Optical SETI At Harvard-Smithsonian

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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) a thousand times brighter than our sun in broadband visible light; even at ranges of 1000 light years a single nanosecond laser pulse would deliver roughly a thousand photons to a 10-meter receiving telescope. We have built a photometer to search for such unresolved pulses, and are using it in a piggyback targeted search of some 2500 nearby solar-type stars. The photometer receives about 1/3 of the light focused by the 1.5-meter optical reflector, otherwise unused by the primary experiment (a stellar radial-velocity survey). A beamsplitter followed by a pair of fast hybrid avalanche detectors is triggered in coincidence to record the time and intensity profile of large pulses. In the first year of operation the system has made ~8500 observations of ~2500 separate stellar candidates, amounting to 50 days of cumulative observation time. We review those observations, and suggest follow-on experiments.

1. Introduction

The merits of optical SETI (as compared to microwave SETI) are well documented elsewhere (Schwartz & Townes 1961, Ross 1965, Townes 1983, Kingsley 1993), but we highlight a few advantages here. First, transmitted beams from optical telescopes are far more slender than their radio counterparts owing to the high gain of optical telescopes (150 dB for the Keck Telescope versus 70 dB for Arecibo). Dispersion, which spectrally broadens radio pulses, is completely negligible at optical frequencies. The capability of radio transmitters has reached a stable maturity, while the power of optical lasers has shown an annual Moore's law doubling extending over the past 30 years. And finally, the computational power and sophistication characteristic of the sensitive microwave searches today is unnecessary for optical SETI. Detection can be quite simple – a pair of fast, broadband photon counting detectors 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 $R_{\max}$ (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) 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 (or more generally, a packet of information of short duration) 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. Backgrounds

When detecting light pulses from the neighborhood of a star, the most obvious background is light from the star itself. We circumvent this difficulty by using fast detectors ($\sim$ns speed) so that the light from the star is just a slow drum beat of essentially single photons. A G2V star at 1000 ly ($m_V = 12$) delivers $\sim 3 \times 10^5$ photons/sec to a 1-meter telescope. The Poisson-distributed arrivals do not significantly pile up; observing a single photon is rare in a nanosecond and large pulses are exponentially suppressed.

Early experiments by Dan Werthimer at Berkeley demonstrated the need for a pair of photodetectors wired in coincidence to reject the occasional large pulses due to instrumental effects. This technique virtually eliminates detection of events due to radioactive decay in the detector glass, from ion feedback, from scintillation in the glass due to electron collisions from within, and from cosmic-ray muons (expect for a few rare muons with a trajectory through both detectors or though common optics). These last events can be vetoed with a muon "paddle" detector.

Cerenkov radiation produces potentially problematic short optical pulses. Although the observed atmospheric flash of light within the ~150 m footprint is fast (~5 ns), its diffuse source size of ~2° (as seen from the ground) ensures that multiple photons are rarely observed; within a 10 arcsec field of view, a 1-m telescope sees $\sim 6 \times 10^{-5}$ photons from a 10^{12} eV event. More energetic cosmic-rays, which might be detected from their electron showers, are sufficiently rare that they form a negligible background (Grindlay 1998).

Reflected lightning from distant storms (we do not observe during *local* storms) and other atmospheric and cultural effects do not contribute background with a nanosecond characteristic time scale. Airglow and scattered zodiacal light is a source of *steady* background, however it is entirely negligible ($\sim 10^3$ photons/arcsec^2 per second).

2.3. 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 transmission scheme: a "Helios" laser [1] 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 $N_R = \pi^2 D_K^2 D_K^2 E_p 10^{-4R/5R_E} / 16 \lambda_H R^2 hc = 1200$ photons 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), $\lambda_H = 1.047$ μm 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.

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[1] "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 ~10 Hz rep-rates (Krupke 1996).

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.

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. The Oak Ridge Observatory Experiment

3.1. How it works

During the past year, we have searched for the short optical pulses described above. Our experiment runs piggyback on the stellar radial-velocity surveys at Oak Ridge Observatory. These experiments use an Echelle spectrograph to look for periodic Doppler shifts in stellar spectra indicating the presence of unseen companions. Our apparatus takes roughly half of the light that reflects off the entrance slit of the Echelle (about one third of the total light), 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 optical photons. By time stamping level crossings with a LeCroy MTD-135, we obtain an approximate "waveform" of incoming pulses. Coincident pulses seen in each channel trigger the microcontroller to record the waveform profile and arrival time in the two channels. A "hot event" veto filters out a class of large amplitude, bipolarity signals which are likely produced by breakdown events in the photodetectors. Fiber-coupled LED test flashers, counters, and various controls and monitors allow us to test the apparatus before every observation and monitor its long term fitness. This 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 their data are incorporated into a web-enabled database for easier analysis.

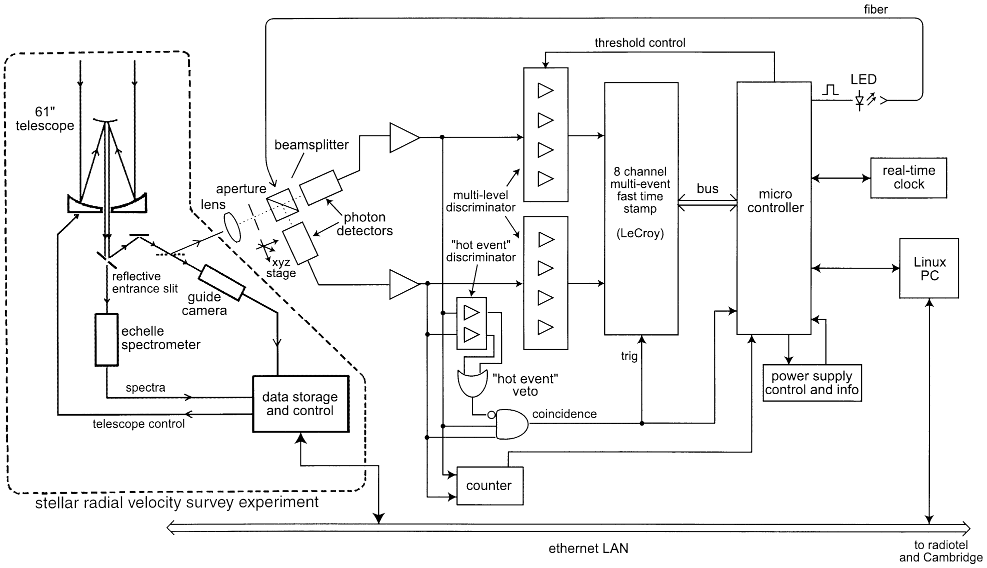

Figure 1. Block diagram of Oak Ridge Observatory experiment.

3.2. Results

From October 1998 through November 1999, we have made some 8500 observations of ∼2500 stars yielding ∼2200 events (or hits). Of these hits, approximately 850 pass a "reasonableness" test: the pulse pair overlap in time and match in peak amplitude to within one level of each other (hits passing this test are hereafter called "good hits").

All of these events clearly cannot be "real signals" for several reasons. The most compelling is that a set of "dome closed" runs, taken during cloudy nights, produced roughly the same hit rate. We also note that the hit rate dramatically increased during the summer months of 1999 and fell back to pre-summer levels in the fall. We suspect that the photodetectors are strongly temperature and/or humidity sensitive, and plan to control the detector environment[2]. Finally, the events show no correlation with stellar magnitude, indicating that they do not result from photon pileup.

Removing the summer months with their apparent detector artifacts, we are left with a residue of a good hit every 5-10 hours of observation. These events are distributed roughly evenly over about 100 stars with a handful of stars having more than one good hit. At this point, we have no evidence for intentional laser signals in our observations.

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[2] We initially suspected that the high count rates were due to muon-induced Cerenkov scintillation in the beamsplitter. To check this theory, we replaced the cubical beamsplitter with a "thin" (1 mm) dielectric film beamsplitter; the background hit rate was unchanged.

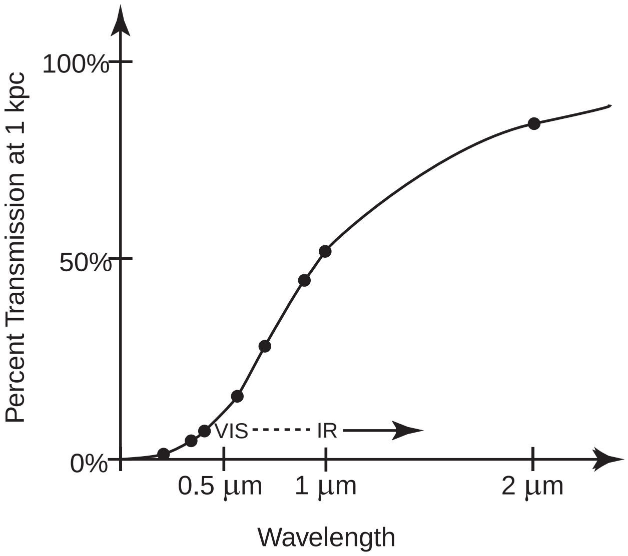

Figure 2. Transparency of the interstellar medium as a function of wavelength (after Allen 1973).

3.3. Future Plans

Simultaneous observations: Given our background rate of roughly one good hit (of nanosecond timescale) per observing night (apart from summer months), it is highly desirable to make simultaneous observations from a pair of widely spaced observatories; a good hit seen simultaneously at both observatories from the same source is likely an intentional laser signal, or a previously unknown astrophysical phenomenon (also of great interest). We are cooperating with Dave Wilkinson and colleagues at Princeton University to duplicate our electronic and optical hardware on their 36″ optical telescope. This system should be online sometime in the year 2000. With identical electronics, the Princeton experiment will be automated to follow the Oak Ridge telescope. Each site will use an accurate real-time clock to tag incoming events with a relative accuracy of a millisecond, or better.

Longer wavelengths: Extinction (see Section 2.3) limits our receiving range to ∼1000 pc, roughly the local thickness of the galactic disk, if the pulse is transmitted in the visible part of the spectrum. However, if the transmitting civilization sends pulses in the infrared, say at λ=10 μm, then our receiving range extends to ∼10,000 pc, where we can see most of the galaxy (see the trend in Fig. 2). As a bonus, more laser photons ($\propto \lambda$) are received for a given pulse energy in the infrared. Additionally, fewer photons from the parent star are received since the blackbody spectra of solar-type stars fall as one goes from the visible to longer wavelengths. We therefore have a strong interest in extending our search to the infrared and are actively exploring schemes to do this.

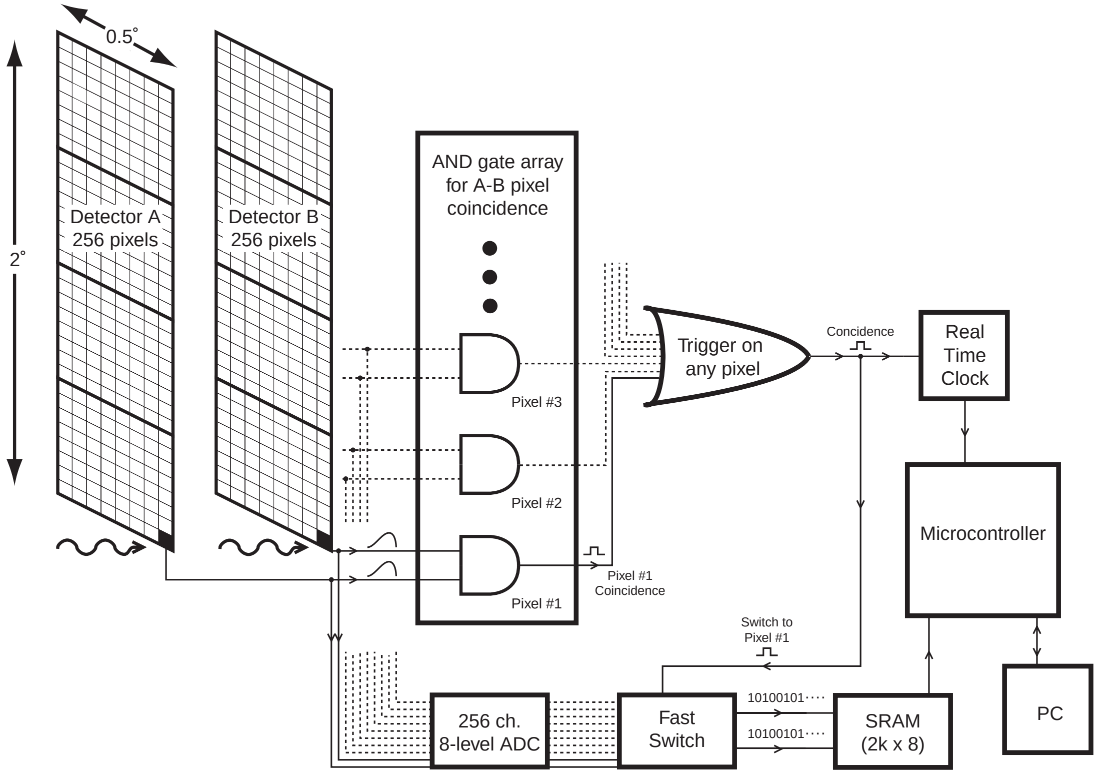

Figure 3. Block diagram of the electronics for the all-sky optical transit survey. In the example shown, a large optical pulse strikes Pixel #1 on Detector A and Detector B. The resulting electrical pulses are recognized as a coincidence and trigger a fast switch to steer the digitized pulse profile data into fast SRAM at 500 Msps. The time of coincidence is noted with a real time clock and the information is read out by a microcontroller and passed on to a PC.

4. Future Experiments

Our present search for pulsed optical beacons tacitly assumes that extraterrestrial signals will originate from the neighborhoods of nearby stars. It covers only 10^{-6} of the total sky area. This targeted strategy begs for a complementary all-sky optical survey.

We are in the initial stages of developing just such an experiment. We envision a large (∼2 m), wide field (a few degrees) optical telescope performing a meridian transit survey. The primary mirror need not be diffraction limited since individual pixels may be ∼5 arcminutes on a side, limited only by photon pileup from sky background. With such an arrangement, we could cover the full sky ($-30^\circ < \delta < +60^\circ$) in ∼150 clear nights. During that period of time, every object in the Northern sky would have transited our detector array (covering 2° declination $\times$ $0\overset{\circ}{.}5$ hour angle) with a minimum dwell time of two minutes. This new experiment will likely be placed in an existing dome at Oak Ridge

Observatory. We plan to use a fast (f/1 to f/2) prime-focus "light bucket" of ~2 m diameter, made of composite or glass.

We are experimenting with multi-anode photomultiplier tubes made by Hamamatsu for use in this all-sky survey. Each tube has 64 independent pixels, on a 2 mm square grid, with a visible light spectral sensitivity. One potential scheme is shown in Fig. 3. We construct two "declination stripe" detectors (on matched focal planes) out of eight of the Hamamatsu tubes. Each pair of corresponding pixels then acts like the Oak Ridge Observatory experiment. We look for large coincident pulses from corresponding pixels of each detector.

We plan to use some level of parallelization to process the glut of data generated by the all-sky survey. In one scheme, we digitize each of the 512 channels with a 8-level nonlinear discriminator on custom integrated circuits (perhaps 32 A & B channels per chip). The fast (perhaps 500 MHz) chips would also include logic to recognize large coincident pulses in corresponding pixels, fast switches to steer the coincident channels to SRAM where the waveforms would be stored ($\sim$ 10 ns of waveform data before the trigger and $\sim$ 10 μs after) as well as various controls and monitors. A microcontroller connected to all eight chips would read the stored waveforms out and transfer them to a computer. These events would be processed and cataloged in much the same way as our single-pixel experiment.

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