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Planet Seeker Interferometer (PSI)

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22nd September 2022

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 establish settlements on 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

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we call the ‘Planet Seeker’, to be placed in a geostationary orbit, minimising the cost of deployment, and providing great stability, see Figures 1 and 2 for an overview of the entire telescope.

The telescope will be a visible-light interferometer, with a possibly extended range including ultraviolet and far-infrared, and will be 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.

It should be noted that there is no fundamental reason why a baseline of say, 5,000 kilometres, could not be used instead of 100 kilometres. We chose the latter mostly for reasons of presenting a more conservative design, and because much of the literature deals with a baseline of 100 kilometres. Ultimately, it may be decided that a larger baseline would be preferable and easily achievable, after all, the array of floating in space. A larger baseline would permit an even higher resolution at any given distance.

2 Science Goals and Objectives

The goals of the Planet Seeker are: (1) locate, characterise, and study from afar habitable worlds suitable for human settlement, (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) perform 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 perform routine maintenance and upgrades on the interferometer array, and also the massively redundant number of the very simple individual

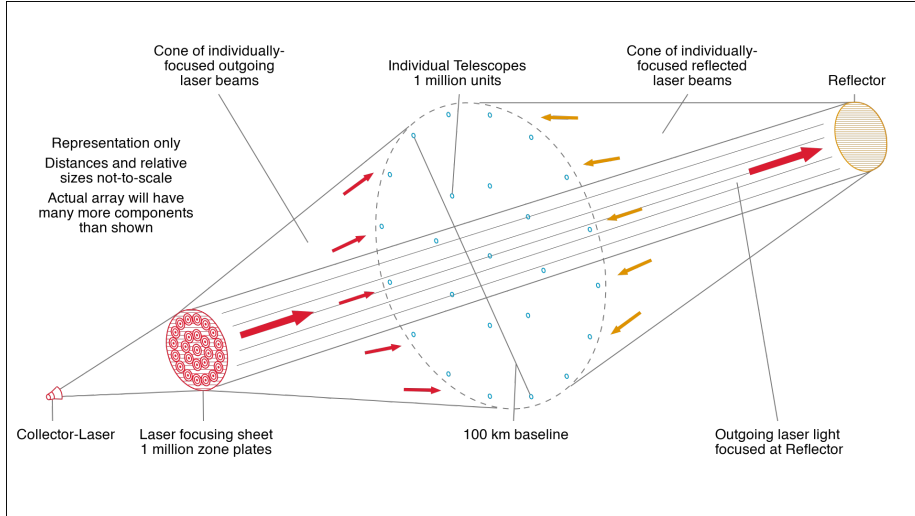


Figure 1: The Planet Seeker Interferometer, in a three-quarters orthographic projection, showing the position-keeping lasers.

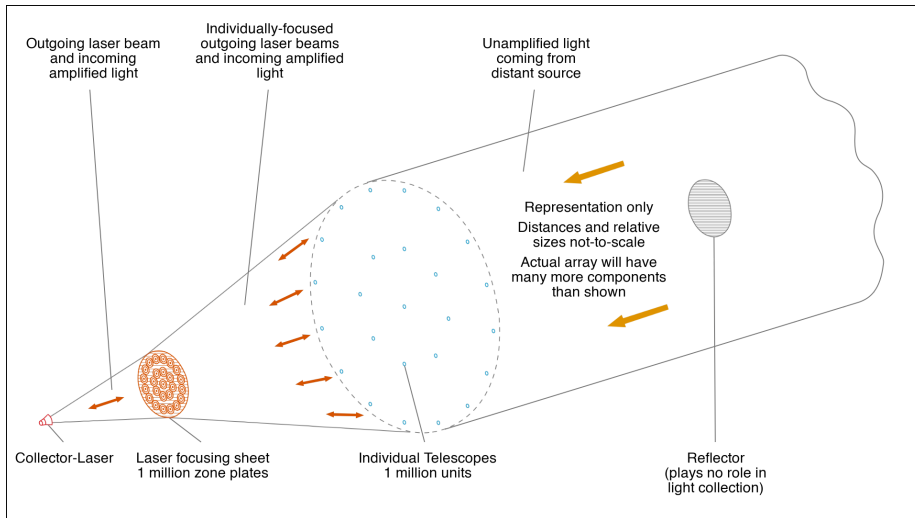


Figure 2: The Planet Seeker Interferometer, in a three-quarters orthographic projection, showing how incoming light is collected and amplified.

‘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 perform 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 μ as
Biomarkers	CO ₂ , O ₃ , H ₂ O, CH ₄ , chlorophyll-equivalent, urban lighting
Orbit	Geostationary Earth orbit or Lagrange point
Mission duration	Indefinite
Launch vehicle	Falcon Heavy equivalent or better

2.1 Biosignatures

With an angular resolution of 1.25 μ as (microarcseconds), the Planet Seeker could resolve features as small as continents or large islands, at such resolutions it will not only be possible to detect the signature of photosynthetic pigments like chlorophyll or an extraterrestrial equivalent, or other biologically-produced substances, but to resolve large-scale urbanisation. Below you can see figure 3, which is a blurred image simulating what Earth’s nightside would look like from ten and half light years away, below that, figure 4 is a simulated image of a heavily urbanised exoplanet at the same distance.

As you can see, the resolution of the Planet Seeker, while not high enough to make out smaller features, is more than sufficient to detect even the relatively moderate levels of urbanisation on our planet.

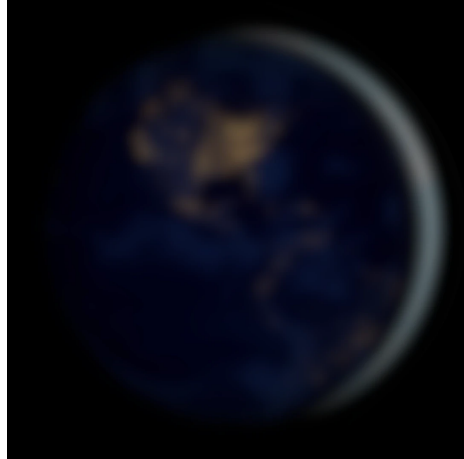


Figure 3: Simulated image of Earth from 10.5 light years away, as would be seen by the Planet Seeker Interferometer.

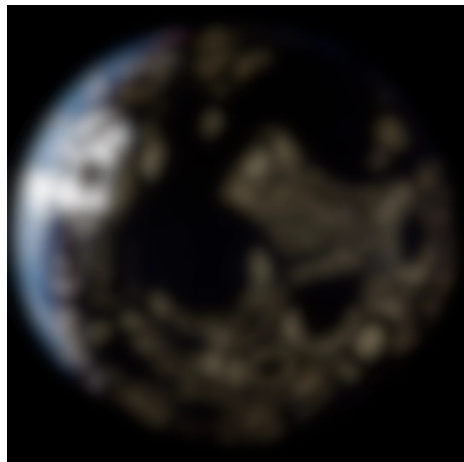


Figure 4: Simulated image of a heavily urbanised exoplanet 10.5 light years distant.

2.2 Wandering Black Holes

Wandering or ‘rouge’ black holes with minimal or non-existent accretion disks could be more readily located, either via direct imaging, utilising the Planet Seeker’s large collection area, or indirectly via observation of gravitational lensing, utilising the telescope’s very high resolution.



Figure 5: Simulated image of a black hole with a relatively modest accretion disc.

2.3 The Nemesis Hypothesis

The Nemesis hypothesis, originally put forward by palaeontologists David Raup and Jack Sepkoski in 1984[4], proposes that Sol, our sun, has a low-mass binary companion orbiting on a 26 million year orbit with a semi-major axis of approximately 1 light year. Raup and Sepkoski noted a 26 million year interval between major extinction events, and suggested that there could be a small red or brown dwarf companion disturbing Oort cloud comets at regular intervals.

After decades of debate, in 2010 and 2013 Adrian Melott and Richard Bambach demonstrated that there is indeed a 26 or 27 million year periodicity to major extinction events[5], i.e. extinctions occur at consistent 26 or 27 million year intervals. An independent study in 2021 by Michael Rampino, Ken Caldeira, and Yuhong Zhuc[6], found that Earth has a 27.5 million year geological cycle, a ‘pulse’ as they termed it, where major volcanic events, and mass extinctions on the land and in the sea, appear to reoccur with an average interval of 27.5 million years. However, Melott and Bambach also noted that a sharp peak in extinction events every 27 million years does not appear to be consistent with the Nemesis hypothesis[7]. As they point out, because of Nemesis’ great distance from the Sun, it is expected to have been perturbed by passing stars, and therefore should not produce a sharp peak in extinctions, but a more gradual one.

Regardless, the Planet Seeker will be able to answer this question definitively, first of all, a Jupiter-sized object (as Nemesis appears likely to be) at 1 light

year is well within the Planet Seeker's imaging capabilities, secondly, with the Planet Seeker's large collection area, and despite the great distance of *Nemesis*, the very faint light from the brown dwarf's own thermal emission should be sufficient for imaging, even in the case of an extremely old ($>10,000$ myo) and cold dwarf.



Figure 6: Simulated image of a Brown Dwarf, note that *Nemesis*, if it exists, will be completely black to unaided human vision, visible neither by its own weak thermal emissions nor the Sun's distant light.

2.4 Trans-Neptunian Objects

With its high resolution and large collecting area, the Planet Seeker will be able to discover and image in detail many trans-Neptunian objects, from Eris, to Sedna, even a hypothetical planet that may exist at around 100 AU[8]. Who knows, perhaps we'll find an Earth or Mars mass planet out there[9], an interesting thought.

2.5 Planet 9

First proposed in 2014[10], Planet 9 is a hypothetical super-Earth orbiting the Sun, with an estimated mass of 5 to 10 times that of Earth[11][12], and an estimated semi-major axis of 400 to 800 AU[13]. We have analysed the possibility

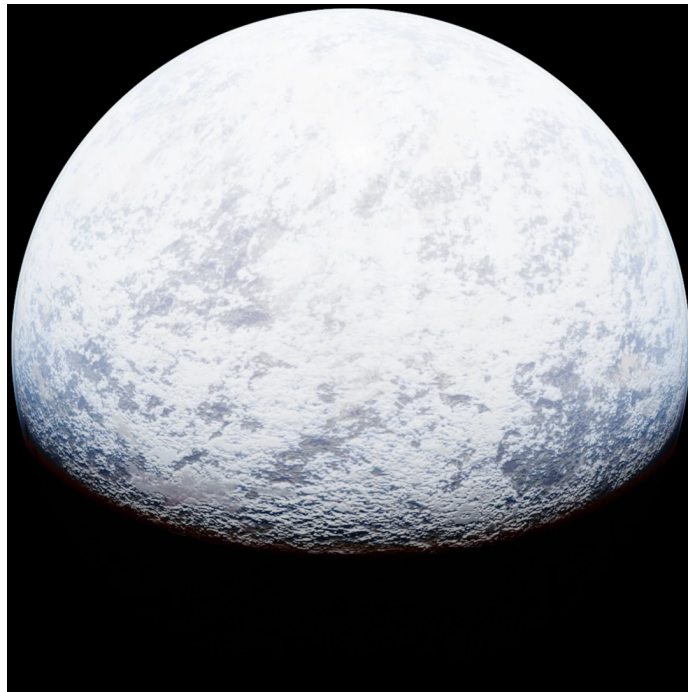


Figure 7: Simulated image of an Earth-sized comet.

of imaging Planet 9, assuming a radius similar to that of Uranus, and with a range of albedos, and have found that the Planet Seeker is able to image the planet quite easily in *all* scenarios assessed.

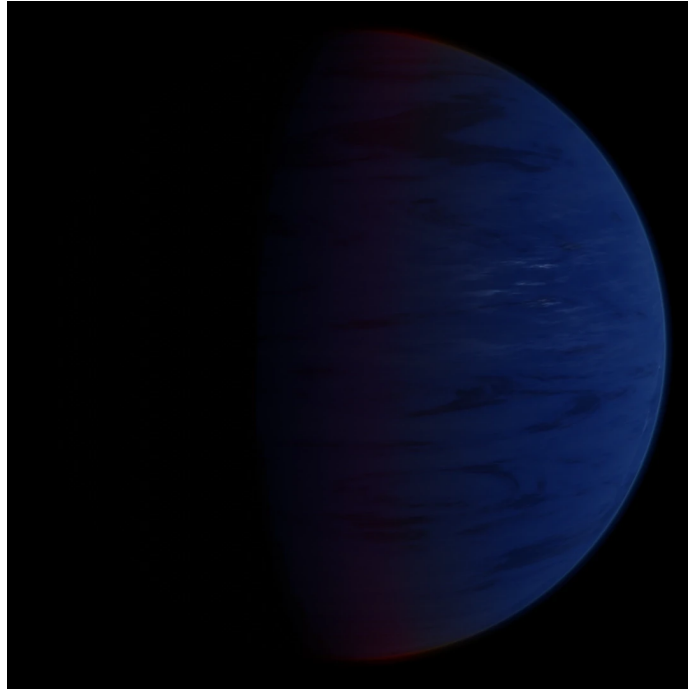


Figure 8: Simulated image of the proposed ‘Planet 9’.

2.6 Follow Up Projects and Future Plans

As stated previously, the Planet Seeker is intended as the first step on a long road. With the eventual aim being to establish a settlement on a habitable exoplanet before the end of the century, and as soon as possible. To this end, in this section we will briefly list some possibilities for follow up projects and outline our rough future plans.

To begin with, there is much overlap between the Planet Seeker and laser propulsion[3][14][15][16][15][17], as we will discuss shortly in more detail. Post the development and launch of the Planet Seeker Interferometer, or even starting concurrently as an offshoot of research for the telescope, we propose that a project be initiated to continue rapidly development and refinement of laser propulsion, with the aim to develop fast interstellar travel technologies. Though we are of the opinion that ultimately completely different methods of propulsion are required for practical travel into interstellar space and beyond into wider galactic space, research and development of laser propulsion could if nothing

else, act as a platform from which to develop faster and longer range propulsion systems. In fact, there has already been some work involving a kind of atmospheric laser propulsion known as the *Lightcraft*[18][19][20][21][22].

The Lightcraft, and refinements thereof[23][24][25], could be developed concurrently with the Planet Seeker, as an outgrowth of the laser propulsion technology, in order to reduce the cost-per-mass to orbit. This could reduce the launch costs of the Planet Seeker should such be developed in time, or at the very least, reduce space access costs for follow up projects along the line of the previously stated long-term goal of establishing an exoplanet settlement.

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 (perhaps also 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 the out-going phased-locked beam with incoming light, a certain frequency and phase signal is embedded within the now-amplified images, specifically the phase and frequency changes with distance and time. 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 replacing it with several smaller mirrors, scattered around within the area of the former larger mirror. The image remains just as sharp as before, despite the lack of a single continuous mirror, see figures 1 and 2 to get some idea of what this looks like.

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 and metal Fresnel zone plates[26][27], 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][14][15]. By careful design of the lenses, a stable levitation can be achieved, see Figures 9 and 10, as recent work on interstellar beamriders has illustrated[16][15], other research, backed by ESA, successfully demonstrated laser propulsion of a 3 millimetre diameter graphene lightsail in microgravity[17], 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, probably ultraviolet, and possibly far-infrared, 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[16][15][28], (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, (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, and (5) far-infrared permits imaging of very faint objects not detectable otherwise.

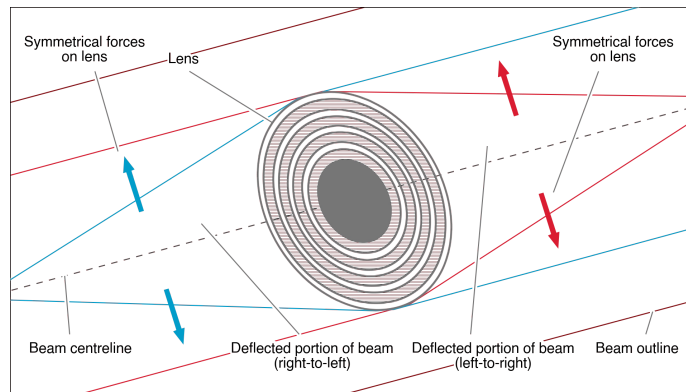


Figure 9: Individual Telescope, centred within opposing beams.

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 sheet using the same technique as used to manufacture the individual telescopes, and suspended via laser light a modest distance away, see Figures 11

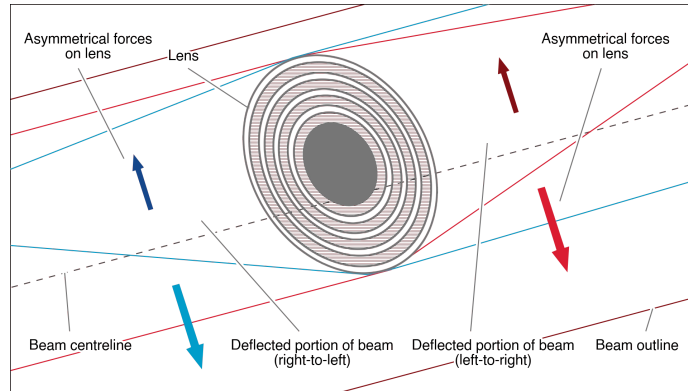


Figure 10: Individual Telescope, offset laterally, the resulting uneven redirection of laser light produces a corrective force, returning the lens to centre.

and 12. 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[29], 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’[26][27], for more information about this type of lens as used to construct a telescope.

Laser According to Labeyrie and the Hypertelescope team, a laser power of 3 milliwatts is required per telescope[3][14], 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[28]. 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[16][15]. Frequency-doubling material in the lenses converts some of the laser light into visible light[30], 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[31]. Later on, additional Collector-Lasers—or a larger focusing sheet and a higher power laser—can be added in order to support additional telescopes.

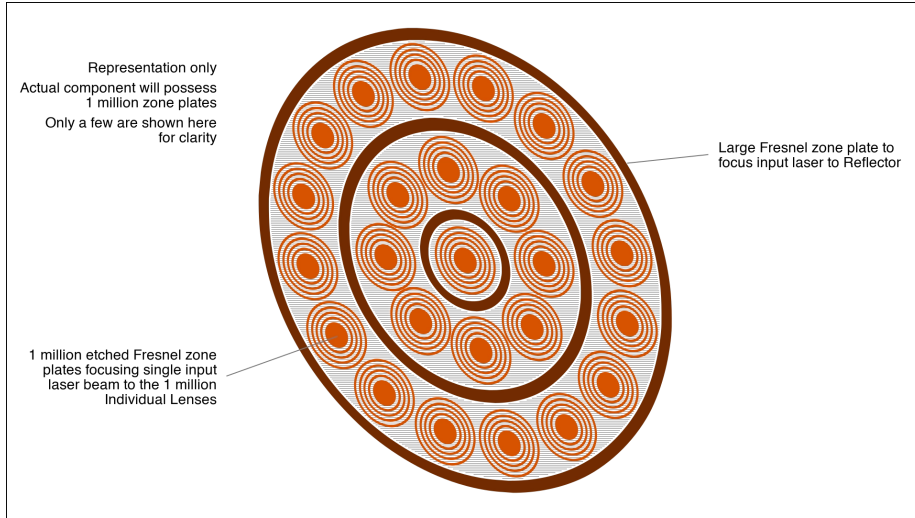


Figure 11: Laser focusing sheet, shown in a three-quarters orthographic projection.

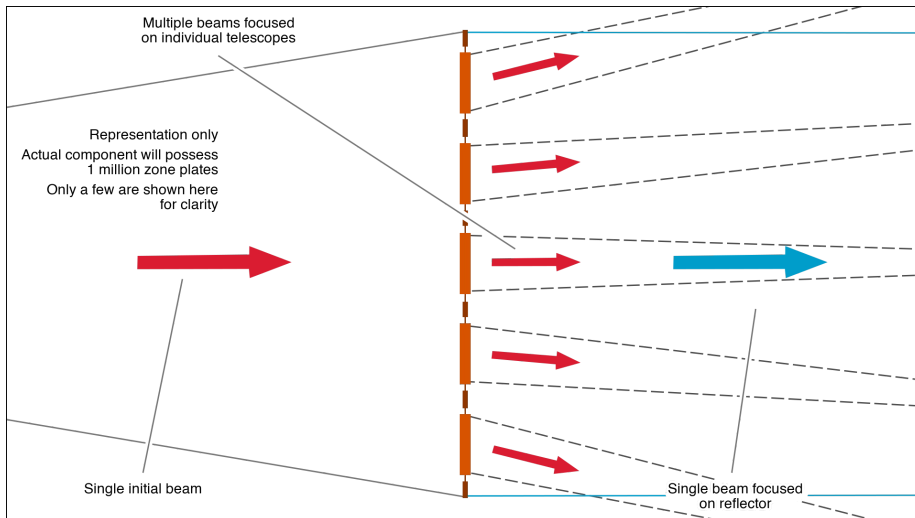


Figure 12: Laser focusing sheet, side view, showing how outgoing laser light is focused separately to each of the Individual Telescopes and the Reflector.

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 13, this requires a convex reflecting mirror to be placed opposite the Collector-Laser[3][14].

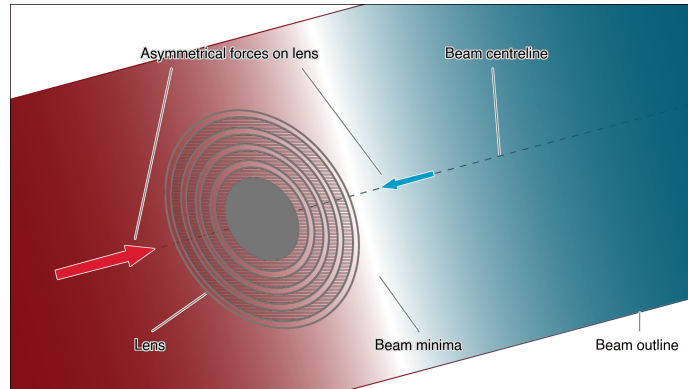


Figure 13: Individual Telescope, offset longitudinally, the telescope/lens is no longer between the beam minima, with the uneven forces returning it to centre

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 possibly deploying the Planet Seeker to a geostationary orbit[14], providing a greater orbit stability, and lower launch costs, compared 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 15. 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[14], 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].

We propose building the ground-based Planet Seeker prototype on Sierra Negra (also, and perhaps more properly, Cerro La Negra), an extinct volcano located in the Mexican state of Puebla, close to the border with Veracruz, specifically, Sierra Negra is located within the Pico de Orizaba National Park. The mountain is the site for two of the world’s premier astronomical instruments, the Large Millimetre Telescope and the High Altitude Water Cherenkov Observatory (HAWC)[32][33]. The latter ended in Mexico largely thanks to the efforts of then-recently graduated postdoc Magdalena González, and also physicist Brenda Dingus[34].

We would like to put a call out here to González, Dingus, and the team who built both telescopes[34], including Alberto Carramiñana, also Arturo Menchaca, Andrés Sandoval, and Arnulfo Zepeda, inviting them to participate and see this telescope get off the drawing board, on the ground, and soon, in space.

HAWC is today a joint collaboration between many US-American and Mexican universities and scientific institutions, including the University of Maryland, the National Autonomous University of Mexico, the National Institute of Astrophysics, Optics and Electronics, Los Alamos National Laboratory, NASA/Goddard Space Flight Center, the University of California, Santa Cruz, Michigan Technological University, Michigan State University, Benemérita Universidad Autónoma de Puebla, the Universidad de Guadalajara, the University of Utah, the University of New Mexico, the University of Wisconsin–Madison and the Georgia Institute of Technology[32].

As stated, the ground-based prototype of the Planet Seeker would have only a minimal footprint (practically no footprint) on the environment. By placing it on Sierra Negra, given the site’s latitude, many astronomical targets in both the

northern and southern skies could be photographed. The remote/semi-remote and mountainous location will minimise light pollution and enable clear imaging of many targets.

As we discuss near the end of the following section, the ground-based prototype would already provide a very high resolution and could potentially detect the presence of comparatively small planets, both in terms of mass and radius, around nearby stars.

The preexisting technical infrastructure and scientific collaboration at Sierra Negra would make the development and operation of the prototype comparatively simple and unproblematic.

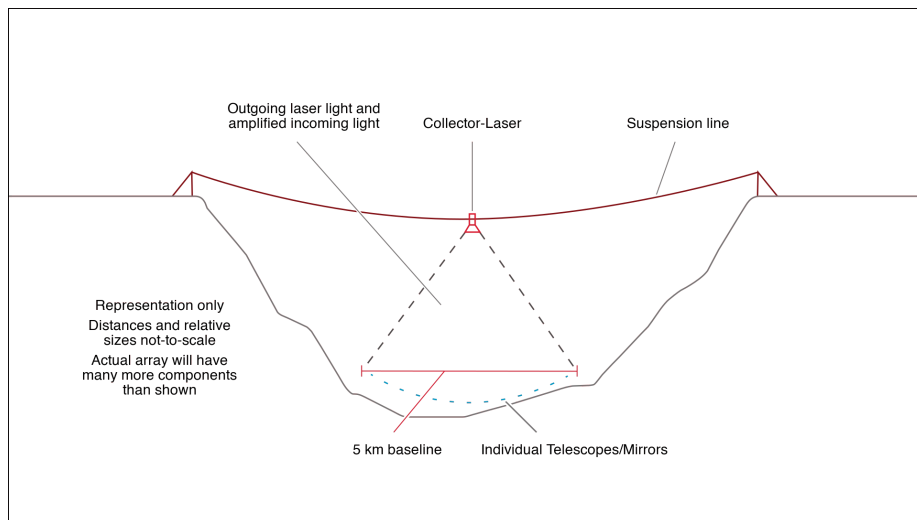


Figure 14: Ground-based prototype of the Planet Seeker Interferometer, shown situated in a hypothetical mountain valley.

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

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

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[35].

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

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

or approximately 1.25×10^{-6} arcseconds ($1.25 \mu\text{as}$). 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

$$C = 2\pi D, \quad (3)$$

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 (9.91×10^{16} m). Solving for C , we find the circumference of our imaginary circle to be equal to 6.227×10^{17} 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

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

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

$$N_\gamma = \frac{L_\epsilon}{L_\gamma}, \quad (5)$$

where L_ϵ is the luminosity of Ran (Epsilon Eridani), given in solar luminosity as $0.34 L_\odot$, as defined by the International Astronomical Union, that is, $1 L_\odot =$

3.827×10^{26} W [36], 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 (3.973×10^{-19} J). Solving for N_γ we find that the approximate number of photons emitted per second by Ran is equal to

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

$$N_\gamma = \frac{0.34 (3.827 \times 10^{26} \text{ W})}{L_\gamma}, \quad (6)$$

$$N_\gamma = \frac{1.301 \times 10^{26} \text{ J/s}}{3.973 \times 10^{-19} \text{ J/photon}} = 3.275 \times 10^{44} \text{ photons/s.}$$

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[37], given by the equation

$$\pi r^2 = 1.2752 \times 10^8 \text{ km}^2, \quad (7)$$

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

$$4\pi R^2 = 2.812 \times 10^{17} \text{ km}^2, \quad (8)$$

where R is the radius of the orbit, taken as 1 astronomical unit[38], we now find the fraction of the radiant flux emitted by Ran intercepted by this planet, via

$$\frac{1.2752 \times 10^8 \text{ km}^2}{2.812 \times 10^{17} \text{ km}^2} = 4.535 \times 10^{-10}. \quad (9)$$

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

$$A(3.275 \times 10^{44} \text{ photons/s} \times 4.535 \times 10^{-10}) = 4.455 \times 10^{34} \text{ photons/s}, \quad (10)$$

where A is the Bond albedo of the hypothetical planet, which we assume here to be an Earthlike 0.3[39].

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

$$(\pi r^2) 1000000,$$

$$\left(\pi (15 \text{ mm})^2\right) 1000000, \quad (11)$$

$$706.9 \text{ mm}^2 \times 1000000 = 7.069 \times 10^8 \text{ mm}^2,$$

where r is the radius of each telescope unit.

As we can see, the total collection area of the array is 706.9 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

$$4\pi R^2 = 1.234 \times 10^{35} \text{ m}^2, \quad (12)$$

where R is the distance from the planet to collector, specifically $9.91 \times 10^{16} \text{ m}$ (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,

$$\frac{706.9 \text{ m}^2}{1.234 \times 10^{35} \text{ m}^2} = 5.7285 \times 10^{-33}, \quad (13)$$

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

$$4.455 \times 10^{34} \text{ photons/s} \times 5.7285 \times 10^{-33} = 255.2 \text{ photons/s}, \quad (14)$$

this is roughly 2 to 7 times the minimal photon flux detectable by the human eye[40], 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,

$$(255.2 \text{ photons/s}) 60 = 15312 \text{ photons/min}. \quad (15)$$

Alternatively, we can take the collection area of the James Webb Telescope, that is, 25.4 square metres[41], 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,

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

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

$$(9.17 \text{ photons/s}) 60 = 550.2 \text{ photons/min}, \quad (17)$$

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

$$\frac{2.54 \times 10^7 \text{ mm}^2}{706.9 \text{ mm}^2} = 35930 \text{ units.} \quad (18)$$

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.

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[42],

$$\begin{aligned} R_T &= \frac{0.305 D \lambda}{R_L}, \\ R_T &= \frac{0.305 (1 \times 10^6 \text{ m}) (1 \times 10^{-6} \text{ m})}{6 \text{ m}}, \\ R_T &= \frac{0.305 \text{ m}^2}{6 \text{ m}}, \\ R_T &= 0.0508 \text{ m}, \end{aligned} \quad (19)$$

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 (1×10^{-6} m), 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 and metal film, several tens of metres 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 as shown in Figure 11.

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, otherwise we can make use of the Reflector to hold the sheet in position, see Figure 11, also reference Figures 9 10 13 to get an idea of how the sheet can be held in place via laser light. We might also simply tether the focusing sheet to the Collector-Laser.

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%, an intentionally low estimate, as efficiencies of 85% have been reported[30], 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[42],

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

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][14], 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[15], 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 14.

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 (1×10^3 m), giving us the following result:

$$\theta = 6.1 \times 10^{-10} \text{ radians.} \quad (21)$$

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

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

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 confident estimation of the surface conditions and habitability of the planet.

Suppose it will be practical to build a larger ground-based array, or perhaps a small space-based array, with a baseline of, let us say 5 kilometres, in which case

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

then the size of the smallest resolvable feature is around 95% of Earth's equatorial diameter[37], 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.

4.4 Testing the Nemesis hypothesis

An interesting question that is worth pursuing and finally putting to rest one way or another, is whether *Nemesis* exists. Therefore, we must assess whether the Planet Seeker could image this theorised brown dwarf twin of the Sun. In this section we assess the feasibility of directly imaging *Nemesis*, which will be incredibly faint if it does indeed exist.

Where L_\odot is the Solar luminosity, defined as $1L_\odot = 3.827 \times 10^{26} \text{ W}$ [36], and where L_γ is the energy of an average photon of light emitted by Sol, approximated here as the energy of a 500 nm photon ($3.973 \times 10^{-19} \text{ J}$). Solving for N_γ we find that the approximate number of photons emitted per second by Sol is equal to

$$\begin{aligned}
N_\gamma &= \frac{L_\odot}{L_\gamma}, \\
N_\gamma &= \frac{3.827 \times 10^{26} \text{ W}}{L_\gamma}, \\
N_\gamma &= \frac{3.827 \times 10^{26} \text{ J/s}}{3.973 \times 10^{-19} \text{ J/}_{\text{photon}}} = 9.633 \times 10^{44} \text{ photons/s}.
\end{aligned} \tag{24}$$

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

$$4\pi R^2 = 2.541 \times 10^{27} \text{ km}^2, \tag{25}$$

where R is the radius of the orbit, which for Nemesis is equal to 95,000 AU ($1.422 \times 10^{13} \text{ km}$), from here we can find the fraction of the Sun's radiant flux intercepted by Nemesis, where A_N is the surface area of Nemesis, which we will approximate with Jupiter's surface area[43], where A_O is the surface area of a sphere enclosing Nemesis' orbit, and where ϕ_f is the fraction of Sol's radiant flux intercepted,

$$\begin{aligned}
\frac{A_N}{A_O} &= \phi_f, \\
\frac{6.142 \times 10^{10} \text{ km}^2}{2.541 \times 10^{27} \text{ km}^2} &= 2.417 \times 10^{-17}.
\end{aligned} \tag{26}$$

Next, to find the fraction of photons that will reach and reflect off of Nemesis, we take the total number of photons emitted, as given by (24) and multiply it by the fraction given by (26), and then multiply this value by the Bond albedo of Nemesis, giving us

$$\begin{aligned}
A(9.633 \times 10^{44} \text{ photons/s} \times 2.417 \times 10^{-17}) &= \phi_\gamma, \\
0.1(2.328 \times 10^{28} \text{ photons/s}) &= 2.328 \times 10^{27} \text{ photons/s}, \\
0.3(2.328 \times 10^{28} \text{ photons/s}) &= 6.984 \times 10^{27} \text{ photons/s}, \\
0.5(2.328 \times 10^{28} \text{ photons/s}) &= 1.164 \times 10^{28} \text{ photons/s},
\end{aligned} \tag{27}$$

where ϕ_γ is the intercepted radiant flux as photons per second, and where A is the Bond albedo of the hypothetical brown dwarf, as the albedo is unknown, we tried values of 0.1, 0.3, and 0.5.

If we multiply these values by the fraction of the radiant flux intercepted by the telescope, from 13, so

$$\begin{aligned}
5.7285 \times 10^{-33} \times 2.328 \times 10^{27} \text{ photons/s} &= 1.3335948 \times 10^{-5} \text{ photons/s}, \\
5.7285 \times 10^{-33} \times 6.984 \times 10^{27} \text{ photons/s} &= 4.0007844 \times 10^{-5} \text{ photons/s}, \\
5.7285 \times 10^{-33} \times 1.164 \times 10^{28} \text{ photons/s} &= 6.667974 \times 10^{-5} \text{ photons/s}.
\end{aligned} \tag{28}$$

Even with an arguably highly-unrealistic albedo of 0.5, *Nemesis* would only reflect 1 photon once per *four days*,

$$\frac{(1/6.667974 \times 10^{-5} \text{ photons/s})}{3600 \text{ s}} = 4.1658 \text{ d.} \quad (29)$$

This is probably not a feasible brightness to image anything with. Instead it appears we will be forced to either *get lucky* and catch an occultation of a background star by *Nemesis*, something which could take decades, centuries, even millennia, and which in the meantime does nothing to prove or disprove the existence of *Nemesis*. Alternatively, we might look for the faint thermal emissions of *Nemesis itself*, it is after all, hypothesised to be a brown dwarf **star**.

The question we arrive at next is this: what would *Nemesis*' luminosity be? What would be *Nemesis*' peak emission frequency? And how bright would it be to the Planet Seeker? This assumes that we modify the Planet Seeker to be capable of focusing and detecting whatever the *Nemesis*' peak frequency might be. To answer the first question we can turn to Barnes and Heller's work [44], where they have derived luminosity and temperature plots from Burrows and Baraffe[45]. Initially, we will assume *Nemesis* to be roughly the same age as the Sun, from this we find that a 4,500 million year-old brown dwarf with a mass of 13 Jupiter masses, roughly the lower end for brown dwarves (see Spiegel et al[46]), to have luminosity of roughly $10^{-5} L_{\odot}$, or $3.827 \times 10^{21} \text{ W}$, and an effective surface temperature of around 300 K. Using an equation from[47]

$$\frac{(0.29 \text{ cmK})}{T_N}, \quad (30)$$

where T_N is the temperature of *Nemesis*, which we assume for now is equal to 300 Kelvin, which gives the following as the peak wavelength for a 300 Kelvin blackbody

$$\frac{(0.29 \text{ cmK})}{300 \text{ K}} = 9.667 \times 10^{-4} \text{ cm} = 9.667 \mu\text{m.} \quad (31)$$

Using equation 5, and starting from an assumed surface temperature of 300 K (in turn derived from an assumed age of 4,500 myo), a luminosity L_N of $10^{-5} L_{\odot}$ (ditto), and a energy-per-photon L_{γ} of $2.055 \times 10^{-20} \text{ J}$, solving for N_{γ} we can find the approximate number of photons emitted per second by *Nemesis* to be

$$\begin{aligned} N_{\gamma} &= \frac{L_N}{L_{\gamma}}, \\ N_{\gamma} &= \frac{3.827 \times 10^{21} \text{ W}}{L_{\gamma}}, \\ N_{\gamma} &= \frac{3.827 \times 10^{21} \text{ J/s}}{2.055 \times 10^{-20} \text{ J/}_{\text{photon}}} = 1.863 \times 10^{41} \text{ photons/s.} \end{aligned} \quad (32)$$

Not half bad for something that isn't even as hot as a hot day in Death Valley... Alternatively we can assume a temperature of something around 100 Kelvin, and a luminosity of something around $10^{-7} L_{\odot}$, or 3.827×10^{19} W, which would correspond to a minimum-mass (~13 Jupiter masses) brown dwarf over 10 thousand million years old, which still gives us

$$\begin{aligned}
 N_{\gamma} &= \frac{L_N}{L_{\gamma}}, \\
 N_{\gamma} &= \frac{3.827 \times 10^{19} \text{ W}}{L_{\gamma}}, \tag{33} \\
 N_{\gamma} &= \frac{3.827 \times 10^{19} \text{ J/s}}{6.853 \times 10^{-21} \text{ J/}_{\text{photon}}} = 5.5844 \times 10^{39} \text{ photons/s}.
 \end{aligned}$$

We can take both of these values and see if the Planet Seeker could actually spot Nemesis, provided the telescope can be adapted to work for far-infrared. If we divide the total collection area of the Planet Seeker, as given by 11 and divide it by the surface area of an imaginary sphere with a radius equal to between Nemesis and the Planet Seeker as given by 25, so

$$\frac{706.9 \text{ m}^2}{2541 \times 10^{27} \text{ m}^2} = 2.782 \times 10^{-28}. \tag{34}$$

Multiplying this by the number of photons emitted by Nemesis, as given by 32 and 33 gives us

$$(1.863 \times 10^{41} \text{ photons/s}) \times (2.782 \times 10^{-28}) = 5.183 \times 10^{13} \text{ photons/s},$$

and,

$$(5.5844 \times 10^{39} \text{ photons/s}) \times (2.782 \times 10^{-28}) = 1.554 \times 10^{12} \text{ photons/s}.$$

Even with a much dimmer 100 Kelvin brown dwarf, the Planet Seeker would receive over one and half million-million photons per second! Even if we assume a much, much lower luminosity, say 1×10^{30} photons/s, the Planet Seeker with it's roughly 700 square metres of collection area, would still capture over 270 photons per second. The next and final question, is whether or not the Planet Seeker could **resolve** Nemesis. To start with we will assume that the lenses can be made to diffract wavelengths down to 9.5 micrometres, putting the wavelength and distance to Nemesis into 1, 3, and 4...

$$\begin{aligned}
 1.22 \left(\frac{9.667 \times 10^{-6} \text{ m}}{1 \times 10^5 \text{ m}} \right) &= 1.179374 \times 10^{-10} \text{ r}, \\
 2\pi (1422 \times 10^{13}) &= 8.9347 \times 10^{16} \text{ m}, \\
 R_m &= C \left(\frac{\theta}{2\pi} \right), \\
 8.9347 \times 10^{16} \text{ m} \left(\frac{1.179374 \times 10^{-10} \text{ r}}{2\pi} \right) &= 1.67707 \times 10^6 \text{ m},
 \end{aligned}$$

we find that the smallest resolvable feature is 1677.1 km, which is more than sufficient to spot a brown dwarf. As the individual telescopes of the Planet Seeker are *Fresnel zone plates* it would seem that an extremely broad spectrum could be managed easily, if needed, multiple materials with varying opacities to different wavelengths could be used, making each telescope a multi-lens[48][49][50][51][26][27].

4.5 Imaging transneptunian objects

The next major question is whether the Planet Seeker can in fact image transneptunian planets, such as the theoretical *Planet 9*. To start with we will investigate if Planet 9 can be imaged, then we will investigate if our telescope can image a hypothetical planet or comet of roughly Earth-mass (and presumably very roughly Earth-sized) in the Kuiper belt[8][9].

We will start by approximating Planet 9's surface area as the area of a disc with a radius roughly equal to the equatorial radius of Uranus[52]:

$$\pi (2.5556 \times 10^7 \text{ km})^2 = 2.052 \times 10^{15} \text{ km}^2. \quad (35)$$

Now we look at the hypothetical Earth-mass comet or planet[8][9], for convenience we will call it 'Shiva', after the Hindu god of creation and destruction. Assuming a density roughly equal to Earth's we can therefore assume a size and approximate surface area roughly equal to Earth's as well, which we already found by 7 (again, approximated as the area of a disc with a radius equal to Earth's equatorial radius), therefore: $1.2752 \times 10^8 \text{ km}^2$. Continuing on. . .

The surface area of an imaginary sphere with a radius equal to *Planet 9's* likely semi-major axis of 460 AU ($6.882 \times 10^{10} \text{ km}$)[10][11][12][13] is given by

$$4\pi (6.882 \times 10^{10} \text{ km})^2 = 5.952 \times 10^{22} \text{ km}^2, \quad (36)$$

and the surface area of an imaginary sphere with a radius equal to '*Shiva's*' possible semi-major axis of 100 AU ($1.496 \times 10^{10} \text{ km}$)[8][9] is given by

$$4\pi (1.496 \times 10^{10} \text{ km})^2 = 2.812 \times 10^{21} \text{ km}^2. \quad (37)$$

Dividing Planet 9's assumed surface area 35 by 36, and 'Shiva's' assumed surface area 7 by 37 gives us the following fractions

$$\frac{2.052 \times 10^{15} \text{ km}^2}{5.952 \times 10^{22} \text{ km}^2} = 3.448 \times 10^{-8}, \quad (38)$$

and,

$$\frac{1.2752 \times 10^8 \text{ km}^2}{2.812 \times 10^{21} \text{ km}^2} = 4.535 \times 10^{-14}. \quad (39)$$

If we now take the photons per second emitted by the Sun, given by 24 and multiply it by these fractions and the estimated albedos of Planet 9 and 'Shiva', respectively: ~ 0.3 [53], and 0.03 to 0.2[54] (assuming 'Shiva' is a typical

transneptunian object dark enough to have thus far evaded detection), respectively,

$$(9.633 \times 10^{44} \text{ photons/s}) (3.448 \times 10^{-8}) 0.3 = 9.964 \times 10^{36} \text{ photons/s}, \quad (40)$$

$$(9.633 \times 10^{44} \text{ photons/s}) (4.535 \times 10^{-14}) 0.03 = 1.311 \times 10^{30} \text{ photons/s}, \quad (41)$$

and,

$$(9.633 \times 10^{44} \text{ photons/s}) (4.535 \times 10^{-14}) 0.2 = 8.737 \times 10^{30} \text{ photons/s}. \quad (42)$$

Finally, we can see how much of the reflected photons would be intercepted by the Planet Seeker,

$$\begin{aligned} \left(\frac{A_T}{A_0}\right) E_{r0} &= 1.183 \times 10^{14} \text{ photons/s}, \\ \left(\frac{A_T}{A_1}\right) E_{r1} &= 3.296 \times 10^8 \text{ photons/s}, \\ \left(\frac{A_T}{A_1}\right) E_{r2} &= 2.196 \times 10^9 \text{ photons/s}, \end{aligned} \quad (43)$$

where A_T is the collection array of the telescope, given by 11, A_0 and A_1 are the areas of spheres encompassing the orbits of Planet 9 and ‘Shiva’, given by 36 and 37 respectively, E_{r0} is the radiation reflected (in photons per second) by Planet 9, given by 40, E_{r1} and E_{r2} is the radiation reflected by the theoretical Earth-mass comet which we are conveniently referring to as ‘Shiva’, assuming albedos of 0.03 and 0.2, given by 41 and 42. As we can see, both Planet 9 *and* ‘Shiva’ would be easily bright enough to be seen by the Planet Seeker, and as both are far closer than any exoplanet, the incredibly high resolution of this telescope will mean that both objects would be resolvable.

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, and 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[55] 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[56], as the million lenses are only 30 millimetres across and microns thick, easily fitting within a rather small volume. If the entire assembly, including the collector-laser, reflector, and individual telescopes, have a combined mass under 800 kilogrammes, then according to the information provided on SpaceX’s website with regards to their rideshare program[56], the entire telescope might be lofted into space for under \$5 million USD, though if a more distant orbit is required the cost may go up considerable, but likely less than \$100 million USD, and again, possibly as little as \$70 million USD.

5.2 Construction of the Planet Seeker Interferometer

Estimating the cost of development and construction of the telescope components themselves is more difficult. The individual telescopes are nothing more than micron thick metallic films on suitable plastic or another thin, vacuum-tolerant and transparent substrate, alternatively, the metallic zone plates might be removed from the underlying substrate after manufacture. Either way, mass production at low cost-per-lens is easily achieved[2]. The focusing sheet is manufactured much the same as the individual telescopes, and will likely cost about the same, or perhaps a couple of times the total cost of manufacturing all of the lenses. The most expensive components will probably be the large reflector, and especially the collector-laser. The collector-laser will likely be of similar size and complexity as ESA’s *CHEOPS* telescope, which went from paper to launch in only five years and for a cost of only 150 million Euros, [57]. We would like to note that, using the design and development techniques common in the software industry and employed with success outside of the software development field by SpaceX and Tesla, it looks quite possible to develop and construct the Planet Seeker for much less than CHEOPS.

The primary costs involved in the manufacture of the lenses, and other components, 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.

5.3 Ground based prototype cost

It must be noted that 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. The Hypertelescope Association has already produced images with a small ground-based prototype of their own telescope design, we suggest that our own will be significantly less expensive to develop and manufacture, for reasons stated and outlined in this document.

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. Furthermore, it may soon be in our technological capabilities to seriously begin the construction and development of starships, perhaps not as most expect it, using propulsion systems that are strange and unusual to most, but effective nonetheless. **We do not intend to sit idly by**, it is our intention to do everything possible to see that terrestrial human beings set foot on and establish a settlement on a habitable exoplanet **before the end of the century and in fact as soon as is possible**. This will require drastic improvements in propulsion technologies, energy production technologies, shielding, materials, etc. **But this can all be done and is in now just in our reach**.

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 settle 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

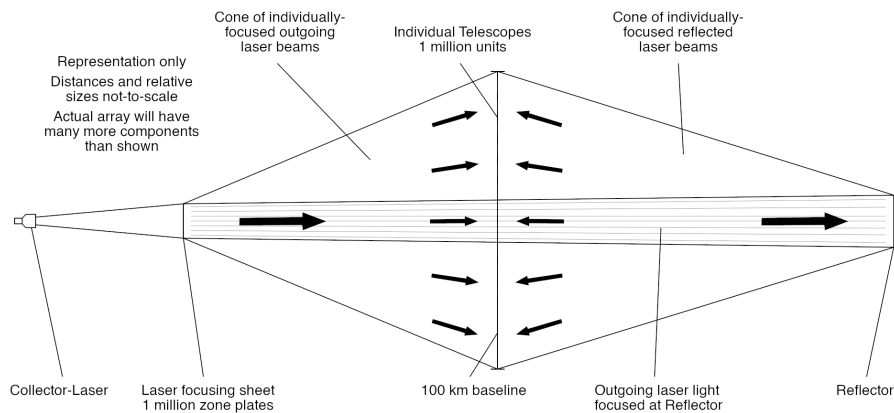


Figure 15: The Planet Seeker Interferometer, side view, showing the position-keeping lasers.

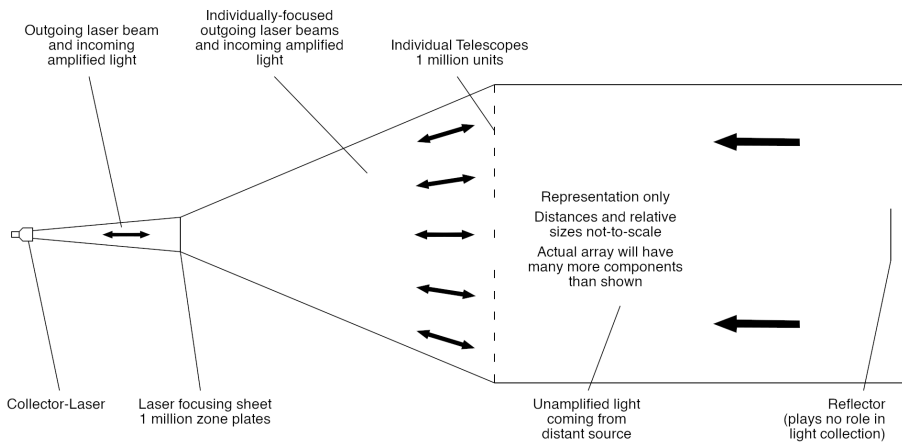


Figure 16: The Planet Seeker Interferometer, side view, showing how incoming light is collected and amplified.