Panoramic SETI: An all-sky fast time-domain observatory

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Abstract

Optical and infrared Search for Extraterrestrial Intelligence (SETI) searches offer the ability to explore observational and experimental phase-space that is unique to traditional astrophysical observations. In the next decade, new SETI experiments will be developed, and coupling these to astrophysical programs will yield potentially transformative discoveries. We are designing a new optical and near-infrared (350 - 1650 nm) observatory designed to greatly enlarge the current SETI phase space. The Pulsed All-sky Near-infrared Optical SETI (PANOSETI) observatory will be a dedicated SETI facility that aims to increase sky area searched, wavelengths covered, number of stellar systems observed, and duration of time monitored. This observatory will offer an "all-observable-sky" optical and wide-field near-infrared pulsed technosignature and astrophysical transient search that is capable of surveying the entire northern hemisphere. The final implemented experiment will search for transient pulsed signals occurring between nanosecond to second time scales. The optical component will cover a solid angle 2.5 million times larger than current SETI targeted searches, while also increasing dwell time per source by a factor of 10,000. The PANOSETI instrument will be the first near-infrared wide-field SETI program ever conducted. The rapid technological advance of fast-response optical and near-infrared detector arrays (i.e., Multi-Pixel Photon Counting; MPPC) make this program now feasible. The PANOSETI instrument design uses innovative domes that house 80 Fresnel lenses, which will search concurrently over 8,000 square degrees for transient signals.

Keywords

Ground-based Instrumentation — SETI — Technosignatures — Time Domain — Astrophysical Transients — Optical — Near-Infrared —

1. Key Science Goals

This program aims at developing an "all-sky" optical and wide-field near-infrared pulsed SETI experiment that is capable of surveying the entire northern hemisphere. The observatory design may easily be replicated for southern skies as well. The requirements for this program address *seven* essential "missing corners" of current optical/infrared astrophysical transient and technosignature programs.

1. Extending wide-field searches to the desirable near-infrared, boosting wavelength coverage by 1.7 octaves.
2. Investigating the entire "observable" sky, increasing instantaneous field coverage by a factor of 25,000 (Harvard Horowitz et al. (2001)) and 2,500,000 (Automated Planet Finder Tellis & Marcy (2015)).
3. Adding first capability of an "all-time" optical search, increasing the fraction of time observed on *any* given source by a factor of 100,000.
4. Enlarging the number of observed stellar sources to 100's of millions stars.
5. Implementing search methods for pulse transients and variable sources over 10

decades: nanosecond to seconds.

6. Operating the first dedicated, simultaneous all-sky, all-time dual optical SETI facility. This duality is essential for unambiguous and immediate confirmation of a candidate signal (e.g., compare with gravitational wave detection with LIGOAbbott et al. (2009)).

7. Explore a new time domain that is capable of revealing unknown astrophysical optical transient or variable phenomena arising from compact objects and mergers over nanosecond to second time scales.

Optical and infrared SETI instrumentation that explores the very fast time domain, especially with large sky coverage, offers a prime opportunity for new discoveries that complement Multimessenger and time domain astrophysics. Furthermore, the critical need for additional SETI/technosignature experiments in the next decade has been highlighted in a number of recent works, including the NAS Astrobiology Strategy Report (NAS, 2019), a series of science white papers to the Astro2020 decadal survey (Wright, 2019; Wright et al., 2019; Wright & Kipping, 2019; Lesyna, 2019; Margot et al., 2019; DeMarines et al., 2019), and an Astro2020 APC white paper (Wright et al. 2019d).

1.1 Astrophysical time-domain observations

Current astronomical wide-field sky surveys have poor sensitivity to optical transients or variable sources with a duration less than a second, as most sky surveys utilize low-noise (CCD or CMOS) cameras that integrate for several minutes or longer. This largely unexplored phase space of sub-second optical and near-infrared pulse widths is perfectly suited for a technosignature survey and has the potential to enable new discoveries of astrophysical transient and variable phenomena.

Wide field optical and infrared surveys make use of fast optics (i.e, low f/#) apertures that are challenging to fabricate with good optical performance. Fast optical telescopes are expensive and need to make use of optical corrector lenses to reduce aberrations. Large optical surveys like Pan-STARRS Huber et al. (2015), Zwicky Transient Factory Smith et al. (2014), and the future Large Synoptic Survey Telescope Ivezic et al. (2008) have been designed to meet increasing interest in astrophysical transients and variable (repeating or stochastic) sources. In the last decade, new flavors of Type Ia and II supernova and novae have been discovered with optical transient surveys, expanding both observed lumonisities and characteristic time scales (see Figure 1). Typical instantaneous fields of view of these surveys are $\sim$10 - 50 sq.degrees, with a minimum time resolution of seconds-to-minutes. Gamma ray bursts (GRB) that trigger with space-based telescopes (e.g., Swift and Fermi) take minutes to hours for optical telescopes to respond for rapid follow-up of their afterglow. The fastest follow-up occurred on GRB 080319B (z=0.937), where data were taken within a few seconds because a wide-field optical imaging camera was already taking observations at the same sky location Racusin et al. (2008). GRB 080319B was also one of the most energetic GRB events discovered with a peak visual magnitude of V=5.3 mag, making it even visible to the human eye Bloom et al. (2009). The luminosity function of GRBs are still highly uncertain. The majority of optical counterparts have a typical peak magnitude range of V=10-18 mag within $<$ 1000 sec of follow-up Wang et al. (2013).

At optical and infrared wavelengths, fast time (ms - μs) domain studies have been limited to targeted searches of already known variable sources like pulsars, cataclysmic variables, and extremely luminous stars. Extending to nanoseconds has been limited to a few sources like the Crab Pulsar Eikenberry et al. (1997); Leung et al. (2018). Fast $>$GHz photometers are now being explored for quantum phenomena on future Giant Segmented Mirror Telescopes ($>$20m) where the aperture is sufficient to not be photon starved Barbieri et al. (2007); Shearer et al. (2008). All of these current programs have a low duty cycle on-sky and will only make a few observations per field over the course of their operation. Many order of magnitudes in time scales are not currently covered by space- and ground-based optical observatories, as seen in Figure 1.

In contrast, radio observatories have dominated searches for fast transient and variable sources at milli- to micro-second time scales. Historically, radio transient observations have targeted single compact objects like pulsars, X-ray binaries, and active galactic nuclei. But with the recent discovery of Fast Radio Bursts (FRBs) Lorimer et al. (2007), fast radio transient searches have enjoyed a boom. Discovery of the original FRB was made possible by reprocessing archival data from the Parkes radio telescope and searching for transients at millisecond time scales. Once the time domain and luminosity of FRBs were known, subsequent discoveries easily followed using other wide-field radio telescopes Petroff et al. (2016). Even though FRBs eluded discovery for decades, remarkably the implied rate is 10,000 events per day per 4π steradians (or 1 FRB per day per 4 sq.degrees) Thornton et al. (2013).

With ground-based gravitational wave detectors in full operation, LIGO-Virgo Abbott et al. (2009) will be capable of discovering mergers of black hole binaries, neutron binaries, and black hole - neutron star binaries at distances of several Mpc. The possibility of electromagnetic follow-up is a prime directive of the time domain astronomy community. This has ignited the MultimessengerSmith et al. (2013) community that has developed multi-wavelength facilities on ground- and space-based observatories for rapid follow-up. For instance, in 2017 the Fermi satellite discovered GRB 170817A, and LIGO confirmed detection of a binary compact merger associated with the GRBGoldstein et al. (2017). This was the first electromagnetic counterpart discovered of a gravitational wave event. An electromagnetic counterpart may be either precursor or an afterglow of the gravitational wave event, possibly a flash triggered during the merger event or the ring-down after the merger. Timescales and luminosities of such an electromagnetic counterpart event are largely unexplored, and current multi-wavelength surveys are only planning to achieve follow-up within minutes-to-hours from a gravitational wave event, with an observational time resolution of a few seconds.

1.2 Optical SETI background

Optical and infrared communication over interstellar distances is both practical and efficient. Just a year after the invention of the laser, it was suggested that laser technology could be used for optical communication over modest interstellar distances Townes & Schwartz (1961). Two decades later a detailed comparison of interstellar communication at a range of electromagnetic frequencies was exploredTownes (1983), showing that optical and infrared wavelengths were just as plausible as the usual microwave/radio frequencies favored by SETI strategies of that era Cocconi & Morrison (1959).

Lasers and photonic communication have improved considerably since then, with continuous wave laser power reaching into the megawatt regime, and pulsed laser power up to petawatts. Both continuous wave and pulsed lasers are plausible candidates for techno-signature searches. CW and high duty cycle laser pulses could be easily detected with high-resolution spectroscopic programs that target individual stars Tellis & Marcy (2017). Collimated with a Keck-size telescope, pulsed laser signals can also be detected: the pulses maybe can be orders of magnitude brighter than the entire broadband visible stellar background Howard et al. (2004). As an example, if we consider an ETI that transmits a 1PW laser with a 1 ns pulse width every $\sim 10^4$ seconds to a set of target stars, a receiving civilization conducting an all-sky search would see the flash

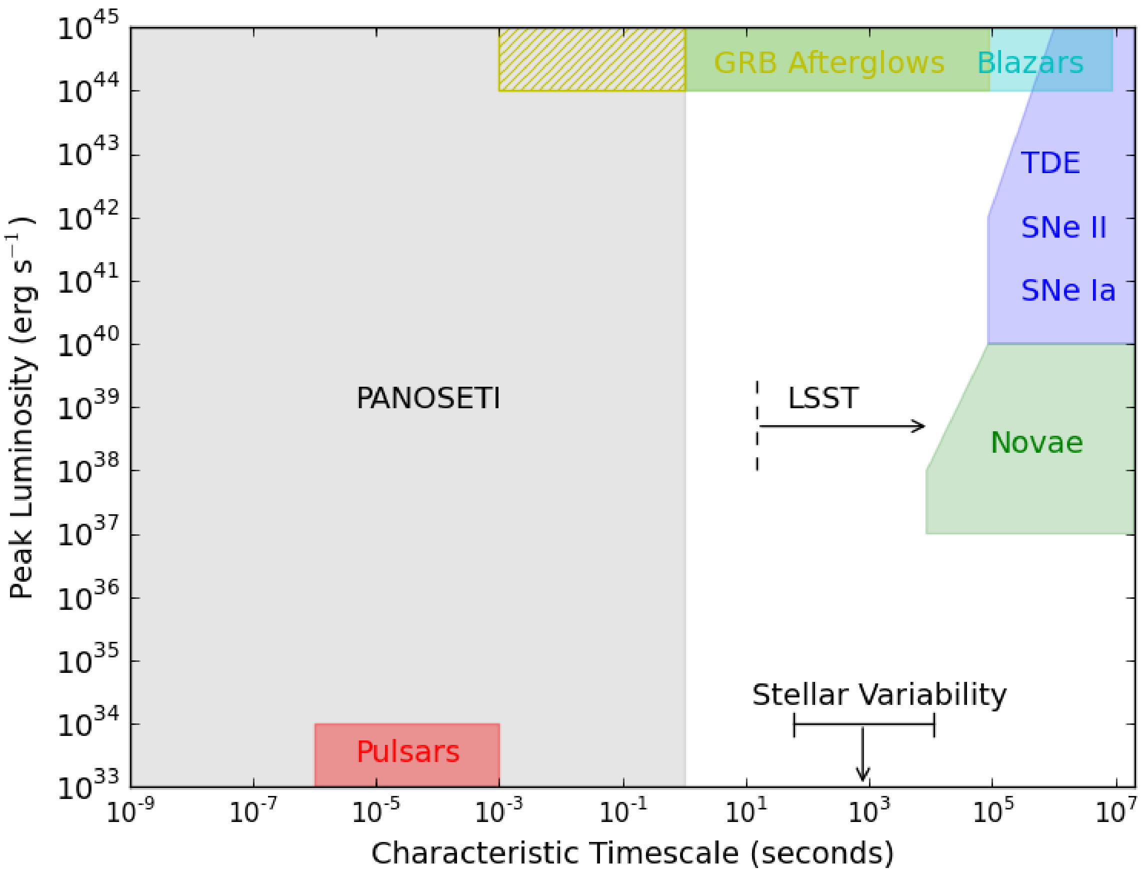

Figure 1. Time domain of optical astrophysical transients and variable sources: pulsars, supernova (Type Ia, II) and Tidal Disruption Events (TDE), classical novae, gamma ray burst afterglows, Blazars, and stellar sources. Fast time resolutions (nano-seconds $-$ seconds) have barely been explored and represents an observational limit with current ground and space-based facilities, especially since facilities are unable to achieve large sky coverage with high duty cycles. Even with these limitations, new transient sources are being found at shorter timescales (seconds), e.g., ASASSN-15lh. Cenko (2017). GRB afterglows can be observed for seconds to hours after the initial triggering event, but there have been no known observations that extend down to milli-seconds to seconds for rapid follow-up (hatched area). GRB 080319B Racusin et al. (2008), the brightest recorded GRB in 2008, resides above the y-axis at $\sim 10^{51}$ erg s^{-1}. Stellar variability from cataclysmic variables, Cepheids, stellar flares are typically $< 10^{34}$ erg s^{-1}. The Large Synoptic Survey Telescope (LSST) will have unprecedented sensitivity, but its fastest time cadence is 15 seconds. PANOSETI will be capable of exploring luminous transient and variable phenomena from nanoseconds to seconds (grey area).

$\sim 10^4$ times brighter than its host star. In this scenario, the sending civilization expends only 100W average power per target. The basis of this capability has already framed optical SETI search parameters for over two decades.

Using current technology, pulsed optical SETI searches have the flexibility of being either targeted or covering large areas of the sky. An optical *targeted* search of integrated visible spectra using the Automated Planet Finder (APF) at Lick Observatory is highly sensitive to continuous wave (CW) lasers and high duty cycle pulses (> 1 Hz) from individual starsTellis & Marcy (2017). Spectroscopy is limited to targeted searches, with little possibility of a large field of view survey *or* an all-time SETI search. Combining both pulsed and CW SETI targeted searches, the community has surveyed >10,000 stars with no detection Horowitz et al. (2001); Werthimer et al. (2001); Covault (2001); Wright et al. (2001); Reines & Marcy (2002); Howard et al. (2004); Stone et al. (2005); Howard et al. (2007); Hanna et al. (2009); Wright et al. (2014); Abeysekara et al. (2016); Schuetz et al. (2016), although the dwell time per source observed has been very low (∼10 min). Targeted SETI is poorly matched to intermittent signals sent by ET, and neglects millions of nearby stars that fall outside of the typical SETI target lists, as well as other potential astrophysical sources. There has been one wide-field optical (350 - 800 nm) SETI program that used a dedicated telescope for scanning the sky, but this search also had low dwell times Horowitz et al. (2001). The missing link for laser SETI searches is the capability of continuous observations with large sky coverage, to increase phase space searched and likelihood of detection.

Extending the search into the near-infrared offers a unique window with less interstellar extinction and less background from our galaxy than optical wavelengths, meaning signals can be efficiently transmitted over larger distances. The infrared regime was specifically identified as an optimal spectral region for interstellar communication Townes (1983), yet has remained largely unexplored territory for SETI. The challenge has been lack of adequate near-infrared fast response (∼ ns) sensitive detectors. Infrared detector technology has matured rapidly in the last decade, offering higher quantum efficiency and lower detector noise. Taking advantage of recent progress with infrared detectors, we developed the first near-infrared (950 to 1650 nm) SETI experiment that made use of the latest avalanche photodiodes for a targeted pulsed search Wright et al. (2014); Maire et al. (2014, 2016). This program has motivated our team to develop both wide-field optical and near-infrared SETI instrumentation.

In this white paper, we describe design and plans for a new observatory network that is capable of searching for extremely rapid (nanosecond to second) optical and near-infrared events from either artificial or natural phenomena, over the entire "observable" sky. This new observatory is being designed for a large-scale SETI experiment, and given its wide sky coverage and long duty cycles, it is equally capable of making new astrophysical discoveries within the fast time domain.

2. Technical Overview

2.1 Opto-mechanical Design

Our observatory design reduces the cost per aperture on sky while maintaining sky coverage and flexibility of wavelength bandpass. Instead of using a traditional optical telescope we have designed a system that uses Fresnel lenses (f/1) for each collecting aperture. Each Fresnel lens will be housed in a module unit that will baffle stray light. We define a module as an aperture unit that contains both the Fresnel lens and detector plane. We have now designed a prototype module that includes opto-mechanical housing of the 0.5m Fresnel lens, detector mount, focus stage, and position angle mechanism.

The opto-mechanical design and thermal analysis of the individual module is presented in Cosens et al. (2018). Briefly, the opto-mechanical lens mount includes a protective acrylic transparent cover to protect the Fresnel lens from dust and scratches. The air gap between Fresnel lens and protective cover reduces potential condensation. Four struts connect the lens mount to the detector housing and back-end electronics. A focus stage at the detector plane derives initial focus and compensates for focus shifts at the telescope due to temperature changes or drift. Both on-axis and off-axis spot sizes of the Fresnel lenses are well-matched to the optical pixel sizes and small shifts in focus will not impact the optical performance. Chromatic aberration dominates the aberration terms for the Fresnel lens. We will determine focus at the central wavelength for the optical and near-infrared bandpasses. We further describe the optical quality and characterization of Fresnel lenses at optical wavelengths in Maire & Wright (2018). Given the smaller near-infrared pixel sizes (200 μm) we are exploring a corrector lens for these Fresnel modules.

2.2 Detectors

We will use multi-pixel photon counter (MPPC) detectors for optical (300–850 nm) and near-infrared (850–1650 nm) wavelengths. An MPPC is an array of independent Geiger-mode avalanche photodiodes (APD), whose outputs are summed to a single terminal; this single pixel exhibits excellent pulse-height resolution, since each sub-pixel generates either a fully saturated pulse or is dormant.

For the optical we are using the Hamamatsu silicon photomultipliers (SiPM), which are photon-counting devices using multiple APD pixels. Each Fresnel lens will illuminate a focal plane tessellated with 32x32 optical MPPCs in an array covering an instantaneous field of view of 81 deg^2. Four 8×8 SiPM arrays with individual 3mm$\times$3mm pixels (i.e., Hamamatsu p/n S13360-3050CS) will be tiled 2×2 on the optical axis, thereby achieving a continuous 32×32 pixel field of view. MPPC detectors are good at detecting single photon events even with the high background count rates we expect with varying sky conditions at optical wavelengths. We are designing a custom readout board that makes use of 64-bit Application-Specific Integrated Circuit (ASIC) Weeroc Maroc-3A that is capable of pulse shaping and providing trigger detection of individual pulses. We have designed our prototype detector board with four 8×8 pixel SiPM arrays that each feed a MAROC-3A ASIC that amplifies the signal from the SiPMs and provide a per-pixel trigger signal to a Kintex Field Programmable Gate Array (FPGA). A four-channel high voltage controller provides precise high voltage bias to each SiPM array. A 10^6 sample per second analog-to-digital converter (ADC) will read the detected events of all pixels whenever any single pixel is triggered. A 1 Gb per second fiber connection provides data communication to a host. We are planning to use White

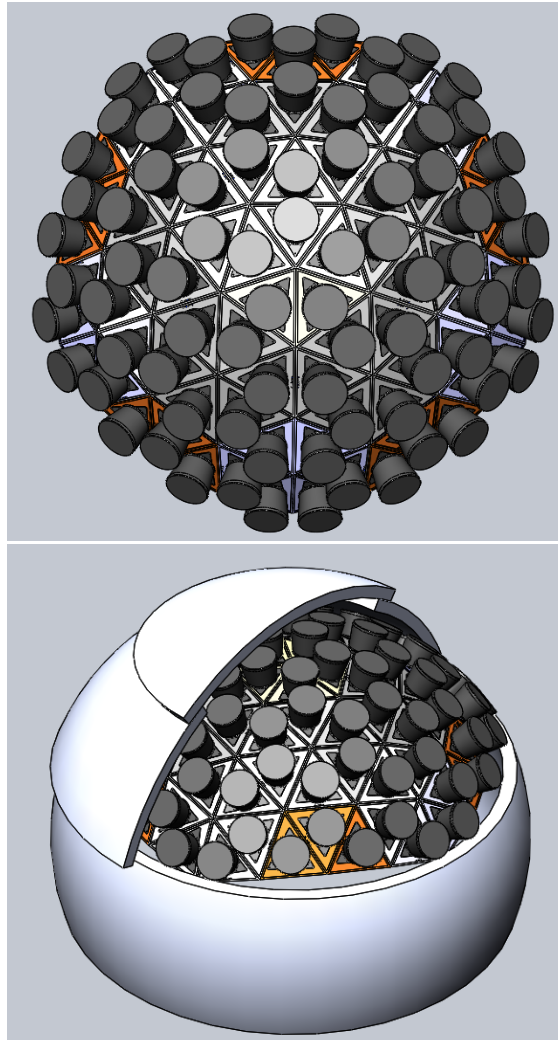

Figure 2. (Top) Conceptual design of a geodesic dome. This geodesic dome design is made of a tessellated shell that holds 80 Fresnel lens modules. (Bottom) The geodesic dome filled with Fresnel modules placed inside an Astrohaven 20-foot diameter dome enclosure.

Rabbit (Moreira et al. (2009)) precision time protocol functionality that will provide ∼1ns time-stamping for each event. The four quadrant boards will be arranged to form a 32×32 array field of view.

We plan to have at least four near-infrared arrays; two in each PANOSETI observatory. Our current detector source (Amplification Technologies, a division of Powersafe Technology Corp.) has made crucial advances in semiconductor detection technology for extremely high sensitivity, high bandwidth photon detection. Their near-infrared InGaAs detectors (850−1650 nm) have low noise, and are fast (1 GHz) with very low quench times (<1 ns). For final production we are designing around a custom-made array from Amplification Technologies that will have a single package thermal-electrically cooled (-30°C) APD array with configuration of 30×4 pixels and pixel pitch of 200 μm.

2.3 Observatory Design

We plan to construct a geodesic dome populated with ∼100 Fresnel modules with fast-response detectors Maire & Wright (2018). A geometric layout of a single geodesic dome is shown in Figure 2 that highlights our potential sky coverage.

Our planned operation is to have at least two geodesic domes per hemisphere to allow for unambiguous detection of a source simultaneously visible from both sites, as shown in Figure 3. We believe this is imperative to rule out false alarms at a single observing site that would otherwise be affected by noise emanating from cosmic ray showers, atmospheric phenomena, or other site specific noise. Multiple copies of this instrument could be placed at more sites for both efficiency, hemispheric coverage, and confirmation of detection, as illustrated in Figure 3. A dome shelter will be dedicated to protection of each geodesic dome, and will operate autonomously with a dedicated weather center.

The current design for optical wavelengths has each Fresnel module achieving a field of view of 9° × 9° with 20 arcminute per pixel, so the total geodesic dome will achieve an instantaneous sky coverage of >8,500 square degrees. In each geodesic dome, there will be at least two modules dedicated for a near-infrared wavelength wide-field search. Each near-infrared

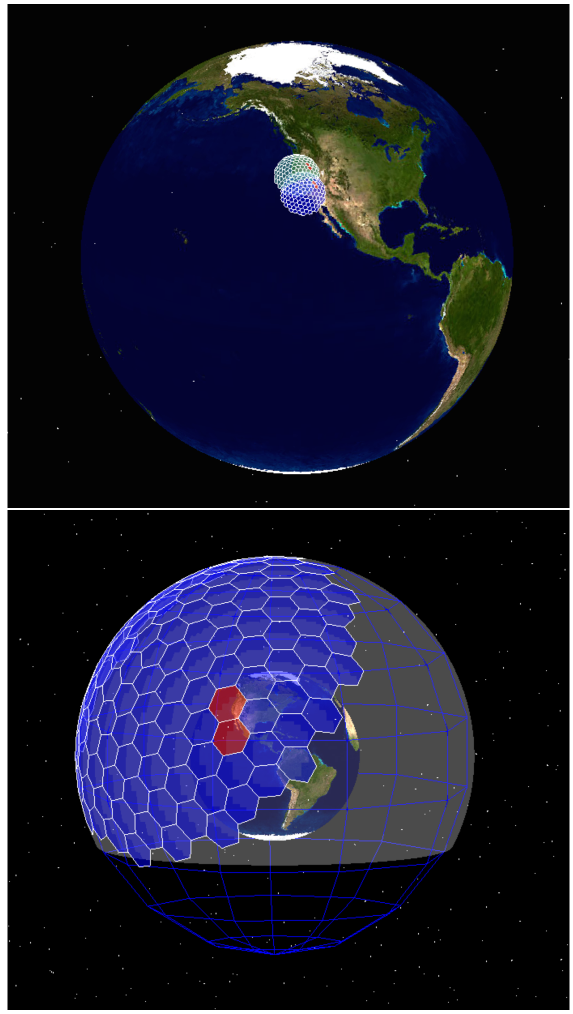

Figure 3. (TOP) A pair of optical and near-infrared PANOSETI dome facilities located in the northern hemispheres. (BOTTOM) Instantaneous field of view from both PANOSETI facilities projected on the celestial sphere. Each hexagon maps to a 0.5m Fresnel lens. The entire “observable” northern hemisphere will be observed from both locations at optical wavelengths. Several lenses per site will be dedicated to near-infrared drift scan observations.

Parameter	Optical component	Near-Infrared component
Light collecting areas	80 x 0.5-m f/1 Fresnel lenses	2 x 0.5-m f/1 Fresnel lenses
Detectors	Hamamatsu arrays 3mm pixels	InGaAs 200μm-pixels 30x4 pixel array
Sensitivity	25 photons per pulse	100 photon/pulse
Wavelength coverage	$300-850$	$850-1650$
Time waveform resolution	$\sim$10 ns	1 ns
Target Goal	Observable sky	Drift scan mode
Plate scale	0.36 degree per 3mm pixel	82.5 arcsec/pixel
Sky coverage	$>$ 8,000 sq. deg.	0.06 sq. deg. in drift scan mode

Table 1. PANOSETI Instrumental Parameters for a Single Observatory.

module will achieve 82.5 arcsecond per pixel with a total instantaneous field of view of 0.06 square degree. The near-infrared component will operate in drift scan mode, as seen in Figure 4. The geodesic dome allows us to move the near-infrared modules in elevation along the meridian and is capable of mapping the entire observable sky in 230 clear nights. Instrument specifications for both the optical and near-infrared components are summarized in Table 1.

3. Organization & Partnerships

Our team consists of a collaboration of core members from University of California San Diego, University of California Berkeley, Harvard University, and California Institute of Technologies. The technical team also consists of electronic, mechanical, and software engineers that are contracted outside of our academic institutions. The locations of each of the PANOSETI observatories will be at Lick Observatory and Palomar Observatory. This project will benefit from accessing existing observational facilities, which provide and maintain logistical elements such as access roads, internet, and electricity. UC San Diego leads the overall management, budget, opto-mechanical design, and fabrication and assembly. UC Berkeley and Harvard lead the electronics and detector design and development of this program. Caltech is in collaboration with site selection and aiding in data product development and deliverable, as well as coordinating with other time-domain programs. An important component of the PANOSETI program is graduate and undergraduate student training, which is vitally important for the longevity and health of the SETI field. We will involve University of California students in instrument fabrication, testing, observations, and data analysis.

4. Schedule & Cost Estimates

We have structured our instrument development to be conducted in multiple phases that aim to reduce risk and complexity of the project. We are currently in the preliminary design phase and developing an end-to-end prototype of the opto-mechanical Fresnel module and detector electronics, as well as finalizing major design for the observatory. Both the conceptual and preliminary design phase of PANOSETI is fully-funded. During this phase we aim to build four Fresnel units with a small set of detectors (2 optical and 2 near-infrared). The first phase will be dedicated to developing prototype systems, as well finalizing all major designs for both optical and NIR SETI facilities. We expect the program to take five years for full implementation of the domes at two sites followed by a year-long commissioning, as outlined in Figure 5.

Total cost of the project with two sites and instrumentation that cover the full 8,473 sq. degrees is $\sim$\$8 Million. The 5-year project development includes a prototyping & design phase, followed by progressive construction of two dedicated SETI observatories. Science operation will be able to commence after Phase II during the first deployment. The full experiment when

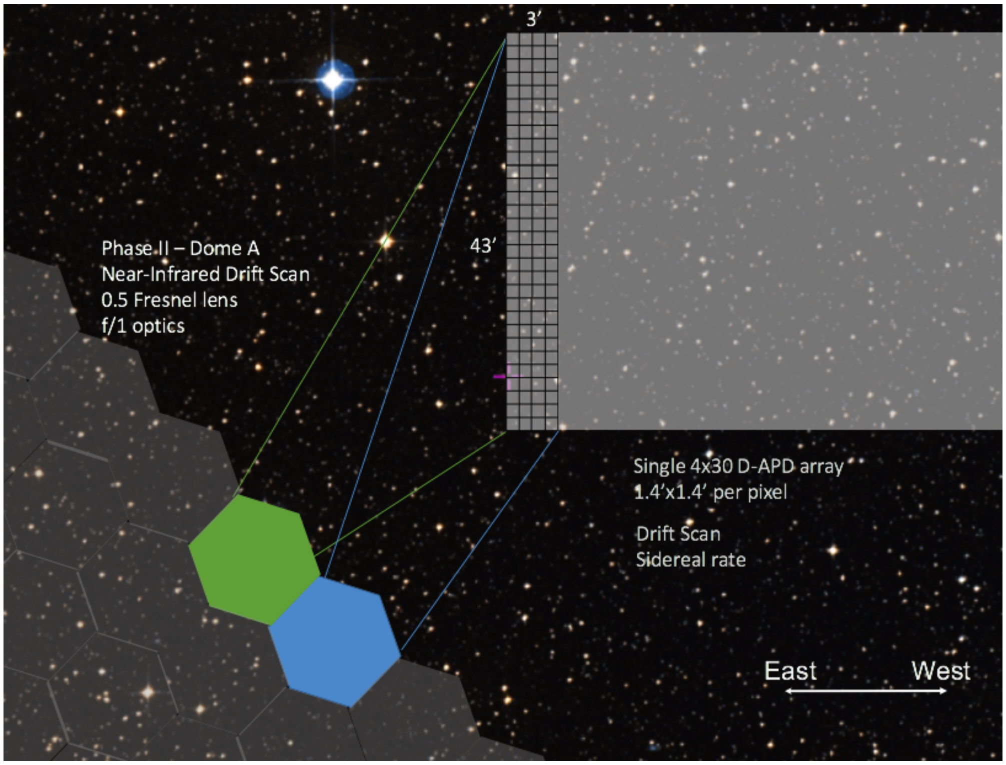

Figure 4. Two 0.5 m lenses installed in the geodesic dome will be dedicated to a near-infrared wide field search. Each near-infrared module will use a custom-made 4×30 near-infrared APD array with an individual pixel size of 200 μm. These modules would operate in a drift scan mode covering different elevations over time, and would be able to sample the entire northern hemisphere in 230 clear nights.

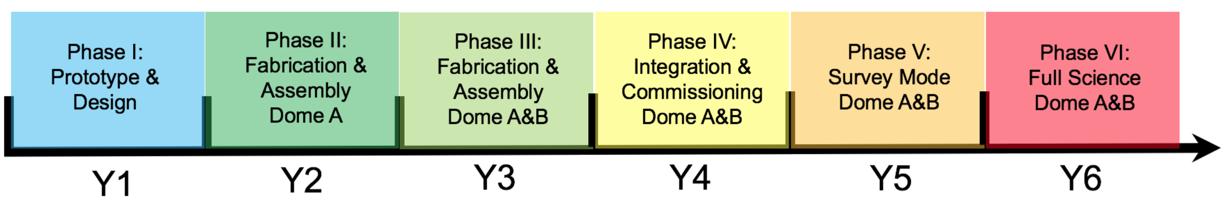

Figure 5. The timeline and phases of the PANOSETI program.

deployed is ~$1k per square degree. If this is compared to previous/current wide-field optical SETI experiments (with comparable sensitivity) this cost is a factor of 1,000 less per square degree.

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