Is there "RFI" in pulsed optical SETI?

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ABSTRACT

In the 40 year history of SETI, radio frequency interference (RFI) has proven to be the dominant background in microwave searches. As the SETI community broadens its electromagnetic scope and searches for optical beacons, it must characterize and identify backgrounds for pulsed optical SETI. We must ask the question: What is the "RFI" for pulsed optical SETI? This paper seeks to answer the question by examining the astrophysical, atmospheric, terrestrial, and instrumental sources of optical pulses of nanosecond timescale. Potential astrophysical/atmospheric sources include airglow and scattered zodiacal light, stellar photon pileup, muon events, and cosmic-ray induced Čerenkov flashes. Terrestrial sources, including lightning and laser communications, appear negligible. Instrumental backgrounds such as scintillation in detector optics and corona breakdown have been the dominant background in our experiments to date, and present significant design challenges for future optical SETI researchers.

Keywords: Optical SETI, interstellar communication, radio frequency interference (RFI), high-speed astrophysics.

1. INTRODUCTION

It was just two years after Cocconi and Morrison's famous 1959 paper[1] on SETI at the 21 cm hydrogen line that Schwartz and Townes[2,3] suggested searching for extraterrestrial signals in the optical spectrum. Experimental SETI has been dominated by radio SETI since that time. Expanding searches at ever increasing sensitivity have been carried out at microwave wavelengths more or less continuously since the original suggestion. Perhaps slowed by the lack of technology to even imagine constructing optical transmitters of sufficient power, scientists have been reluctant to build detectors capable of identifying interstellar optical transmissions. However, with forty years of steady Moore's Law growth in the laser industry, we can now contemplate sending continuous megawatt optical signals and *peta*watt (10^{15} W) peak power optical pulses (demonstrated at picosecond and planned for nanosecond duration).[4] We have recently calculated that one of these modern pulsed lasers, directed with an equally modern 10 m telescope, would outshine our Sun by a factor of 5000 during its brief pulse in the direction of its slender beam[5,6]; in other words, optical SETI transmission from Earth is possible. These developments have spurred several scientists to propose and develop experiments capable of *detecting* continuous wave (cw) and pulsed signals from other civilizations.

Optical SETI researchers are also motivated by the relatively high gain of optical transmitters which allow optical beacons to be tightly focused on target systems. High data rates are not forbidden in the optical by the dispersive pulse broadening that is seen in the radio spectrum. Further, the computational power and sophistication that is required to Fourier transform and analyze radio SETI data is not necessary in pulsed optical SETI when broadband photon-counting detectors are used.

Early observational work in optical SETI included Shvartsman's MANIA,[7] and Betz and Townes' infrared search atop Mt. Wilson.[8] More recently, groups and individuals at Harvard,[5,6] Berkeley,[9] Santa Cruz (CA),[10] Princeton,[6] Columbus,[11] the University of Western Sydney,[12] and elsewhere have developed and are developing pulsed optical SETI experiments. These experiments use optical telescopes (typically in the 0.5-2 m class) to focus light onto two or more photon-counting detectors. The optical beam is usually split into two or three equal beams and projected onto an equal number of photodetectors. The electronics behind these photodetectors look for two or more *photoelectrons* arriving simultaneously – that is, the ∼1–2 ns wide (FWHM) electrical pulses must overlap in time. Because of the inefficiencies in photon-counting detectors, and in the optical system, ∼100 or more *photons* arriving at the telescope in a nanosecond window are required to trigger a typical OSETI experiment. The technique of splitting the optical beam and using multiple photodetectors wired in coincidence (pioneered in optical SETI by Dan Werthimer at U. C. Berkeley) dramatically reduces most backgrounds, as we demonstrate below.

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In the field of cw optical SETI (for which we do not calculate backgrounds, but mention for completeness), Geoff Marcy and colleagues are "mining" their radial-velocity data for unexplained narrow peaks in the optical spectra (lines that are not thermally broadened) – possibly extraterrestrial lasers.[13] Likewise, we have pointed out that NASA's Terrestrial Planet Finder[14] – a proposed space-borne interferometer capable of observing the chemical signatures of basic life (e.g. CO_2, H_2O, CH_4, and O_3) in the infrared spectra of extrasolar planets while nulling the light from the parent star – has a serendipitous sensitivity to extraterrestrial lasers. We calculated that a $10\,\mu$m kilowatt-class laser orbiting a Sun-like star that is 15 pc from Earth (TPF's maximum range for planetary spectroscopy) could be detected by TPF *without* any modifications to the proposed design.[15]

Despite the recent flurry of observational programs, there has been scant discussion (at least in the literature) of backgrounds for pulsed optical SETI. This paper seeks to partially fill the gap. We will discuss astrophysical sources of short optical bursts, high energy particles that – through their interaction with the atmosphere or the experimental apparatus – manifest themselves as short optical pulses, cultural backgrounds, detector pathologies, and miscellaneous other sources. These are the "RFI" of pulsed optical SETI.

Throughout this paper, we will refer to our targeted search, and our upcoming all-sky survey. To this end, the reader is encouraged to look at a companion paper[6] in this proceeding, and other articles.[5,16]

2. ASTROPHYSICS ON SHORT TIMESCALES

Breakthroughs in astrophysics are often the result of technological advances. As astronomers have broadened the parameter space in which they search (this first happened in wavelength, and then in spatial and temporal resolution), a wealth of new phenomena have presented themselves: pulsars, quasars, active galactic nuclei, just to name a few. Will astrophysics on milli-, micro-, and nanosecond timescales offer similar discoveries?

In preparation for the construction of the Very Large Telescope (the VLT – four 8 m telescopes working in tandem), D. Dravins has reviewed this problem in a paper[17] in *The Messenger*. He notes that using fast detectors, astronomers may learn about the rapid variability of astronomical objects. The scales that short-time techniques hope to probe are remarkably small, and certainly un-imageable – down to perhaps kilometer scales at galactic ranges. Dravins lists the following phenomena as candidates for milli-, or possibly microsecond timescale emission:

1) Plasma instabilities and fine structure in accretion flows onto white dwarfs and neutron stars.
2) Small-scale [magneto-]hydrodynamic instabilities in accretion disks around compact objects.
3) Radial oscillations in white dwarfs ($\approx$100–1000 ms), and non-radial ones in neutron stars ($\leq 100\mu$s).
4) Optical emission from millisecond pulsars (≤ 10 ms).
5) Fine structure in the emission ('photon showers') from pulsars and other compact objects.
6) Photo-hydrodynamic turbulence ('photon bubbles') in extremely luminous stars.
7) Stimulated emission from magnetic objects ('cosmic free-electron laser').
8) Non-equilibrium statistics (non-Bose-Einstein distributions) in sources far from thermodynamic equilibrium.

Note, however, that *none* of these phenomena is expected to produce nanosecond speed flashes of light.

The physical requirements for nanosecond speed optical flashes are quite restrictive. The transmitting region must be centimeters in size (or, if larger, it must be coherent), and yet able to emit an enormous power in the form of optical photons (greater than a solar luminosity in EIRP) in nanoseconds. We cannot think of a region in which such physical conditions exist.

We do however rest easy knowing that the discovery of such a novel phenomenon would be of tremendous astrophysical interest. Until we have evidence of such phenomena, we will have to concern ourselves with more pedestrian astrophysical and terrestrial backgrounds – the topics of the remainder of this paper.

3. STELLAR PHOTON PILEUP

One obvious candidate for nanosecond-speed optical pulses is the candidate star itself. This light is spatially unresolved from laser light, which presumably is produced on or around a planet orbiting the target star. On a nanosecond timescale, most stars are observed as a patter of single photons arriving individually; multiple photons rarely arrive during the same nanosecond. For example, a solar luminosity at 1000 ly ($m_V = 12$) delivers only 10^6

photons $m^{-2}\,s^{-1}$, or 1 *milli*-photon per nanosecond into a square meter aperture. Most of these photons are not converted to photoelectrons since photo-counting detectors have peak quantum efficiencies of ~20%, and with an average of ~10%. Because of this, and further losses in the optical system, it is more useful to speak in terms of the observable quantity: counts of photoelectrons per unit time.

The probability per unit time ("false alarm rate") of detecting two or more photoelectrons during a time interval τ, with a photoelectron arrival rate r, (assuming that the arrival times are Poisson distributed) is $r^2\tau = 20$ per second for $\tau = 2\,\mathrm{ns}$, and $r = 10^5$ Hz. More generally, the false alarm rate for n photoelectrons is $R = r^n\tau^{n-1}e^{-r\tau}/(n-1)!$; in the limit of $r\tau \ll 1$, the false alarm rate for n *or more* photoelectrons goes to $R = r^n\tau^{n-1}/(n-1)!$ (note that the quantity $r\tau$ is the expected number of photoelectrons in a time τ). The Poisson formula is interpreted as follows: One factor of r gives the arrival rate of single photoelectrons, the factor of $(r\tau)^{n-1}$ comes from the probability of $(n-1)$ additional photoelectrons arriving within τ, the factor of $e^{-r\tau}$ comes from the probability of all of the other photoelectrons *not* arriving in τ, and the factor of $(n-1)!^{-1}$ accounts for the rearrangement of the $(n-1)$ additional photoelectrons. Sometimes the false alarm rate, in the above limit, is quoted as $R = r^n\tau^{n-1}$, without the factor of $(n-1)!^{-1}$. Although this factor is typically less important compared with factors of $r\tau$, it belongs there, and is important for careful calculations, particularly when $(n-1)$ is large.

This means, for example, that for a countrate of 2×10^4 Hz in each of the two photodetectors – which roughly corresponds to observing an $m_V = 0$ star, the brightest object we observe in our targeted search – the rate of detecting two photoelectrons in one photodetector during the same 2 ns is $r_1 = 8\times10^{-1}$ Hz. The rate of pileup of these two-photoelectron events in both detectors, by chance alone, is $r_2 = r_1^2\tau \approx 1\times10^{-9}$ Hz, or once every 30 years. To get this false alarm rate up to, say, once per hour the countrate has to be greater than $\sim 10^6$ Hz.

There are at least two different strategies for dealing with stellar photon pileup. Our group sets a fixed threshold of three photoelectrons in the electronics that follow our hybrid avalanche photodiodes. Other groups, such as the Berkeley OSETI program, have variable thresholds for their multiple photomultiplier tubes. With this strategy, the thresholds are set for each object so as to keep the false alarm rate reasonably low, while maintaining high sensitivity to faint objects.

The above false alarm rate formula immediately demonstrates why two or more detectors, wired in coincidence, are used with most optical SETI experiments. In addition to reducing the rate of stellar pileup, this technique immunizes OSETI experiments to many detector pathologies. As we discuss in §5.1, photon-counting detectors occasionally produce large amplitude pulses due to corona discharge, ion feedback, cosmic-rays, etc., at a rate of, say, 1 per second. With just a single photodetector, the false alarm rate due to these internal detector pathologies is just that, one per second. With two photodetectors wired in coincidence, the false alarm rate is $r^2\tau \sim 10^{-9}$ per second, or about three per century. In practice, we find that the false alarm rate is closer to one per night of observation (~5 hours) because of correlations – some of the large amplitude pulses produced in one detector are seen by the other.

Scattered zodiacal light and airglow are completely negligible when looking for nanosecond speed pulses with narrow field of view telescopes. A typical observing site has a nighttime "sky background" of 18–22 magnitudes per square arcsec. Thus, for our 1.5 m telescope in Harvard, MA (sky brightness of 19-20 mag per square arcsec) with a 15 arcsec-diameter field of view, the sky contributes about 13.5–14.5 magnitudes – two to three magnitudes dimmer than the faintest objects we observe. For our proposed optical sky survey, each $1'\!.5 \times 1'\!.5$ pixel will see 9–10 magnitudes of sky brightness.

In fact, *daytime* optical SETI is possible. The daytime sky brightness has been measured[18] at 8000 candelas/m^2, or, in more familiar terms, $\sim 3\times10^{-10}\,\mathrm{W/m^2/arcsec^2}$. In astronomical terms, this corresponds to ~7 magnitudes per square arcsecond. For a telescope with a rather narrow field of view, the countrates are large, but manageable; for our targeted search, the sky background is ~1.5 magnitudes – bright by astronomical standards, but nearly invisible to pulsed OSETI experiments (the false alarm rate is substantially less than once per hour). Our group has not yet observed during the day (the targeted search runs piggyback on nighttime observations), but may experiment with it soon. Experiments with larger fields of view could use neutral density filters to attenuate the sky background down to manageable levels, at the expense of sensitivity. Care should be taken to avoid pointing the telescope at the Sun with its $1.4\,\mathrm{kW/m^2}$ (most of which would be focused onto the detectors).

4. COSMIC-RAYS AND GAMMA-RAYS

Cosmic-rays – the most energetic particles in the known universe – produce optical photons and other particles when they interact with the atmosphere, which form a potential background for optical SETI experiments.* Under the broad definition, cosmic-ray primaries are made of individual atomic nuclei (most commonly), electrons, gamma-rays or neutrinos. Their energies range from less than 10^6 eV to greater than 10^{20} eV. The differential flux for these particles is strongly energy dependent: $dN/dE \sim E^{-\alpha}$, where $\alpha \approx 3$ for most of the energy range†, meaning that for every factor of ten increase in energy, the flux of particles (which scales as N) goes down by a factor of 100. At an energy of 10^{12} eV, the flux on the Earth's atmosphere is modest: about one particle per square meter per second. At 10^{16} and $10^{18.5}$ eV, the fluxes are down to one particle per square meter per year, and one particle per square kilometer per year, respectively.

Gamma-rays – although technically part of the cosmic-ray family – are typically lower in energy: gamma-rays in the 3×10^{11} to 10^{14} of eV are considered "very high energy."‡ Like cosmic-rays, gamma-rays interact with the Earth's atmosphere producing an electromagnetic cascade of particles, and a flash of Čerenkov light.

When a cosmic-ray (or gamma-ray) collides with the nucleus of an atom (usually oxygen or nitrogen) in the Earth's upper atmosphere, the nucleus disintegrates into neutrons, protons, pions, kaons, hyperons, etc., and their antiparticles. These fragments are extremely energetic themselves, given the kinetic energy of the cosmic-ray; they too collide with atoms and produce even more particles. Many of these are unstable and decay (via the weak interaction); pions, for example, decay into muons and neutrinos, if charged, or into a pair of photons, if neutral. Other processes are also at work. Energetic positrons and electrons braking in the electric field of nuclei emit bremsstrahlung radiation (gamma-rays). Pair production generates positron-electron pairs (and positive-negative muon pairs to a lesser extent) out of the energy of neutral particles and gamma-rays. Many of these relativistic particles are also speeding: by exceeding the speed of light in air, they radiate Čerenkov radiation and slow down.

The survivors of these processes (which are observed on the ground) are electrons, positrons, muons, neutrinos and photons. The charged particles and photons are both potential backgrounds for optical SETI experiments. We investigate them in greater detail below.

4.1. Muons

Most of the charged particles that survive to sea level are muons,§ with a mean energy of 2×10^9 eV. Their total flux (all energies) is given[19] approximately by $I(\phi) = I_\nu \cdot \cos^2\phi$, where ϕ is the zenith angle (muons arriving at angles close to the horizon are attenuated by more atmosphere), and $I_\nu = 8 \times 10^{-3}\,\mathrm{cm^{-2}\,s^{-2}\,sr^{-2}}$. These particles are essentially unimpeded by an observatory dome roof, or the 1.25 cm thick aluminum (a few $\mathrm{g\,cm^{-2}}$) experimental enclosure in our targeted search. Muons pass through individual photodetectors at a rate of once every few seconds. The rate of two muons randomly striking the two detectors in the same nanosecond is therefore of order 10^{-9} per second.

It takes a lucky hit for a single muon to pass through *both* photodetectors. We can roughly calculate the angle-averaged rate as follows: assume that the detectors are 10 cm apart and that each have a $0.25\,\mathrm{cm}^2$ cross-section; the rate of muons traversing both detectors is $\sim 10^{-5}$ per second, or once every ∼25 hours (also assuming that the average flux is half the maximum). Although it is unlikely that a muon would trigger a false alarm in one night's observations, this rate is significant for experiments that have observed for many thousands of hours, such as our targeted search. We have not attempted to correlate the zenith angle (which is a function only of the sky coordinates of the object being observed and the time) of the photodetectors for the residual background events (about one false alarm every eight hours of observation) to look for a $\cos^2\phi$ dependence yet, although this is certainly warranted. This background can of course be completely eliminated by placing a scintillator and PMT in anti-coincidence with the two photodetectors.

*For classic and recent reviews of cosmic-rays, see Rossi[19] and Cronin,[20] respectively. For gamma-rays, the paper by Catanese and Weekes[21] is relevant and useful.

†For primaries in the range $10^{12}\,\mathrm{eV} \le E_{\mathrm{pri}} \le 10^{15}$ eV, the differential flux scales as $\alpha \approx 2.7$; for $E_{\mathrm{pri}} \ge 10^{15}$ eV it scales as $\alpha \approx 3.3$. The most energetic cosmic-rays observed to date have E_{pri} of order 10^{20} eV.

‡The fact that we observe *charged* cosmic-rays, but not neutral gamma-rays above a certain energy threshold probably implies that the most energetic cosmic-rays are accelerated by very large, extended magnetic or electric fields.

§The atmosphere is $\sim 10^3\,\mathrm{g\,cm^{-2}}$ thick, while high-energy photons have a typical "interaction length" – a fraction $1/e$ of particles remain after traversing this distance – of $30\,\mathrm{g\,cm^{-2}}$.

Another way to have a false alarm is to capture a muon in an atom in the beamsplitter where it will subsequently decay into an electron and a neutrino. The energetic electron will then scintillate – the process of ionization of matter by an energetic charged particle and the subsequent photon emission that occurs as the excited molecules return to their ground states – in the beamsplitter glass and might be detected by both photodetectors. However, such an event would be exceedingly rare since the capture cross section for $\sim 10^9$ eV muons is small. It is also unlikely that a muon would be slowed down to energies where capture becomes more likely; a cosmic-ray muon dissipates $\sim 5 \times 10^6$ eV per g cm^{-2}, and the longest dimension in the beamsplitter (density of order g cm^{-3}) is a few cm. We have further reduced the possibility of this by replacing our cubical beamsplitter with the "thin slide" style beamsplitter in our targeted search.

4.2. Čerenkov Radiation

As we mentioned above, Čerenkov radiation is formed when a particle exceeds the local speed of light. The radiation is beamed down in a narrow cone with an opening angle $\theta_C = \arccos(1/\beta n)$, where $\beta = v/c$ and n is the index of refraction, and is emitted over a broad range of frequencies in proportion to $1/\lambda^2$ (i.e. blue Čerenkov photons are more common than red ones).

Fortunately for optical SETI, the image of a cosmic-ray (or gamma-ray) induced Čerenkov pulse is too diffuse to be detected by the current OSETI experiments. A typical 10^{12} eV primary cosmic-ray does produce a short (5 ns duration) optical pulse with about 30 photons/m^2 falling on the base of the narrow light cone ($\sim$150 m radius). But, the source appears diffuse – about 2^o FWHM. Thus, the narrow field of view of our targeted search telescope will observe only $\sim 2\times\, 10^{-4}$ photons per flash, i.e. rarely one photon, and never two or more.

The rate of such events, as seen from an arbitrary point on the ground, is given by flux$\times A_{\rm footprint} \times \Omega_{\rm image} \approx 15$ per second for 10^{12} eV primaries. Scaling the above result (and using the fact that the photon fluence per flash is roughly proportional to $E_{\rm pri}$), we find that a $10^{17.5}$ eV primary would deliver $\sim$100 optical photons to our targeted search telescope; however such events happen about once every thousand years in an arbitrary part of the sky as viewed from an arbitrary point on the ground.¶

One also has to worry about Čerenkov radiation produced by cosmic-ray muons (or from alpha-particle decays) passing through the beamsplitter glass. The number of Čerenkov photons in one of these pulses is a function of the energy of the relativistic particle, and the distance it traverses in the material: $d^2N/dEdx = 370 \sin^2\theta_C(E)$ per eV–cm. For glass ($n = 1.5$, $\theta_C = 0.84$ rad), this means that about 500 "visible" photons ($\sim$1.5 eV average energy) are produced per muon per centimeter traveled. With the right geometry, our targeted search might be able to see such a flash. The probability of this was reduced though when we installed a lower volume beamsplitter.

Scintillation in the beamsplitter is also a potential source of pulsed light. We have calculated that, as long as the yield is less than $\sim 10^{-3}$ of NaI (a classic scintillator), the flux of optical photons is insufficient to trigger our targeted search.

5. INSTRUMENTAL AND TERRESTRIAL BACKGROUNDS

In our experiments to date, the dominant backgrounds are not astrophysical or atmospheric, but instrumental. We explore these, and others, below.

5.1. Photodetector Problems

There are a host of potential problems with high-voltage photodetectors (radioactive decay in the PMT glass, ion feedback, scintillation of electron impacts from within). Corona discharge is the largest background in our targeted search though. This process occurs in high voltage environments when sharp points (e.g a dust particle, or a burr on metal) produce an extraordinarily high electric field. This field ionizes the gas between the sharp point and an electrode resulting in corona radiation (a short burst of optical photons) and crackling noise. This is the familiar hum heard around high-voltage power lines. Humidity tends to accentuate this highly non-linear phenomenon. It is also characterized by discharges clustered in time.

The hybrid-avalanche photodiodes (HAPDs) in our targeted search run "negative cathode" (that is, the anode is grounded) at a voltage of -7.5 kV. The common wisdom in the photodetector community is that the negative-cathode arrangement is prone to corona discharge, a tradeoff against its convenient output signal coupling.

¶Detecting the Čerenkov radiation from such energetic cosmic-rays requires effective collecting areas measured in km^2 and a wide angular acceptance.

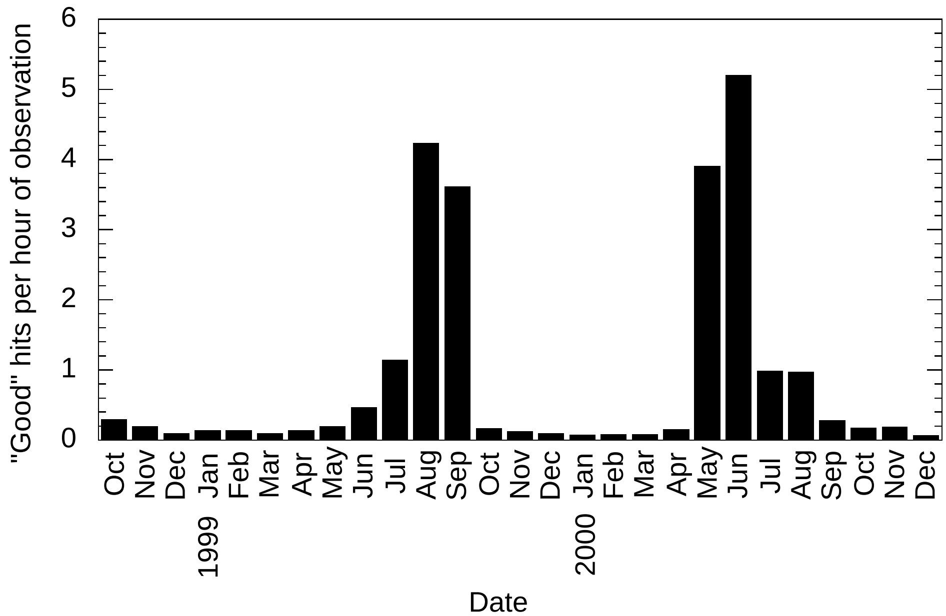

Figure 1. Here we show the humidity-induced seasonal trend in the "good" hit rate. This is likely the result of corona discharge.

As shown in Figure 1, there is a marked systematic seasonal trend in the rate of coincident hits that is consistent with corona discharge. During the cold, dry months of fall, winter, and early spring (October-April), the data exhibits a good hit rate of 0.12 hits per hour of observation and a total hit rate of 0.50 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 tens of minutes.

We believe that humidity promotes corona breakdown in one detector, which affects the other detector via electromagnetic (EMI) and optical coupling. 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. Most of these upgrades were completed during the summer of 2000 and the good hit rate appears to have gone down to manageable levels – less than 0.2 good hits 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.

To further reduce our background rate, we are collaborating with Dave Wilkinson and colleagues at Princeton University to duplicate our experiment on their 0.9 m Cassegrain telescope in the Fitz-Randolph Observatory. This telescope will follow the Harvard telescope through its nightly observing programs, beginning in a matter of months. Even with a coincidence rate of 5 good hits per hour, the rate of inter-observatory coincidence is once every 600 years, with a 1 ms time window.[††]

Our upcoming all-sky survey will use multi-anode photomultiplier tubes that run at 900 V. At this lower voltage, we do not expect the corona discharge to be as severe as in our targeted search.

[‖] "Good" hits are a subset of the coincident events that pass basic sanity checks.[6]

[**] The origin of this small residual background is unclear.

[††] We plan to time stamp incoming coincidences to an absolute accuracy of 0.1μs at each observatory! See the companion paper[6] for details.

5.2. "Cultural" Backgrounds

The world is full of pulsed optical lights – sparks, lightning, automobile turn signals, disco lights, etc.; the question though is: are there any cultural phenomena that will deliver of $\sim$100 or more optical photons into one of our telescopes during a nanosecond interval? Fortunately, most cultural backgrounds are either insufficiently bright on nanosecond timescales, or they couple poorly into the experiment, i.e. one would never point a telescope at them.

Lightning is of course a source of intense, pulsed light. Measurements[22] have shown that the flashes are $30\,\mu$s long on average, with structure on the single μs level, and perhaps even faster. However, OSETI researchers do not observe during *local* storms. And it is difficult to imagine lightning reflecting into a telescope from an overhead haze with sufficient intensity, while retaining the short time structure, that would trigger an OSETI experiment.

Artifical satellites orbiting the Earth form a background of steady (or transient over a few milliseconds) light. Most of these satellites are small and reflect only modest amounts of sunlight; the Hubble Space Telescope, for example, appears as a magnitude 4.5 object. (Our targeted search program observes stars with $m_V = 0$–12; the brightest star in the night sky, Sirius, has $m_V = -1.7$.) Satellites with larger surface areas are brighter still: the International Space station and Mir have $m_V = -2.8$ and –3.5, respectively. The constellation of 66 Iridium low Earth orbit communications satellites are bright enough at times, $m_V = -8$, to be seen during the day. What about planets? They look approximately like the brightest spacecraft. The brightest two, Venus and Jupiter, have maximum brightnesses of –4.4 and –2.7, respectively, during their peaks.

The question still remains though: will these bodies give a "false alarm" to optical SETI systems? Since they are constant sources of optical photons, we need to worry about pileup. Scaling the result that an $m_V = 0$ star delivers $\sim 2 \times 10^4$ photoelectrons per second in each of the two photodetectors in our targeted search, an Iridium satellite – 8 magnitudes or a factor of 1500 brighter – would give countrates of 3×10^7 in each detector. When the latter passes directly through the 15 arcsec field of view of our targeted search (for a few milliseconds), the false alarm rate with 2 and 3 photoelectron thresholds would be 60 and 0.006 per *milli*second, respectively. Note, however, that satellite and planetary orbits are well characterized and well documented; OSETI observers can simply avoid observing locations where satellites will flare.

NASA is experimenting with pulsed laser communication between Earth-orbiting satellites and the ground, and between deep-space satellites and the Earth.[23] Their conclusions are similar to those of optical SETI researchers: Beamed laser communication offers a low-power, low-mass, and high-bandwidth alternative to RF communication. The tradeoff, for both NASA and optical SETI applications, is that the transmitter has to be aimed very precisely. Consequently, it is unlikely that a narrow beam would be accidentally intercepted by an OSETI experiment. The transmitter and detector would both have to be pointed at each other to within a beam width (each having a probability of order 10^{-9}). On the other hand, laser pulses intentionally beamed from a satellite to an optical SETI experiment is an ideal *test* of the latter.

Could the blinking lights on an airplane cause a false alarm? To calculate this, let us assume that the light is 500 W and radiates isotropically. If the plane is flying at an altitude of 3,000 meters, then it has the same brightness as a solar luminosity 0.3 ly away ($m_V \approx -5$), i.e. somewhat dimmer than an Iridium flare. Although one cannot predict when airplanes will fly overhead (or look them up in a database, as one can for satellites), the probability that they would fly through the beam is quite small; only 15 arcseconds in diameter, our targeted search telescope observes less than $\sim 10^{-9}$ of the sky at any one time.

All of the other potential cultural backgrounds that we have dreamed up so far – local light pollution, electrical sparks, etc – would fail to trigger pulsed OSETI experiments because either (1) they are relatively low power sources of continuous radiation and are therefore insufficiently bright on nanosecond timescales to show multiphoton pileup, or (2) they are short and intense, but do not couple directly into the experiment.

6. SUMMARY

The foregoing is a brief review of the possible sources of backgrounds for nanosecond timescale pulsed optical SETI experiments. The shortest timescale for astrophysical phenomena appears to be in the microseconds. Pileup of stellar photons is negligible provided two or more photodectors are used in coincidence. The Čerenkov radiation produced by cosmic- and gamma-rays appears innocuous, while the flux of muons from these sources is a potential background at the one event per day level. Detector pathologies (dominated by corona discharge in our targeted search) are the largest background our experiments thus far. Cultural backgrounds, such as satellites and blinking airplane lights, are manageable at worst.

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