OSETI Workshop Report

Contents

1 Executive Summary

This report summarizes discussions and conclusions of a workshop (conducted during 21–22 Aug 2016, under the auspices of Breakthrough Listen) and followup communications among those participants.[1] The subject is what we believe to be a "missing corner" of the Breakthrough Listen ("BL") initiative, namely the absence of searches for plausible optical transmissions other than the program at Lick/APF (targeted long-integration visible spectroscopy). These include whole-sky searches for highly intermittent optical pulses (§§3.1 and 3.2), searches in the arguably more-favorable infrared (§§3.3, 3.5), and data mining at extreme sensitivity (<1 photon/m^2, visible) of the existing VERITAS (Cherenkov array) database (§3.4).

We do not attempt to rank these proposals, because their respective merits (sensitivity, wavelength, coverage, duty-cycle) map differently onto plausible source scenarios; put another way, there is no universal figure-of-merit. To make this concrete, §3.1 is optimized for ETI Starshot events, §§3.2 and 3.3 are optimized for ETIs making intentional repeated transmissions aimed at civilizations with good sensitivity to fast pulses (in both visible and near-IR), and §3.4 achieves by far the greatest sensitivity, but limited to the blue end of the visible band. We do not know what kind of signals (if any) are reaching Earth from other civilizations, so an optimal search should devote resources to the full range of plausible signaling modes. We therefore recommend that the Breakthrough Foundation include these in its Listen initiative, with initial funding (∼0.5M$ each) appropriate for first-phase deployment.

2 Introduction: the case for optical SETI

As described in detail in an appendix (§6.0 – Optical SETI: A Perspective), optical communication over interstellar distances is both practicable and efficient. Just a year after the invention of the laser, Schwartz & Townes (1961) proposed optical communication over modest interstellar distances, and two decades later Townes (1983) published in the Proceedings of the National Academy a fine comparison of interstellar communication at radio versus optical frequencies, stating in the Abstract that "...the infrared is as good as, and may be a more favorable region for SETI than, the microwave region on the basis of reasonable assumptions," and concluding the paper with these words: "...I believe the above discussion does show that we have no assurance the microwave region is the one of choice for a civilization trying to communicate with us. This may affect the scale and style with which SETI is carried out on Earth even in the immediate future."

Lasers and photonic communication have improved considerably since then, with continuous laser power in the megawatts, and pulsed laser power of a petawatt. The

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[1] Eliot Gillum, Gerald Harp, Paul Horowitz (editor and co-leader), Andrew Howard, Curtis Mead, Lee Spitler, Dan Werthimer (co-leader), David Williams, Ed Wishnow, and Shelley Wright. Additional contributors include Jim Cordes, David DeBoer, Frank Drake, Mike Lampton, Phil Lubin, Jill Tarter, and Jason Wright.

latter, collimated with a Keck-size telescope, would generate a light pulse that outshines the broadband visible light of the Sun by a factor of 10^4 (and independent of distance). Both CW and pulsed lasers are plausible candidates for SETI. However, BL's current optical program at APF is insensitive to the latter, being designed to detect instead spectrally narrow emission features. And it does not extend into the infrared, a favorable wavelength regime owing to interstellar extinction. Finally, the APF program looks at selected target stars, one at a time, thus is insensitive to infrequent transmissions, or transmissions from source locations (stellar or otherwise) not on the target list.

In the remainder of this report we sketch out several optical SETI proposals that aim to capture some of this overlooked search space: searches for optical pulses; searches in the infrared; and searches that see the whole sky (albeit at lower sensitivity).

3 Four Proposed Searches

These are described in detail in the corresponding appendixes; here we provide compact descriptions of their features and capabilities. In order, they are

§3.1: Allsky all-the-time centimeter-aperture dispersive search
§3.2: Large-sky (>1000 deg^2) meter-aperture nanosecond pulse search
§3.3: Small-sky (<1 deg^2) near-IR meter-aperture nanosecond pulse search
§3.4: Gamma-ray telescopes for optical SETI (and other data-mining)

with a possible future addition of

§3.5: Mid-IR searches

3.1 Allsky (20,000 deg^2) all-the-time centimeter-aperture dispersive search

This search idea (from Eliot Gillum and Gerry Harp; full details in §6.1) takes aim at full-sky all-the-time sensitivity to visible light signals, using wide-angle camera-sized apertures (24 mm focal length, $f/1.4$) and a dispersive grating in front of a medium-format 10 Mpxl focal plane, the latter operated in fast TDI[2] mode. Each line in the resulting sequence thus captures a millisecond snapshot[3] of the full 75° sky image, but flattened into a line. Each star in the field appears as a symmetrical

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[2] "Time delay and integration," in which successive rows of a CCD imager are shifted in synchronization with the moving image being captured. Unlike conventional TDI, the idea here is to shift at maximum possible rate ("overclocking," about 1 ms/line), thus flattening the two-dimensional image into a single line pancake. Each pixel in the successive output lines represents 1 ms of dwell on each possible source point in the sky; thus during its 3000 shifts through the image plane it integrates 3 seconds of other image points in the shift direction.

[3] But skewed in time; photographers refer to this as "rolling shutter" artifact.

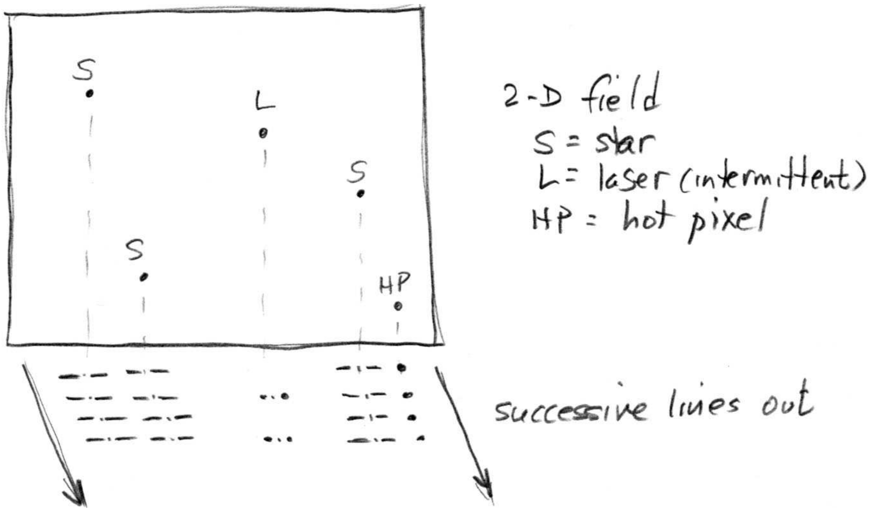

Figure 1: *Readout technique of the allsky dispersive camera: The 3x×3k 2-dimensional CCD imager is read out in overclocked (1 kHz) TDI mode, generating successive 1-dimensional lines that represent the integrated image as sampled during that line's traverse down the image plane. In the successive 3k-point lines, stars create persistent spectra, a hot pixel generates a single persistent pixel, and an intentional laser transmission (continuous or intermittent) generates a pair of points.*

pair of (mostly first-order) spectra, while a laser signal appears as a pair of points (see Fig. 1); both are thus distinguished from a misbehaving "hot pixel." Two such cameras in orthogonal orientation are needed for a 2-dimensional reconstruction (and to disambiguate time and space).

Such a system has a time resolution corresponding to the shift rate ($\sim$1 ms), a spectral resolution set by the dispersive element and pixel density ($\sim$30 nm), a spatial resolution set by the focal length and pixel density ($\sim$1.4 arcmin), and a sensitivity set by aperture, sky and stellar background, optical path and quantum efficiency, and readout noise ($\sim 10^6$ photons/m^2). These approximate values correspond to a baseline design that is the minimum to cover the whole sky; those can be traded or enhanced: for example, a lens of longer focal length and larger aperture increases the sensitivity, at the cost of sky coverage (or the need for additional cameras). The baseline system has been prototyped, with some sky observations at a suburban setting to establish expected backgrounds and capabilities.

This search idea is well-suited to detection of highly intermittent but intense illuminations, as for example one might expect for an ETI's Starshot-style propulsion. Given the expected rarity of such events, full-sky coverage is important; just as important (and perhaps essential) is the presence of a second physically remote observatory covering the same sky (think LIGO!). To achieve full-sky coverage requires 6 sites (3 per hemisphere), each with its confirming twin, thus 12 sites in all. To achieve *complete* sky coverage each site needs 8 cameras (4 orthogonal pairs), thus a total of 96 cameras. The baseline system has been sized to accommodate such a quantity at an affordable level, hence the relatively modest aperture.

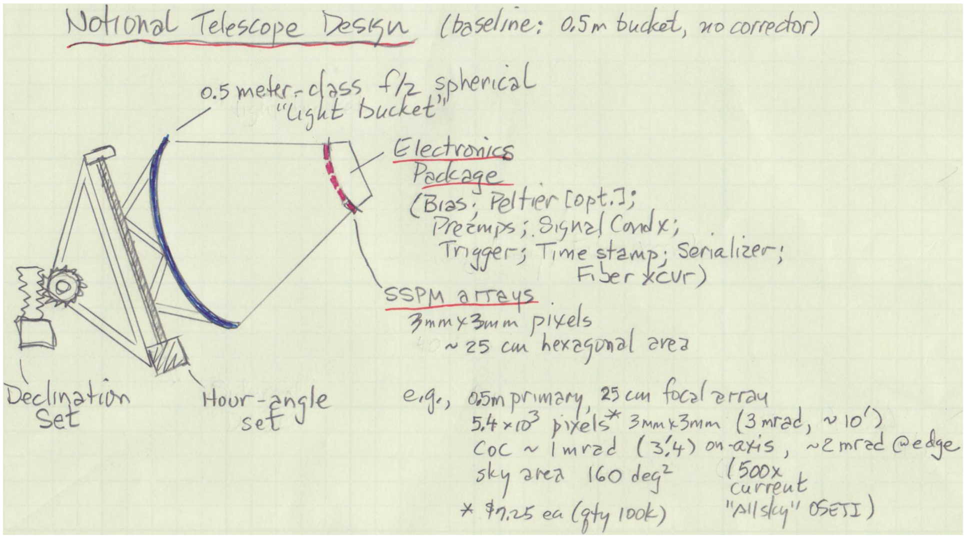

Figure 2: *One aperture of the cluster of 0.5-m light buckets needed to cover a large portion of the sky. Each pixel feeds a video amplifier and comparator, the latter set for a threshold of, say, 4.5 photoelectrons. The many channels combine in several FPGAs, which time-stamp each trigger, and forward the pixel address and time in its serial stream. These data are compared with analogous data from a separate site, creating a robust 2-site authenticating protocol.*

3.2 Large-sky ($>1000\,\mathrm{deg}^2$) meter-aperture nanosecond pulse search

This search idea (from Horowitz, with help from Wishnow; full details in the Appendix §6.2) is an elaboration of the ongoing Harvard "Allsky" search (Howard et al. (2004)), which images a declination stripe of the sky ($0.2^\circ \times 1.6^\circ$) onto a paired array of multipixel PMTs to detect nanosecond-scale flashes of the kind described in §2 and §6.0.4; this transit search is sensitive (1.8 m aperture) and fast (~1 ns), but its small angular acceptance ($0.32\ \mathrm{deg}^2$) means that any point in the sky is seen for only a minute in a year.

New detector technology, in the form of inexpensive multi-pixel photon counters (MPPC), makes it possible to expand such a system to cover a large portion of the sky simultaneously: such a system (Fig. 2) would use an array of ~0.5 m spherical light-buckets, each illuminating a focal plane tessellated with 5000 MPPCs in a staring array covering $160\ \mathrm{deg}^2$. A few dozen of these, deployed at paired observing sites (to eliminate "singles"), would provide sensitive all-time coverage of a substantial portion ($>1000\,\mathrm{deg}^2$) of the night sky.[4] A preliminary (and inexpensive) deployment might consist of a single telescope pair installed at the same dedicated Lick site described in §§3.3 and 6.3, with subsequent build-out as appropriate.

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[4] Going to all-sky all-the-time coverage is prohibitively expensive at current prices. But the history of semiconductor costs have shown that one need only wait a few years.

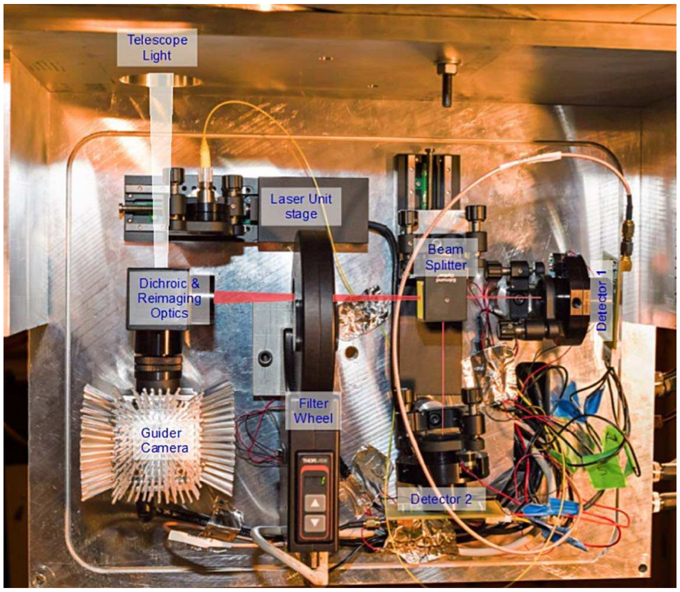

Figure 3: *Single-pixel near-IR optical SETI apparatus, currently deployed on the 1 m Nickel telescope at Lick. (photo: Laurie Hatch)*

Such a system has a time resolution set by the detectors (∼1 ns), a spatial resolution set by the primary plate scale and the pixel size (∼10 arcmin), and a sensitivity set by the primary aperture (∼100 photons/m^2).

This search idea is well-suited to detection of intermittent laser pulses of short duration, an attractive beacon scenario for a transmitting civilization wishing to establish contact with any of its 10^3–10^4 neighboring planetary systems (see discussion in §6.0). Depending on how many sites are deployed, it can achieve relatively high duty-cycle (% of time any source point is observed). It makes no assumptions about particular laser technologies, being sensitive to wavelengths in the detector's passband (visible light, for current Hamamatsu MPPCs, perhaps evolving to near-IR).

3.3 Small-sky (<0.1 deg^2) near-IR meter-aperture nanosecond pulse search

This search idea (from Shelley Wright; full details in the Appendix §6.3) takes searches into the near infrared (NIR, 950–1700 nm), building on an existing targeted NIR search underway at Lick observatory. The latter exploits a recently available NIR MPPC, analogous to the visible MPPCs described in §3.2 and Appendix §6.2; these devices are hermetically packaged, Peltier cooled, and have small active area (200 μm square or less). Currently that search uses a single cooled MPPC behind field lenses (Fig. 3), to create a single 4.4 arcsec sky pixel. That's fine for guided observations of selected stellar targets, but hopeless for a sky survey.

So the new proposal (called SWIS: SETI Wide-field Infrared Surveyor) is to use tessellated arrays of NIR MPPCs to increase the instantaneous sensitive field. It is likely that arrays of 10×10, or even 32×32, will become available in the near term, permitting drift scans with coverage of order $2' \times 15'$ or more. That would allow a survey of the northern sky in some 5 years time. Such a system is fast (∼1 ns), and single-photon sensitive in the near-IR; as with the visible MPPC system in §3.2, it is broadband (not spectroscopic). Because of the small instantaneous field of view, the sidereal drift time is short – some 10 seconds per candidate source point – amounting to a duty cycle of 10^{-7} over a 5-year survey. A suitable telescope dome and associated facilities is available at Lick Observatory, who have offered exclusive use of the retired Carnegie Astrograph, where the existing mount would be repurposed to hold one or more 0.6 m apertures. The dome is large, having held substantial dual refractors. It could support multiple NIR telescopes; alternatively (or in addition) it could do double-duty by housing a pair of light-buckets performing the visible-light OSETI of §3.2.

This search idea is aimed at intentional near-IR emitters with high repetitive duty-cycle (>0.1 pulse/sec) anywhere in the northern sky. It explores a favorable spectral region, and would constitute the first all-sky NIR search.

3.4 Gamma-ray telescopes (∼10 deg^2) for optical SETI

Large light-gathering telescopes are being used for gamma-ray astronomy, in particular by imaging the nanosecond-scale streaks of light in the atmosphere caused by gamma-induced showers of charged particles exceeding the speed limit.[5] This is called Cherenkov radiation, and the instruments are known as IACTs, for "Imaging Atmospheric Cherenkov Telescopes." An early example is the 1968 Whipple 10 m IACT on Mt. Hopkins; the more recent VERITAS array of four 12 m telescopes (Fig. 4) has been observing since 2007. At the focal plane these instruments place some 500 photomultiplier tubes, to capture a coarse image of the triggering Cherenkov event.

Because IACTs are seeking source images extending up to ∼1° on the sky, they have fields of view several degrees in diameter, and their trigger systems discriminate against single-pixel events. The latter are, of course, just what we seek in optical SETI; however, the optical quality of these large telescopes is such that a point source produces an image that often enough spreads across several PMT image-plane pixels. So one can recruit IACTs in the cause of optical SETI. Furthermore, the large optical apertures and large fields of view allow deep searches over comparatively large swaths of sky.

A nice example of this is described in an excellent recent publication from the VERITAS group.[6] It demonstrates outstanding sensitivity (1 photon/m^2), far surpassing any previous OSETI efforts. And it was done on a shoestring, exploiting data-mining of the existing archive of years of VERITAS observations.

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[5] The speed of light *in air*, reduced slightly by the index of refraction from everyone's favorite c=2.99792458×10^8 m/s.

[6] *A Search for Brief Optical Flashes Associated with the SETI Target KIC 8462852*, available at arXiv:1602.00987v2.

Figure 4: *The Veritas array of imaging Cherenkov telescopes in Arizona consists of four 12 m light buckets, each with a focal plane of 499 photomultipliers.*

Owing to VERITAS's relatively wide field of view (3.5° diameter), some 30% of the northern sky has been observed during its 10^4 hours of operation so far.[7] The archive is a treasure-trove of SETI data, and this proposed search consists initially of two parts: (a) a thorough data-mining of all archived data; and (b) some dedicated IACT time to explore ways to improve the sensitivity to OSETI-specific sources.

Part (a) is a no-brainer: the data is all there (though proprietary to the VERITAS Collaboration), needing only an interested researcher(s) with plenty of computer time. The VERITAS publication[6] even spells out a good starting recipe. Part (b) is open-ended, and more of a research program than a search. Some ideas include fashioning a focal-plane overlay to spread the focus over several PMTs, or altering the trigger logic. The Cherenkov Telescope Array (CTA)[8] will soon start construction, and these tests could lead to suggestions for design enhancements to make it more capable for OSETI.

In the near term, it may be possible to get some dedicated VERITAS observations of targets of particular interest that are not covered by existing observations. Longer term, as the utility of existing IACTs as gamma-ray instruments is superseded by CTA, it could be possible to consider a substantial portion of their observations dedicated to OSETI. CTA itself will have tremendous optical collection power that could also potentially be brought to bear for OSETI.

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[7] The coverage is not uniform, because it does not operate in survey mode; rather, it dwells on targets of interest – some as long as 200 hours, others as little as an hour. See Fig. 15 in the appendix.

[8] http://cta-observatory.org

3.4.1 Other Data-mining Searches

Besides VERITAS, there are several ongoing and planned astronomy surveys and asteroid searches that produce copious data sets that could be mined for extraterrestrial signals. Data mining searches are attractively inexpensive; here are several examples of datasets on which data mining searches could be carried out: Panoramic Survey Telescope and Rapid Response (Pan-STARRS), Catalina Sky Survey (CSS), Palomar Transient Factory (PTF), Zwicky Transient Factory (ZTF), Advanced Technology Large Aperture Space Telescope (ATLAS), Dark Energy Spectroscopic Instrument (DESI), Kepler, the Large Synoptic Survey Telescope (LSST), and the James Webb Space Telescope (JWST).

Figure 5: *Mid-infrared array of three 1.65 m telescopes at Mt. Wilson, used in interferometer configuration to measure stellar diameters and their surrounding disks.*

3.5 (A Future Path: Mid-IR searches)

Beginning in 1988, Townes et al. have developed a three-aperture mid-IR ($\sim$10 μm) interferometric array (Fig. 5), with isotopic CO_2 lasers providing the "local oscillator" for direct optical mixing to microwave intermediate frequency bands. At these wavelengths the galaxy is largely transparent, and communication at favorable S/N is possible, as well described in Townes (1983). One of these apertures could be used for targeted observations of selected stars, with very narrowband ($\sim$10 kHz) resolution within instantaneous bandwidths of some 3 GHz. Alternatively, it may be possible to replace the spectroscopic detector and narrowband backend with a simpler broadband *intensity* detector (the method favored by Townes).

Another mid-IR possibility is to exploit staring-array technologies that have been developed for defense applications to perform a large-area survey, in the manner described in §3.1 for visible light.

These ideas have not yet been fleshed out, but we mention them here because they represent an important part of the optical spectrum, and one that has been little explored.

4 Perspective: A Parametric Table

In comparing the coverage of different OSETIs it may be helpful to summarize in tabular form their respective sensitivities and sky coverage; this we have attempted in Table 1 – but we caution that this provides a truncated overview, blurring much important detail (which can be found in the appendixes). For example, the data in the table cannot be used to derive reliable figures-of-merit or to make quantitative comparisons among the several searches.

Table 1: Optical/IR SETI Parametric Comparisons

Technique	Sensitivity[a] (ph/m^2)	λ Range (nm)	Pulse Energy[b] (MJ)	Time Resolution[c] (s)	Sky Coverage[d] (deg^2/scope)
§3.1 (widefield)	2×10^6	400–900	1.3×10^8	10^{-3}	5600
§3.2 (ns visible)	100	400–900	2	10^{-9}	160
§3.3 (near-IR)	100	950–1700	5	5×10^{-10}	0.008
§3.4 (γ-ray scope)	0.96	300–600	1×10^{-4}	5×10^{-9}	9.6
Breakthrough-APF	5×10^5	374–980	2000	1200	3×10^{-7}
LSST[e]	18	300–1100	1×10^{-3}	15	12
Harvard OSETI[f]	60	400–900	0.42	10^{-9}	0.32

[a] Threshold sensitivity (photons/m^2) per resolution element per field/exposure.
[b] Assuming 10 m transmitter at 100 pc with pulse duration equal to time resolution.
[c] Minimum instrumental time resolution.
[d] Instantaneous field-of-view.
[e] Near-term astronomical facility, for comparison.
[f] Existing Oak Ridge Observatory Allsky OSETI (Mead et al.).

5 Summary and Recommendations

Breakthrough Listen has launched with an impressive program in the microwave spectrum, but its optical counterpart (targeted searches of integrated visible spectra) is sensitive to only a limited range of signal types. Specifically, it is poorly suited to highly intermittent signals, or pulses of very short duration (∼nanoseconds), or wavelengths (such as the desirable near-IR) outside of APF's spectral range, or sources not associated with a star on its target list. It would not detect an alien Starshot, nor the infrared laser envisioned by Townes in his remarkable 1983 paper.

We on Earth do not know how extraterrestrial civilizations conduct their interstellar communications or propulsion, nor how they invite new members into the galactic club. The best we can do is to exploit available technology to search the scientifically most plausible modalities. Our optical SETI workshop identified a handful of promising searches that can be done now; as described in the individual sections (and corresponding appendixes), the various proposals map interestingly onto plausible ETI signaling scenarios. For that reason there is no way to rank them – each of them falls in a sweet spot for someone's favorite signaling scenario – thus all of them should be part of Breakthrough Listen. Happily, in an initial modest deployment they are of comparable cost,[9] so there's no incentive to go for the low bidder. When these searches are underway, Breakthrough Listen will have opened its eyes to rare but intense (Starshot-like) events (§§3.1 and 6.1); to short pulsed lasers in the visible (§§3.2, 3.4, 6.2, and 6.4) and infrared (§§3.3 and 6.3); and, if technology allows, searches in the 10 μm mid-IR (§3.5). It is also possible that optical signals have already been collected and reside in some dataset; data-mining (§3.4.1) is an efficient way to ride on the coattails of existing large-scale astronomical surveys.

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[9] With the stunning exception of VERITAS data-mining, §3.4 and 6.4, which is a bargain.

6 Appendixes

6.0 Why *Optical* SETI?

(taken from Howard et al. (2004))

6.0.1 Introduction

Historically the Cocconi & Morrison (1959) suggestion that SETI be carried out at the 21 cm emission 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 operational 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 (Cordes & Lazio, 1991) 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 in frequency to millimetric wavelengths.

Moreover, there are other considerations that might well encourage the use of still shorter wavelengths. 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 versus 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 ultra-high resolution spectroscopy one must use such a system, mixing the optical signal 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) (Ross, 1965). 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.

Taking these and other factors into account in a comparison of received SNR versus wavelength, and making reasonable assumptions about antenna apertures and accuracies, detection methods, transmitter power, and so on, Townes (1983) concluded 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 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 be reconsidered (Schwartz & Townes, 1961).

Laser technology has been in a phase of rapid catchup relative to the mature technology at radio frequencies. Lasers with several megawatts of continuous optical output have been built, and picosecond pulses of more than 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 to produce repetitively pulsed megajoule nanosecond pulses. Optical pulsed beacons formed with that sort of technology permit detection with a very simple apparatus – just a telescope with a pair of white-light photomultipliers in coincidence.

6.0.2 Pulses vs. Carriers

Are pulses the best beacon? Or should we be looking for laser lines, transmitted continuously at some guessable wavelength, analogous to the microwave searches that have been conducted?

What is natural at radio frequencies may not be so at optical. At *radio* frequencies it is easy to do coherent detection, using the ordinary heterodyne techniques of mixing with a local oscillator to a complex (quadrature) baseband. With classical filter techniques, or with contemporary digital processing with discrete Fourier transforms, one can achieve extremely narrow bandwidths, limited only by oscillator stability (a part in 10^9 is routine) and patience (the resolution is the inverse of the coherent integration time). Furthermore, the interstellar medium is kind to carriers—at gigahertz frequencies a carrier is broadened only *milli*hertz in its passage through the interstellar medium, if one avoids the most congested region of the galactic center, and even there the broadening is only a few hertz (Cordes & Lazio, 1991). Scattering and absorption are also small or negligible over galactic distances for such signals. In other words, a signal that is a spike in the *frequency* domain is a natural candidate for interstellar signaling at microwave frequencies, for reasons both scientific and technical.

Moreover, interstellar dispersion, and the presence of natural and "cultural" impulsive interference (switching transients, spark plugs, and so on), make pulses in time less effective. Finally, the relatively low carrier frequency (along with dispersion) prevents high bandwidth communications.

By contrast, at *optical* wavelengths the situation is reversed: One cannot realize extremely narrowband systems with optical filters or gratings, but is forced to optical heterodyne techniques, ultimately applying precise radiofrequency spectroscopic methods at the microwave IF. This results in added noise, as mentioned above and well described by Townes (1983). Furthermore, at optical wavelengths the higher carrier frequencies ($\sim 10^{14}$ Hz) result in much larger absolute Doppler shifts; for example, $1\,\mathrm{km\,s^{-1}} \leftrightarrow 5\,\mathrm{kHz}$ at 1.4 GHz, whereas $1\,\mathrm{km\,s^{-1}} \leftrightarrow 1\,\mathrm{GHz}$ at $1\,\mu$m. However, dispersion is negligible at optical wavelengths, even at nanosecond timescales (Cordes, 2002). Furthermore, natural and cultural sources of nanosecond flashes of significant intensity appear to be entirely absent (Howard & Horowitz, 2001). In other words, a signal that is a spike in the *time* domain is a natural candidate for interstellar signaling at optical wavelengths, for reasons both scientific and technical. An added bonus is that, at nanosecond time scales, the stellar background becomes negligible.

6.0.3 The Case for Optical SETI

In view of the above, and put most compactly, the primary arguments in favor of conducting SETI at optical (rather than radio) wavelengths are: 1) Transmitted beams from optical telescopes are far more slender than their radio counterparts owing to the high gain of optical telescopes.[10] 2) Dispersion, which broadens radio pulses, is completely negligible at optical frequencies. 3) The capability of radio transmitters has reached a stable maturity, while the power of optical lasers has not yet plateaued and has shown an annual Moore's law doubling extending over the past 30 years. 4) Natural and cultural backgrounds are negligible (though instrumental backgrounds are significant, but manageable in the current optical searches). And finally, 5) the complexity, computational power, and sophistication characteristic of sensitive microwave searches today is unnecessary for optical SETI. Detection can be quite simple—a pair of fast, broadband photon counting detectors in coincidence.

It is also worth noting that scattering and absorption limit the range of transmission in the visible spectrum to a few kiloparsecs (within which there are tens of millions of Sun-like stars); however, at far-infrared wavelengths (as at microwave wavelengths) transmissions can penetrate nearly the entire galaxy unattenuated. Thus, choice of transmission wavelength may reflect the average separation between civilizations, the number of civilizations in the galaxy, and, more speculatively, the average lifetime of a civilization (by way of the Drake Equation).

In the following sections we describe the philosophy, design, implementation, and results of such a detector system, in two incarnations: A targeted search, now in its sixth year of continual observations, of some 10^4 Sun-like stars; and a synchronized twin, in its third year of observations, operating at Princeton University.

6.0.4 Feasibility with Present Technology

We do not propose transmission[11]; nonetheless it is important to look at the field broadly: If we wanted to *transmit*, what could we do now, using only "Earth 2000" technology? This is a useful exercise, first to establish plausibility, and then to select

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[10] 150 dB for the Keck Telescope at λ=1μm versus 70 dB for Arecibo at λ=21 cm, an 80 dB advantage at optical wavelengths.

[11] We justify an asymmetrical *listen only* strategy by noting that (a) any civilization we could contact is overwhelmingly likely to be more technologically advanced (given evolutionary timescales and the fact that we have only recently crossed the communicative threshold), and (b) because contact with another civilization is unlikely to be *its* first contact, we would be dealing with a civilization experienced in interstellar communication, perhaps adhering to a galactic protocol. It therefore seems prudent to devote our limited resources to receiving, not transmitting.

an optimum receiving system scenario: among transmit/receive possibilities, a scheme that works well at both ends is a better bet.

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 illuminate, with a beacon distinguishable from astrophysical phenomena and from noise, the planetary zones of the nearest N Sun-like stars within some range $R_{\max}$ (comparable to the average separation between intelligent civilizations). In our region of the galaxy $N \approx 10^3$ for $R_{\max} = 100\,\mathrm{ly}$ and $N \approx 10^6$ for $R_{\max} = 1000\,\mathrm{ly}$.

We assume that the transmitting civilization has a catalog of target stars, their positions ($\boldsymbol{\theta_0}$), proper motions ($\boldsymbol{\mu}$), ranges (D), and radial velocities (v_r) with sufficient accuracy to permit aiming with an error no greater than $\sim$10 AU when the beam reaches the target. The sky position at which the transmitting civilization must aim ($\boldsymbol{\theta}$) is

$$\boldsymbol{\theta} = \boldsymbol{\theta_0} + \boldsymbol{\mu}\frac{2D}{c - v_r}. \tag{1}$$

Note that $D/(c - v_r) \approx D/c$ is the light travel time. At $D = 1000\,\mathrm{ly}$, 10 AU beaming accuracy corresponds to a proper motion uncertainty of $33\,\mu\mathrm{as\,yr}^{-1}$ and a positional accuracy of 33 mas. The required *range* accuracy depends on the star's proper motion; for example, to target the planetary zone (say 10 AU) of a star whose proper motion is $10\,\mathrm{km\,s}^{-1}$, the range uncertainty cannot exceed 5 ly. These requirements are certainly within the grasp of an advanced civilization, given that our astrometry will achieve micro-arcsecond precision in the coming decades (Danner & Unwin, 1999); and in any case these accuracies are relaxed if the transmitted beam is broadened to illuminate a larger zone, at the expense of received signal strength.

To send a pulse (or more generally, a packet of information of short duration) to each of $N = 10^6$ 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 $\sim$10 ms (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 intelligently selected subset of the targets and/or by using multiple transmitters; it seems altogether reasonable to expect a pulse period of 10^3 seconds or less.)

The recipient would be able to observe these pulses only if *a)* the received fluence per pulse corresponds to at least some tens of photons delivered to the receiving telescope aperture, and *b)* the flux of laser photons, during the pulse, exceeds the stellar background. It is a remarkable fact, as we'll show presently, that *using only "Earth 2000" technology we could generate a beamed laser pulse that outshines the Sun by four orders of magnitude, in white light, independent of range.* One might consider this the "fundamental theorem of optical SETI."

These pulses could be detected with an optical 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 photomultiplier tubes, and all known significant backgrounds disappear at this time scale; see Howard & Horowitz (2001)). The electronics can be as simple as 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 tens of 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.

Backgrounds

Searches for radio signals of intelligent extraterrestrial origin are plagued by the overwhelming background of radio signals from terrestrial and orbital sources. What is the situation in the optical regime: against what backgrounds must the putative pulsed optical beacon compete?

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 irregular drumbeat of essentially single photons. A G2V star at 1000 ly ($m_V = 12$) delivers $\sim 3 \times 10^5$ photons s^{-1} 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 pileup pulses are greatly suppressed; and by using a beam splitter and a pair of photodetectors in coincidence, the rejection of photon pileup is enhanced further (while additionally suppressing single-detector "hot event" artifacts)[12]. For example, the rate of simultaneous 2-photon coincidences in each of a pair of detectors exposed to Poisson distributed arrivals is $R = (r_1^2\tau)(r_2^2\tau)\tau$, where r_1 and r_2 are the individual rates, and τ is the coincidence window. For typical values $r_1 = r_2 = 10^5\,\mathrm{s}^{-1}$ and $\tau = 1\,\mathrm{ns}$, the coincidence rate caused by simultaneous 2-photon pileups in both detectors is $10^{-7}\,\mathrm{s}^{-1}$, or less than one pileup per observing year. In other words, light from the parent star itself is unimportant on a nanosecond time scale.

As far as we can tell, both from calculation (Howard & Horowitz, 2001) and from some 16,000 observations conducted so far, there appear to be few astrophysical, atmospheric, or terrestrial mechanisms able to produce events like the nanosecond photon pileup expected from an intentional and powerful pulsed laser beacon. Potential sources we considered include lightning (too extended in time); cosmic-ray induced atmospheric Cherenkov flashes (fast enough, but fluence less than 10^{-3} photon per pulse owing to its extended source sky region and large terrestrial footprint); and local effects of the background muon flux (rate of scintillation events in the optics upstream of the beamsplitter, plus estimated direct ionization events in the detectors themselves, produce event rates $\lesssim 10^{-5}\,\mathrm{s}^{-1}$).

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[12] Dan Werthimer's group at UC Berkeley tested the first pulsed multiple detector system in 1997.

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[13] beamed 1000 ly between two 10 m Keck telescopes, each orbiting a Sun-like star. Although this "Earth 2000" scheme is surely modest in technological sophistication and scale for a truly advanced civilization, we note that our search reported here is less sensitive than this example, which is given primarily as a plausibility argument.

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

$$\begin{aligned} N_R &= \frac{\pi^2 D_K^2 D_K^2 E_p 10^{-2R/5R_E}}{16\lambda_H R^2 hc} \\ &= 1500 \text{ photons.} \end{aligned} \tag{2}$$

If the beam is broadened to illuminate a 10 AU disk, then the number of received photons is reduced to ~600 per pulse.[14] Here D_K is the telescope diameter, $10^{-2R/5R_E} = 0.87$ is the extinction factor ($R_E \approx 2\,\mathrm{kpc}$—a rapidly increasingly function of wavelength—is the distance over which the intensity of a $1\,\mu$m pulse will decrease by one magnitude (Mathis, 1990)), $\lambda_H = 1.047\,\mu\mathrm{m}$ is the wavelength of the transmitted photons, $R = 1000\,\mathrm{ly}$ is the distance between the telescopes, and h and c are Planck's constant and the speed of light, respectively. The stellar background is small by comparison, $\sim 3 \times 10^{-2}$ photons ns^{-1} for a G2V star (thus ≈ 0.1 photons during the 3 ns duration of the laser pulse).

The "pileup" of laser photons here is a desirable situation (unlike normal pulsed observations), because it is the mechanism by which we distinguish an intense laser pulse from Poisson-distributed single photon arrivals from background sources.

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 (Cordes, 2002). The prompt pulse ("ballistic" photons) is unscattered (therefore unbroadened in time) and reduced in amplitude. Absorption acts also to reduce the prompt pulse height, so that the total surviving fraction is $e^{-\tau}$, where $\tau = (2R/5R_E)\log_e 10$ is the total optical depth, as mentioned above. Note that the ~13% extinction (at visible wavelengths) is modest for the range considered above (1000 ly), but becomes unmanageable[15] for targets within the galactic disk at

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[13] Helios refers to a diode-pumped Yb:S-FAP laser designed at Lawrence Livermore National Laboratory for inertial confinement fusion, potentially capable of generating 3 ns, 3.7 MJ pulses (10^{15} W) at 349 nm (or 4.7 MJ at its native $1.047\,\mu$m wavelength) at ~10 Hz rep-rates (Krupke, 1997).

[14] For nearby targets, large transmitting apertures, or very short wavelengths, the beam may be too small, given the astrometric errors. Note, however, that the transmitter can adaptively tailor its aperture (and therefore the beam size) so that the photon fluence through the target system is fixed, independent of range.

[15] At those ranges, the situation is rescued by the use of infrared wavelengths, $\lambda \approx 2$–$10\,\mu$m.

distances substantially greater than R_E.

Thus in this example the laser outshines its parent star, in broadband visible light, by a factor of 1500/0.1, or approximately 10^4. Moreover, advanced civilizations are expected to be more *advanced* than we, thus "Earth 2000" technology should be a lower bound to 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 laser technology, we conclude that a moderately advanced civilization should have no trouble outshining its parent star by six or more orders of magnitude.

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6.1 Allsky all-the-time centimeter-aperture dispersive search

ALL-SKY ALL-THE-TIME OPTICAL SETI

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ABSTRACT

The SETI 2020 roadmap established two decades ago identified simultaneous coverage of the entire night sky as a landmark objective. The reason it has not yet been realized, however, is not technical impossibility but financial impracticality. The SETI Institute has therefore developed the "minimum viable product" to achieve all-sky all-the-time observations for interstellar laser pulses with maximal science per dollar, and scale it far beyond that as funding allows.

1 Design Goal

The goal of our instrument is to maximize the parameter space coverage of signal duration, modulation frequency, duty cycle and frequency coverage, while achieving all-sky coverage, (2×10^4 deg^2) at sufficient sensitivity. Specifically, we expect to cover pulse durations up to 10^2 seconds, duty cycles from 10^3 to 10^{-7} Hz (milliseconds to years), and sensitivity across the entire optical spectrum. For comparison, the most comprehensive optical survey to date, the Harvard "All Sky" Optical SETI survey, had a FOV less than a square degree and was sensitive to pulse durations shorter than 10^{-8} and duty cycles 10^8 to 10^{-1} Hz. Multiplying these dimensions together, and including sensitivity (discussed below), the instrument proposed herein covers 10^{10} more. In simplistic terms, we will eclipse its total sky coverage in the first hour of observing.

One might reasonably argue there is an inverse correlation between parameter space coverage and ETI assumptions. Complete spatial coverage has three additional aspects of particular note. It makes 1) no assumption of proximity to us or 2) any star at all, and 3) automatically finds the brightest signal directed our way.

2 Optics and Detector

The basic physical components of the system are a camera, lens, and transmission grating.

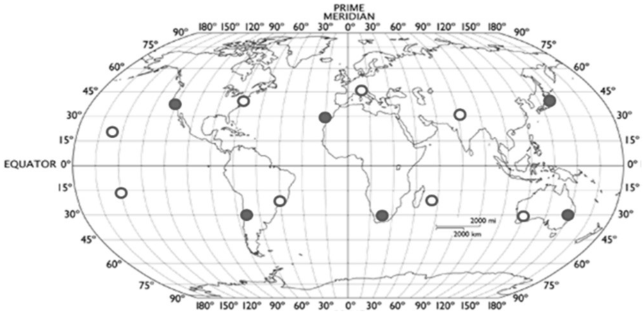
A large field of view is paramount to minimize costs, so we selected a large-format sensor (52 mm diagonal) and short focal length lens (24 mm, $f/1.4$), resulting in a 75° FOV, a spatial resolution of 1.4 arcmin/pixel, and a spectral resolution of 30 nm/pixel. This small-aperture implementation has thus far only operated under sub-par skies, but the estimated sensitivity at a SNR of 10 is 10^6 photons/m^2. Analysis of initial data is under way and already suggests that 1st-stage threshold could be lowered to at least 5, as later stages would still provide extremely high confidence. Much larger apertures, e.g. 0.2 - 0.4 meter, are available off-the-shelf and in quantity for the same unit cost and would increase sensitivity by 10^2 or more; the associated cost increase is solely due to and directly proportional to the decrease in FOV. Indeed, a sensible addition to the program proposed here would operate large aperture devices in parallel with panoptic devices, allowing for quantitative comparison and slewed automatically for high-sensitivity, rapid event follow-up.

To discriminate events of interest, the detector applies two techniques: slit-less spectroscopy and TDI readout. A low-resolution binary transmission grating in the optical path maximizes throughput of the ±1 order spectra, enabling discrimination of monochromatic sources from broadband simply by aspect ratio. Reading the CCD out via overclocked TDI at 10^3 Hz provides temporal resolution, serves to reduce shot noise from stars and pixels lost to saturation from bright sources. Since the TDI is overclocked with respect to the movement of the FOV, vertical information is conflated with time and rendered inaccessible. However, two cameras pointing at the same patch of sky but oriented perpendicular to each other allows coincident events to matched and accurate vertical position and timestamp recovered.

The output of the detector is a set of events that can then be analyzed for similarity and patterns, such as regular recurrence or beamed-power sweep pairs, originating from a common point on the sky.

3 Global Deployment

Two cameras per field of view also provide a needed increase in statistical confidence of detected events to the required levels for a global system of many such devices. Thus a site requires minimum of eight cameras to cover its sky down to 30° above the horizon. Six sites are required, three per hemisphere, to cover the full celestial sphere. Fortunately, Earth's continental arrangement is reasonably accommodating to this requirement, and the system easily supports additional cameras in arbitrary locations.



We further recommend pairing another 6-8 sites to these, separated by at least 1000 miles, so that co-observed events can be subjected to strong physical validation by comparing the angle of incidence vs. arrival time. Further, since no site has perfect weather, paired sites provide continued observing in the face of inclement weather at one site, bringing the All-The-Time aspect of the vision significantly closer to 100%.

The global nature also facilitates the exciting potential of global support, partnership, and inspiration.

4 Cost, Operations, and Status

Currently, a single prototype is operational. The master grating has been fabricated, software developed, and initial observations begun—albeit with suburban skies that are much brighter than a typical observatory's, which contributes significant additional noise over the large FOV. The detector algorithm requires only ~5% of a current Intel i7 processor to process one camera's input in real-time. A simplified overestimate, using preliminary data and completely ignoring the dual-site validation concept, suggests we should expect one false positive per single camera every 30 hours of observing. Given the high system data rate, this extrapolates to a global rate of once every 10^7 years—essentially never.

The unit cost is projected to be ~$11k in bulk, hence detector hardware alone for the worldwide observatory is about $1.1M. We estimate support hardware and deployment costs to be another $500-700k each, and operating costs over a nominal 5-year observing campaign to be at least $200k/year, without hosting fees. Second-round funding is sought for a first set of paired observatories, to validate the statistics and co-observing strategies over a period of approximately 6 months. The $480k cost splits roughly evenly between hardware and development, again assuming hosting at friendly, zero-cost sites—presumably on the US east and west coasts. The final stage, worldwide deployment, is largely gated on logistics and the desired tradeoff between speed and cost of the site and operator selection, and is expected to take 6 to 18 months.

No known barriers stand in the way of completion, and indeed it's worth noting the simplicity of the system. With no tracking mounts or sub-degree alignments required, no moving parts besides camera shutter, only one (non-fragile) optical surface exposed to the elements, no real-time communication required between cameras or central database, and no single points of failure, the system is eminently robust and maintainable.

5 Secondary Science

We believe this novel instrument is uniquely suited to detecting and characterizing meteors. Despite its stellar all-sky coverage resulting in "only" 850,000 square miles or 1.6% of Earth's upper atmosphere, it is sensitive enough to detect even small debris entering the atmosphere and has sufficient spectral resolution to identify basic meteoric composition, burn evolution, and hence 3D structure. It would likely perform a very effective survey of the low-mass end of man-made space debris as well. This idea has only been explored superficially due to limited resources but is tantalizing, particularly if paired with existing meteor triangulation networks such as NASA's CAMS network, also headquartered at the SETI Institute.

6.2 Large-sky ($>$1000 deg^2) meter-aperture nanosecond pulse search

At the Breakthrough Discuss conference at Stanford (15–16 April 2016) we presented a notional design for an "all-sky, all-the-time" search for nanosecond-scale optical pulses from a distant civilization having the means and desire to establish contact with a directed beacon transmitting brief and intense laser-like pulses.

This appendix fleshes out in some detail how apparatus could be constructed using available technology, in a timescale of a few years.

6.2.1 Signal Type

As described in great detail in a previous paper from our group,[16] a robust and plausible optical beacon consists of a nanosecond-scale pulsed laser, collimated with a Keck-size mirror. The interstellar medium is kind to such a signal, causing only negligible temporal broadening (in contrast to the situation at radio frequencies), as calculated by Cordes (SETI 2020, Appendix M). And the received signal is impressively strong: taking as an example the Helios laser design (1 PW for 3 ns, capable of 10 pulses per second; see the Krupke reference in Howard et al.) transmitting from 1000 light-years away,[17] a 10-m Keck telescope would receive $\sim$1500 photons during the brief 3 ns interval, during which the source civilization's parent star would deliver a negligible background of just 0.1 photon. Scaling to an inexpensive 1-m aperture, we would receive a photon pileup of 15 photons, against a stellar background of 1/1000 photon. Nice!

The rest of this document describes a system to detect such a putative optical pulse signal, with full-time coverage of most of the sky.

6.2.2 Overall Design

We propose an elaboration of our current transit-mode optical search, enhanced by replacing the thin stripe covered with our current multipixel photomultipliers with a full array of the new solid-state photomultiplier (SSPM) devices (each pixel of which is an array of some 10^4 Geiger-mode avalanche photodiodes[18]); these devices are fast ($\lesssim$ 10 ns), exhibit excellent linearity (pulse-height resolution) and low noise (well below 1 photoelectron equivalent), and are remarkably inexpensive in quantity ($7.25

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[16] Howard, A., Horowitz, P., et al., *Search for Nanosecond Optical Pulses from Nearby Solar-type Stars.* Astrophysical Journal **613** 1270–84 (2004). Available at https://dl.dropboxusercontent.com/u/24682491/oseti_apj_published.pdf

[17] Within which there are some 10^6 sun-like stars, and perhaps 10^5 habitable planets.

[18] Hamamatsu calls theirs MPPCs, for "multi-pixel photon counter." We'll adopt this nomenclature.

each/qty 100k); see Figure 6. Figure 7 shows the excellent pulse-height discrimination of one of these devices (S13360-3025CS: 3 mm square, populated with 14400 25 μm APD cells). An array of some 5×10^3 of these devices, in a 3 mm square form factor, positioned behind a 0.5-m scale $f/2$ spherical light-bucket, covers 160 deg^2 of sky. That is 500 times the instantaneous coverage of our current transit search (Figure 8). Some thirty such apertures nicely cover the southern sky (see Figure 9). If the angular subtend were increased by 1.5×, fifteen telescopes would suffice.

Owing to the photon-sensitive detectors and 0.5-m apertures, this design is sensitive to nanosecond-scale light pulses of $\geq$100 photons per square meter, the expected fluence from the model Helios–Keck system described in §6.2.1, sent by a civilization up to 500 light-years distant.

6.2.3 Some Details

Figure 10 shows a spherical light bucket with its focal plane tessellated with abuttable MPPCs. Based on our measured single-photoelectron dark-count rate of $\sim 4\times10^5$ cps, the sensors can probably be operated at ambient temperature, eliminating the hassles of condensation, etc. Each MPPC output drives a wideband MMIC amplifier (e.g., NXP BGA2874: dc–750 MHz, G=31 dB, P=40 mW) coupled to an analog comparator (integrated, or single BJT, or – best – a single-ended or LVDS input of an inexpensive FPGA), thence to one of several FPGAs. The latter perform buffering, serializing, and outputting of the time-stamped and addressed events. The detectors' 3 mm square pixel size (3 mrad, or 10 arcmin) nicely captures the point-spread blur circle of the primary ($\sim$1 mrad on-axis, double that at the field's edge). Each primary in the cluster is fixed in declination and hour angle, configured to tessellate the sky with the hexagonal patterns from the array of dishes.

Figure 11 suggests a layout of the multiple dishes, though for our purposes no telescope drives are needed. For robustness against local effects (optical and electrical interference, cosmic ray streaks, and the like), a spatially separate second observatory operates simultaneously. Photon pileup events from both observatories are compared, to eliminate events not seen at both observatories, in corresponding pixels and with appropriate timing.

6.2.4 The Numbers

To put some flesh on these bones, here are some numbers to guide the ultimate detailed design, operation, and budget.

<u>Count Rates</u>

Dark Count Rate We measured a 3 mm (square) part on the bench, at ambient temperature (thus the traces in Figure 7), setting the threshold at successive integral numbers of photoelectrons. Here are the results:

Threshold	Count Rate
0.5 p.e.	425 kcps
1.5 p.e.	145 cps
2.5 p.e.	0.4 cps (40 counts in 100 sec)
3.5 p.e.	0.0017 cps (6 counts in 60 min)
4.5 p.e.	0.0003 cps (1 count in 60 min)

The 2-photon and 3-photon rates are plausibly consistent with Poisson statistics for a 1 ns aperture, but the 4- and 5-photon pileups are not; presumably we are seeing occasional "crosstalk," a documented effect in these detectors. This effect is reduced when running at lower gain (we ran at the recommended $V_{\rm br}$+5V), but even at this gain ($\sim 7{\times}10^5$ according to the datasheet) the pileup rates are manageable: a telescope with $5{\times}10^3$ MPPC sky pixels would produce just one trigger in an hour; these are time-stamped (to 10 ns, say), logged, and subsequently compared with analogous events from the matching telescope at the other site. The odds of two such events (if random) providing a false match is less than 1 in 10^{10} per telescope and per day of observing. Bottom line: the dark count rate of uncooled detectors is of no consequence.

Stellar and Sky Count Rates A G2V (sun-like) star at 1000 lyr is m_V=12, delivering about 10^5 photons/sec to a 0.5-m aperture; allowing for detector quantum efficiency of ~30%, that's about 3×10^4 counts per second, well below ambient dark count rate.

Excellent dark sky is about $m_V{\approx}22$ per square arcsec. Our strawman design, with its pixels subtending 10 arcmin square (thus 100 square arcmin), therefore sees a sky brightness of about $m_V{\approx}8$, thus about 4×10^6 visible photons per second, reduced by quantum efficiency to about 10^6 single p.e. counts per second. This is roughly double the room-temperature dark count rate, and therefore manageable.

In fact the situation with MPPC detectors is really quite good, even with considerably greater background count rates one gets with less-than-ideal sky conditions: In a series of benchtop experiments we generated short LED flashes (circuit in Fig. 13), superposed on variable levels of steady illumination. We found clean and consistent detection of solitary pulses at the 6 p.e. level, even with backgrounds of >10 megacounts/second. Figure 14 shows a completely typical screenshot, where the background illumination was set to produce ~5 megacounts/sec.

Telescope Optics
We favor a simple prime-focus spherical cap, whose focal spot (for f/D=2) is a glob of order 3 arcmin for on-axis illumination.[19] For our baseline design the area of each detector pixel is about triple this spot size. For off-axis rays (away from the center of the field) the aberrations are greater, reaching 9 arc minutes at the edge of the field

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[19] A parabolic primary is far better on-axis, but has degraded to the performance of a sphere beyond 1.5° off-axis. Note further that, to obtain linearity from an MPPC, one must illuminate many APD micro-cells; i.e., a soft focus is necessary – a diffraction-limited spot size is in fact a liability.

(±7° off-axis), approximately filling the pixel's active area.[20]

Sensitivity

These numbers were summarized in §6.2.1: a civilization 500 light-years distant, at only our (primitive) level of technology, could launch nanosecond bursts of 15 visible photons into our 0.5-m aperture, enough to trigger the system. We hope for more – for the advanced civilizations we expect to detect, such a meager effort would be embarrassing, akin to a high-school science project. We could build larger telescopes, but let's assume they are willing to do the heavy lifting.

Our design aims at maximizing sensitivity to highly intermittent nanosecond-scale flashes, through the use of single-photoelectron detectors operated in what might be termed "instantaneous mode" (i.e., no integration, in the manner of CCDs, etc.).[21] This approach is complementary to the spectroscopic methods described in two talks at Breakthrough Discuss (Session 1: [a] Eliot Gillum and [b] Amy Reines), which are directed to observations of [a] full-sky synoptic imaging with small apertures and modest spectral resolution, and [b] targeted stars at very high sensitivity and spectral resolution.

Cost Estimates

A rough estimate, for sanity checking, of the incremental[22] *materials* costs:

Each telescope:	
mirror	$10k
MMPCs	$40k
electronics/computing	$10k
total per telescope	$60k
Array of 10 apertures:	$600k

In a measured implementation program, one would begin with one aperture only, for checkout and tuning locally. After all is good, the next step is to populate one site (with perhaps 10 telescopes, covering 1600 deg^2), then the paired site. Including the observatory structures, we're talking about $2M for the full program.[23] We've not included in the above any indirect costs, operating costs, nor student support, all of which are required. However, based on previous SETI activities at our universities, we anticipate significant volunteer interest – many technically talented people find SETI irresistible.

Schedule

Based on past projects of similar scale, we estimate a prototype telescope with detec-

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[20] For this baseline combination of aperture and f-number these aberrations present no problem. However, for larger apertures or faster optics some correction is needed, e.g., a single corrector element, in the manner of a Schmidt telescope; Figure 12 shows the improvement wrought by a single plano-convex acrylic corrector lens near the focal plane.

[21] Ideally one would prefer extended sensitivity in the red and near-IR (analogous to Shelley Wright's targeted pulse search, but with full-sky coverage), but appropriate detector technology is still in the development stage.

[22] I.e., for the n-th unit; S/N 01 always costs more… sometime a lot more.

[23] And triple that for a whole-earth program sited at three Earth-girdling longitudes.

tors and electronics in something like 2–3 years; another 2–3 years to build out the system.

Variations

The baseline system sketched above is just a starting point for a serious look at the "trades" – aperture, f-number, detector size, and the like. For instance, Ed Wishnow's optical design of a 1-m $f/2$ sperical primary with spherical acrylic corrector (Fig. 12) would quadruple the sensitivity (while permitting use of the same 3 mm square detectors), thus extending the range at which a signal of given pulse energy is detectible by a factor of two – that's an 8-fold increase in habitable *volume.* The costs increase, of course: a factor of four in detectors and electronics, and likely somewhat more in telescope cost; but a habitable volume increasing as the 3/2 power of system cost is certainly a temptation to go larger – where does one stop?[24] These sorts of trades must take account of available resources, as well as factoring in likely improvements in detector and computing hardware.

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[24] Maybe when the plausible sensitive volume encompasses the $\sim$1 klyr thickness of the galactic disk, after which the sensitive volume scales only linearly with system cost.

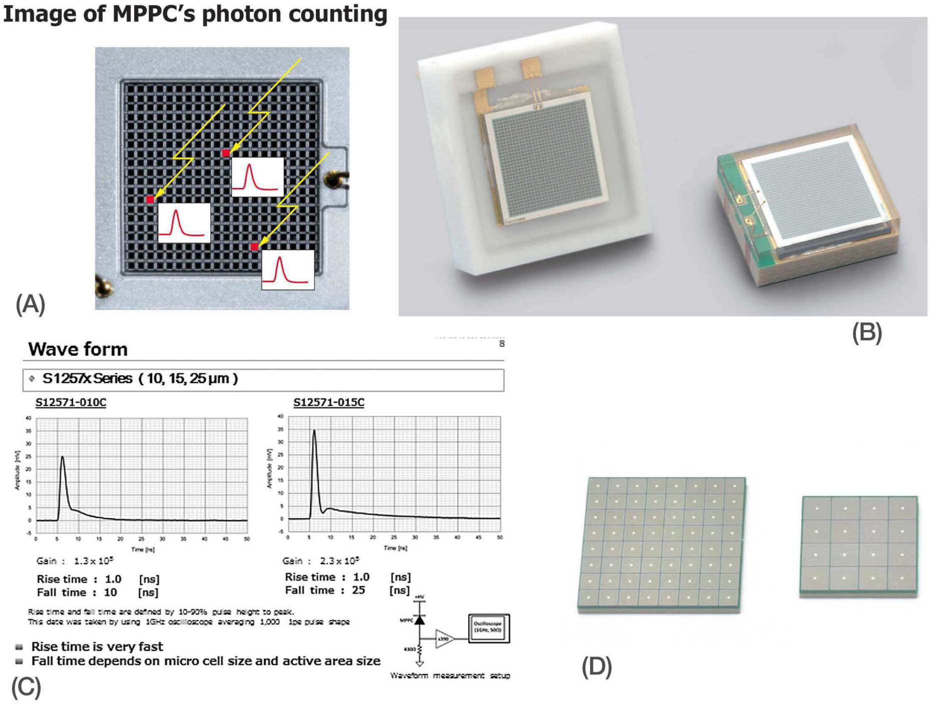
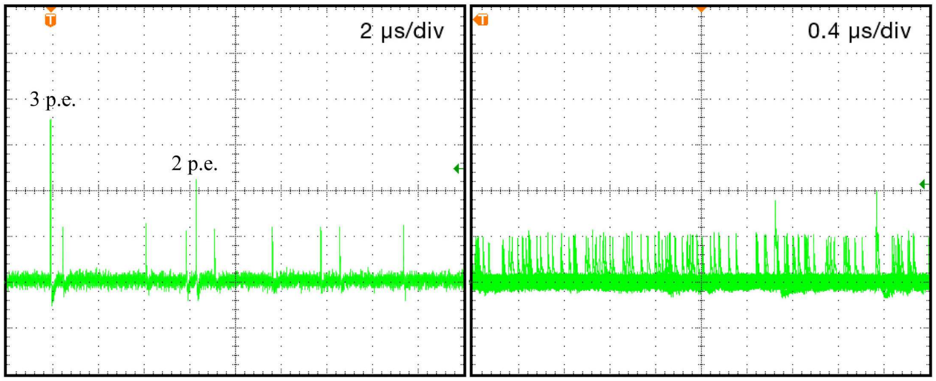


Figure 6: Hamamatsu array photodetectors. **(A)** Notional concept – an array of independent Geiger-mode avalanche photodiodes, whose outputs are summed to a single terminal; this single pixel exhibits excellent pulse-height resolution, even though each sub-pixel generates either a fully saturated pulse or is dormant. **(B)** The individual sub-pixels are visible in this photograph of an MPPC pixel. **(C)** Illustrating pulse characteristics – fast rise, moderate fall. **(D)** Chip-packaged MPPC pixels are abuttable, factory matched in operating voltage to enable a single bias supply.



single sweep, showing linear pulse-height response to n-photon pileup

accumulated sweeps, showing prevalence of single-photon dark counts vs 2-photon pileup

Figure 7: Dark counts from an MPPC (Hamamatsu 3 mm square, with 14400 25 μm cells) operated at recommended bias, loaded into 50 Ω and amplified with a UTO-style RF amplifier. Note the clean discrimination of single photoelectrons, excellent linearity, and low noise floor. Vertical: lefthand trace – 10 mV/div; righthand trace – 12.5 mV/div.

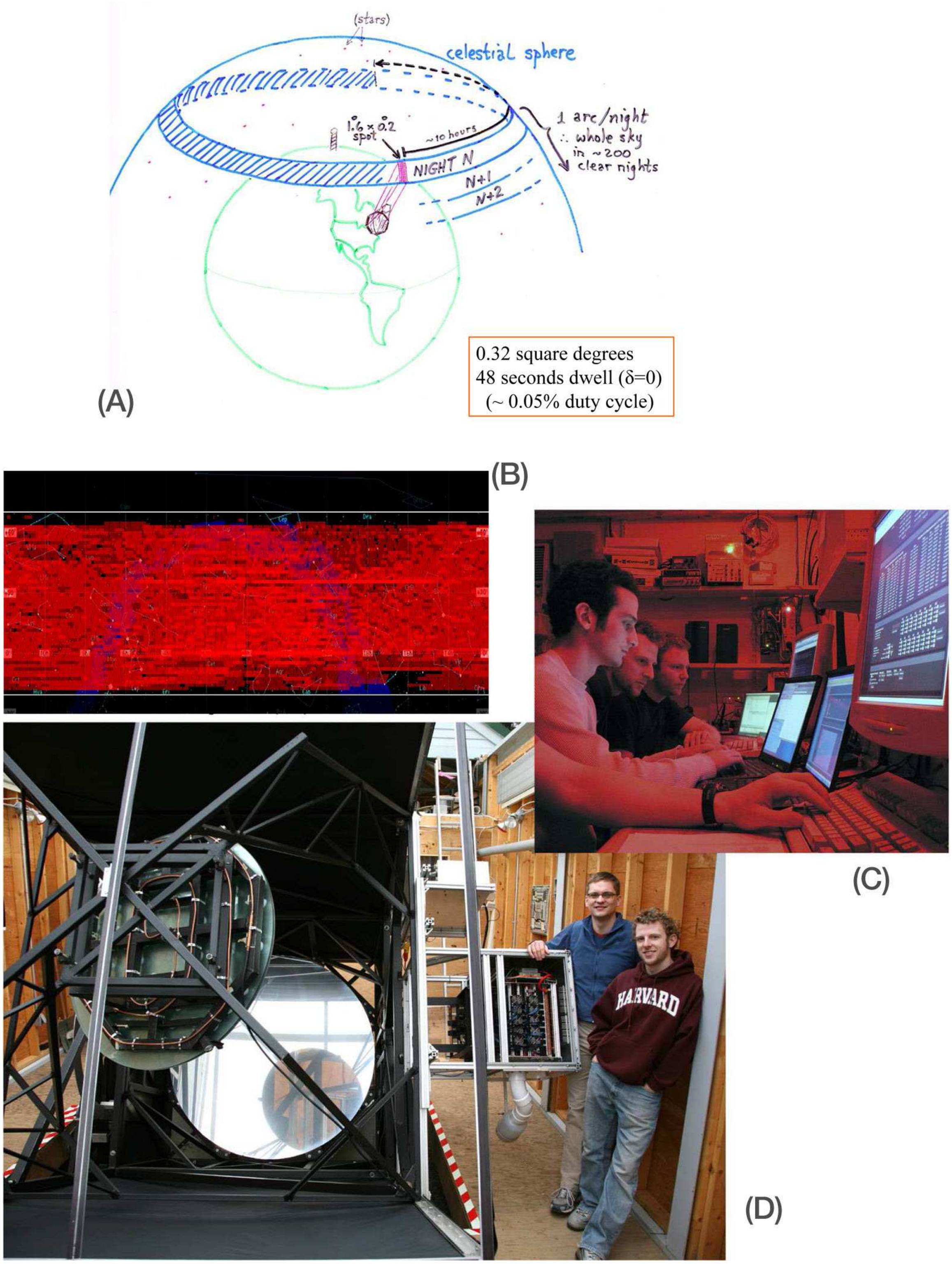


Figure 8: Transit search at Oak Ridge Observatory in Harvard, MA. **(A)** Transit-mode search, pixel stripe 8×64 pixels (duplicated with beam-splitter) sweeps the sky at sidereal rate. **(B)** Sky coverage after 5 years of observations. **(C)** First night. **(D)** Creators Andrew Howard and Curtis Mead admire the beast. The primary is a 1.8 m $f/2.5$ spherical light-bucket, with 0.9 m flat secondary.

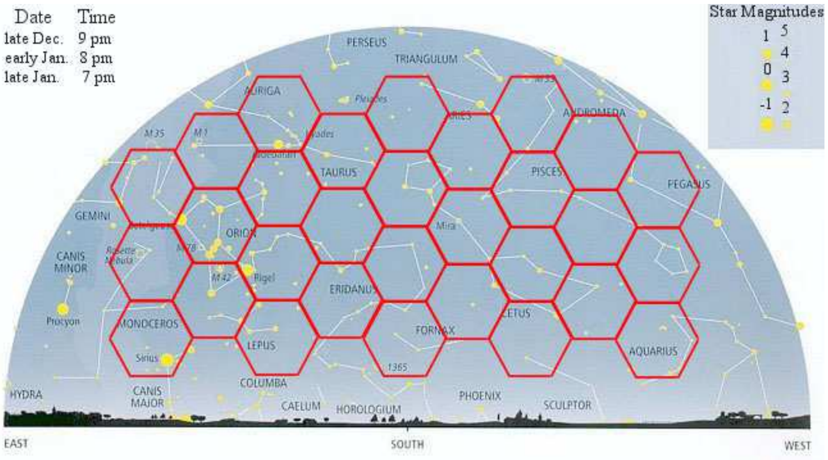


Figure 9: Some thirty 0.5-m light buckets with 160 deg^2 field of view cover most of the southern sky as seen from northern latitudes. (notional overlay, not corrected for flat projection.)

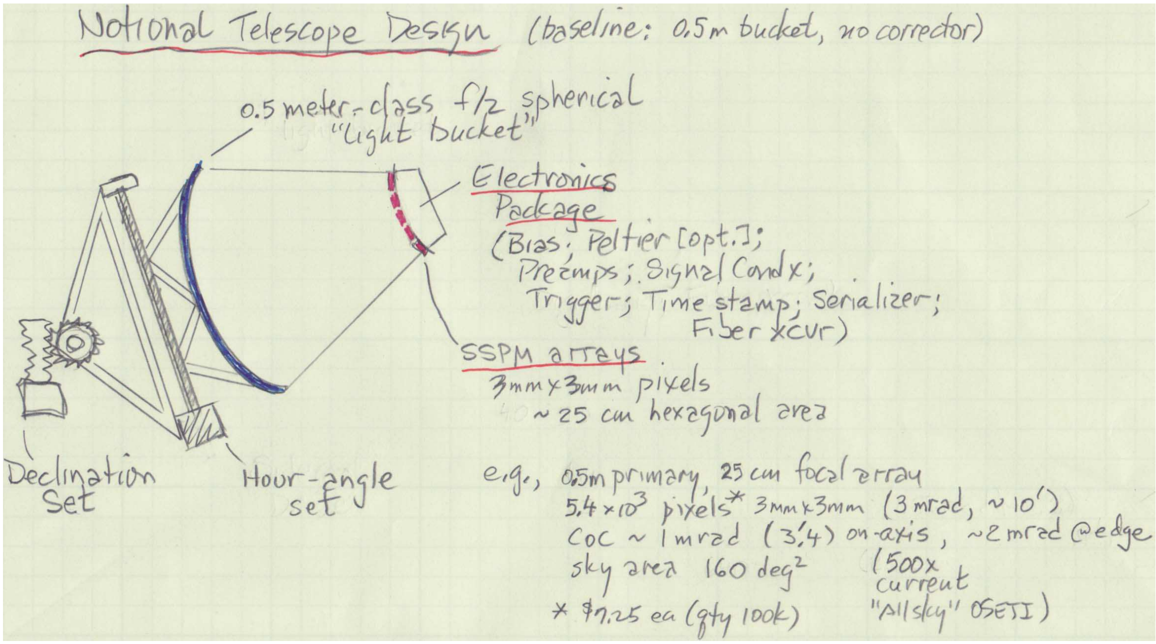
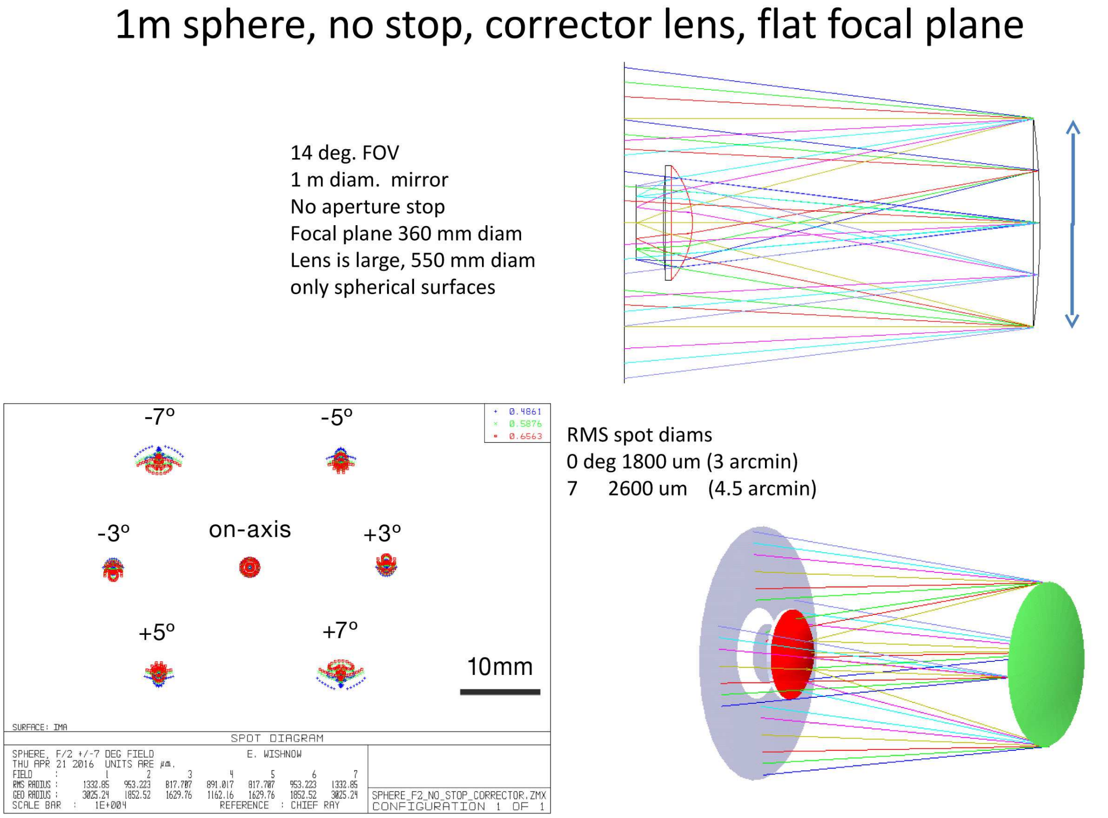


Figure 10: One aperture of the cluster of 0.5-m light buckets needed to cover a large portion of the sky. Each pixel feeds a video amplifier and comparator, the latter set for a threshold of, say, 4.5 photoelectrons. The many channels combine in several FPGAs, which time-stamp each trigger, and forward the pixel address and time in its serial stream. These data are compared with analogous data from a separate site, creating a robust 2-site authenticating protocol.

Figure 11: One of two sites of the “MEarth” project, with its array of 0.5-m Cassegrain telescopes. For the SETI project no drives are needed.



1m sphere, no stop, corrector lens, flat focal plane

14 deg. FOV
1 m diam. mirror
No aperture stop
Focal plane 360 mm diam
Lens is large, 550 mm diam
only spherical surfaces

RMS spot diams
0 deg 1800 um (3 arcmin)
7 2600 um (4.5 arcmin)

```
SPHERE, F/2 +/-7 DEG FIELD                    E. WISHNOW
THU APR 21 2016  UNITS ARE µm.
FIELD      :         1        2        3        4        5        6        7
RMS RADIUS :   1332.85  953.223  817.707  891.017  817.707  953.223  1332.85
GEO RADIUS :   3025.24  1852.52  1629.76  1162.16  1629.76  1852.52  3025.24
SCALE BAR  :    1E+004                REFERENCE  : CHIEF RAY
```

```
SPHERE_F2_NO_STOP_CORRECTOR.ZMX
CONFIGURATION  1  OF  1
```

Figure 12: Going from the baseline 0.5 m design to a larger 1 m aperture, a single 0.5 m plano-convex corrector is adequate for a 14° telescope field and 3 mm detector pixels. (Optical design and ray tracing by Ed Wishnow at UCB Space Sciences Lab)

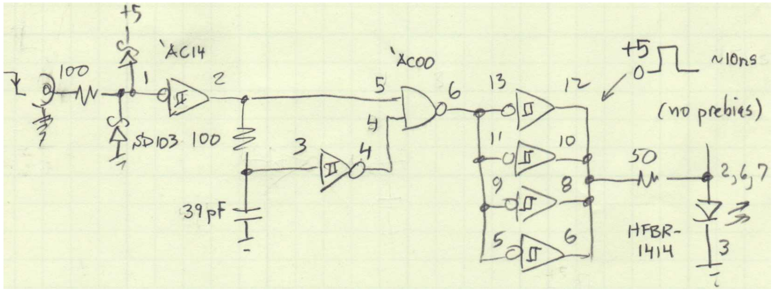


Figure 13: Cheap and dirty LED ST-fiber pulser circuit.

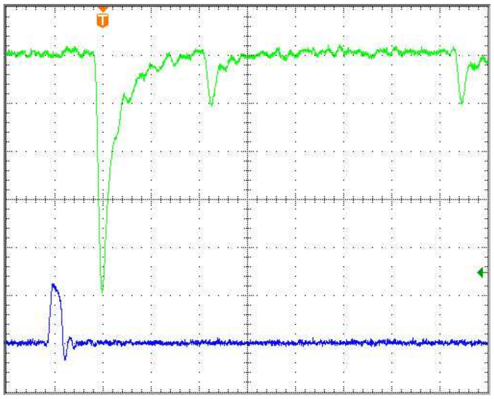


Figure 14: A test flash (lower trace) is detected consistently (here at the 5 photoelectron level, upper trace), even in the presence of background illumination producing 10 megacounts/sec rate or more of single-p.e. events. (The 40 ns delay is caused by a lengthy fiber run from LED flasher to dark-box.) Horizontal: 40 nsec/div.

6.3 Small-sky ($<0.1\,\mathrm{deg}^2$) near-IR meter-aperture nanosecond pulse search

Breakthrough Listen

September 2016
Pages 1–7

SETI Wide-field Infrared Surveyor (SWIS)

Shelley Wright[1], Jérôme Maire[1], Remington Stone[2], Richard Treffers[3], Frank Drake[4], Dan Werthimer[5], Geoffrey Marcy[5]

1. UC San Diego, Department of Physics, Center for Astrophysics & Space Sciences
2. University of California Observatories, Lick Observatory
3. Starman Systems, Alamo, CA
4. SETI Institute, Mountain View, CA
5. UC Berkeley, Department of Astronomy

Instrument Conceptual Design (v1)

1 BACKGROUND

Optical SETI experiments have been underway for over 15 years to search for laser pulsed signals. In the last decade, optical SETI instruments have matured in their reliability (e.g., discriminating against false positives), sensitivity (e.g., improved optical detectors), and search strategies (e.g., targeted versus wide field of view surveys). Near-infrared offers a unique window with less interstellar extinction and less background from our galaxy than optical wavelengths, meaning that signals can be efficiently transmitted from larger distances within the plane of the galaxy. The near-infrared regime was identified early on as an optimal spectral region for interstellar communications (Townes 1983), yet has remained largely unexplored territory for SETI. For many years our team was interested in pushing pulsed SETI experiments into near-infrared wavelengths, but was discouraged by lack of adequate near-infrared fast response ($\sim$ GHz) sensitive detectors. Infrared detector technology has matured rapidly in the last decade, offering higher quantum efficiencies and lower detector noise.

Three years ago our team began designing a near-infrared SETI experiment that made use of the latest avalanche photodiodes for a targeted pulsed search. This instrument, operating from 950 to 1650 nm, achieved first light in March 2015 (Figure 1) on the 1-m Nickel telescope at Lick Observatory (Wright et al. 2014; Maire et al. 2014, 2016). Since this was the first pulsed optical and infrared SETI experiment to use discrete amplification avalanche photodiodes, our team had to fully characterize these detectors to optimize sensitivity and minimize false alarm rates. We had two primary instrumentation goals for our program: (1) develop and extend optical SETI experiments to near-infrared wavelengths and (2) significantly advance pulsed laser SETI software and data analysis techniques.

The current NIROSETI instrument has been carrying out an active near-infrared SETI survey of targeted stars and galaxies.[1] Analysis tools developed for this near-infrared program are more advanced than for previous optical SETI experiments, with the ability to perform searches for varying pulse widths and duty cycles. We also store data for future post-processing. This was a unique approach, as previous optical SETI experiments did not archive raw waveforms for future analysis. Our experiment is the first near-infrared SETI search, and is in many ways similar to the first generation of optical SETI instruments - we discovered instrumental and programmatic challenges that we now wish to address in a next generation system. In this document, we describe the conceptual design for a new wide field-of-view near-infrared SETI instrument.

2 SETI WIDE-FIELD INFRARED SURVEYOR (SWIS)

A leading challenge for near-infrared fast-response detectors compared to current optical detectors is overcoming the small size of active area of the sensors. The NIROSETI experiment had to be designed around 200 micron active area sensors with a small field of view of 5”x5”, whereas typical sizes of single optical photometers are 10-100 times larger. Subsequent to our first design and commissioning, these discrete-amplification (DA-)APDs[2] have been developed into small arrays. We have generated a conceptual design for a new instrument based on arrays of DA-APDs. Note that these arrays are similar and complementary to the multi-pixel photon counters (MPPC) using silicon APDs that Paul Horowitz is designing for the proposed all-sky all-time optical SETI experiment. We have designed a dedicated wide-field (2x30 arc-minute) near-infrared pulsed SETI experiment, able to survey the entire northern hemisphere in less than 5 years[3] using a drift scan technique (Figure 2). Projected instrument specifications for our new instrument are summarized in Table 2. Multiple copies of this instrument could be placed on more telescopes for both efficiency, hemispheric coverage, and confirmation of any detections. A preliminary budget including hardware/software and labor is projected in Table 1. A single instrument on one telescope has an estimated cost of $\sim$\$0.7 Million.

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[1] Stellar and galaxy target lists have thus far been coordinated with the Breakthrough Listen program.

[2] http://www.amplificationtechnologies.com/Products.html

[3] Assuming 60% observing efficiency.

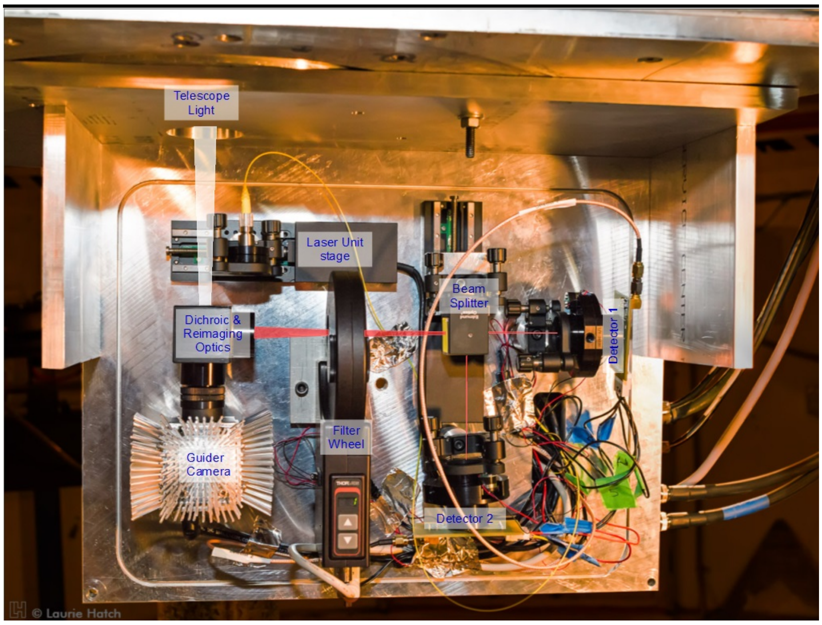

Fig. 1. The near infrared SETI instrument (cover removed) as mounted on the Nickel 1-m telescope at Lick Observatory. The instrument has been running in full campaign mode since summer 2015 with a dozen nights per month on the telescope. Photo Credit: Laurie Hatch.

2.1 Dedicated Near-Infrared SETI Experiment

2.1.1 *Dome and Facility Access*

One appealing site for our program is University of California's Lick Observatory. They generously offer exclusive access to the otherwise retired Carnegie Astrograph, including control room space, and the usual utilities plus fast internet access via the UC network, all complemented by a very competent staff. This dedicated facility would no longer require us to share observing time with other programs, and eliminate the present overhead of constantly removing and remounting our instrument. We will be able to observe all clear nights, which will greatly accelerate our program, and will motivate us to roboticize our facility. The superbly well-mounted Astrograph and large dome were used for a photographic survey of Northern skies, a program which lasted half a century.

We are unable to utilize the present twin refractor tubes on the telescope, since they yield too much chromatic aberration and focus shift for the DA-APD detector arrays. As described in Section 2.1.2, we are actively searching for substitute optical tube assemblies (OTA) which best meet our requirements. Perhaps the greatest potential advantage of this very strong and stable telescope mount is the possibility of adding additional OTAs onto the single sturdy mount. Such OTAs could have apertures up to the 1.8m practical limit prescribed by the 2m dome aperture. These additional OTAs could be used to increase collecting area (and thus sensitivity) on a single patch of sky, or to simultaneously scan additional contiguous bands of sky to increase the area of sky observed per night.

The dome and telescope have been mothballed for the last 20 years or so, but a recent inspection showed the interior space and its contents had been well cared for. The exterior has degraded but the interior shows no sign of leakage. Regardless of our intended use, Lick Observatory has plans in place to imminently reseal and repaint the exterior. Some interior remedial mitigation is required of the sort common to older structures (asbestos and mold). The Observatory recently obtained bids from a UCSC approved mitigation service for the interior work, which will be approximately $8,500. We have discussed our intent of using the Astrograph for the SWIS instrument, and received positive feedback from the UCO Director.

2.1.2 *Telescope Designs*

Our team has been investigating several telescope designs which could satisfy our requirements for wide-field observations over a large near-infrared bandwidth (900 to 1800nm) and small detector pixels (200 μm). The telescope plate scale (i.e. arcsec/mm) is a crucial optical design parameter to optimise dwell-time and maximize field-of view of the instrument (section 2.3). Hence, plate scale should be as large as possible with considerations of sky background (section 2.2) and optical aberrations. Telescope diameters with a 0.4-1m range were considered to satisfy sensitivity, field-of-view, and plate scale requirements. Given detector pixel and array size, it is necessary to have fast telescopes (f-ratio < 5) with plate scales larger than 90 arcsec/mm and 30 arc-minute field-of-view.

Given our large plate scale requirement, off-axis aberrations and focus offsets will affect spot sizes. Our team has been investigating trade-offs between several telescope designs (e.g., spherical, parabolic) using optical design simulations. Spherical primary mirrors, like those used in optical SETI large sky surveys, suffer spherical aberrations too large for the given near-infrared pixel size. Although parabolic primary mirrors suffer from off-axis coma, addition of a Wynne corrector can optimize for small spot sizes well-suited to the pixel-size and field

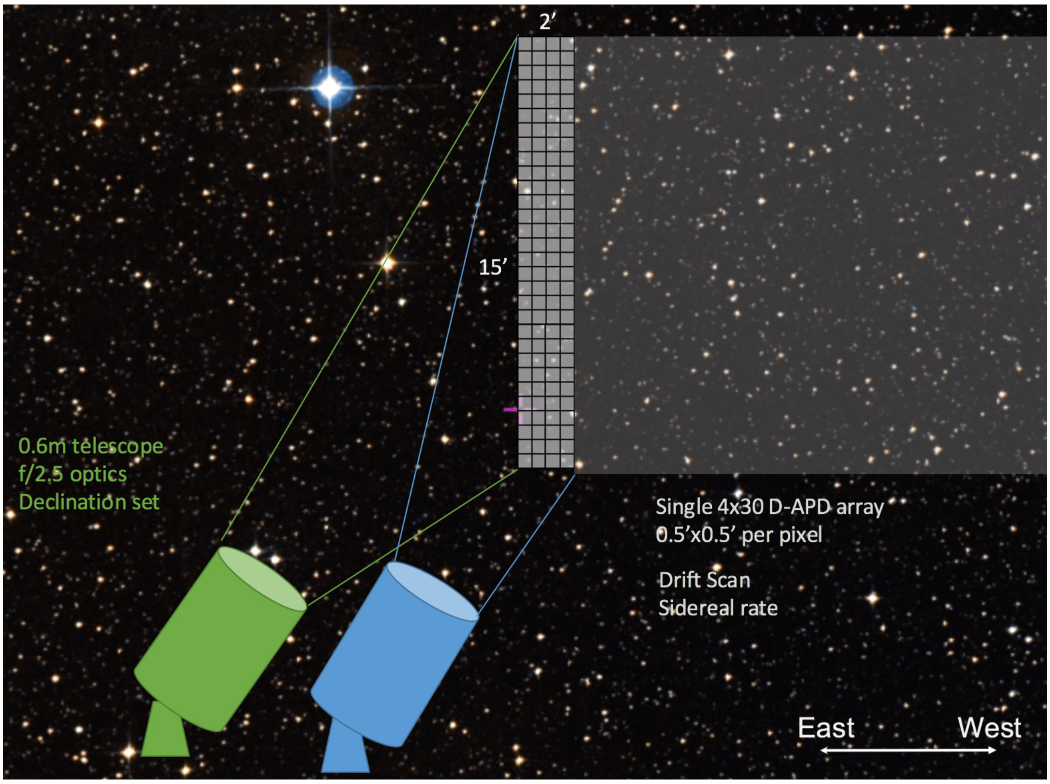

Fig. 2. Conceptual design for two 0.6-m telescope for drift scan observations using a tile of 4x30 near-infrared D-APD arrays. The pixel size would be 0.5'x0.5' and would be able to sample the entire northern hemisphere from a site like Lick Observatory in 4.5 years. The background image is to scale.

coverage of our detectors. Hyperboloid and Ritchey-Chretien telescope designs were also considered, but their cost were usually higher than parabolic mirrors.

For this conceptual design document, as an example we consider the choice of a 0.56m Wynne-Riccardi telescope[4] which provides a plate scale of 147 arcsec/mm. The Wynne-Riccardi telescope has very good mechanical design and construction with f/2.5 primary. These telescopes are designed to have small spot sizes at 4 microns (on-axis) to 8 microns (full field) over a 2.5x2.5 degrees field-of-view (Fig.4). This company also supplies twin telescopes, as can be seen in Fig.4, that would be useful for coincidence detection and confirmation between telescopes. Both telescopes also may be used to double the field of view, reducing the total duration for covering the northern hemisphere. A twin telescope looking at the same field-of-view with identical detector arrays would increase sensitivity of the entire instrument for coincidence detection.

The Astrograph dome and slit size allows a primary mirror as large as 1.8-m, so we have the opportunity to scale the project to larger aperture telescopes should funding become available.

2.2 Near-infrared background and maximal field-of-view per pixel

At nanosecond resolution, the instrument is dark count limited rather than stellar photon-limited (for stars fainter than J>1 in a 1-m telescope configuration, according to NIROSETI measurements). Sensitivity of the instrument is improved by relatively low dark-noise detector capability in the near infrared (less than one megacount per second). The design of a wide-field near-infrared instrument such as SWIS requires investigation of the near-infrared sky background to determine the maximal field-of-view per pixel beyond which instrument sensitivity is sky background limited. Near-infrared sky background is dominated by OH emission lines generated by reactions between O_3 and H in the upper atmosphere. Strength of the OH emission is site-dependent and highly variable on minute timescales. Sky brightness due to the Moon also varies by 0.9 magnitude in J-band and 1.2 magnitude in H-band (Vanzi *et al.* (2003)) depending on the lunar cycle.

To assess the maximal field-of-view M in arcseconds, we determine when the instrument sensitivity would be sky background-limited. We derive the number of counts per second per pixel due to sky background using measurements of sky brightnesses B_J in J-band (in magnitude/arcsec^2) and B_H in H-band, and determine when it is equivalent to number N of dark pulses per second. For a circular telescope

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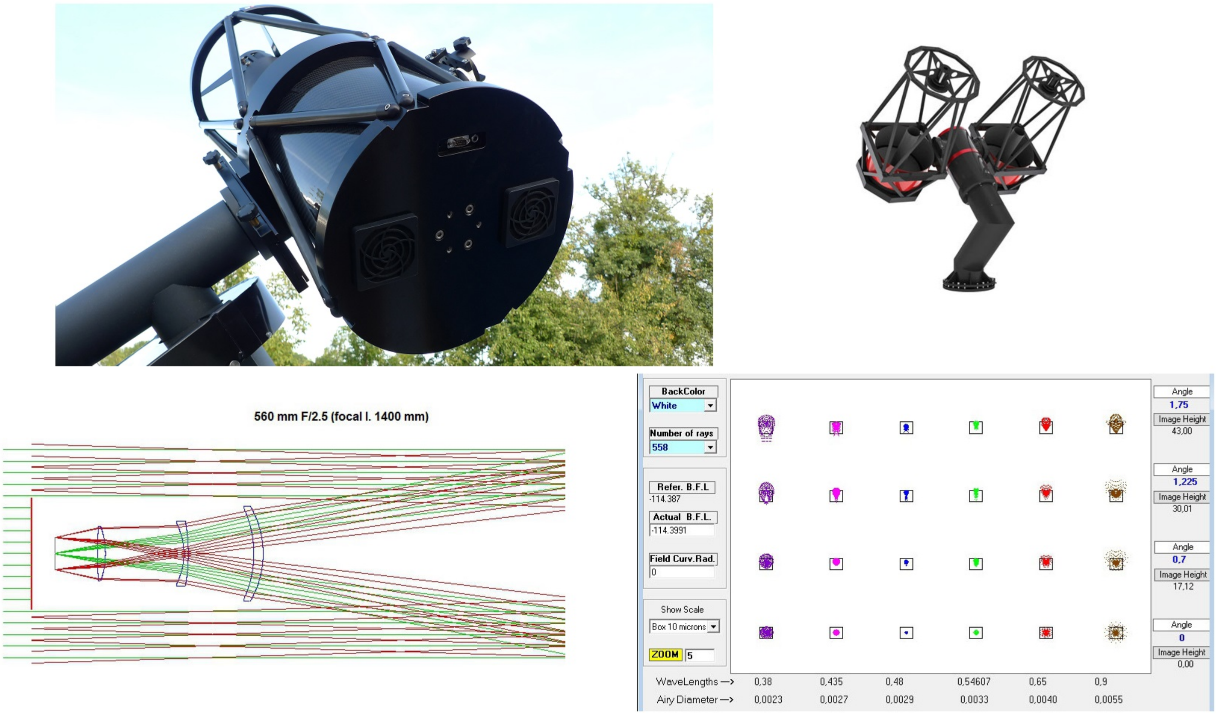
[4] `http://www.professional-telescopes.net/Product-Line/Astrographs/Wynne-Riccardi`

Fig. 3. LEFT: Exterior of the Astrograph dome is scheduled to be refurbished this year. RIGHT: Astrograph telescope mount and dual refractor telescopes with wood lens covers at the top. Our proposed plan is to make use of the dome and mount, and remove the dual telescopes for storage.



BackColor: White
Number of rays: 558
Refer. B.F.L: -114.387
Actual B.F.L.: -114.3991
Field Curv.Rad.: 0
Show Scale: Box 10 microns
ZOOM: 5

Angle 1,75 Image Height 43,00
Angle 1,225 Image Height 30,01
Angle 0,7 Image Height 17,12
Angle 0 Image Height 0,00

WaveLengths —> 0,38 0,435 0,48 0,54607 0,65 0,9
Airy Diameter —> 0,0023 0,0027 0,0029 0,0033 0,0040 0,0055

Fig. 4. Example telescope that could be selected for the SWIS experiment. This is a 0.56-m Wynne-Riccardi with a 1400mm focal length and 2.5x2.5 degree corrected field-of-view. These astrographs may be conveniently mounted in pairs for greater sensitivity and coincidence detection, or for observed field-of-view enlargement. Spot size is 4 microns (on-axis) to 8 microns (full field).

of diameter D (in meters), this can be written as

$$N = Q(\frac{z_J}{2.5^{B_J}}\Delta\lambda_J + \frac{z_H}{2.5^{B_H}}\Delta\lambda_H)M^2\frac{\pi}{4}D^2 \qquad (1)$$

where Q is the effective efficiency of the detector pixel (in counts/photon), z_J and z_H are magnitude zero-points[5] in photons/s/nm/m^2, $\Delta\lambda_J$ and $\Delta\lambda_H$ the effective bandwidth in J- and H-bands in nm. The maximal field-of-view M can be deduced from Eq.1 which can be rewritten

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[5] http://www.gemini.edu/?q=node/10257

such as

$$M = \frac{1}{D}\sqrt{\frac{4N}{\pi Q(\frac{z_J}{2.5^{B_J}}\Delta\lambda_J + \frac{z_H}{2.5^{B_H}}\Delta\lambda_H)}} \tag{2}$$

Using this equation and considering Q=15%, z_J=2.10^7 ph/s/nm/m^2, z_H=1.10^7 ph/s/nm/m^2, $\Delta\lambda_J = 300nm$, $\Delta\lambda_H = 150nm$ (to take into account of the 1.65μm cutoff wavelength of the detector), $N = 2.5.10^6$ cts/s, B_J=16.1mag/arcsec^2 measured by the Gemini instrument[6] at Lick Observatory, B_H=14.3mag/arcsec^2, the maximal field-of-view **M** per pixel at Lick Observatory is 111.6 arcseconds for a 0.56-m telescope. The maximal field-of-view per pixel beyond which the sensitivity of the instrument is sky-background limited for a 0.4-m, 0.5-m, and 1-m aperture is respectively 156.5 arcsec, 125 arcsec and 62.5 arcsec.

2.3 Near-infrared Detector Arrays

Our current detector source (Amplification Technologies, a division of Powersafe Technology Corp.), has made crucial advances in semiconductor detection technology for extremely high sensitivity electronic and photonic detection. Their near-infrared detectors have low noise, and are fast (1 GHz) with very low quench times (<1 ns). The DA-APD 5x5-pixel array developed by Amplification Technologies has recently become available (Figure 5), while even larger pixels DA-APD arrays are slated to be available by the end of 2016. Our team is currently working with the 5x5-pixel DA-APD arrays in the UC San Diego Laboratory. Amplification Technologies can also provide rectangular arrays of square pixels that conserve the same total number of pixels, if needed for our instrument design. According to private communications with Amplification Technologies, they are able to design a single package thermal-electrically cooled (-30 C) DA-APD array with configuration of 30 x 4 pixels and pixel pitch of 200 μm.

Given the 147-arcsec/mm plate scale provided by Wynne-Riccardi telescope (section 2.1.2), each 200μm pixel covers a 29.4-arcsec square field-of-view, well below the 111.6-arcsec sky background limit (see section 2.2) for this 0.56-m telescope. With a rectangular array of 30x4 pixels (30-pixels in declination and 4 pixels in right ascension), the total field-of-view of the instrument becomes 14.7-arcmin x 1.98 arcmin (Figure 2). In drift scan mode, the instrument can therefore scan the entire North hemisphere in less than 4 years (assuming 60% time efficiency), or 864 10-hours long nights of observations. The *minimum* dwell-time given by the shortest side of the array (4 pixels) is 7.8 seconds (minimum of 2 seconds per pixel) with this configuration. Given the nanosecond time resolution of the instrument, we note that it covers a minimum of 10 decades of pulse period.

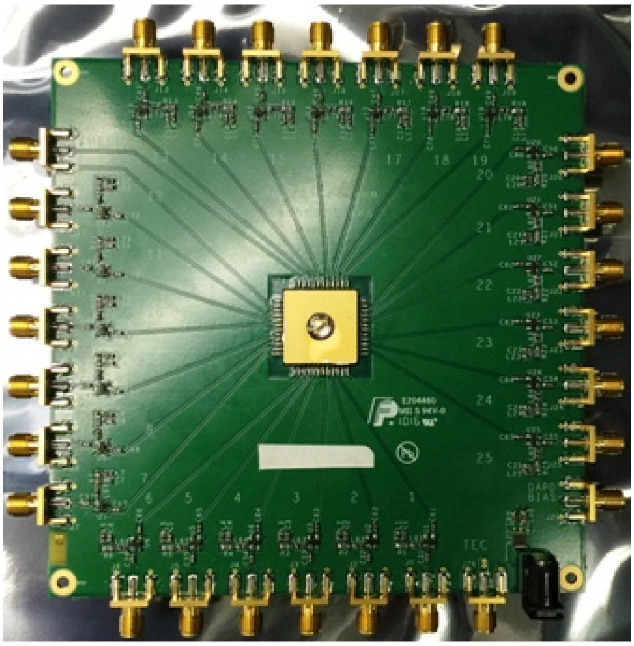

Fig. 5. The discrete amplification avalanche photodiode 5x5-pixel array developed by Amplification Technologies became available in March 2016. 10x10-pixel DA-APD arrays are slated to be available by the end of 2016. Each of the 25 SMA connectors services one of the individual pixels.

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[6] `http://mthamilton.ucolick.org/techdocs/instruments/gemini/gemini_signal_to_noise.html`

2.4 Data Storage

At nanosecond resolution, long observations can generate huge amounts of data, requiring development of thoughtful strategies for handling. This issue is usually tackled with real-time signal processing using comparator circuits or computer processing to discard signals without specific interesting features. However, this approach prevents any re-analysis of the lost data, and we are investigating feasibility of recording observations for further analysis.

The most favorable scenario would be to trigger on each pulse from each pixel, with a threshold on pulse height detection just above amplification noise fluctuations in order to detect all dark or light pulses (10^6 pulses/s/pixel). It is possible to choose voltage thresholds on the detector signal in order to discard low amplitude pulses, but at the expense of reduced sensitivity. Conversely, lowering this threshold will increase sensitivity, but will result in retention of a higher number of pulses requiring bigger storage capacity. If one solely records the pulse height and timestamps (8 Bytes/pulse), it generates a data flow rate of 8MB/s/pixel, an appropriate rate for data transfer and storage given current capacities.

In the case of a 30x4-pixel detector array without binning, the total amount of data per second will become 0.96GB, or 3.45TB/hour. This storage capacity can be decreased exponentially by increasing the voltage threshold of pulse detection at the expense of diminished sensitivity. Measured dark pulse height distributions of these detectors (Maire *et al.* (2014)) show that we can reduce the number of dark pulses by a factor of 8 while the sensitivity is reduced by a factor of 1.3. With such a threshold, the total amount of data becomes 4PB for the entire survey (8,640 hours of observations). Assuming a cost of $0.005 per GB [7], storage and maintenance of data would cost about $20k per instrument.

2.5 Cost

The driving costs of this program are the telescope(s) and detector arrays. This project benefits from major support from UCO Lick Observatory, which provides and maintains infrastructure elements such as the dome, internet, and electricity. Total cost of the instrument with one telescope is ∼0.9$ Million as summarized in Table 1.

Table 1. Estimated cost of the SETI Wide Field Infrared Experiment for one telescope, based on predicted costs from Amplification Technologies and previous experience with NIROSETI. As the number of telescopes increases cost of the program should reduce, particularly unit cost of detectors based on our order amount. We also investigate lowering cost per telescope with custom designs currently being investigated by Richard Treffers. Total cost does not include institutional overhead.

Dedicated SETI Wide-Field Near-Infrared Experiment with Two Telescopes	
Dome and facility	UCO
Telescope Mount	UCO
2 x Telescopes (e.g., Wynne-Riccardi)	$150k
Dome, mount, telescope modifications	$50k
2 x DA-APD detector arrays (4x30)	$150k
Detector electronics and readout	$100k
Opto-mechanical	$50k
Personnel (3 years)	$300k
Waveform data storage (4 PB)	$20k
Contingency/Risk (∼10%)	$80k
TOTAL	**$900k**

2.6 SWIS Team

Our team consists of all original core members of the Lick Optical SETI instrument (2001-2009) team, as well as key near-infrared SETI members. The SWIS instrument team members thus far are Frank Drake, Jérôme Maire, Geoffrey Marcy, Remington Stone, Richard Treffers, Dan Werthimer, and Shelley Wright. Remington Stone was Director of Operations at Lick Observatory, led operations for the optical SETI instrument, and offers useful knowledge for the Astrograph upgrade, instrumentation, and SETI strategies. Richard Treffers is a black belt optical designer who has built and rebuilt numerous astronomical telescopes all over the world, and will consult on the telescope and instrument optical design. Long time SETI experts Frank Drake, Dan Werthimer, and Geoff Marcy will be critical team members who will aid in the instrument design and observational strategies. Jérôme Maire, Project Scientist at UC San Diego, will lead instrument assembly, integration, and verification. Shelley Wright will manage the overall SWIS instrument, and aid instrument design, fabrication, and the observational program. An important component of the SWIS project will be student training. We will involve University of California undergraduate students in instrument fabrication, testing, and observations.

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[7] `https://www.backblaze.com/b2/cloud-storage-providers.html`

3 SUMMARY

Near-infrared SETI has been underway for only one year, but we are already prepared to make huge improvements to our fledgling search. Our team is developing a natural extension from our targeted near-infrared pulsed SETI work to a larger field of view "all-sky" near-infrared program. We present a conceptual design for the SETI Wide-field Infrared Surveyor (SWIS) instrument that will be capable of conducting the first near-infrared pulsed SETI search over the entire Northern hemisphere. This SWIS instrument is being designed with advanced post-processing analysis routines with the ability to save large fractions of data for future data mining. Our team will also involve Physics and Astronomy undergraduate students in the project for crucial SETI instrumentation and observational training.

Table 2. Specifications of wide field of view near-infrared SETI (SWIS) experiment

PARAMETER	**VALUES**
Telescope	0.6-m (or larger) f/2.5 existing apertures
Sensitivity (w/ false alarm rate)	$\sim$100 photon/m^2 (assuming 5% false alarm rate per night of scan)
Sky coverage	37.5 degrees^2 per night (10h observations)
Wavelength coverage	950 - 1700 nm
Lambda resolution	none
Pulse duration	1 ps - 100 ns
Time waveform resolution	0.5 ns, rise and fall
Pulse Repetition Rate	0.25 to 10^9 Hz ?
Target goals	Drift scan mode
Average duration	Sidereal rate
Detectors	InGaAs Discrete Amplification APDs 30x4-pixels Arrays
Plate scale	29.4 arcsec/pixel

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(2) Wright, S. A., Werthimer, D., Treffers, R. R., et al., "A near-infrared SETI experiment: probability distribution of false coincidences", Proceedings of the SPIE, Volume 9147, id. 91470J 10 pp. (2014).

(3) Maire, J., Wright, S. A., Werthimer, D., et al., "A near-infrared SETI experiment: instrument overview" , Proceedings of the SPIE, Volume 9147, id. 91474K 11 pp. (2014).

(4) Maire, J., Wright, S.A., Dorval, P., et al., "A near-infrared SETI experiment: commissioning, data analysis, and performance results", Proceedings of the SPIE, Volume 9908, id. 990810 (2016).

(4) Vanzi, L. and Hainaut, O. R. "Sky Background at ESO - La Silla in the Visible and Near IRs", Astrophysics and Space Science Library, Volume 284, (2003).

6.4 Optical SETI with IACTs: Data mining and beyond

IACTs are designed to record faint flashes of Cherenkov light, lasting a few nanoseconds against the background night sky, and determine the position of the flash on the sky with camera pixels about 0.15° in diameter.[25] They are sensitive in the 300–550 nm spectral range populated by the blue and near-UV Cherenkov light that reaches the ground and is readily detected by PMTs. These instruments, with their multiple optical collectors (the VERITAS array, for example, comprises four collectors, each of area $\sim$100 m^2), are also well suited to the detection of short optical pulses from extraterrestrial sources. As discussed in §3.4, the trigger system that decides which images to record is designed to find images extended on the sky, by requiring clusters of neighboring pixels in each telescope to have detected a signal. An OSETI signal would be a point source on the sky. The optics of IACTs are designed primarily for low-cost, not resolution, and the on-axis optical PSF is comparable to the camera pixel size and degrades further off axis (where most of the field of view lies). Therefore, given sufficient intensity, a point source can illuminate the three nearest-neighbor pixels needed to provide a trigger in the VERITAS telescopes. Parallax between the four telescopes with $\sim$100 m separation provides information on the height of emission. Requiring all four telescopes to see a flash consistent with a point source at infinity is a powerful discriminant against Cherenkov showers and terrestrial sources, forming the basis of the published VERITAS search[6] for KIC 8462852.

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[25] See, for example, J. Holder, *Atmospheric Cherenkov Gamma-ray Telescopes*, arXiv:1510.05675.

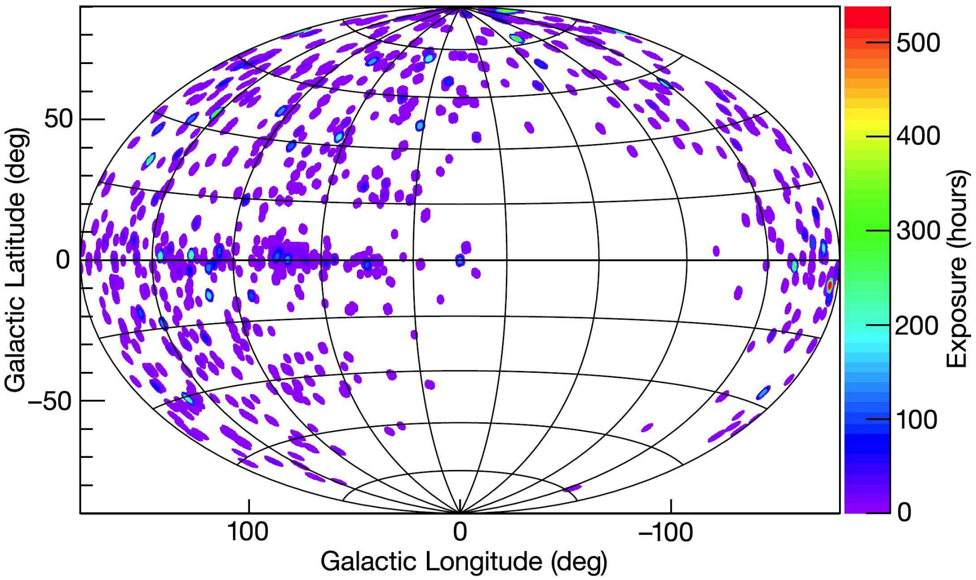

Figure 15: The exposure map of the entire VERITAS data archive (through summer 2016) in Galactic coordinates. Approximately 30% of the northern sky has been observed, with exposures in some regions reaching hundreds of hours. (Figure courtesy of Jamie Holder)

The VERITAS archival data set currently contains ~10k hours of data, distributed on the sky as shown in Fig. 15. Re-analysis of these data to search for candidate OSETI flashes would require a few CPU hours per hour of data – a significant but manageable task. A substantial portion of the effort needed to produce robust OSETI results from this large data set will be to automate the process of rejecting spurious pointlike images, of the sort identified in the KIC 8462852 analysis and attributed to meteors and satellites. Once the analysis tools were developed, it would be possible to run them in more or less real time and potentially generate prompt alerts to the SETI community from interesting events.

A dedicated project at this level would also benefit from additional effort to characterize better the VERITAS optical and trigger response, which was estimated conservatively for the published result. This can be studied using stars, for example, measuring the PMT currents in drift scans of stars across the camera to determine how light is shared among neighboring pixels and how the response drops off near the edge of the field of view.

With the development of the machinery to do a sensitive OSETI search in VERITAS data, it would be natural to identify regions of the sky not covered in the archival data and that would be of particular value for the search. Dedicated VERITAS observations could be proposed for these regions. Several hours per year could almost certainly be accommodated in the VERITAS program, especially if it is part of a Ph.D thesis. A few tens of hours per year might be possible if the observations can be arranged during bright time (under moonlight) or less than ideal weather. These observations would be made in the normal VERITAS observing mode.

Looking to the future, this project could also include the investigation (but presumably not yet the implementation) of hardware modifications or enhancements that would improve the VERITAS sensitivity to OSETI signals. Examples would be reprogramming the existing trigger electronics, slightly defocusing the telescopes to increase optical spillover across pixels, or implementing a parallel, parasitic trigger system.

All of the work described here would lay a foundation for similar OSETI studies in the future with CTA; the latter is designed to be an order of magnitude more sensitive to very-high-energy gamma rays than existing facilities. With as many as 100 telescopes at the southern site over baselines exceeding a kilometer and with wider field of view, it is likely that it could also deliver an order of magnitude improved sensitivity to optical flashes from an ETI. The signature of a distant optical pulsed beacon in this case will be completely unique, and the sensitivity to such pulses far better even than VERITAS. Furthermore, the science plans include surveys of the entire Galactic plane and one quarter of the "extragalactic" (i.e., high Galactic latitude) sky, far exceeding the sky coverage of existing IACT data. CTA, and in particular the trigger and data acquisition systems, have not been designed with OSETI in mind. Studies made now of how to improve the design for OSETI could pay off handsomely in the future, but need to be initiated soon, before design choices are completely locked in.

This scope of work – combining science, data analysis, and instrumentation – is suitable for full-time Ph.D thesis research. VERITAS data are propriety to members of the VERITAS Collaboration,[26] and the VERITAS collaboration maintains two independent analysis and calibration chains, requiring that all results are verified using both chains before publication. Given this policy, and the broad scope of work that goes well beyond merely processing the >100 TB data archive through the standard chains, two graduate students at separate institutions would be the ideal combination to push this work forward. Observing with the VERITAS telescopes is a responsibility shared by members of the collaboration. Collaboration members are also expected to share their progress and results at semiannual collaboration meetings. In addition to full-time research support for two students, the budget for this project should therefore also include travel funds for the students to fulfill a two-week per year observing obligation and to attend the collaboration meetings. In order for both the graduate students and the advisors to be engaged with the SETI community, funds for each to attend a SETI conference or workshop annually are also appropriate. The resulting budget is about $107k per year in direct costs, not including any required overhead or indirect costs.

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[26] Workshop participant David Williams at UCSC is a VERITAS member and is prepared to supervise a student on this project, as is Jamie Holder at the University of Delaware, who has a long-standing interest in OSETI. Both are also members of the CTA Consortium.