SETI in the Spatial-Temporal Survey Domain

James. R. A. Davenport[1]

[1]*Department of Astronomy, University of Washington, Seattle, WA 98195, USA**

ABSTRACT

Traditional searches for extraterrestrial intelligence (SETI) or "technosignatures" focus on dedicated observations of single stars or regions in the sky to detect excess or transient emission from intelligent sources. The latest generation of synoptic time domain surveys enable an entirely new approach: spatial–temporal SETI, where technosignatures may be discovered from spatially resolved sources or multiple stars over time. Current optical time domain surveys such as ZTF and the Evryscope can probe 10–100 times more of the "Cosmic Haystack" parameter space volume than many radio SETI investigations. Small-aperture, high cadence surveys like Evryscope can be comparable in their Cosmic Haystack volume completeness to deeper surveys including LSST. Investigations with these surveys can also be conducted at a fraction of the cost, since they require analysis of data already being gathered. However, SETI methodology has not widely utilized such surveys, and the literature is in need of new search algorithms that can incorporate signals from both the spatial and temporal domains. Here I describe the broad potential for modern wide-field time domain optical surveys to revolutionize our search for technosignatures, and illustrate some new example SETI approaches that utilize the spatial-temporal domain

1. INTRODUCTION

Despite more than half a century of activity, the Search for Extra-Terrestrial Intelligence (SETI) is a field of study very much in its infancy. Wright et al. (2018) note the volume of parameter space for SETI (or the search for a needle amongst the "cosmic haystack") at radio wavelengths has been barely explored, and that many obvious signals may indeed be awaiting our discovery. The lack of SETI activity by the astronomical community can be partially understood as due to funding limitations in recent decades, as well as social pressures against studying SETI experienced by professional astronomers and organizations (Wright & Oman-Reagan 2018).

Traditional SETI work also requires time-consuming observations, often through dedicated monitoring of nearby stars by radio telescopes. Such observing campaigns are expensive and difficult to obtain given the competitive nature of telescope allocation. Recent progress for systematic "technosignature" searches has been made by Breakthrough Listen (Worden et al. 2017; Isaacson et al. 2017), primarily at radio wavelengths (e.g. Price et al. 2018).

The SETI conundrum has always been not only "*What should we look for?*", but also "*When, where, and how*

to look?". While Wright et al. (2018) suggest the completeness of our search of the "cosmic haystack" at radio wavelengths is akin to the ratio of a swimming pool compared to the Earth's ocean's ($\sim 10^{-20}$), SETI at optical wavelengths is surely many orders of magnitude less complete. However, new wide-field time domain surveys will enable us to greatly expand our search in two key dimensions of parameter space: 1) collectively observing nearly the entire night sky, and 2) providing time resolved monitoring over many years.

Surveys like the currently running Zwicky Transient Facility (ZTF Bellm 2014) and the upcoming Large Synoptic Survey Telescope (LSST Ivezić et al. 2008) will be transformative in enabling both reproducible and cost-efficient SETI. By developing search strategies that utilize public survey databases and real-time "alert streams", both of which are being developed to facilitate a wide range of science goals from these facilities, optical survey SETI can be conducted automatically. As new search algorithms are developed, these databases can be quickly re-analyzed, providing a much-needed level of reproducibility and transparency that will help reduce the "giggle factor" stigma for SETI (Wright & Oman-Reagan 2018).

In this paper I explore the potential for wide-field time domain surveys in conducting a new generation of technosignature searches, starting with an overview of the motivation for doing SETI with optical surveys in §2. In §3 I describe the general principles behind

* DIRAC Fellow

technosignature searches in time domain surveys, including spatial over-densities of light curve signals and coordinated signals between multiple sources, for example. In §4 I introduce several relevant surveys, and use the "Cosmic Haystack" search volume metric developed by Wright et al. (2018) to quantitatively compare these surveys to current radio SETI approaches. The data-driven spatial-temporal domain explored by these surveys necessitates new SETI approaches be developed, and in §5 I outline an example signal where transiting planets around many stars could act as a spatially distributed beacon network. Finally in §6 I discuss ideas for other search approaches, and the advantages in cost and reproducibility of conducting SETI with current and upcoming optical time domain surveys.

2. WHY OPTICAL SURVEY SETI?

Wide-field imaging surveys, and their associated infrastructure, are an ideal data source for carrying out technosignature searches that augment efforts in other wavelengths or with different observing strategies. By covering large portions of the night sky with repeated imaging, and with surveys that span years to decades in duration, we can substantially reduce the challenge of deciding *when* and *where* to look. Increasingly, multiple surveys obtain imaging that overlaps in both time and sky coverage, but with complimentary properties (e.g. imaging depth, cadence, wavelength coverage), which allows for rapid vetting and characterization of rare or low signal-to-noise events.. This also results in survey data providing some "ground truth" about the nature of most known objects in our Galaxy (e.g. their positions, temperatures, etc), and allows us to eliminate uncertainty on *what* objects we're studying for SETI.

Optical surveys are also an excellent platform for exploring *how* to conduct technosignature searches. The large archives of data produced from these surveys become valuable legacies that enable science long after data acquisition has concluded. Searches for new phenomena in time-domain astronomy can be carried out both in the future with new observations and in the past by re-analyzing survey archives. Using survey archives for SETI as opposed to targeted observations allows us to compare the results of competing algorithms or strategies, and enables reproducible science. Search algorithms are also portable, and ideally can be used to carry out SETI on any appropriately structured large survey. As future survey data is gathered, new classes of technosignature signals may be detectable that rely on decades worth of data. Since any candidate technosignature detection will (or should) be the subject of great scrutiny, making the data and algorithms open and reproducible will be critical for comparison and independent validation.

Large surveys, particularly ground-based efforts like LSST, are a highly prioritized component of the current and future development landscape in astronomy (Council 2010). As such, great efforts are being made to develop survey tools and technologies to enable science from these missions, such as new database technologies (Juric 2012). These developments are especially needed to utilize the new forms of data being made available, including real-time data analysis (e.g. Schwamb et al. 2019) and broadcasting real-time alerts for events (Patterson et al. 2019). The infrastructure needed to conduct technosignature searches with these large optical surveys is therefore already being developed. As with many areas of astrophysics in the "survey era", the biggest restriction to SETI with large surveys is therefore the availability of supported researchers mine the data.

3. POTENTIAL STRATEGIES

SETI with large surveys falls into two basic approaches: 1) classify every object or phenomena in the data, and any remaining outliers are technosignature candidates, or 2) search for specific "impossible" or unusual types of signals in the data, which I advocate for in this work. While the latter strategy does not guarantee a complete search for all SETI signals in the data, it is technically feasible for almost any time domain survey.

Several types of signals have been suggested that may be viable for use with optical surveys. For example, Villarroel et al. (2016) searched two wide field, single-epoch optical surveys for objects "disappearing" over decades timescales. Lacki (2019) outline a method to search for specular reflections of interplanetary objects, particularly in wide field surveys. Arnold (2005) describe the the observable signature of transits from artificial objects, which could be searched for with exoplanet transit surveys. Kipping & Teachey (2016) find that exoplanet transits could be hidden or "cloaked" to an observer by using directed laser emission.

Here I describe a few general classes of technosignature signals that may be well suited to developing new detection algorithms for spatial-temporal surveys:

1. **Unusual variability profiles or statistical distributions of fluxes** – either on short timescales such as Boyajian's Star (Boyajian et al. 2015), or long timescales such as disappearing stars (Villarroel et al. 2016) or occasionally missing transits (Kipping & Teachey 2016)

2. **Spatial correlations of events or phenomena** – e.g. coordination of transiting systems, or rebroadcasting events such as novae along the "SETI ellipse" (Makovetskii 1977; Lemarchand 1994; Tarter 2001; Shostak 2004)

3. **Spatial over-density or distribution** – e.g. an over-density of a given phenomena, such as within the Earth Transit Zone (Heller & Pudritz 2016)

4. **Unnatural patterns** – particularly patterns of otherwise normal astrophysical variability, such as broadcasting a prime or fibonacci sequence of transits (Wright et al. 2016).

4. COMPARING OPTICAL SURVEYS TO RADIO SEARCHES

Wright et al. (2018) have provided a framework to quantify the volume of observable parameter space covered by various SETI projects – dubbed the "Cosmic Haystack". The properties for several major radio SETI projects yield a Haystack volume coverage of 10^{-20} to 10^{-18}, or as Wright et al. (2018) illustrate, akin to a drinking glass of water compared to the volume of Earth's oceans. While this tool was developed with radio surveys in mind, it is broadly applicable to surveys at other wavelengths that are not explicitly designed for SETI (e.g. see Forgan 2019).

While the potential for optical time domain surveys to advance technosignature searches has been qualitatively laid out in §2, it is important to quantitatively compare them to traditional searches in the radio. For typical optical surveys using broadband photometry (Djorgovski et al. 2013), the key parameters that determine the Cosmic Haystack volume coverage are the sky coverage (Ω in sq deg), total integration time per target (T in sec), and survey sensitivity or per-epoch depth (S in Jy). Since these terms all act as scalers in the Haystack volume integration, surveys with different properties (e.g. few deep exposures versus many shallow exposures) can have comparably large Haystack coverage, filling out very different portions of the search volume. For maximum impact, SETI should therefore be conducted on many types of surveys.

As a demonstration, I have computed the Cosmic Haystack volume coverage for five representative current and future optical time domain surveys, as shown in Figure 1. This includes the Catalina Real Time Transient Survey (CRTS; Drake et al. 2009), Zwicky Transient Facility (ZTF; Bellm 2014), the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008), and the Evryscope (Law et al. 2015). These include space-
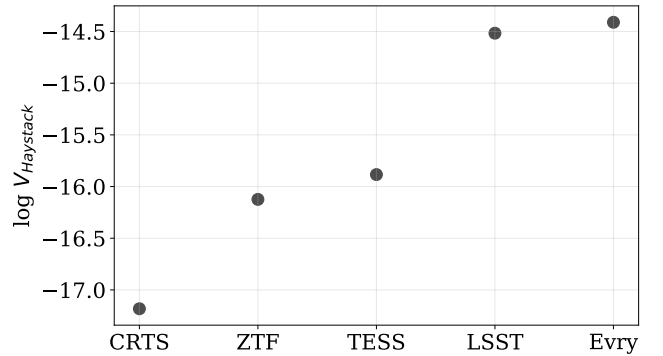

Figure 1. comparison of the 8D "Cosmic Haystack" volume fraction defined by Wright et al. (2018) using five optical surveys with varying designs.

based and traditional ground-based surveys, and vary greatly in telescope collecting area, total numbers of visits, and survey footprint design. I have assumed sensitivity (S) is the published per-visit photometric depth for each survey. The total integration time per target (T) was computed as the average number of visits per target in the survey multiplied by the per-visit exposure time. The same power of transmitter is assumed as in Wright et al. (2018). The code to generate the figures in this manuscript is online.[1]

Typical values for the Haystack fraction for radio SETI programs as presented in Wright et al. (2018) are in the range of $\log V_{Haystack} = 20$ –17. However, these programs are mostly targeted observations of nearby stars. The largest program featured in Wright et al. (2018), by Tingay et al. (2018), had $\Omega = 400$ sq deg and $T = 10800$ seconds, and yielded $\log V_{Haystack} = -17.36$.

By comparison, the wide field optical surveys I have featured all out perform the radio programs explored by Wright et al. (2018) in their Haystack fraction. Due to its very wide field coverage, and near continuous monitoring each night, Evryscope ranks as the best optical survey for technosignature searches of those surveyed here. The remarkable similarity in Haystack fraction between Evryscope, which uses 7-cm diameter telescopes, and the 8.4-m LSST survey reinforces the need to sample the Cosmic Haystack volume with as many different survey "shapes" as possible.

While Wright et al. (2018) likened their Haystack fraction to searching for fish in a drinking glass of water compared to the Earth's oceans, our results are closer to 1-2 Olympic sized swimming pools (each 2500 m³, accord-

---

[1] https://github.com/TheAstroFactory/survey_seti

ing FINA standards) compared to the Earth's oceans[2]. While optical surveys still only cover a tiny fraction of the total volume of parameter space, it is a substantial improvement.

5. EXAMPLE: SPATIAL-TEMPORAL TRANSIT BEACONS

5.1. *Coordinated Transit Networks*

imagine a Type N civilization with the ability to both travel to nearby star systems, and to build large enough structures in orbit around other stars to produce a visible transit in our data.

give the detailed example i have thought up.

becons placed at distances

for clarity, this is what the ideal signal might look like on the sky

this type of beacon network is advantageous because it points directly back towards their home. only a few systems actually need to be transiting from any given line of sight.

NOW THE FULL SIMULATION... - computation to do: if had 100 beacons, each placed at random orbital alignment, in 3d sphere around home system. - assume G stars, - odds of observing transit of a fixed sized object versus orbital distance... goes down. need that plot to figure out probability. - assume ET places beacons with uniform RADIAL density in 3d space out to some maximum distance (even # of systems as function of radial distance) in bins of 10pc out to 100 pc (i.e. 10 beacons in each 10pc bin) - orbital period is exact for each system, no bins of period - do Monte Carlo sim with these parameters to figure out how many transiting systems we'd observe

—- make the plot for one MC realization of RA,Dec.... open circles for systems with no observed transits, colored for transits

IDEA: could improve the efficiency of these beacons if we consider a bit of galactic structure, aligning the median orbital inclinations of the beacon systems with the Galactic plane, and only allowing a smaller range of possible inclinations. How much more efficient would it be if we forced $i < 10°$, instead of $i < 90°$?

for a million system model w/ 90deg max, 0.46% total detection efficiency. by constraining the inclination to 10deg max, get 4.3% detection efficiency of planets. 30deg max gets 1.4%

PROBLEM: as Forgan (2017) note, an interstellar communications based on transits may only be stable for ∼10,000 years due to evolution of planetary orbits

and relative motion between stars within the Milky Way. The beacon systems centered around the host system would have to be traveling as a moving group to maintain their respective trilateration signals, or have the transiting bodies actively over time. In other words, as the beacon systems moved relative to the ET host star due to differing Galactic orbits, the semi-major axis of the transiting bodies would have to be adjusted to compensate.

5.2. *Searching for Correlated Transits in Kepler*

we compute the 2-point correlation between all transits in the Kepler sample in 2D space (radius)

we find there is no correlation. Thats OK, but at least we searched

Coughlin et al. (2014) find some correlations that are apparently removed in KOI catalog creation... due to contamination by RRlyr or other thing? See also TCE histogram in Twicken et al. (2016)

6. DISCUSSION

so far we have focused on the need for developing SETI approaches that utilize the new spatial-temporal domain. The data streams from these surveys also enable many other search strategies that could be implemented. these might include: VASCO-type events, stars appearing or disappearing. (Villarroel et al. 2016) - Esp. stars appearing that do not have a Gaia DR2 detection, for example. - need to account for novae, etc... - stars disappearing will be very interesting

coordination/synchronization (Makovetskii 1977; Shostak 2004) - especially the SETI ellipsoid, a'la SN1987A (Lemarchand 1994) - could use galactic novae to provide time/place - -

unnaturals patterns of otherwise normal events - look for e.g. flares or novae that recur w/ prime or fibonacci sequences - see forthcoming paper

Surveys like ZTF (and soon LSST) publish real-time alerts of variability from sources. These alert streams could be monitored in real-time for signals as well: alerts from the stars within the "restricted Earth Transit Zone" (Heller & Pudritz 2016) - anytime we can see them w/ ZTF - especially at our opposition (i.e. when we transit) - with Gaia we can track stars that are leaving the ETZ as well, but might have seen us transit previously (or by the time the signal reaches us)

alerts from known exoplanet host systems, especially coinciding with any known transit conjunction (mid-transit), - allow some tolerance window to account for TTVs

The cost of deploying such SETI is remarkably low, since they can "piggyback" on databases and search
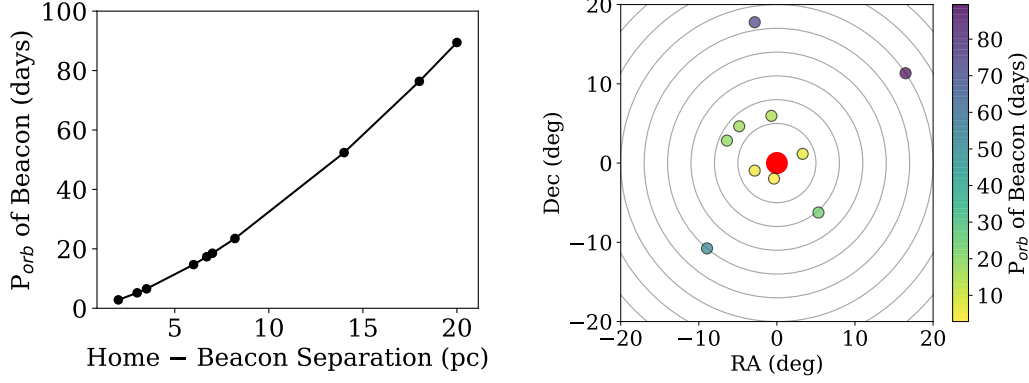
---

[2] Calculation done via Wolfram|Alpha

Figure 2. schematic figure of the signal to detect in 2 dimensions. ra,dec in arbitrary units. red circle in middle is the home system
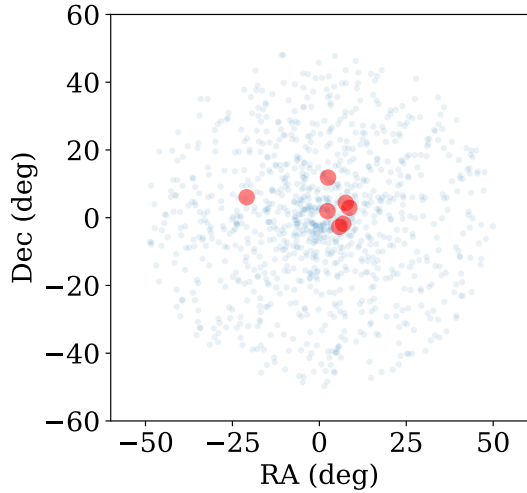

Figure 3. the model in 3 dimensions projected into the sky plane. 1000 simulated systems that span the galactic distance of 5-50 pc (blue) with 10 recovered transits highlighted (red). these would be hot Jupiters at the short P end.

tools being developed for the primary science drivers of each survey (e.g. transients for ZTF).

REFERENCES

Arnold, L. 2005, in SF2A-2005: Semaine de l'Astrophysique Francaise, ed. F. Casoli, T. Contini, J. M. Hameury, & L. Pagani, 207

Bellm, E. 2014, in The Third Hot-wiring the Transient Universe Workshop, ed. P. R. Wozniak, M. J. Graham, A. A. Mahabal, & R. Seaman, 27–33

Boyajian, T. S., LaCourse, D. M., Rappaport, S. A., et al. 2015, ArXiv e-prints, arXiv:1509.03622

Coughlin, J. L., Thompson, S. E., Bryson, S. T., et al. 2014, AJ, 147, 119

Council, N. R. 2010, New Worlds, New Horizons in Astronomy and Astrophysics (Washington, DC: The National Academies Press), doi:10.17226/12951

Djorgovski, S. G., Mahabal, A., Drake, A., Graham, M., & Donalek, C. 2013, Sky Surveys, ed. T. D. Oswalt & H. E. Bond, 223

Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870

Forgan, D. 2019, Research Notes of the AAS, 3, 32

Forgan, D. H. 2017, ArXiv e-prints, arXiv:1707.03730

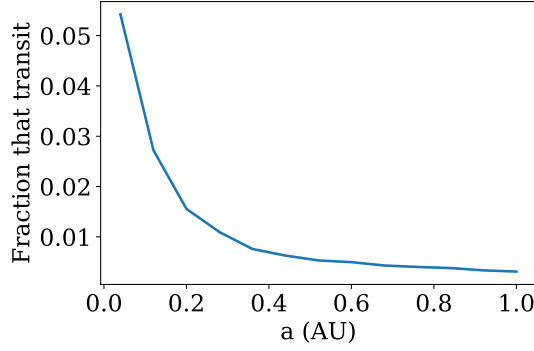Heller, R., & Pudritz, R. E. 2016, Astrobiology, 16, 259

Figure 4. fraction of hot Jupiter-like systems recovered in 1000 realizations of our 1000-star simulation. This curve is dependent on the ratio of the occulter-to-star size, and the orbital period range sampled. The average from our model is 10 ± 3 systems recovered for these parameters.
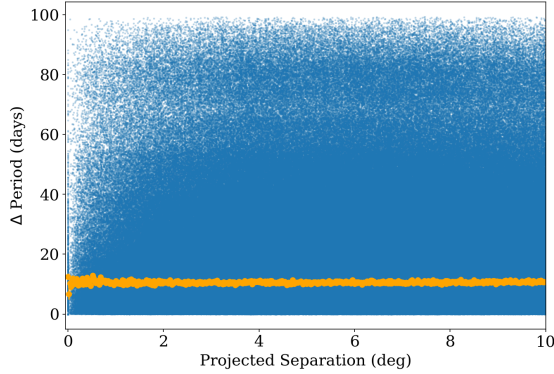

Figure 5. searching for correlation between transit periods and projected separations between all exoplanet systems out to 2deg in the Kepler data. median period differences are computed for bins of separation distance (orange points). there is no trend in these medians, indicating a distribution of orbital periods that are random on large scales.

Isaacson, H., Siemion, A. P. V., Marcy, G. W., et al. 2017, PASP, 129, 054501

Ivezić, Ž., Tyson, J. A., Acosta, E., et al. 2008, ArXiv e-prints, # 0805.2366, arXiv:0805.2366

Juric, M. 2012, LSD: Large Survey Database framework, , , ascl:1209.003

Kipping, D. M., & Teachey, A. 2016, MNRAS, 459, 1233

Lacki, B. C. 2019, arXiv e-prints, arXiv:1903.05839

Law, N. M., Fors, O., Ratzloff, J., et al. 2015, PASP, 127, 234

Lemarchand, G. A. 1994, Ap&SS, 214, 209

Makovetskii, P. V. 1977, Soviet Ast., 21, 251

Patterson, M. T., Bellm, E. C., Rusholme, B., et al. 2019, PASP, 131, 018001

Price, D. C., MacMahon, D. H. E., Lebofsky, M., et al. 2018, ArXiv e-prints, arXiv:1804.04571

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003

Schwamb, M. E., Hsieh, H., Bannister, M. T., et al. 2019, Research Notes of the AAS, 3, 51

Shostak, S. 2004, in IAU Symposium, Vol. 213, Bioastronomy 2002: Life Among the Stars, ed. R. Norris & F. Stootman, 409

Tarter, J. 2001, ARA&A, 39, 511

Tingay, S. J., Tremblay, C. D., & Croft, S. 2018, ApJ, 856, 31

Twicken, J. D., Jenkins, J. M., Seader, S. E., et al. 2016, AJ, 152, 158

Villarroel, B., Imaz, I., & Bergstedt, J. 2016, AJ, 152, 76

Worden, S. P., Drew, J., Siemion, A., et al. 2017, Acta Astronautica, 139, 98

Wright, J. T., Cartier, K. M. S., Zhao, M., Jontof-Hutter, D., & Ford, E. B. 2016, ApJ, 816, 17

Wright, J. T., Kanodia, S., & Lubar, E. 2018, AJ, 156, 260

Wright, J. T., & Oman-Reagan, M. P. 2018, International Journal of Astrobiology, 17, 177