfs is being probed for close-in giant planetary companions to determine their galactic frequency and metallicity distribution. Various other programs observe a variety of other targets (A dwarfs, very young stars, very old stars in the Solar neighborhood, etc.).

3.2. Results

From October 1998 through January 2001, the targeted search has performed 18,000+ observations of 5,000+ stars, for a total of 95+ days of observation. We do not have any evidence for pulsed optical beacons from extraterrestrial civilizations.

During this time, we have had over 4300 "hits." We define a hit to be an instance when the lowest thresholds are simultaneously exceeded in both channels. Although all hits are recorded, the "waveforms" are automatically passed through a filter which enforces certain sanity checks: the signals seen in each channel must be roughly the same amplitude (within one level of each other), and they must overlap in time (this is used to filter a class of hits in which one channel rises again after the other channel shows no signal). The subset of hits which pass this test are labeled "good hits"; to date, we have registered over 1400. We do not believe that this categorization scheme misses extraterrestrial beacons: the LED test flashes, which are done before every observation, have *never* failed this test.

There is a marked systematic seasonal trend in the rates of coincident hits; in particular, the detectors appear to be sensitive to ambient humidity. During the cold, dry months of fall, winter, and early spring (October-April), the data exhibits a good hit rate of 0.15 hits per hour of observation and a total hit rate of 0.64 hits per hour of observation. However, the hit rates are 30-40 times higher during the warmer and more humid summer months (May-September). Furthermore, we see a memory effect: observations following wet weather exhibit hit rates many times higher than the summer average, but drop back after 1–2 nights of clear weather. Opening the camera (which is normally kept tightly closed and flushed with dry nitrogen) for maintenance work similarly raises hit rates, but with a longer decay time constant ($\sim$15 days). These hits tend to be clustered in time with, say, 10 hits in 3 minutes followed by many quiet 10's of minutes, a characteristic typical of corona discharge.

We believe that humidity promotes corona breakdown in one detector, which affects the other detector via electromagnetic (EMI) and optical coupling. The small hybrid avalanche photodiodes run at 7.5 kV (compared to photomultiplier tubes, which typically run at 1 kV), and are prone to corona breakdown. To combat this problem we have added gas lines to the optical and electrical compartments, to keep them under a slight positive pressure of dry nitrogen, and we installed a glass entrance window. We also installed bakeout heaters (250 W total) to the aluminum exterior of the experiment to purge absorbed moisture. Al-

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times of a waveform through the four levels. This arrangement does not record detailed measurements of complex waveforms (double pulses, for example).

though most of these upgrades were completed only recently, the summer good hit rate appears to have gone down to 0.2-0.4 per hour of observation. We believe that we have largely mitigated the humidity problem, and that regular bakeouts can reduce it to levels such that no seasonal data needs to be excluded.

We have ruled out stellar photon pileup as a significant source of hits. At nanosecond time scales, photons arrive at our detector individually; multi-photon pileups are exponentially suppressed.

In order to check if the distribution of objects with a given number of good hits is consistent with the distribution of integration time per object and the good hit rate we performed a Monte Carlo simulation. The simulation randomly distributes the good hits over the list of integration times. We found that the distribution of actual good hits is entirely consistent with randomly timed good hits.

4. Amateur Optical SETI

It seems entirely reasonable that a dedicated amateur astronomer could build a targeted optical SETI search, similar to the one described above, on a modest budget. The following this author's suggestions for such a system.

Since modest size telescopes cannot support the weight of an optical SETI experiment bolted onto the side, the light could fed into a separate box via optical fiber.

Photomultiplier tubes or photodiodes could be used in place of the more expensive hybride avalanche photodiodes. Some academic optical SETI programs (such as the one at UC Berkeley) use these tubes and they function adequately for optical SETI (although they do suffer from inferior pulse height resolution). The beamsplitting/coincidence technique is essential for low background rates though, and should not be sacrificed.

The electronics which discriminate and read out pulses need not be "event driven"; an alternative is to design a system that simply counts the number of nanosecond optical flashes in a time interval (perhaps a second).

Coordination of multiple observers simultaneously looking at the same object is essential for a large scale amateur effort. The coordination could be semi-automated online with GPS clocks providing exquisite time precision. As I demonstrated above, even with moderate background rates at one observatory, the rates of inter-observatory coincidence are astronomically low. Coordinated multiple observatories also add to the believability of a potential detection.

The electronics for an amateur OSETI experiment could be simplified and put on to a single chip or on a standard board. This design could simply be a variation on one of the currently running OSETI experiments.

This paper is based on previous works by this author (paper IAA-00-IAA.9.1.08 presented at the 51st International Astronautical Congress, and a paper (**?**) presented at Bioastronomy '99), and by Paul Horowitz (the "technical paper" available at http://www.oseti.org). The targeted search program at Harvard was designed, built and maintained by Paul Horowitz, Jonathan Wolff, Charles Coldwell, and others. This experiment has continued through the efforts of tireless astronomers at Agassiz Station: Robert Stefanik, David Latham, Joe Zajac, Joe Caruso. I graciously acknowledge the enlightened and continued support of The Planetary Society, the Bosack-Kruger Charitable Foundation, and the SETI Institute. I also wish to thank Nathan Hazen and James Oliver for their invaluable engineering input and for their technical drawings.

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