# Exo-Life Finder (ELF):
# A Hybrid Optical Telescope for Imaging Exo-Earths

Astrobiology Science Strategy for the Search for Life in the Universe
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| Lead contact: | Kuhn, J.R., | IfA, University of Hawaii, USA / PLANETS Foundation, USA |
| | | kuhn@ifa.hawaii.edu, 34 Ohia Ku St, Pukalani, HI, 96790 |
| Contributors: | Berdyugina, S.V., | KIS, Freiburg, Germany / PLANETS Foundation, USA |
| | Apai, D., | Astrobiology, Arizona State University, USA |
| | Berdyugin, A.V., | Tuorla Observatory, Turku University, Finland |
| | Catling, D.C., | Astrobiology, University of Washington, USA |
| | Darnell, T., | Deep Astronomy, USA |
| | Diamond, B., | SETI Institute, USA |
| | Emilio, M., | Ponta Grossa University, Brazil / PLANETS Foundation, USA |
| | Finster, K., | Microbiology, Aarhus University, Denmark |
| | Gedig, M., | Dynamic Structures Ltd., Canada |
| | Grenfell, J.L., | DLR Institute of Planetary Research, Germany |
| | Halliday, D., | Dynamic Structures Ltd., Canada |
| | Harlingten, C. | SearchLight Observatories, Canada |
| | Jefferies, S.M., | Physics & Astronomy, Georgia State University, USA |
| | Klupar, P., | Breakthrough Prize Foundation, USA |
| | Kagitani, M., | PPARC, Tohoku University, Japan / PLANETS Foundation, USA |
| | Krissansen-Totton, J., | Astrobiology, University of Washington, USA |
| | Langlois, M., | CNRS, ULyon, ENS de Lyon, France / PLANETS Foundation, USA |
| | Lewis, K., | PLANETS Foundation, USA |
| | Marchis, F., | SETI Institute, USA |
| | Mennesson, B., | JPL, NASA, USA |
| | Minardi, S., | AIP, Potsdam, Germany |
| | Moretto, G., | CNRS, ULyon, ENS de Lyon, France / PLANETS Foundation, USA |
| | Norton, A.P., | Physics, Stanford University, USA |
| | Okano, S., | PPARC, Tohoku University, Japan / PLANETS Foundation, USA |
| | Pedretti, E., | AIP, Potsdam, Germany |
| | Piirola, V., | Tuorla Observatory, Turku University, Finland |
| | Ritter, J., | IfA, University of Hawaii, USA / PLANETS Foundation, USA |
| | Sakanoi, T., | PPARC, Tohoku University, Japan / PLANETS Foundation, USA |
| | Santl-Temkiv, T., | Microbiology, Aarhus University, Denmark |
| | Shostak, S., | SETI Institute, USA |
| | Tarter, J., | SETI Institute, USA |
| | Worden, S.P., | Breakthrough Prize Foundation, USA |

## Summary

**Finding and studying life in the Universe beyond the solar system is an ultimate goal of astrobiology. Here we describe technologies that will greatly accelerate the ability to find and study extrasolar life (exolife) within 10 years.** Our paper presents a new concept for a hybrid telescope-interferometer, the Exo-Life Finder (ELF), that can directly image Earth-size water-bearing planets in the optical and IR within tens of light years from the Sun. High-contrast direct imaging of exo-Earths is a far-reaching optical-IR remote sensing goal that will allow the measurement of biosignatures and exoplanetary reflected light. Robust numerical light curve inversions will yield wavelength-dependent albedo surface maps of potentially unambiguous signals of exoplanetary life, from single-cell photosynthetic organisms to advanced life-forms. Such data may even provide technomarkers of civilizations through heat-island signatures or artificial mega-structures on the planetary surface and its near-space. The ELF ground-based telescope consists of between nine to twenty-five large (4-8m) off-axis telescopes assembled on a common pointing structure. The primary mirror segments have identical off-axis parabolic shapes, and are served by corresponding adaptive secondary mirrors, each creating a diffraction-limited image with high-accuracy wavefront control. The synthesized point-spread-function (PSF) created by image-combining and properly phasing the ELF segments can produce a $10^{-7}$ contrast dark spot that can be moved, shaped, and achromatized within the field-of-view (FOV) by modifying segment phases. ELF's narrow FOV and hybrid technology reduce its cost by a factor of 10 compared to general-purpose extremely large Keck-era telescopes. Current ELF concept studies, involving experienced engineering groups, like Dynamic Structures Ltd., that are currently designing other Extremely Large Telescopes 'ELTs', suggest that ELF can be built within 7 years. **On a scale of $100M (less than the cost of a small NASA mission) ELF could yield a statistically valuable census of life on nearby exoplanets.** As a dedicated telescope for detailed exoplanet characterization, its first targets, like Proxima b, Ross 128 b, Alpha Cen A and B, as well as dozens of stars and exoplanetary systems in the solar neighborhood, will provide a wealth of new information for exoplanetary science.

## 1. Why ELF?

Currently planned ELTs are optimized for relatively wide-field general astronomy and will not necessarily address many exoplanetary science goals. We believe the rapid growth in exoplanetary science justifies a dedicated narrow-FOV instrument that is capable of high-contrast direct imaging in the optical and infrared. **ELF is a hybrid interferometric telescope that will be sensitive to exolife biosignatures from many near-by extrasolar planets.** Within a decade it could image Earth-size planets and acquire high signal-to-noise ratio (SNR) continuous reflected light curves at 0.3–5μm.

The signal integration time needed at fixed SNR for exoplanet photometry scales to a higher power than $1/D^4$ (where D is telescope aperture) and depends critically on exquisite wavefront control (reaching rms wavefront errors of a few nanometers) for high contrast. As a narrow-FOV optic ELF will combine interferometric concepts with a relatively "floppy" and lower mass mechanical structure to significantly decrease the cost per $m^2$ of light collecting aperture while realizing extremely high photometric dynamic range. These ELF advantages are likely to make comparable-aperture space-based systems non-competitive in both cost and time-to-realization.

**An ELF with an effective aperture of at least 20 m will fulfill an astrobiology strategic goal to sensitively search for life beyond the Solar system.** It will, for example, allow detailed exoplanet albedo maps to be inferred from light curves in various spectral bands. This dedicated telescope may also “see” exo-Earth oceans, continents, and colonies of surface life like extremophiles and vegetation as well as deserts, volcanos, polar caps (see Fig. 1), and even civilization heat-islands and artificial megastructures on the surface and in the near-exoplanetary space [1,2]. It may detect $O_2$, $O_3$, $CO_2$, $CH_4$, $H_2O$ and other biosignature gases and habitability markers, like disequilibrium biosignature gas pairs, organic haze in anoxic atmospheres [3], or photosynthetic and non-photosynthetic pigments [4,5].

ELF will be capable of characterizing atmospheres and surface bulk composition of the nearest m-dwarf exoplanet Proxima b [6], and over a period of a few months it will map its surface (and/or clouds) which may harbor life. Obtaining surface maps versus wavelength will yield spatially resolved spectra of features that can enable geologic and biologic studies of the planetary surface (Fig. 1). ELF will easily reveal and characterize Earth-size (and larger) planets in the Alpha Centauri A and B system, potentially expanding the number of nearest exoplanets for detailed studies. Finally, ELF will deliver timeseries of albedo maps of all exoplanets (from Earth- to Jupiter-size) within 25 light years (up to $V=13^m$, Fig. 2). It will create the first complete census of exo-life on nearby exoplanets and will allow weather, seasons, geological and biological activity studies on a significant sample of exoplanets.

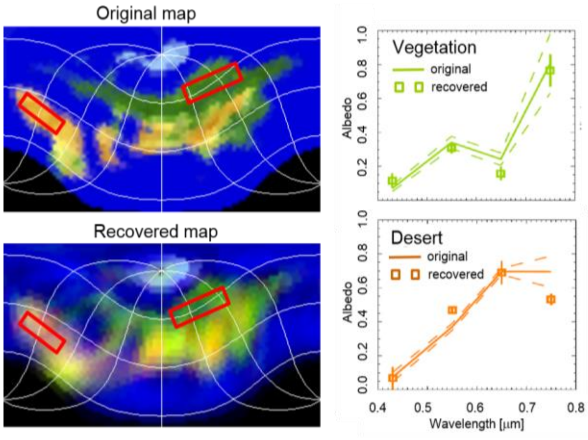

**Figure 1.** Example of an exo-Earth with an ice polar cap, ocean, and continents with deserts and vegetation. An Earth-like map is used to simulate reflected light curves in four passbands within 0.4–0.8 μm. The recovered map is a three-color image inferred using light-curve inversion. Spectra of two surface patches reveal vegetation “red-edge” and a typical desert composition (on the right). [1].

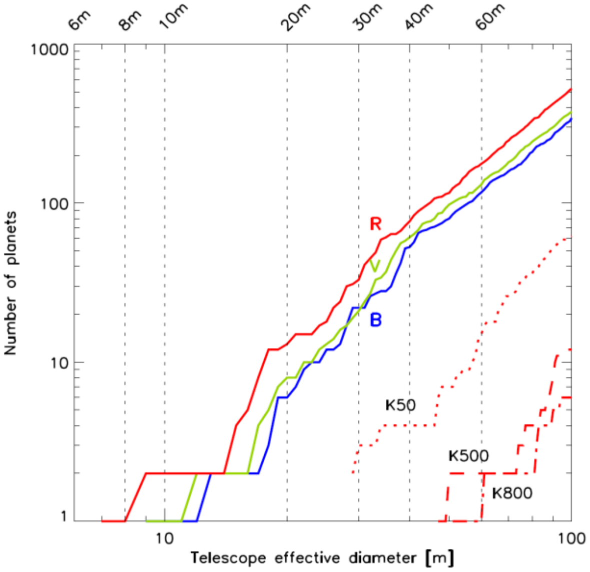

**Figure 2.** Number of detectable exoplanets ($SNR \geq 5$, $V \leq 13^m$, 4h exposure) depending on the low-scattered-light hybrid telescope aperture in BVR bands (solid lines) and comparable estimates for a Keck-like telescope (K50-800) with 50-800 segments.

## 2. ELF Design Concepts

The technology for building a powerful exoplanet “imager“ that exceeds the capabilities of Keck-era telescopes already exists. With minimal development, we can force the cost per aperture area down by an order of magnitude, so that an ELF could be built for less than the cost of a small NASA explorer mission. Such a ground-based telescope for direct imaging exoplanet studies benefits from several design principles [7,8]: 1) the total effective aperture should be large, 2) the subapertures should also be as large as practical while accounting for wavefront and diffraction control, 3) the moving mass should be minimized, 4) there must always be a relatively bright star in the FOV, so that wavefront control for phasing and adaptive optics can be performed accurately, 5) the synthesized optical PSF should yield a practical diffraction minimum in the FOV, so that the effect of residual wavefront errors does not spoil high dynamic range photometry. These principles and the ELF concept naturally lead to a “scalable” optical system design.

ELF’s intrinsically narrow FOV and its fundamental requirement for a bright central star allow an optical system that is similar to the phased-array radars that create “synthetic” PSFs, but in this case the phasing and wavefront control are achieved with a closed-loop system that uses the exoplanet’s near-point-like host star as a guide. Many elements of this strategy have been developed by the “Colossus Group” and more recently by the PLANETS Foundation [7–12]. The primary conclusions relevant for ELF are as follows:

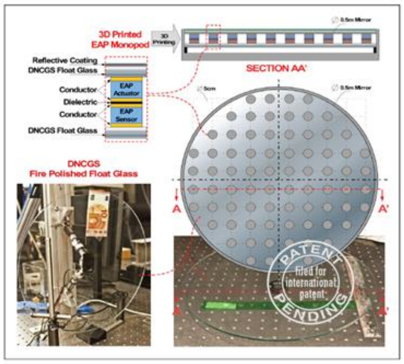

**Figure 3.** Live-Mirror proof-of-concept (0.5m) developed by the PLANETS foundation.

1) With additive (3D printing) technologies we can create an active structure on smooth fire-polished window glass that creates “stiffness” with considerably less mass than the glass-steel backing structure of, e.g., Keck-era mirror segments [11]. Current glass technologies allow patent-pending “live-mirrors” (Fig. 3) to be as large as 8m in size with an area-mass-density that approaches 1/10th of Keck-era mirrors. These optical elements could be constructed at the telescope site and would never undergo abrasive polishing.
2) The moving mass for the large diffraction-limited subapertures need not be as stiff as current ELTs, if each subaperture comes from a common parent parabolic optic shape and each independent subaperture secondary mirror provides the required adaptive and active tip/tilt/phase control. In this active/adaptive/high-Strehl telescope it is wasteful to use the mass budget to build an optical system that is “stiffer” than the intrinsic atmospheric and thermal wavefront errors that will be corrected by the active/adaptive control.
3) We have demonstrated how the necessary subaperture phase information can be efficiently recovered from the common-path full-aperture final image.
4) The moving optical support structure mass can be further minimized with a “bicycle wheel-like” structure that combines pre-tensional and compressional mechanical elements.

All of these features lead to a new type of extremely large aperture telescope that has extraordinary wavefront control and a small moving mass in comparison to Keck-era optical systems.

## 2.1. Optical and mechanical designs

As an example, the ELF optical design in Fig. 4 combines 16 eight meter diameter off-axis “live-mirror” parabolic segments with 16 off-axis elliptical secondaries in a basic Gregorian configuration. The subapertures are constructed from active “live-mirror” 6mm thick smooth no-polish glass. Each corresponding temporally fast adaptive secondary optic is about 15cm across and includes tip/tilt/piston control. The Gregorian focus provides additional articulated wavefront measurements for the temporally slow active shape control needed for the primary subapertures. The full optical system creates a final diffraction-limited Gregorian focus near the vertex of the parent optic. The narrow FOV allows for a very fast optical system (with a focal ratio less than 0.5) and a correspondingly small enclosed volume of the system moving mass.

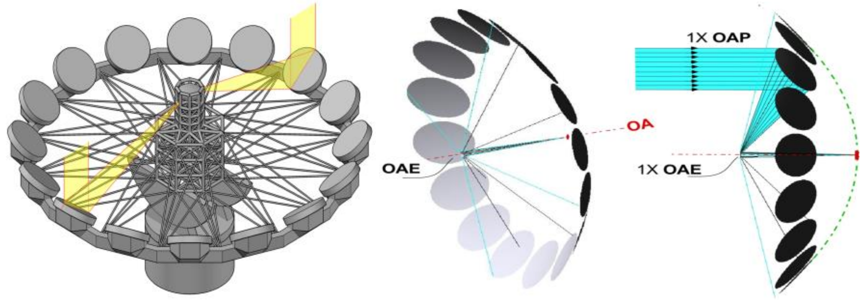

**Figure 4.** ELF Gregorian-focus off-axis parabolic optical configuration.

A mass-efficient mechanical design allows a 45 degrees zenith pointing distance and uses a "bicycle wheel" pretensioned moving support structure for the optical payload. Fig. 5 illustrates two concepts, one utilizes a wind fence enclosure and a telescoping central tower that allows the optical system to be lowered into a stowed position, while the second shows how separate retractable subaperture enclosures could be implemented.

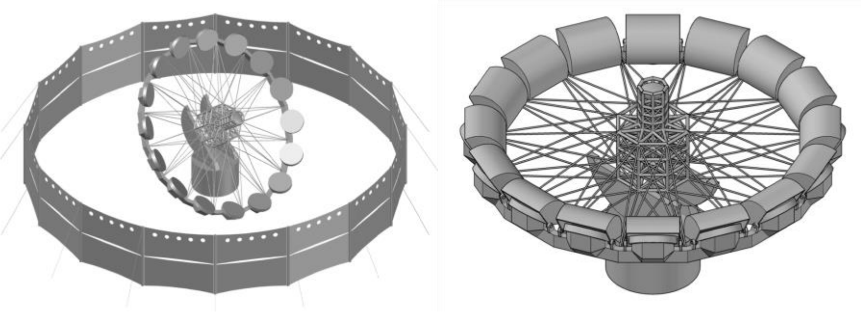

**Figure 5.** ELF Mechanical enclosure concepts: wind fence (left) and mirror covers (right).

## 2.2. Wavefront control and coronagraphy

ELF is fundamentally an adaptive/active telescope – it relies on photons from the exoplanet host star to create a high-strehl diffraction-limited PSF. Residual wavefront errors, larger than the fundamental wavefront measurement accuracy allowed by the stellar photon flux, are inevitable but their deleterious effects are minimized by an optical system with a diffraction pattern that has a dark hole in the FOV where we measure the exoplanet reflected light. ELF does not depend on a post-focus coronagraph since its synthesized "coronagraphic" PSF is created by the telescope itself. This has the important well-known advantage that the system PSF, that modulates residual wavefront errors, attenuates the photometry-limiting speckle noise near the exoplanet (i.e. "speckle-pinning" [12]). Figure 6 shows how a fixed phase introduced in each subaperture (by displacing the agile elliptical secondaries) can create a diffracted dark spot, and how the residual wavefront phase-induced intensity noise is correspondingly attenuated in the dark spot.

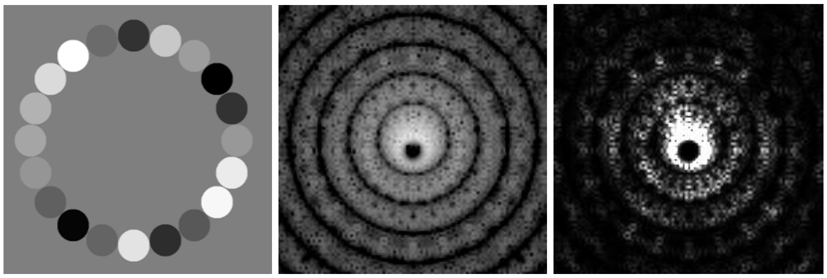

**Figure 6.** *Left:* Subaperture darkspot phase solution represented on 360deg linear greyscale. *Center:* PSF on log-scale 8 decades. *Right:* RMS speckle noise on log-scale 6 decades.

## 3. The ELF Proposal

The development of the ELF and the related Colossus and PLANETS telescopes, so far has relied on private and institutional support from Dynamic Structures Ltd., MorphOptic Inc., PLANETS Foundation, KIS, Tohoku University, CRAL/CNRS/Lyon University, and recently from the SETI institute. The ELF working group includes more than two dozen scientists and engineers. With this brief paper we seek public support for a fully vetted construction proposal over an 18-month period. The needed technology demonstrations and a detailed engineering design could be completed within a $1.8M budget, possibly leveraged by the partner institutions, scientists, engineers, and entrepreneurs included here.

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