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To cite this version:

Rene Kay, Todd Kay. Planet Seeker Interferometer (PSI). 2020. hal-02870885v2

HAL Id: hal-02870885
https://hal.science/hal-02870885v2

Preprint submitted on 11 Aug 2020 (v2), last revised 23 Sep 2022 (v3)

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Planet Seeker Interferometer (PSI)

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16 June 2020

Abstract

In this paper we present a novel design for a very large space-based optical interferometer that can be manufactured and launched within the next five years. The Planet Seeker Interferometer builds on previous work on laser-linked and multipart telescopes, such as the Hypertelescope and Fresnel Imager, as well as recent work on laser etching of thin-film Fresnel zone plates, to enable a very robust, simple and inexpensive design. The purpose of our work here is to lay a foundation, which serves as a call to action, in order to build enthusiasm and encourage further discourse, research, and development, towards the aim of building a telescope similar to the one outlined herein within the next five years.

1 Introduction and Overview

Our mission is to seek out and colonise habitable exoplanets, of course, a number of organisations are aiming to do the same. However, the entire field of interstellar travel seems to be in something of a rut, with even the most optimistic projections of interstellar travel suggesting we will not set foot on a planet under an alien sun for at least a century, probably more. Yet is this truly an accurate assessment? We are of the opinion that it is not, that in fact interstellar travel could be achieved not within *ten* decades, but within a *single* decade.

This paper is but the first, as we build a iron-hard case, that interstellar travel is in fact far easier, and far more near term, than anyone is currently expecting. Firstly, we must find a suitable exoplanet, no barren rock nor oversized comet will do, we must find a blue and green world potentially capable of supporting human life.

To this end, a new telescope operating on a colossal scale is needed, we have put together a design for just such a telescope, in fact a multipart telescope which we call the 'Planet Seeker', to be placed in a geostationary orbit, minimising

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the cost of deployment, and providing great stability, see Figures 1 2 for an overview of the entire telescope.

The telescope will be a visible-light and possibly ultraviolet interferometer, able to directly image even quite small exoplanets with a substantially higher resolution than currently possible with traditional telescopes. To minimise costs we have decided upon a ‘dumb’ array, consisting of hundreds of thousands of tiny, inexpensive thin-film plastic Fresnel zone plates, what the late Dr. Robert Forward referred to as ‘holographic tissue lenses’[1], which can be inexpensively mass produced at a fraction of the cost of conventional lenses[2], allowing the production and launch of upwards of one million individual telescope units.

The basic design will be something like the Hypertelescope, proposed by Prof. Antoine Labeyrie in 1996[3], and which he and his team have steadily worked on for almost three decades. When completed, the array will consist of up to one million units, with a total collection area of over 700 square metres, a baseline of 100 kilometres or more, and an angular resolution of approximately 1.25 micro arc seconds. For those who are not versed in the field: the resolution of a telescope is the angular size of the smallest resolvable object, a ‘higher’ resolution refers to a smaller minimal resolvable angle, therefore, an angular resolution of 1.25 micro arc seconds is an extremely high resolution, not a low resolution.

Once deployed, the Planet Seeker will possess a high enough resolution to successfully resolve features as small as 600 kilometres on a hypothetical planet in the Ran/Epsilon Eridani system, some 10.5 light years distant, as one example.

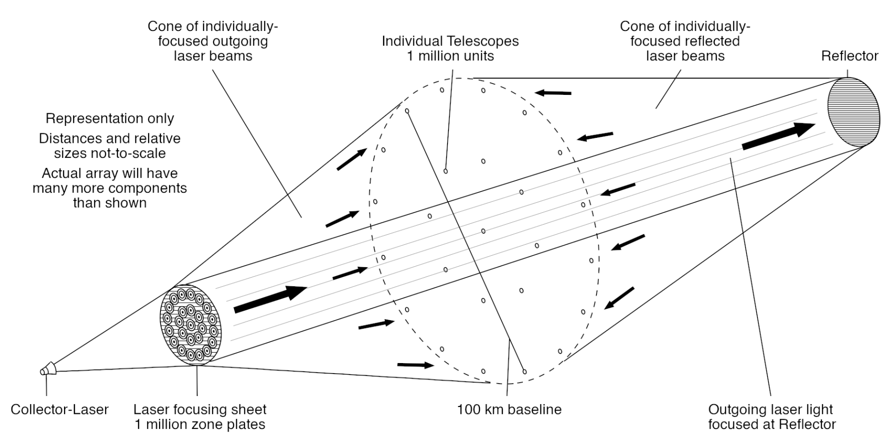

Figure 1: The Planet Seeker Interferometer, in a three-quarters orthographic projection, showing the position-keeping lasers.

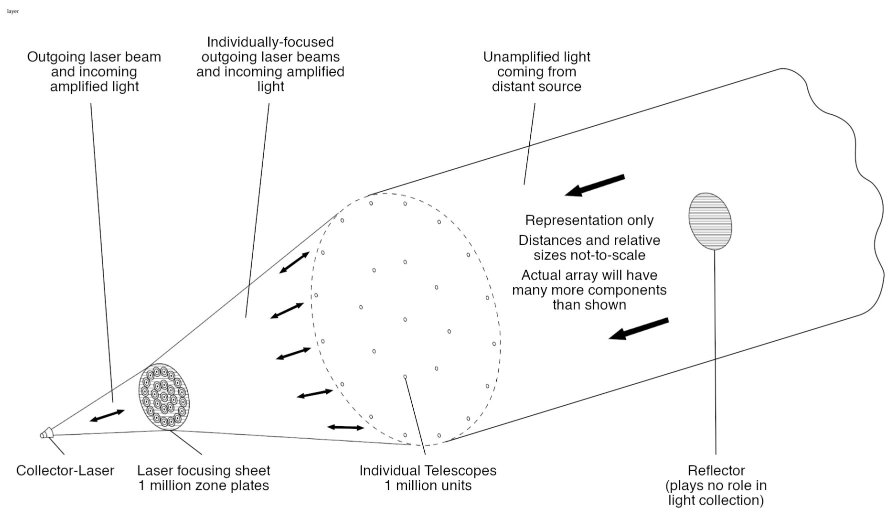

Figure 2: The Planet Seeker Interferometer, in a three-quarters orthographic projection, showing how incoming light is collected and amplified.

2 Science Goals and Objectives

The goals of the Planet Seeker are: (1) locate, characterise, and study from afar habitable worlds suitable for human colonisation, (2) investigate exoplanets for signs of intelligent activity, (3) study and locate, known and unknown distant bodies within our solar system, such as confirming and/or studying ‘Planet 9’, and (4) preform scientific study of innumerable cosmic phenomena.

An indefinite mission lifetime is intended, taking advantage of recent advances in space travel, such as the SpaceX Falcon 9, Falcon Heavy, Dragon, and Starship, to preform routine maintenance and upgrades on the interferometer array, and also the massively redundant number of the very simple individual ‘telescopes’, ensuring that the collective system can operate for years or decades with minimal maintenance.

Aside from its primary mission of seeking out habitable exoplanets, the Planet Seeker Interferometer will eventually also be available to preform many simultaneous ad-hoc studies of phenomena all over the sky, by making use of several light collectors and a spherical configuration to act as a multi-telescope, able to take images in many directions at once, much as Labeyrie’s proposed Hypertelescope[3].

We expect the Planet Seeker to revolutionise astronomy and science in general, and we also expect certain social, political, cultural, and technological changes arising from discoveries the Planet Seeker will make.

Table 1: Properties of the Planet Seeker Interferometer

Parameter	1 Million Unit ‘Dumb Array’ Interferometer
Collector	1 million 30 mm diameter Fresnel zone plates
Array shape	1:1 circular array
Array size	100 km
Wavelength range	approx. 100–800 nm
Angular resolution	1.25 μas
Biomarkers	CO_2, O_3 , H_2O, CH_4, chlorophyll-equivalent, urban lighting
Orbit	Geostationary Earth orbit
Mission duration	Indefinite
Launch vehicle	Falcon Heavy equivalent or better

3 Principle of Operation

We are reaching the limit of what is possible with conventional and ground-based telescope designs, light pollution is ever-increasing, and conventional telescopes with large reflectors quickly become unwieldy. In order to achieve the greatest advances possible, we must instead turn to space-based interferometers.

3.1 Introduction to interferometers

Interferometers collect the feeble light from distant stars, planets, nebulae, black hole accretion disks (and in principle, Hawking radiation), and galaxies, amongst other celestial objects and phenomena, from multiple individual telescopes. A phased-locked laser beam is sent out to each of the many telescopes, where it interferes constructively and destructively with the incoming light, increasing the brightness whilst preserving contrast. By mixing with the out-going phased-locked beam, a certain frequency and phase signal is embedded within the now-amplified images, specifically the phase and frequency changes with the distance and time travelled. The amplified images are sent on to a collector unit and combined, and by measuring and analysing the shift in both frequency and phase, a central computer can determine where in space and time each image was taken, sending this information to a ground-based supercomputer which processes the separate images into a single large image with a very high resolution, far higher than what any near-future mirror could achieve, and theoretically expandable to sizes that would be completely infeasible to manage with any single reflector.

This is analogous to taking the mirror out of a conventional reflecting telescope, and instead using several small mirrors, scattered around within the area the large single mirror formerly occupied, the image is just as sharp as before, despite the lack of a single continuous mirror.

3.2 Specific design of the Planet Seeker Interferometer

The design and operating principle of the Planet Seeker can be broken down into a few primary components.

Individual Telescopes Very small and extremely low mass plastic Fresnel zone plates[4][5], or 'holographic tissue-lenses'[1], mass produced, and easily suspended via laser light in a free-flying formation, against both Earth's gravitational pull and light pressure from the Sun [3][6][7]. By careful design of the lenses, a stable levitation can be achieved, see Figures 3 4, as recent work on interstellar beamriders has illustrated[8][7], other research, backed by ESA, successfully demonstrated laser propulsion of a 3 millimetre diameter graphene lightsail in microgravity[9], intriguingly, the researchers measured thrust an order of magnitude higher than expected from light pressure alone. Also recently, a new laser ablation manufacturing technique was developed by Zhao et al[2], which opens the door for very inexpensive mass-production of the required lenses.

We have preliminarily decided on a visible-light, and possibly ultraviolet, telescope, the reasons are as follows: (1) visible and ultraviolet light requires smaller optical elements than near-infrared for the same image brightness, minimising cost, (2) near-infrared lasers able to produce a strong force on the tiny individual telescopes are inexpensive and commonly used[8][7][10], (3) a Sun-like star has a peak output in the middle of the visible spectrum, again maximising image brightness, minimising the size, complexity, and cost of the needed optics, and (4) visible light astronomy simply produces beautiful and inspiring imagery, where folks will know that the image they are seeing is something akin to what they would see with their naked eyes, were they in orbit, the potential for stirring up enthusiasm cannot be overlooked, especially as this is one of the primary purposes of the Planet Seeker.

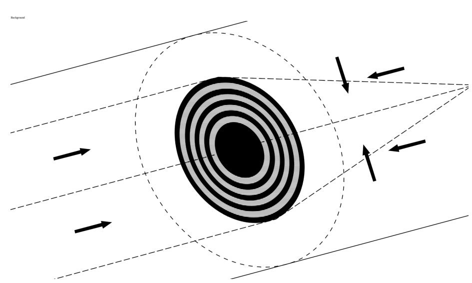

Figure 3: Individual Telescope, centred within opposing beams.

Collector A two-part device, consisting of a housing for the CCDs used to collect incoming starlight, and a separate focusing element, made as a thin-film

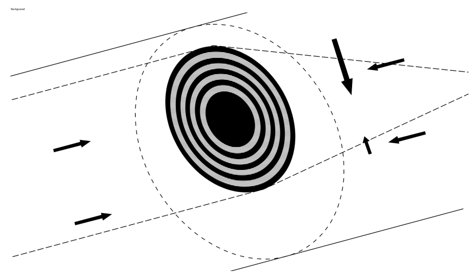

Figure 4: Individual Telescope, offset laterally, the resulting uneven redirection of laser light produces a corrective force, returning the lens to centre.

sheet using the same technique as used to manufacture the individual telescopes, and suspended via laser light a modest distance away, see Figures 5 6. This design allows for light to be collected from over 1 million individual telescopes, with the etched collecting lenses also functioning in reverse, as demonstrated by Khatri et al[11], where a laser beam is sent out through one or more beam-splitters, and then focused to a 'spot' at each of the telescopes, making this component a combined Collector-Laser. Internal measurement arms of a fixed and predetermined length allow comparison of incoming signals with a reference signal, permitting the all-important combination—interferometry—of the many images. See the work by Koechlin et al, on the 'Fresnel interferometric imager'[4][5], for more information about this type of lens as used to construct a telescope.

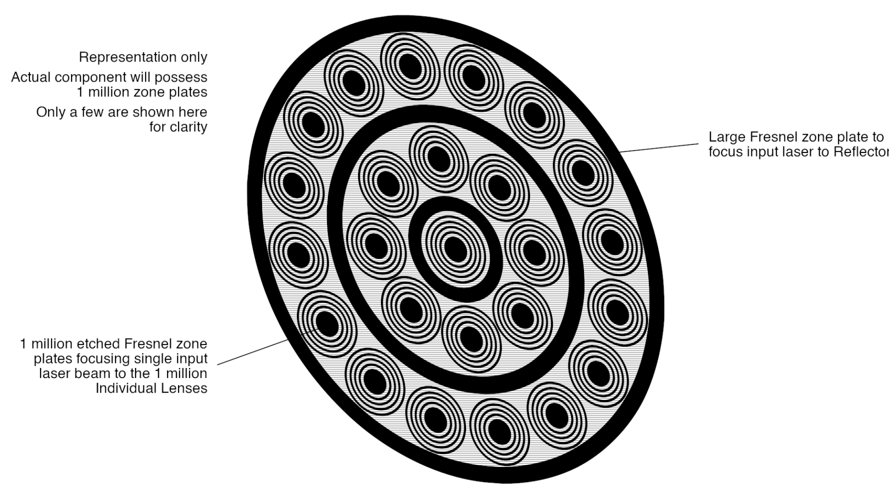

Figure 5: Laser focusing sheet, shown in a three-quarters orthographic projection.

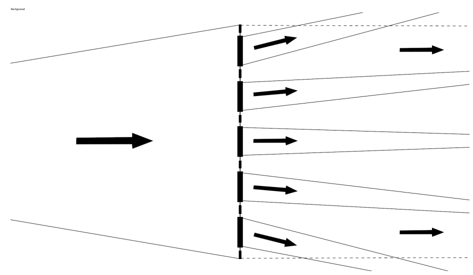

Figure 6: Laser focusing sheet, side view, showing how outgoing laser light is focused separately to each of the Individual Telescopes and the Reflector.

Laser According to Labeyrie and the Hypertelescope team, a laser power of 3 milliwatts is required per telescope[3][6], in order to levitate them against Earth's pull and solar light pressure, this amounts to 3 kilowatts for 1 million telescopes, a relatively modest laser that is easily available, indeed, near-infrared lasers of this power level are frequently used in the manufacturing industry[10]. The lenses are designed such that near-infrared laser light is unable to completely pass through, only partially penetrating and thereby producing a strong force on the tiny telescopes[8][7]. Frequency-doubling material in the lenses converts some of the laser light into visible light[12], that is able to interfere with incoming light in order to amplify the resulting image. Outgoing near-infrared laser light is focused to the individual telescopes by 1 million holographic lenses—etched into the focusing sheet—which, due to their unique properties, will also collect and refocus the incoming 400 to 700 nanometre wavelength starlight to a different spot than reflected 700+ nanometre, near-infrared laser light[13]. Later on, additional Collector-Lasers—or a larger focusing sheet and a higher power laser—can be added in order to support additional telescopes.

Reflector In order to suspend the telescopes, laser beams must act on the lenses from opposing directions, or else the laser light pressure will push the telescopes away, see Figure 7, this requires a convex reflecting mirror to be placed opposite the Collector-Laser[3][6]. Alternatively, the lens structure and focus length of the laser could be adjusted so that the beam is focused to a point a short distance behind the lens (relative to the laser source), creating a region of more intense light, that can then act on the lens to counteract the pressure of the laser, alleviating the need for a separate reflector, see Figure 8, this requires further investigation, and would be preferable if practical.

Geostationary Orbit Typically it is the Lagrange Points that are considered for telescope placement, permitting a view uninterrupted by Earth, or in the case of the Earth-Sun point L2, at least partially benefiting from Earth's shadow. However, we plan on instead deploying the Planet Seeker to a geostationary orbit[6], providing a greater orbit stability, and lower launch costs, compared

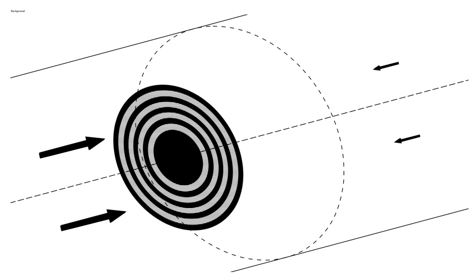

Figure 7: Individual Telescope, offset longitudinally, the telescope is no longer within the minimum between the opposing beams, with the resulting uneven forces returning the lens to centre.

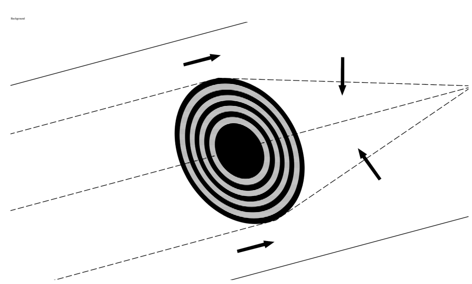

Figure 8: Individual Telescope, held in position without the Reflector by re-direction of the single beam, this configuration would eliminate the need for a separate Reflector, but may be unstable.

with the Lagrange Points. As the telescopes of the array are very low mass and easily suspended via laser beams, the only parts of the telescope that are in purely gravitational orbits are the Collector-Laser and the Reflector, see Figure 10. The easiest way then to achieve a stable arrangement is to place the Collector-Laser in a geostationary orbit some degrees ahead of, or behind, the Reflector, the telescopes are then suspended via laser light between the two, which will face each other. For comparison, if we wished to take advantage of Earth's shadow over L2, we would find that over time the Collector-Laser and Reflector would tend to either drift toward the central region of L2, or away, requiring constant adjustment and therefore use of propellant, creating a limited lifetime for the telescope, or else continual refuelling. By carefully angling the telescopes via adjustment of the outgoing laser beams, and by taking advantage of the new laser ablation manufacturing technique, to make lenses nearly without glare, we can avoid the problem of unwanted light from the Sun spilling into our images. Of course the telescope array would be unable to take images directly away or near the Sun, but that can be managed, such as by waiting for nightfall, and besides, over the course of a year nearly anywhere in the sky could still be imaged.

Image Processing Computer A central computer aboard the Collector-Laser analyses the frequency and phase shift, as well as the angle, of returning laser beams, now carrying amplified images acquired by the individual telescopes, in order to determine where in space and time the image was taken. This information is beamed down to the ground, where a waiting supercomputer uses raytracing, as well as conventional digital interferometry techniques, to electronically produce a very high-resolution final image, even reproducing the effects of additional, more sophisticated optics, such as the 'pupil densifier' designed by Labeyrie et al[6], without the added mass and physical complexity such equipment would introduce.

Ground-Based Prototype In advance of a space-based telescope array, a ground-based prototype can be developed and built within the next year or so. The prototype would be very minimalistic and non-disruptive to the environment, consisting of little more than an array of lenses on tripods. This way it can be built in a remote location, even in a designated wilderness park, without disturbing or altering the environment. Since 2011, the Hypertelescope team has been developing a similar prototype in the Alpes de Haute-Provence, in France[3].

Many of the nearest star systems of a similar type to the Sun are located within the southern sky, therefore from the northern hemisphere they are either not visible at all or are visible only near the horizon, where there is greater atmospheric turbulence. It is for this reason, that we propose Central to South America as a possible location for the Planet Seeker prototype, specifically in a region with a mountainous landscape, helping to cut down on light pollution.

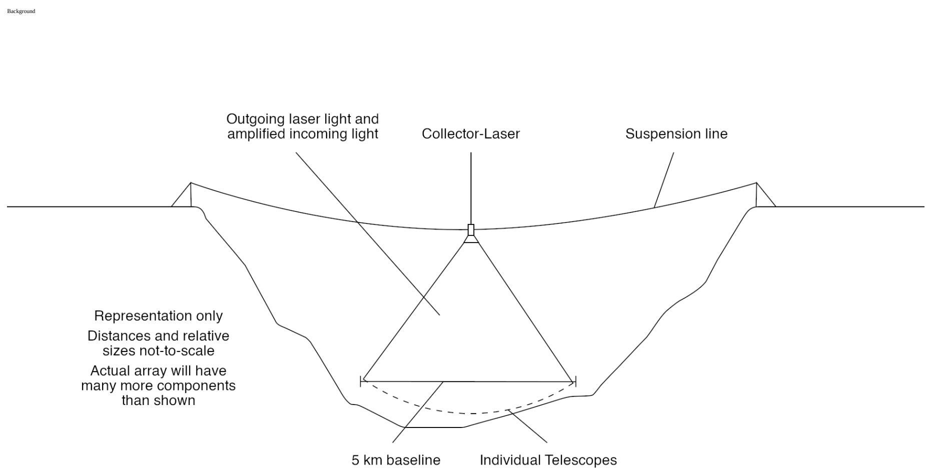

Figure 9: Gound-based prototype of the Planet Seeker Interferometer, shown situated in a hypothetical mountain valley.

4 Methods

The following is a mathematical breakdown of the assumptions and concepts behind the Planet Seeker Interferometer.

4.1 Minimum angle, collection area, and testing assumptions

A telescope's minimum resolvable angle θ is given by the equation

$$\theta = 1.22\left(\frac{\lambda}{D}\right), \tag{1}$$

where λ is the wavelength of observed light in metres, D is distance between the farthest telescope elements (in metres), also known as 'baseline', and 1.22 is the Rayleigh criterion[14].

Fleshing out the equation, for the sake of brevity we will assume a 500 nm $\left(5 \times 10^{-7}\,\mathrm{m}\right)$ wavelength (approximate average wavelength of visible light), and a 100 km $\left(1 \times 10^{5}\,\mathrm{m}\right)$ baseline, with these assumptions we find that

$$\theta = 6.1 \times 10^{-12}\,\text{radians}, \tag{2}$$

or approximately 1.25×10^{-6} arcseconds (1.25 µas). To get an idea what this means, first we need to find the kilometres covered within this angle at some specific distance. To do so, we must define a circle with a radius equal to the distance between the observed object (a planet in this case) and detector, and find the circumference C, this is given by the equation

$$C = 2\pi D, \tag{3}$$

where D is the distance to the observed object, which we will assume to be the distance to Ran (Epsilon Eridani) from the Solar system, approximately 10.47 light years $\left(9.91 \times 10^{16}\,\mathrm{m}\right)$. Solving for C, we find the circumference of our imaginary circle to be equal to $6.227 \times 10^{17}\,\mathrm{m}$. The distance covered by the telescope's minimum resolvable angle, as found in equation (2), will equal some small section of this imaginary circle, the covered distance in metres R_m is given by the equation

$$R_m = C\left(\frac{\theta}{2\pi}\right), \tag{4}$$

where C is the circumference of an imaginary circle with a radius equal to the distance to Ran (Epsilon Eridani) as given by equation (3), and θ is the resolution in radians of the telescope, given by (2), divided by 2π to give the fraction of a complete rotation occupied by this angle. Solving for R_m gives a distance of 604,545 meters, therefore, given a 100 kilometre baseline and a target wavelength of 500 nanometres, the smallest resolvable feature is approximately 600 kilometres.

To assess the feasibility of our design, we must also calculate the collecting area needed to produce a visible image. How many individual telescopes are necessary? Can many tiny telescopes easily achieve the collecting area of a larger single telescope, or does the system face quickly diminishing returns?

To this end we must find the number of photons reflected by a potentially Earthlike world orbiting a given star, which we will assume to be Ran (Epsilon Eridani), if N_γ is the approximate number of photons emitted per second by Ran then

$$N_\gamma = \frac{L_\epsilon}{L_\gamma}, \tag{5}$$

where L_ϵ is the luminosity of Ran (Epsilon Eridani), given in solar luminosity as $0.34\,\mathrm{L}_\odot$, as defined by the International Astronomical Union, that is, $0.34\,\mathrm{L}_\odot = 3.827 \times 10^{26}\,\mathrm{W}$ [15], and where L_γ is the energy of an average photon of light emitted by Ran, approximated here as the energy of a 500 nm photon ($3.973 \times 10^{-19}\,\mathrm{J}$). Solving for N_γ we find that the approximate number of photons emitted per second by Ran is equal to

$$\begin{aligned} N_\gamma &= \frac{L_\epsilon}{L_\gamma}, \\ N_\gamma &= \frac{0.34\left(3.827 \times 10^{26}\,\mathrm{W}\right)}{L_\gamma}, \\ N_\gamma &= \frac{1.301 \times 10^{26}\,\mathrm{J/s}}{3.973 \times 10^{-19}\,\mathrm{J/photon}} = 3.275 \times 10^{44}\,\mathrm{photons/s}. \end{aligned} \tag{6}$$

Now we find the surface area of a disk with a radius equal to the mean radius r of our hypothetical Earthlike world, which we take to be equal to Earth's mean radius, 6371 kilometres[16], given by the equation

$$\pi r^2 = 1.2752 \times 10^8\,\mathrm{km}^2, \tag{7}$$

dividing this by the surface area of an imaginary sphere encompassing the Earthlike world's orbit, given by the equation

$$4\pi R^2 = 2.812 \times 10^{17}\,\mathrm{km}^2, \tag{8}$$

where R is the radius of the orbit, taken as 1 astronomical unit[17], we now find the fraction of the radiant flux emitted by Ran intercepted by this planet, via

$$\frac{1.2752 \times 10^8\,\mathrm{km}^2}{2.812 \times 10^{17}\,\mathrm{km}^2} = 4.535 \times 10^{-10}. \tag{9}$$

Next, to find the fraction of photons that will reach and reflect off the planet, we take the total number of photons emitted, as given by (6) and multiply it by the fraction given by (9), and then multiply this value by the Bond albedo of the planet, giving us

$$A(3.275 \times 10^{44}\,{}^{\mathrm{photons}}\!/\!_{\mathrm{s}} \times 4.535 \times 10^{-10}) = 4.455 \times 10^{34}\,{}^{\mathrm{photons}}\!/\!_{\mathrm{s}}, \tag{10}$$

where A is the Bond albedo of the hypothetical planet, which we assume here to be an Earthlike 0.3[18].

Now we can finally calculate the necessary collection area of the telescope array, as a baseline, we will assume one million telescope units, each with a 30 mm diameter, so

$$\begin{gathered}\left(\pi r^2\right) 1000000,\\ \left(\pi\,(15\,\mathrm{mm})^2\right) 1000000,\\ 706.9\,\mathrm{mm}^2 \times 1000000 = 7.069 \times 10^8\,\mathrm{mm}^2,\end{gathered} \tag{11}$$

where r is the radius of each telescope unit.

As we can see, the total collection area of the array is $706.9\,\mathrm{m}^2$, now to find if this collecting area is large enough to collect sufficient light to see our hypothetical world.

To begin with, we calculate the surface area of an imaginary sphere, centred on the planet, with a radius equal to the distance between the telescope array and planet, given by the equation

$$4\pi R^2 = 1.234 \times 10^{35}\,\mathrm{m}^2, \tag{12}$$

where R is the distance from the planet to collector, specifically $9.91 \times 10^{16}\,\mathrm{m}$ (10.47 light years). Next, taking the collection area from equation (11), and the surface area of the imaginary sphere from equation (12), we can then find the fraction of the sphere's area covered by the telescope array,

$$\frac{706.9\,\mathrm{m}^2}{1.234 \times 10^{35}\,\mathrm{m}^2} = 5.7285 \times 10^{-33}, \tag{13}$$

multiplying this fraction by the photons reflected by the planet, as given by equation (10), we find

$$4.455 \times 10^{34}\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}} \times 5.7285 \times 10^{-33} = 255.2\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}}, \tag{14}$$

this is roughly 2 to 7 times the minimal photon flux detectable by the human eye[19], considering that CCDs are generally more sensitive than the human eye, this is probably a sufficient photon flux to take useful images. Multiplying this by 60 gives us the photons per minute,

$$(255.2\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}})\,60 = 15312\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{min}}. \tag{15}$$

Alternatively, we can take the collection area of the James Webb Telescope, that is, 25.4 square metres[20], and dividing it by area of the imaginary sphere from equation (12), we get a new fraction, which we then multiply by the photons reflected by the hypothetical planet, from equation (10), giving us the photons per second with a collection area equivalent to the James Webb Telescope,

$$4.455 \times 10^{34}\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}} \left(\frac{25.4\,\mathrm{m}^2}{1.234 \times 10^{35}\,\mathrm{m}^2} \right) = 9.17\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}}, \tag{16}$$

so roughly 9 photons will be collected per second, multiplying this by 60, we find the photons collected per minute,

$$(9.17\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{s}})\,60 = 550.2\,{}^{\mathrm{photons}}\!/\!{}_{\mathrm{min}}, \tag{17}$$

probably still sufficient to take useful images. From this, we can find the number of 30 mm diameter telescopes required to achieve a James Webb equivalent collection area, taking the area of each telescope as given by equation (11), so

$$\frac{2.54 \times 10^{7}\,\mathrm{mm}^2}{706.9\,\mathrm{mm}^2} = 35930\,\mathrm{units}. \tag{18}$$

Therefore, we can conclude with only some 40,000 telescope units, each 30 mm in size, the telescope array can already achieve a collection area equal to that of the James Webb Telescope, albeit with a much higher resolution due to possessing a 100 kilometre baseline.

It must be noted that this simplistic formula ignores the curvature of the planet, which reduces the number of photons reflected directly back to the source. The formula also assumes that we can see the entirety of the illuminated surface of the planet, when in reality we will see only a partially illuminated disk. And lastly, the formula approximates the number of emitted photons by dividing the total luminosity in joules per second by the energy in joules of a single photon of blue-green light, specifically a photon with a 500 nm wavelength, when in reality a wide spread of photons of all wavelengths are emitted. Nevertheless, these formulae provide a good first approximation, in order to roughly determine the collection area needed to provide a visible image.

4.2 Laser optics

It is important that we determine the size of the lenses needed to focus outgoing near-infrared laser beams across space to the individual telescopes, and incoming starlight to a waiting CCD. We can use this information to, at a later date, make a comprehensive estimate on the cost of manufacturing and launching the Collector-Laser, which will by far be the most massive, and one of the largest, components of the Planet Seeker Interferometer.

The actual utmost largest single component, though quite low in mass, will be the reflector, consisting simply of an unfolding circular sheet of lightweight aluminium or gold foil, possibly needed to reflect laser beams to the opposite side of the individual telescopes, in order to hold them in position, see Figure 1. If it turns out that a dedicated reflector is unnecessary, then obviously the Collector-Laser becomes the largest single component.

We are relying on lasers to hold the individual telescopes in place against the forces of Earth's gravitational attraction, and light pressure from the Sun, in order to get an idea how large a laser focusing lens is required, to achieve a spot size small enough to produce the needed counteracting force, and therefore how large the housing of the Collector-Laser must be, we must first find the laser spot size R_T, given by the following equation, derived from one of the equations found on Chung's Atomic Rockets website[21],

$$\begin{gathered} R_T = \frac{0.305 D\lambda}{R_L}, \\ R_T = \frac{0.305\left(1\times10^{6}\,\mathrm{m}\right)\left(1\times10^{-6}\,\mathrm{m}\right)}{6\,\mathrm{m}}, \\ R_T = \frac{0.305\,\mathrm{m}^2}{6\,\mathrm{m}}, \\ R_T = 0.0508\,\mathrm{m}, \end{gathered} \tag{19}$$

where D is the distance between the Collector-Laser and the individual telescopes, which we have assumed to be 1000 kilometres, far enough away to easily illuminate the entire array, where λ is the wavelength of the laser light, assumed to be 1000 nm $\left(1\times10^{-6}\,\mathrm{m}\right)$, and where R_L is the radius of the laser focusing lens, in metres. As we can see, to achieve a spot size close to the diameter of the individual telescopes, the focusing lenses must be 6 metres across!

A million focusing lenses, each 6 metres across is hardly practical, or is it? We have already talked of using tissue paper-thin plastic lenses for focusing incoming starlight to the Collector-Laser, why not apply this technique to the laser focusing lenses as well? Rather than a million individual lenses, we can simplify matters by using a single circular piece of plastic film, several kilometres across, and etched with a million Fresnel zone plates, held in place against Earth's gravity by the pressure of the laser beam, which will illuminate the sheet more-or-less equally, as we have mentioned and shown, see Figure 5.

If the sheet deviates to the side of the laser beam in any direction, then as with the free-flying telescope lenses, a correcting force will appear and act on the sheet, moving it back into alignment. To stop the laser light pressure from pushing the sheet away, we can etch and layer up the plastic in very precise diffraction patterns to cause a portion of the laser beam (most of which will miss the focusing lenses anyway) to be refocused a short distance away, producing a counteracting light pressure opposite the Collector-Laser, appearing only once a specific distance is reached, elsewise we can make use of the Reflector to hold the sheet in position, see Figure 5, also reference Figures 3 4 7 8 to get an idea of how the sheet can be held in place via laser light.

Now to find if the laser spot size given by equation (19) provides sufficient brightness, firstly, we will assume a frequency doubling efficiency D_e from near-infrared to blue-green light of 50%, a low estimate, as efficiencies of 85% have been reported[12], we will also assume that the desired photon count at the collecting CCD, N_γ, to be 10,000 photons per second. Given these assumptions, the laser energy at emitter B_P is given by the following equation, also derived from an equation found on Chung's Atomic Rockets[21],

$$\begin{gathered}
B_P = B_{PT}\left(\pi R_T^2\right), \\
B_{PT} = \frac{\left(B_\gamma N_\gamma\right) D_e}{1\,\mathrm{m}^2}, \\
B_{PT} = \frac{\left(\left(1.986 \times 10^{-19}\,\mathrm{J}\right) 10000\right) 0.5}{1\,\mathrm{m}^2}, \\
B_{PT} = 9.93 \times 10^{-16}\,\mathrm{J/m^2}, \\
B_P = 9.93 \times 10^{-16}\,\mathrm{J/m^2}\left(\pi R_T^2\right), \\
B_P = 9.93 \times 10^{-16}\,\mathrm{J/m^2}\left(\pi\left(0.0508\,\mathrm{m}\right)^2\right), \\
B_P = 8.05 \times 10^{-18}\,\mathrm{J},
\end{gathered} \tag{20}$$

where B_{PT} is the energy density of the laser spot, given in Joules per square metre, and R_T is the radius, in metres, of the beam spot at the target, from equation (19), and where B_γ is the energy of single near-infrared photon in Joules, specifically 1.986×10^{-19} J, giving an energy of 8.05×10^{-18} J, an utterly minuscule amount of energy.

Indeed, according to Labeyrie, 3 milliwatts of laser power are required per telescope lens in order to keep them in place[3][6], this far exceeds—by an absurdly wide margin—the calculated laser brightness needed to amplify collected starlight, as given by equation (20). Given this, we could make do with a much larger spot size and correspondingly smaller laser focusing lens, however, if the spot size is too large then the gradient from centre to edge of the laser 'spot' may be too gradual for the individual telescopes to self-centre on the beam.

For the sake of this paper, we have made an educated guess, assuming that a 6 metre laser focusing lenses, producing a spot size of approximately 50 millimetres, is probably a good balance. Refining this estimate will require further investigation, however, as shown by Ognjen Ilic & Harry Atwater, in the case of laser-driven interstellar probes, a high ratio of beam width to beamrider diameter, where the beam width is much greater than the beamrider's diameter, is preferable and more stable than a lower ratio[7], similar conclusions apply to the free-flying telescope lenses.

4.3 Ground-based prototype

The usefulness of a ground-based prototype depends on its resolution, while it would be useful–and necessary–to build a prototype of the Planet Seeker on the ground, regardless of its resolution, if the resolution is great enough then the prototype becomes useful in its own right as an astronomical tool, perhaps even able to image nearby exoplanets directly, see Figure 9.

To ascertain the resolution, and therefore usefulness, of a ground-based prototype, we start once again with equation (1), with the same wavelength, but this time with a baseline of only 1 kilometre $\left(1 \times 10^3\,\mathrm{m}\right)$, giving us the following result:

$$\theta = 6.1 \times 10^{-10}\,\text{radians}. \tag{21}$$

Next we take the result of equation (3) and the angle given by (21) and input it into equation (4),

$$R_m = C\left(\frac{\theta}{2\pi}\right) = 6.04545 \times 10^{7}\,\mathrm{m}, \tag{22}$$

Where R_m is the size, in metres, of the smallest resolvable feature, which we can see is about 60,000 kilometres, too low a resolution to image a hypothetical terrestrial planet at Ran directly, but more than adequate to resolve giant planets. This would, for example, enable confirmation of (or conclusively rule out) the proposed gas giant AEgir, or the other giant planets that have been hypothesised to explain the gaps in Ran's debris belts. Additionally, the light reflected or emitted by a terrestrial world would still be detectable, allowing us to analyse the planet's spectral lines and make a fairly confidant estimation of the surface conditions and habitability of the planet.

If it were practical to build a larger ground-based array, or perhaps a small space-based array, with a baseline of, let us say 5 kilometres, so

$$
\begin{aligned}
R_m &= C\left(\frac{\theta}{2\pi}\right), \\
\theta &= 1.22\left(\frac{\lambda}{D}\right), \\
\theta &= 1.22\left(\frac{5\times10^{-7}\,\mathrm{m}}{5\times10^{3}\,\mathrm{m}}\right), \\
\theta &= 1.22\times10^{-10}\,\text{radians}, \\
R_m &= C\left(\frac{1.22\times10^{-10}\,\text{radians}}{2\pi}\right), \\
R_m &= 6.227\times10^{17}\,\mathrm{m}\left(\frac{1.22\times10^{-10}\,\text{radians}}{2\pi}\right), \\
R_m &= 1.20909\times10^{7}\,\mathrm{m},
\end{aligned}
\tag{23}
$$

then the size of the smallest resolvable feature is around 95% of Earth's equatorial diameter[16], plenty to start with!

From this we can conclude that it would be a useful and worthy effort to build a ground-based prototype, immediately able to directly image nearby giant exoplanets, and possibly terrestrial planets as well, if the prototype is sufficiently large.

5 Construction and Cost

It is almost too early to give even rough estimates of the costs involved in this project, however, a very broad overview can be managed.

5.1 A rough cost analysis

At this stage it appears the two most expensive aspects of the project will be launch costs, as well as the costs involved in the research and development of the Collector-Laser.

Based on figures given on the SpaceX website, we conclude that the entire interferometer will cost at least $62 million USD[22] to be launched, though probably closer to $70 million USD. The individual telescopes themselves can be launched for less than $3 million USD by making use of SpaceX's rideshare program for small satellites[23], as the million lenses are only 30 millimetres across and microns thick, easily fitting within a rather small volume.

The prototype, being ground-based, would cost significantly less simply by avoiding the need to launch it into space, additionally, the prototype would consist of a much smaller number of Individual Telescope units, compared with the final space-based array.

5.2 Construction of the Planet Seeker Interferometer

The individual telescopes of the Planet Seeker are little more than etched pieces of micron-thick plastic, and using the new technique discussed earlier, the 1 million lenses required for the full array could be mass-produced at a very low cost-per-lens[2], perhaps as little as $0.1 USD or equivalent, though this is only an educated guess. Research, and especially development, is required before a firm estimate on the cost of lens manufacture can be given, as the technology must be scaled up from a lab prototype first, or at the very least, this process must be started in order to begin to make an estimate on the cost.

The primary costs involved in the manufacture of the lenses appears to be the initial cost of the laser equipment and clean room, followed by the cost of vacuum-grade plastic with the correct composition and optical properties, and lastly labour and electricity costs.

The Collector-Laser will be more involved to develop and construct, with the bulk of the cost and effort going into the precise arrangement of the laser splitter or splitters, and in maintaining a clean room environment, that said, such expertise and facilities are already in existence.

One of the primary purposes of this paper, and an as-yet unpublished follow-up presentation—on the larger project that this telescope is a part of—is to bring awareness to, and draw the interest of, needed specialists.

6 Call to Action

This paper is a call to action, a foundation to get the ball rolling, to get things started. We have the technological prerequisites to design, develop, build, and launch a telescope capable of finding another Earth, another habitable world.

In a year's time, we could have an organization developing a prototype of the telescope, and in five... We could together be watching its launch, knowing that the Age of Interstellar Discovery is dawning.

To begin with we need to create a flyable design, all the bells and whistles, an absolutely complete and airtight final design. Following this, we will begin research and development of the hardware, and software, needed for the Planet Seeker Interferometer, testing and refining the technology by way of a ground-based prototype.

Ultimately, this is perhaps the grandest and most important project humanity has ever undertaken, we cannot remain on Earth alone forever, nor even within our solar system, sooner or later the Sun will die, and our very distant descendants will die with it, unless we take the actions necessary now, to ensure that we become a star-faring species.

The Planet Seeker is only the beginning of a grand adventure, an adventure of epic proportions, to explore and colonise distant worlds orbiting alien suns. If we take this step, if a brave few of us dare to go against the current, ignore cries of economic irrelevance and the 'impossibility' of the task at hand, then our distant descendants will look back on this moment, from their homes amongst the stars, and wonder at the courage and vision of those mighty pioneers.

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Appendix

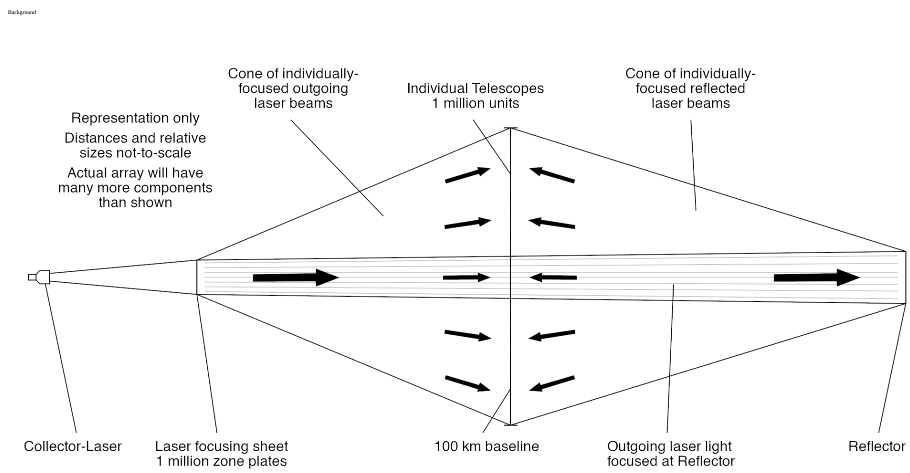

Figure 10: The Planet Seeker Interferometer, side view, showing the position-keeping lasers.

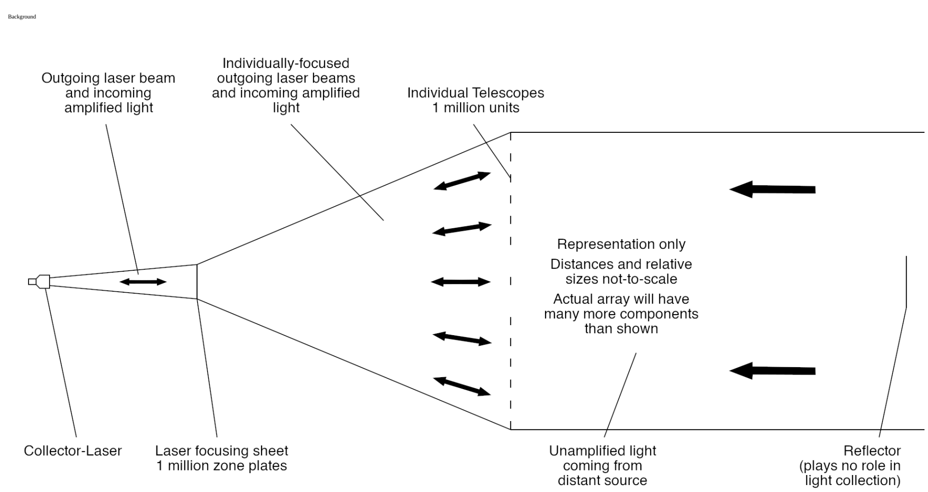

Figure 11: The Planet Seeker Interferometer, side view, showing how incoming light is collected and amplified.