The Breakthrough Listen Search for Intelligent Life: A Roadmap for Advancing Optical & Infrared SETI

Since its inception in 2016, the Breakthrough Listen project has become the largest driver for increasing the capacity and completeness of technosignature searches. This has included strategic investment in radio observations and related software, due to the historical dominance of radio astronomy in the field of SETI. Optical technosignature projects have also been a part of Listen, most notably to date in searches for laser emission within high resolution spectroscopy. Traditional optical astronomy includes imaging and spectroscopy, both in targeted observations and now in wide field and time-domain surveys. As such, the range of technosignature parameter space to explore is potentially enormous.

We are now in the era of large scale time-domain sky surveys, with projects like Rubin/LSST dominating the ground-based Astro 2010 and 2020 Decadal Review priorities. There has been two decades of explosive growth in the field of astrobiology, and steadily rising support for SETI research across the astrophysics community thanks to projects such as Listen. **The time is right to develop a new comprehensive plan for optical SETI programs supported by Breakthrough Listen and its team of international partnerships.** This document outlines some of the key areas for strategic project development over the next 5-10 years.

New Optical SETI Frameworks

Optical/Infrared is the primary wavelength regime for the majority of modern observational astronomy. As such, many universities have dedicated access to medium (2–5 meter) and large (6–10 meter) aperture facilities capable of doing signifiant amounts of monitoring and follow-up. In the era of automated sky surveys, and especially real-time alert systems, many of the established observatories need targets for observations that lead to exciting research. If we can establish and invigorate the practice of optical SETI broadly, through both directly funding projects and building partnerships with other facilities, technosignature work could become a ubiquitous component for observatories around the world.

There is already a large body of literature on optical technosignature theory to draw from, as well as many traditional radio SETI strategies that may be applicable to optical programs. Unlike some established frameworks like TURBOSETI, there is virtually no general purpose software or algorithms designed for technosignature signals from optical/infrared light curves or imaging. We should therefore support, and where applicable require, the creation of generalized and open source methods for optical SETI. Thankfully we can utilize community standard packages for most optical data handling, reduction, and pipeline building (e.g. astropy, lightkurve).

Strategic Goals

- Support technosignature research projects that include developing or building upon general purpose, open source tools as an explicit goal, and using community standard packages or libraries
- Demonstrate and encourage portability of methodologies by using multiple surveys or telescopes
- Seek out partnerships with established small to medium aperture facilities (e.g. 0.5-2 meter) that are interested in, or already committed to, follow-up in the Rubin era. Where possible provide mentorship, and support for outward-facing results such as conference travel and publications.
- Develop public watchlists or targets needing follow-up. These could piggyback off of Alert or Transient frameworks. Even regular social media posts of highly interesting targets can yield community-supported follow-up and characterization (e.g. ASASSN-21qj).

Exploring the Solar System and Moving Objects

Wide field time-domain surveys are the best source for creating a detailed census of the contents of our own solar system, particularly for small bodies with sub-kilometer diameters. A robust community is already using surveys like Pan-STARRS, ZTF, and soon Rubin/LSST to push the envelop for detecting, tracking, and modeling orbits of every possible object in the solar system. This work is critical for advancing solar system (and by extension exoplanet) science, as well as planetary defense. Within the first months of Rubin/LSST, the sample of known asteroids is expected to double. This major leap in small body demographics will allow us to search for outliers that may be consistent with artificial origins or technological remnants within our own solar system.

Many objects found in surveys like Rubin/LSST will have unusual orbital properties, such as non-gravitational dynamics due to cometary outgassing. Since the discovery in 2017 of the first confirmed interstellar asteroid, ʻOumuamua, there is enormous interest in searching for objects on hyperbolic orbits or exhibiting rapid or anomalous accelerations. Only two such bona fide objects have to date been tracked. Projections currently indicate Rubin/LSST might discover confirmed interstellar objects between 1 per month and 1 per year. Along with important preparation and follow-up we could provide, there will be an enormous opportunity for engagement of both the astronomical community and the general public on the search for technosignatures focused on these interstellar objects, especially in the first years of Rubin/LSST.

Strategic Goals

- Build relationships with the existing community of solar system researchers, including the Minor Planet Center, NOIRLab, the LSST Solar System Science Collaboration, etc.
- Engage with working groups to ensure technosignature science is considered in infrastructure development and included in relevant funding opportunities.
- Directly support projects that push the capability of existing or standard frameworks: e.g. improving non-grav object tracking, searching for “missing” asteroids in images, etc.
- Participate in rapid community follow-up of early interstellar object discoveries in early Rubin data.

- Establish firm limits on the presence of artificial objects within and moving through the solar system

Photometry and Time Series

Modern optical/infrared photometric surveys now routinely provide catalogs including tens of millions of stars, with the state of the art being ~1 billion stars from e.g. ZTF and Gaia. The specific properties of these surveys vary wildly, with imaging depths ranging from just below human-eye visibility with e.g. Evryscope and ASAS-SN, to ~28th magnitude with Rubin. Time series cadences span between minutes with e.g. TESS to months with Gaia. As a result, while many of the reduction and processing tools are fairly standardized, and generalized time series analysis is applicable to most all surveys, the properties and timescales for technosignature signals and that can be searched is vast and often difficult to directly compare between surveys. Important new parameter spaces are being probed by these surveys, with Rubin/LSST expected to monitor over 10 billion stars, while Gaia and ASAS-SN already have decade timescale survey baselines. Wherever possible we should utilize existing infrastructure for carrying out technosignature searches with these surveys.

Discoveries of rare objects such as "Boyajian's Star" from Kepler or many of the anomalous variable stars from e.g. ZTF or ASAS-SN have driven an interest in broad searches for unusual variability in large surveys. The technosignature focus for these projects is primarily in detecting transiting megastructures, though other signaling approaches are possible. These studies can be driven by both generalized anomaly searches, and targeted explorations for specific light cure behaviors. Similarly in multi-band imaging surveys, we can pursue searches for both specific technosignatures from e.g. Dyson spheres via infrared excess or parallax-luminosity discrepancies, or looking for general outliers in color space or color evolution in time.

Given the large samples available, and breadth of possible technosignature strategies to explore, the ancillary science potential here is excellent. Searches for anomalous light curves or color outliers from new surveys will almost certainly reveal challenging and exciting objects worthy of deep study. Given the current popularity of naively applying new AI/ML tools to any dataset, we can make a substantial contribution to the impact of studying and understanding rare stars by encouraging detailed follow-up and analysis of exciting objects.

Strategic Goals

- Develop relationships with institutes building AI frameworks for large surveys (e.g. the Transient and Variable Stars LSST Science Collaboration).
- Develop relationships with "citizen science" projects that can inspect and classify large volumes of data, and generate positive public and academic engagement.
- Support projects in both general anomaly finding, and in specific time domain signal searches.

- Since Rubin/LSST will not have dense or long duration light curves for several years (survey operations are currently slated to begin in late 2025), near term time domain technosignature projects for outliers should focus on existing surveys like ZTF, ASAS-SN, and Gaia.
- Rubin/LSST will provide a robust and unique real-time "alert" ecosystem. Immediate investment into technosignature opportunities with Rubin specifically should focus on alerts in Year 1 (e.g. defining expected limits on stellar variability across the color-magnitude diagram, implementing SETI Ellipsoid and Earth Transit Zone type schemes in to Alert Brokers).

Spectroscopic Signals

Spectroscopic capabilities have also experienced explosive growth in the past 20 years. This has included massive jumps in sample size due to multi-fiber surveys like SDSS (2003), as well as steady improvement in spectroscopic precision from radial velocity facilities searching for exoplanets. As a result, spectroscopic archives have reached sizes consistent with photometric catalogs from a generation ago: SDSS and LAMOST have obtained low resolution spectra for over 1 million and 5 million stars, respectively. APOGEE and GALAH both have high-resolution infrared spectra for over half a million stars. This has enabled both statistical analysis of the chemical and dynamical history of the Milky Way, as well as searches for unique, rare, or "chemically peculiar" objects. Developing SETI methods that utilize any spectroscopic survey will enable both the widest reach for technosignature searches in the near term, and can become part of standard processing pipelines that such surveys will run (e.g. the widespread adoption of "The Cannon" for stellar abundances).

As an example, extraterrestrial laser emission, either from targeted signals or unintentional leakage, has long been identified as a well-posed technosignature to search for. The modern foundational work in this area has been done by Breakthrough Listen and its collaborators on smaller, well-characterized samples of stars using very high resolution spectroscopy. The search for extrasolar planets via extreme precision radial velocity monitoring has produced a rich sample of thousands of nearby stars with many epochs of data. Many of these high-impact exoplanet searches are now providing access to their data archives for other science uses, which we could immediately use to expand the Breakthrough Listen optical laser search program. These laser search techniques will be applicable to larger spectral archives such as APOGEE and LAMOST, at all wavelengths and resolutions.

Many medium aperture observatories now have +10 year old workhorse echelle spectrographs (e.g. R~10,000-30,000) that cannot compete with new high precision RV machines, but are well suited for studies of nearby stars. Combining the wealth of existing archival data for nearby stars, and a network of medium aperture telescope facilities, we could produce a volume complete search for laser emission from stars within 100 lyr (~10,000 stars) in the next 2-5 years, and survey the nearest 100,000 stars (out to ~220 lyr) within the decade.

Strategic Goals

- Develop general purpose spectroscopic SETI pipelines, such as searching for anomalous laser emission, that students could install and run for any spectral archive or dataset.
- Amass the most complete census of available spectroscopy for nearby stars using every possible archive and survey. Using Gaia, determine which of the nearest 100,000 stars need observations.
- Find engaged partners at medium aperture observatories to contribute spectra and monitoring. Where possible provide mentorship, and support for positive outward-facing results such as conference travel and publications.
- Carry out volume complete spectroscopic searches for laser emission within 100 lyr and eventually 200 lyr. Begin campaigns for longterm monitoring of these samples for transient laser emission.

Other Opportunities

A wide range of complimentary technosignature approaches need to be be developed and carried out to push Breakthrough Listen into the optical regime. The projects and goals briefly described above are strategically positioned for our efforts in the next 5 years, but leave out many promising avenues we should continue to discuss and consider. These include searching for waste heat in infrared or NEO surveys like WISE, Roman, and NEO Surveyor, high cadence monitoring for laser emission from Cherenkov radiation telescopes such as CTA, multi-messenger technosignatures involving e.g. gravitational waves, and eventually exoplanet atmospheric markers of technology. Many of these are driven by major new facilities or observatories, and we must continue to advocate for SETI and technosignature work to be included in all relevant reviews and consortia for the optical and infrared, and within federal funding agencies. Submitting regular funding proposals to national calls (e.g. NSF-AAG, NASA-XRP) for these projects is an explicit goal to both support the work and ensure community-wide engagement and awareness of optical SETI.

Conclusion

In the next 5 years Breakthrough Listen is well poised to transform the state of optical SETI from its current position of e.g. ad-hoc outlier searches and spectroscopic snapshots for a few thousand stars, into a comprehensive and ongoing search for specific signals such as lasers, megastructures, and moving objects. By investing directly in projects with the goal of developing robust, open source tools, we will extend the reach of our work and see other groups incorporate our methodologies into their pipelines and workflows. Finally, we must act quickly to support nascent efforts in developing technosignature searches with signature facilities, most importantly the Rubin Observatory that is slated to begin operations in mid 2025.