Orbiting Laser Configuration and Sky Coverage: Coherent Reference for Breakthrough Starshot Ground-Based Laser Array

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Abstract. We present the concept of using an orbiting laser as a coherent optical reference to phase a several kilometer diameter array of ground-based lasers designed to accelerate interstellar nano-spacecraft to 20% light-speed by means of laser propulsion. We investigate the geometrical and temporal constraints for the initial case of the target star Proxima b in the Alpha Centauri system using a laser ground site in the southern hemisphere. Based on these constraints, we detail requirements for the mission architecture for an orbiting laser to be used as an optical reference. We then present two orbits which can meet all given requirements and represent a range of engagement times and days between engagements. We also present a range of orbits with periods from 3 days to 4 days and engagement times from 660 to 800 seconds. If desired, the orbit can be matched to the sidereal day, so each orbit period the beacon can align with the ground station and the same target star without maneuvers. A discussion of the trade off between the Earth-based site latitude, time on engagement, and days between engagements is presented.

Keywords: Breakthrough Starshot, interstellar spacecraft, coherent laser array, orbiting guide star, coherent beam combining .

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1 Introduction

The objective of the Breakthrough Starshot project is to send gram-scale spacecraft attached to a meter-class light sail to nearby star systems to explore exo-solar planets. The concept is to use a ground-based array of coherently combined lasers to accelerate the sail to 20% the speed of light in less than 10 minutes.[1,2] The sail and nano-craft would then coast for 22 years to reach the Alpha Centauri star system. The sail/nano-craft would be dispensed from a mothership in a 60 Mm orbit, then captured by the laser beam pointed toward the Alpha Centauri, offset by 77 arcseconds to account for 26 years of proper motion of the target star, four years for Alpha Cen light to be received and 22 for sail flight time.[3] The spatial and temporal intensity profile of the beam and the design of the sail/nano-craft must be complementary so that the sail rides in the beam in a stable

configuration during the acceleration period.[4–7] The current research program aims to bring this concept from a technical readiness level of 1 to a proof-of-concept at 3, acknowledging that is appears not to violate the laws of physics, but many challenges exist.

Phasing 100 millionlasers in a close-packed array 2-3 km in diameter to produce 200 GW of coherent power is an exceptionally difficult challenge.[8,9] Arguably, the most promising phasing architecture solutions involve the use of a laser reference source placed in an orbit that is very near the line of propagation of the laser.[10] This source provides the means to measure and correct fluctuations in the optical path differences between apertures across the array induced by atmospheric turbulence and mechanical disturbances of the optical equipment. The dual lasers of the beacon require tightly controlled spectral separation, long coherence lengths and a known offset to the propulsion beam wavelength. For these reasons the standard approaches to adaptive optics using laser guide stars (Sodium and Rayleigh) are incompatible with this phase control concept. Detailed, comprehensive specifications of the wavelength(s), coherence properties, power, and beam control parameters of the orbiting laser source won't be known until a Preliminary Design is completed, but a requirements envelope for range and angular position in the sky as a function of time during the acceleration phase can be developed. Previous work has been done on hybrid space and ground missions which can be used to align a beaconspaceeraft and a ground station for an astrostationary event.[11–15] These works are adapted here to show that beacon orbits are possible for Starshot and meet preliminary system and mission requirements.

In this paper, we present a range of orbits which can be used to fly a laser reference source in the required orbit which limits the irreparable degradations of anisoplanatism in the wavefront

control system. We describe the observational requirements for the orbit for the Breakthrough Starshot mission in Section 2. These include the initial range determination derived from focal anisoplanatism, the field of interest derived from ordinary anisoplanatism, the observable sky, and a list summarizing all orbit requirements. In Section 3, we discuss a range of orbits which can meet the stated requirements and show the resulting Strehl reduction created by the separation between the beacon and sail. In Section 4 we present a discussion of those results. Finally, in Section 5 we summarize the results of the paper and present future work which should be done on this topic.

2 Observational Requirements

2.1 Initial Range Determination

The orbiting laser needs to be at a range which reduces the effects of focal anisoplanatism.[16–18] As suggested by Noyes and Hart[8] the mean square wavefront error for a target of varying range is given by the scaling law

$$\sigma_{FA}^2 = \left(\frac{D}{d_0}\right)^{\frac{5}{3}} \left(1 - \frac{R_{beacon}}{R_{sail}}\right)^{\frac{5}{3}}, \tag{1}$$

where D is the diameter of the ground based array, d_0 is the characteristic length associated with focal anisoplanatism and depends on the C_n^2 turbulence profile and the range to the reference beacon, R_{beacon}, and R_{sail} is the range to the sail/nano-craft. Using this scaling law and the analytical formula to compute d_0[17] Figure 1 shows the effect on the Strehl ratio due only to focal anisoplanatism for two beacon ranges as the sail moves from its launch point of 60 Mm to the launch end point of 15,000 Mm. These results strongly suggest a minimum range for the orbiting beacon of 160 Mm.

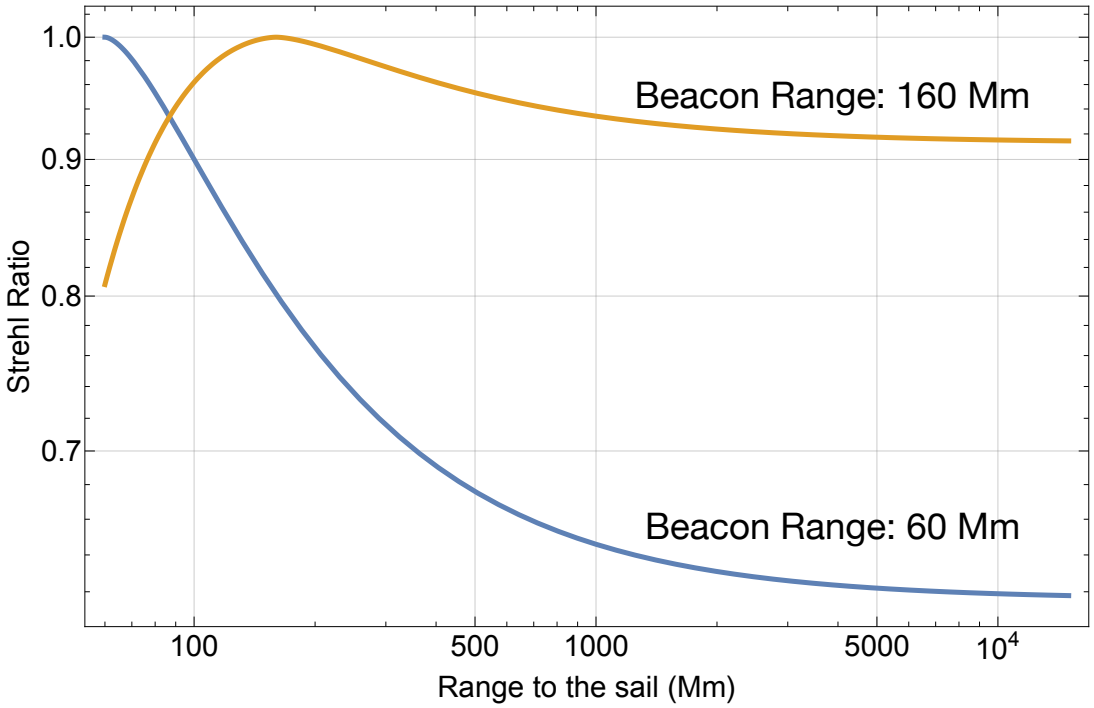

Fig 1 Focal Anisoplanatism Strehl ratio vs range to sail for two orbiting laser reference ranges. Array diameter: 3km, 1060 nm, 48 deg zenith angle, Paranal turbulence profile.[19]

2.2 Field of interest

In addition to focal anisoplanatism, losses due to angular ansioplanatism or "ordinary anisoplanatism" must be determined. The orbiting beacon will be out of the laser beam at an angle θ. A simple but useful scaling law for the anisoplanatic loss in Strehl ratio uses the Maréchal approximation

$$SR_{aniso} = e^{-\sigma^2_{aniso}} \tag{2}$$

where

$$\sigma^2_{aniso} = \left(\frac{\theta}{\theta_0}\right)^{5/3} \tag{3}$$

and where the isoplanatic angle is given by

$$\theta_0 = 0.058\lambda^{6/5}(\sec\psi)^{-8/5}\left[\int_0^\infty C_n^2(h)h^{5/3}dh\right]^{-3/5} \tag{4}$$

The value of the isoplanatic angle θ_0 scaled to a zenith angle of zero degrees and at a wavelength of 500 nm is defined as θ_{0v}. Values of θ_{0v} range from 7 to 20 μrad for atmospheric turbulence profiles characteristic of deserts to island mountain tops, respectively. The Strehl loss due to ordinary anisoplanatism for this range of conditions is plotted in Figure 2.

These scaling laws suggest that the off axis position of the orbiting laser beacon should be less than 10 μrad for sites with excellent seeing and less than 5 μrad for sites with mediocre seeing for a site in the vicinity of 30 deg south latitude.

2.3 Observable Sky

Because the engagements involve an Earth-based site, several requirements are imposed on when engagements can occur. The altitude of the star must be at least 30° above the horizon. Below this altitude, the air mass will be too thick, interfering with the adaptive optics. Additionally, the engagement must be made when the sun is at least 18° below the horizon to ensure target star tracking.

Based on these ground station requirements, a map of the observable sky was created. The map can be seen in Figure 3 below. More details on how this map was generated have been described

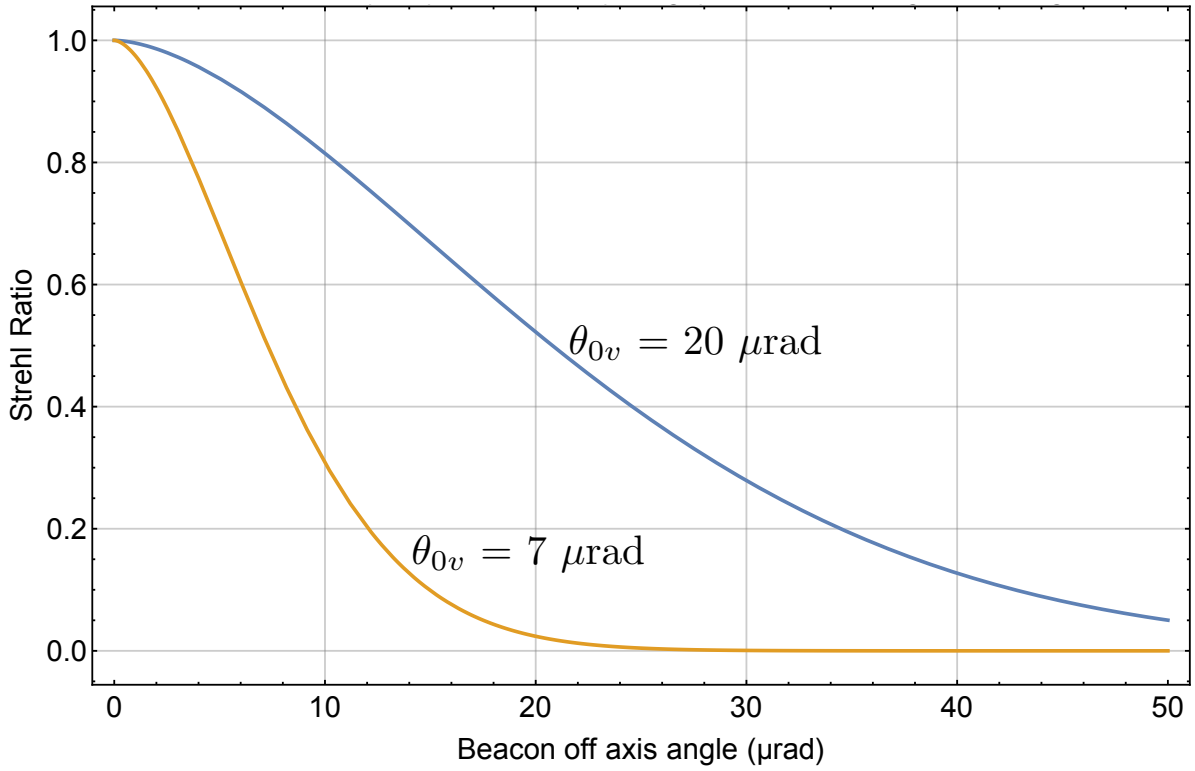

Fig 2 Strehl ratio loss due to ordinary ansioplanatism. Note: $\theta_0 v$ is the value of θ_0 for a wavelength of 500 nm at zenith. The plot shows Strehl ratios computed for θ_0 scaled to a wavelength of 1060 nm at a zenith angle of 48 degrees.

previously.[12]

2.4 Requirements Summary

Table 1 lists the observational requirements for the Starshot engagement mission. These include requirements about the target star, the observation site, the times when observations can be made, and the laser.

The target for the mission is Proxima Centauri, which defines the target declination and right ascension for the orbit. The target proper and apparent motion is also given. The Earth-based site must be in the southern hemisphere between 25 and 65 degrees. The observable sky requirements

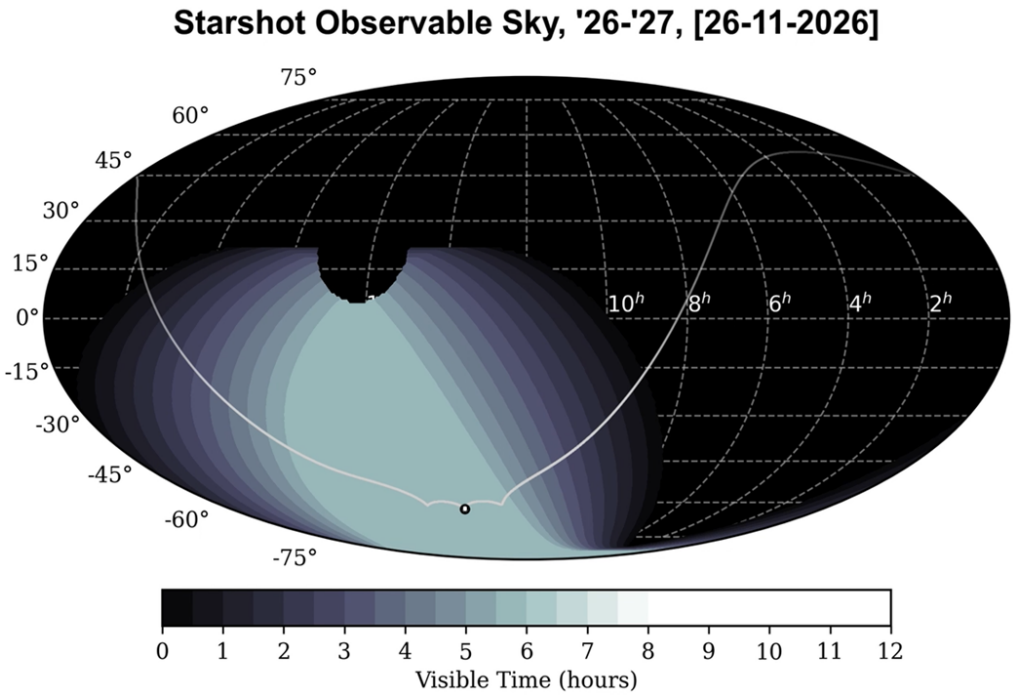

Fig 3 Observable Sky as a function of right ascension and declination, The color bar corresponds to available time due to the observational requirements (not orbit related), the white line marks the beacon trajectory as seen from the ground, the black circle dot marks the beacon location as it reaches the astro stationary observation point.

are also listed.

The Breakthrough Starshot ground laser dominates cost, expected to be of order $10B; however, the individual launches are expected to be relatively inexpensive, allowing frequent launches perhaps with redundant probe instruments to allow for launch or flight instrument casualties or suboptimal launch trajectories. A launch every two to four days is desired. The duration of launch is determined by a cost optimization model[9] currently setting launch at 500 seconds. A longer launch of 800 seconds is given to account for future changes to the optimization model.

Finally, there are several requirements relating to the laser. The orbiting laser's maximum angular distance from the ground laser propagation direction during an engagement is 1 arcsecond for a 7 microradian isoplanatic angle and 2 arcseconds for a 20 microradian isoplanatic angle. In this paper, we assume a field of view of 1 arcsecond for presented results. A field of view of 2

Breakthrough Starshot Orbiting Laser Reference Observational Requirements Date of Information: 15 January 2021		
Item No.	Parameter	Requirement
1	Target: Proxima Centauri	
1.1	Target Coordinates	RA: 14h 29m 42.94853s DEC: -62° 40' 46.1631"
1.2	Target Proper Motion	RA: -37.81.741 mas/yr DEC: 769.465 mas/yr
1.3	Target Apparent Magnitude	10.43-11.1 (V)
2	Earth-Based Site	
2.1	Location	Southern Hemisphere
2.2	Latitude Range	25 deg S to 65 deg S
3	Engagement	
3.1	Direction	$\pm$10 deg of the meridian
3.2	Altitude	Not less than 30 deg above horizon
3.3	Time of Day	Sun more than 18 deg below the horizon
3.4	Time between Engagements	Desired: Not more than 2 days Required: Not more than 4 days
3.5	Time per Engagement	Desired: 800 seconds Required: 500 seconds
3.6	Orbiting Laser's max angular distance from ground laser propagation direction during engagement	1 arcsec for 7 microradian isoplanatic angle (Bad seeing) 2 arcsec for 20 microradian isoplanatic angle (Good seeing)
3.7	Orbiting laser's minimum angular distance from ground laser propagation direction during engagement	0.1 to 1 arcsec depending on contamination from the sail or damage to the beacon
3.8	Min Range to Orbiting Laser	160,000 km
3.9	Minimum Orbit Perigee	1000 km

Table 1 Starshot orbiting laser reference engagement requirements.

arcseconds would increase the engagement time available for an orbit. Next, the orbiting laser's minimum angular distance from the ground laser propagation direction during an engagement should be 0.1 to 1 arcsecond so that the beacon spacecraft does not block the sail and so that the lasers do not directly hit the beacon satellite and damage it. Finally, the minimum range to the orbiting laser is 160 million meters.

3 Results

3.1 Methods

Previous work has been done on designing astrostationary orbits which will allow a spacecraft to inertially align with a ground station.[13,20] Many different orbit families can be used to achieve astrostationary alignment including highly elliptical and libration point orbits. Because the declination of the target, Proxima Centauri, is so high in this case, it would be very difficult to achieve a stable orbit around a libration point that would inertially align with the target, so a highly elliptical orbit was selected.

The development of a highly elliptical orbit to meet given astrostationary requirements has previously been described[13] but will also be reviewed here. A highly elliptical orbit allows a spacecraft to inertially align with a ground station near apoapsis. At the time of engagement, the spacecraft must be on the line of sight from the Earth-based site to the target, and its velocity must match or be slightly below the Earth-based site.

Figure 4 shows the three main reference frames used in the design of this orbit. The blue frame is the standard Earth Centered Inertial (ECI) frame, where $\hat{\mathbf{Z}}_{ECI}$ is aligned with the Earth's spin axis and $\hat{\mathbf{X}}_{ECI}$ is aligned with the vernal equinox. The white frame is the Earth Centered Earth Fixed (ECEF) frame where $\hat{\mathbf{Z}}_{\phi} = \hat{\mathbf{Z}}_{ECI}$ and $\hat{\mathbf{Y}}_{\phi}$ is aligned with the longitude of the ground station. The dotted white line in the figure shows the vector from the center of the Earth to the ground station. Then, the yellow dotted line shows the vector from the ground station to the target.

Orbits have six degrees of freedom. Two position degrees of freedom are defined by the spacecraft being on the line of sight from the ground station to the target at the time of engagement. Next, the distance at engagement (R) can be defined by the user. This is the distance along the line

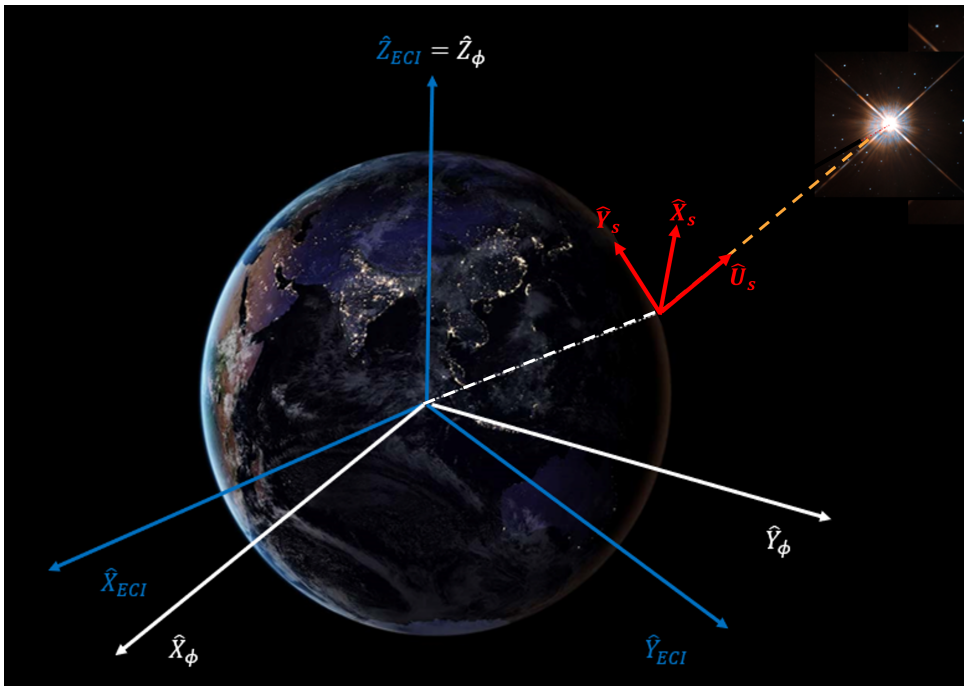

Fig 4 The key reference frames used in the development of astrostationary orbits. These include the ECI frame (blue), the ECEF frame (white), and the Isoplanatic frame (red).

of sight at engagement and constrains the third position degree of freedom, and it can be freely defined within the range of distances given by the requirements. Larger separations will give longer engagement times, but also a longer time between engagements due to a longer orbit period. At this point, the position is fully defined and the following equation can be written

$$\mathbf{r}_{ECI}^{sc} = \mathbf{r}_{ECI}^{gs} + d_{LOS}\hat{\mathbf{U}}_{\mathbf{s}} \tag{5}$$

Note that here, the superscript sc refers to the beacon spacecraft and the superscript gs refers to the ground station. Similarly, two velocity degrees of freedom are defined by the fact that the velocity of the beacon spacecraft perpendicular to the line of sight must match the velocity of the ground station perpendicular to the line of sight. The third degree of freedom is defined by the user selecting the period of the orbit. For this elliptical orbit, it will be useful to choose an orbit period

commensurable to the sidereal day and define the semi-major axis using[21]

$$a = \frac{\mu n^2 T_{sid}^2}{(4\pi^2)^{\frac{1}{3}}} \tag{6}$$

Here, μ is the gravitational constant times the Earth's mass, n is the number of days in the period and T_{sid} is the length of the sidereal day. Having an orbit period commensurable to the sidereal day will allow for repeat observations every n days. The orbit period should be carefully selected by the user, because choosing an orbit period which is too short can result in an orbit which passes very close to Earth and breaks the minimum perigee requirement.

With these requirements, there is still one remaining binary degree of freedom. Since engagement does not occur exactly at apogee, there are two locations on the orbit equidistant from apogee when the engagement could occur. These two locations actually correspond to two different orbits which are the same size and shape but are angled differently corresponding to the different time in the orbit when the beacon must align with the target star. Therefore, the user must determine whether the engagement will take place before apogee (an input of 1) or afterwards (an input of -1). For this paper, all orbits shown have a positive velocity with an input of 1.

Once the design is fully constrained, the orbit position and velocity can be calculated. The Vis-Viva equation is used to relate position ($\mathbf{r}_{ECI}^{sc}$), the semi-major axis (a), and velocity ($\mathbf{v}_{ECI}^{sc}$)

$$\|\mathbf{v}_{ECI}^{sc}\| = \sqrt{2\mu\left(\frac{1}{\|\mathbf{r}_{ECI}^{sc}\|} - \frac{1}{2a}\right)} \tag{7}$$

If the orbit period is commensurable to the sidereal day, the []beacon will align with the same target star every n days without any maneuvers required. As stated earlier, the beacon velocity

perpendicular to the line of sight must be equal to the ground station velocity perpendicular to the line of sight, which can be expressed by

$$\mathbf{v}_{ECI,\perp}^{sc} = \mathbf{v}_{ECI}^{gs} - \left(\mathbf{v}_{ECI}^{gs} \cdot \hat{\mathbf{U}}_{\mathbf{s}}\right) \hat{\mathbf{U}}_{\mathbf{s}} \tag{8}$$

Based on this result, the velocity parallel to the line of sight can be calculated as

$$\mathrm{v}_{ECI,\parallel}^{sc} = \sqrt{\|\mathbf{v}_{ECI}^{sc}\|^2 - \|\mathbf{v}_{ECI,\perp}^{sc}\|^2} \tag{9}$$

The velocity of the beacon taken in the ECI frame is now fully defined. The chosen velocity direction determines the sign of the velocity expressed in the ECI frame parallel to the line of sight. The full definition of the velocity of the beacon is

$$\mathbf{v}_{ECI}^{sc} = \mathbf{v}_{ECI,\perp}^{sc} \pm \left(\mathrm{v}_{ECI,\parallel}^{sc}\right) \hat{\mathbf{U}}_{\mathbf{s}} \tag{10}$$

With the full definition of the position and velocity, the highly elliptical orbit has been fully defined based on three user inputs: the distance along the line of sight R, the period of the orbit T, and the velocity direction (+/-1). A fourth degree of freedom is introduced in the Breakthrough Starshot mission because the ground station location has not been chosen. The ground station latitude will have an impact on the orbits which are feasible given the orbit requirements.

3.1.1 Increasing Time on Target

The time on target for a highly elliptical orbit can be increased by further tuning the orbit. In the original development of the orbit, the highly elliptical orbit is designed to have a velocity perpendicular to the ground station which exactly matches the ground station. Additionally, the

position is designed to exactly match the target star's position. However, the orbit can be further optimized to significantly increase the time on target. First, if during launch the velocity of the beacon perpendicular to the line of sight is slightly lower than that of the ground ground station, the trajectory in the line of sight will become a loop rather than the peak seen previously. Additionally, if the position of the observation point is moved up within the field of view this can also add time in the field of view. Further detail on this process has previously been described.[13] For the results presented in this section, tuning has been done to increase the available time on target, which can be seen in the looped trajectories which appear in the field of view plots presented.

3.2 Possible Breakthrough Starshot Mission Orbits

Based on the given requirements and the methods described for developing a highly elliptical orbit, a range of orbits can be used as the orbit for the Breakthrough Starshot mission. Orbits can be defined for this project by selecting a ground station latitude, a distance at the time of observation, and a number of days between observations. Orbits with variations in these three parameters will have different engagement times and frequency of engagements, so the desired values should be used to inform the final orbit selection.

In the next section, we present two orbits in the available range. Both orbits meet all orbit requirements, and together they give an idea of the type of orbits which can be used to meet the given requirements.

3.3 Example Mission Orbits

Two highly elliptical orbits were developed. The first has an engagement time of 800 seconds and an engagement opportunity every four days. The orbit assumes a latitude of -37.6deg, R = 199,000

km, and θ = 1 arcsec. Figure 5 shows the orbit in the ECI frame, the orbit path in right ascension and declination, and the orbit trajectory as seen from the from the ground site's field of view.

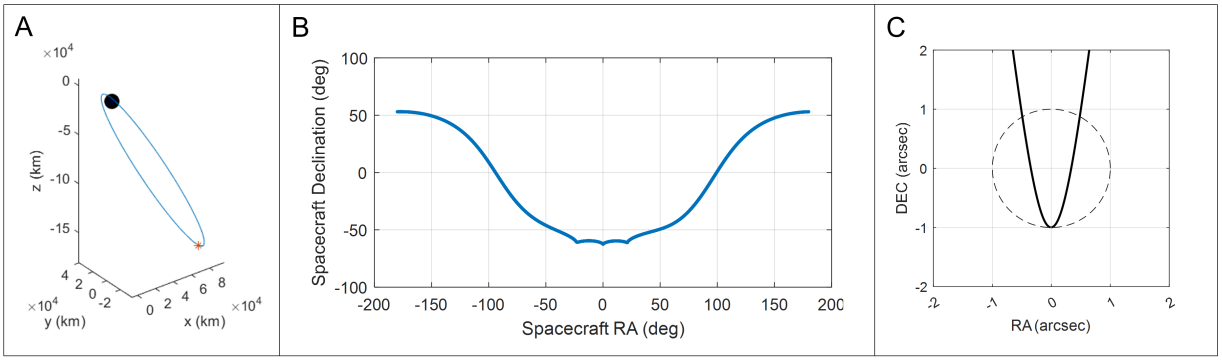

Fig 5 Results for an orbit with a latitude of -37.6deg, R = 199,000 km, θ = 1 arcsec, and a period of 4 days. (A) The orbit in the ECI frame. (B) The beacon spaceraft's right ascension and declination throughout the orbit. (C) The trajectory of the orbit as seen from the telescope in the field of view. The beacon remains within θ = 1 arcsec for 802s.

Tuning has been done on the orbit to increase the engagement time. In order to get the loop seen in Figure 5C, the velocity that the model is matching is 0.5 m/s slower than the ground station. Additionally, the orbit has been shifted 1 arcsecond lower in declination so that the full trajectory is captured within the field of view. As shown, the beacon will remain in the field of view for 802 seconds.

Figure 6 shows the beacon's change in right ascension and declination over one orbit. The shaded regions show the areas where the observable sky requirements are met. As shown, the change in right ascension and declination are both less than 0.1 arcsec/s at one point, and observable sky requirements are met at that point. This is the location of the engagement opportunity for the orbit.

Given the scaling laws for ordinary and focal anisoplanatism and the parameters of a candidate orbit for the laser reference source, it is possible to estimate the losses in Strehl ratio during an engagement caused by (1) the off-axis position of the laser beacon (ordinary anisoplanatism) and

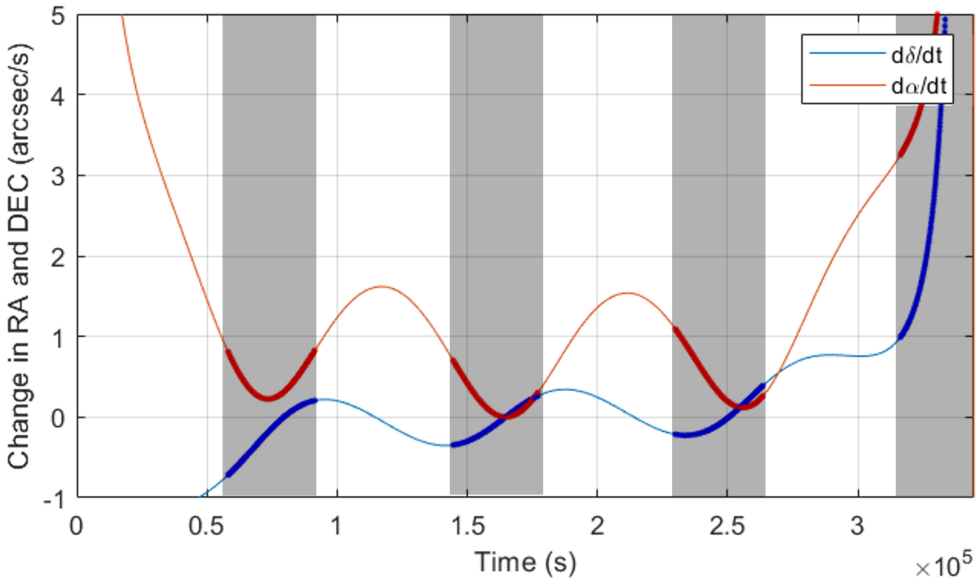

Fig 6 The beacon's change in right ascension and declination over one orbit for an orbit with a latitude of -37.6deg, R = 199,000 km, θ = 1 arcsec, and a period of 4 days. Shaded regions show the areas where observable sky requirements are met.

(2) the effects of focal anisoplanatism as the sail flies out to greater ranges. The resulting Strehl model can be used to update the system model and further refine the estimates of performance.

Figure 7 presents results based on the candidate orbit shown in Figure 5. These results assume excellent seeing given by a Paranal C_n^2 profile but assume a more conservative value of the isoplanatic angle θ_0 of 7 μrad. The results are for a ground site at latitude 37.6 deg south making the zenith angle of the propagating launch beam 25.1 degrees (64.9 degrees elevation) when the engagement occurs as Proxima Centauri crosses the meridian.

The A panel of this figure shows the path of the orbiting laser beacon in relation to the direction of the launch beam as the black line. The angular distance to the orbiting beacon is used as an input to an angular anisoplanatism Strehl ratio computation and the results are plotted as the blue curve in Figure 7A. The blue curve shows how the Strehl ratio varies in time (top axis) measured with respect to the apogee of the beacon orbit. A launch window is defined as when the orbiting laser beacon is less than one arcsec from the launch beam. This criteria establishes an 800 second launch

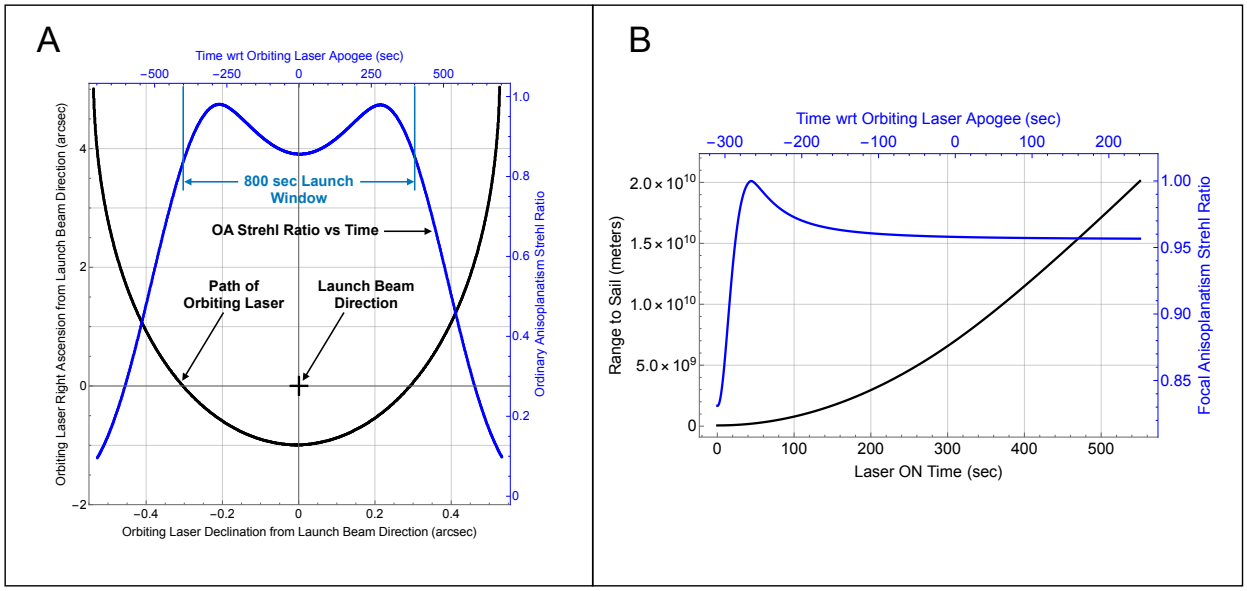

Fig 7 (A) Orbiting laser beacon path and resulting effect on launch beam Strehl ratio caused by being off axis (ordinary anisoplanatism). The black curve shows the position of the orbiting laser beacon during 1400 seconds of flight centered in time on the orbit's apogee (bottom of the curve). The blue line shows the computed Strehl ratio at each position along the orbital path as a function of time with respect to apogee. The plot show that the Strehl ratio remains above 0.85 for 800 seconds centered on the time of apogee of the orbiting laser beacon. (B) The black curve in this figure shows the range to the sail vs time while accelerating in the launch beam for 550 seconds (see text for reference). The blue curve is the computed focal anisoplanatism vs time of the launch engagement. The launch period is slightly offset from the center of the 800 second launch window shown in Figure 7A.

window shown centered on the plot when the angular anisiplanatism Strehl ratio has maximum values. The total time frame of the plot is 1400 seconds.

Figure 7B shows the effects of focal anisoplanatims on Strehl ratio as the sail flies from its starting point at 60 Mm past the orbiting laser beacon at 200 Mm with laser propulsion ending at 550 seconds when the sail is at a range of 20,000 Mm and has a speed of 0.2 c. This range vs time profile was obtained from the Parkin Model.[9] The black curve displays range vs the propulsion laser on time. The blue curve shows the Strehl ratio losses from focal ansioplanatism as a function of the engagement time. The center time of the engagement is just slightly offset from the apogee time of the orbiting laser beacon to take advantage of the peak in the ordinary anisoplanatism profile.

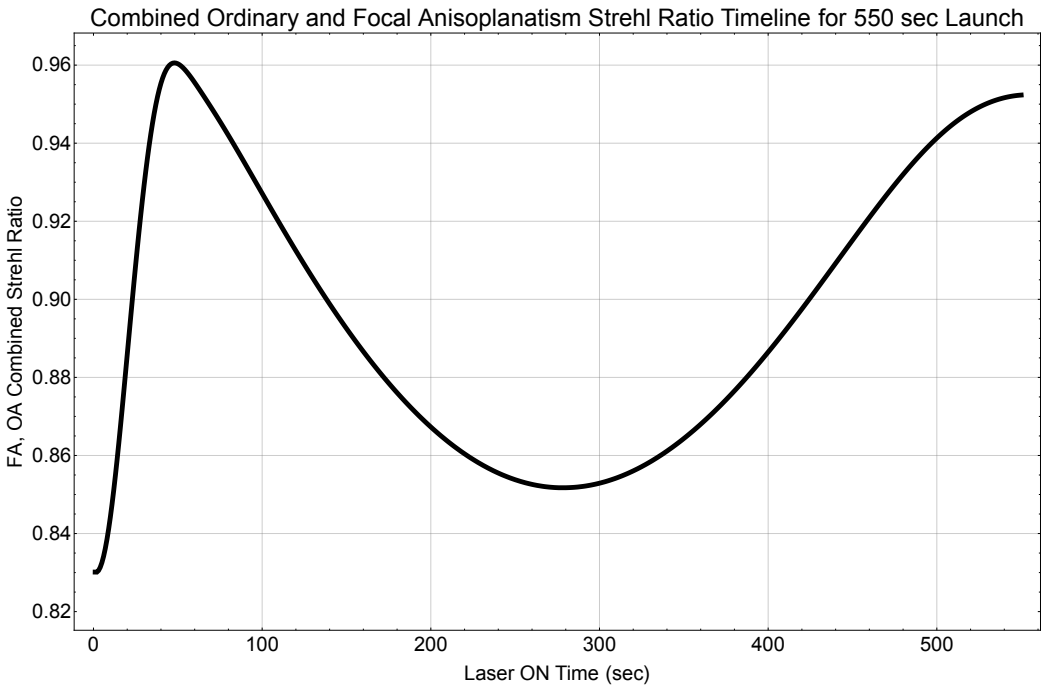

Fig 8 The combined Strehl ratio of the launch beam laser during the 550 second propagation time shown in Figure 7. As a first order estimate the Strehl ratios were combined by root sum squaring the variances. Additional discussion can be found in the text.

Figure 8 is a first order approximation of the combined effects of angular and focal anisoplanatism. This result was reached by computing the root sum square value of the variances given by Equation 2. These effects are not independent but interact by the fact that we are using a cone of light that is offset from the launch beam to correct a beam that is propagating through a different cone that varies with range but is on axis. Additional analyses must be completed to develop a formalism to describe this interaction between angular and focal anisoplanatism. Until that work is done we will use the root sum square of the variances. It is important to note that the curve presented in Figure 8 represents a fundamental ceiling on achievable Strehl ratio created by the use of an orbiting laser beacon for making the array of launch lasers coherent with one another while adjusting for rapid variations in optical path differences caused by phase noise in the equipment and turbulence in the atmosphere. The realization of an orbit for the laser beacon is a significant

step forward in the Breakthrough Starshot project.

This orbit is on the end of the range with a longer time between engagements but also an engagement time of the desired 800 s. On the other hand, a second orbit was designed which would allow for engagements of 700 s every 3.3 days. The orbit period was chosen based on the smallest orbit which would meet perigee requirements, so orbits with less time between engagement opportunities will be very difficult or impossible to achieve. This orbit would have an Earth-based site at a latitude of 25°, R = 174,000 km, and θ = 1 arcsec. Figure 9 shows the orbit in the ECI frame, the orbit path in right ascension and declination, and the orbit trajectory as seen from the telescope in the field of view. The same orbit tuning was done on this orbit as was done on the four-day orbit.

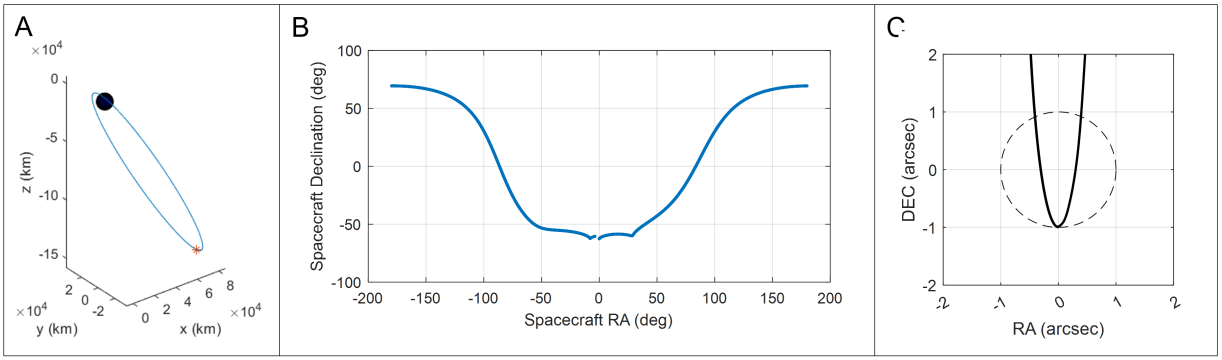

Fig 9 Results for an orbit with a latitude of -25deg, R = 174,000 km, θ = 1 arcsec, and a period of 3.3 days. (A) The orbit in the ECI frame. (B) The beacon's right ascension and declination throughout the orbit. (C) The trajectory of the orbit as seen from the telescope in the field of view. The beacon remains within θ = 1 arcsec for 702s.

Figure 10 shows the beacon's change in right ascension and declination over one orbit. Note that since the orbit is not commensurable with an Earth day, the requirements will not be met for every orbit rotation. After the first engagement the next one will occur 3.3 days later, and so eventually engagements will take place during the day, breaking that requirement.

These are two example orbits which meet the given requirements and represent a range of other possible orbits. On one end is the first orbit with a longer period and also a longer engagement

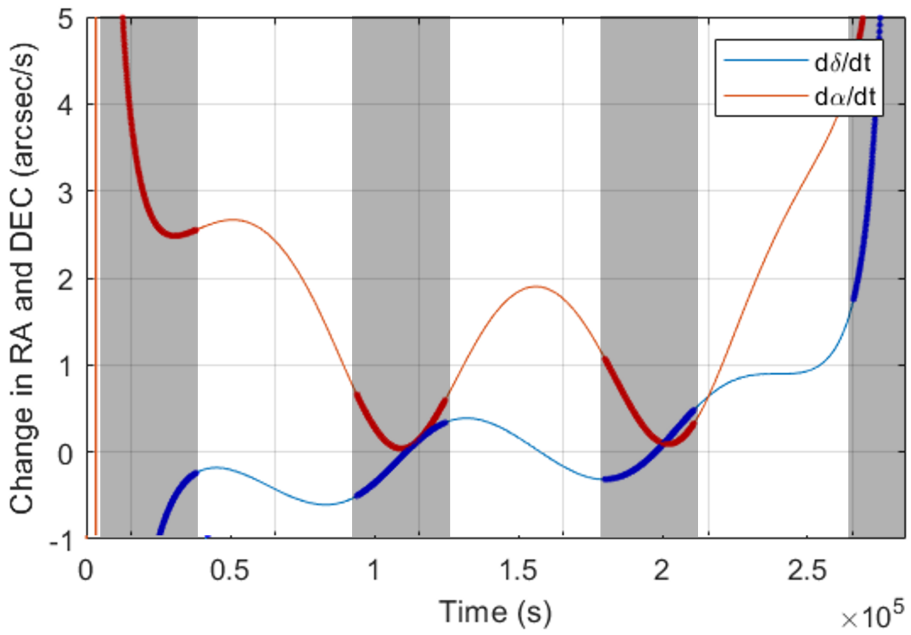

Fig 10 The beacon's change in right ascension and declination over one orbit for an orbit with a latitude of -25deg, R = 174,000 km, θ = 1 arcsec, and a period of 3.3 days. Shaded regions show the areas where observable sky requirements are met.

time, and on the other is the second orbit with a shorter period and a shorter engagement time. These give a sense of what types of orbits are possible for this mission.

The range of available orbits for this mission can be seen in Figure 11. In this figure, data is given for a range of orbit periods. Orbits were designed with periods of 3 to 4 sidereal days. For a given orbit, higher engagement times are seen with ground stations at higher latitudes. However, higher latitudes also have a lower ground station velocity, since the rotational speed of the Earth is constant. Therefore, orbits with lower periods are not possible at higher latitudes. For each orbit period, the maximum engagement time is given as well as the highest latitude that the orbit can be achieved at. Additionally, the distance from the ground station to the beacon at engagement is also given.

In the orbit requirements, the required engagement time is 500 seconds. However, at orbit periods of less than 2.9 days, the beacon is moving too quickly to have the velocity match that

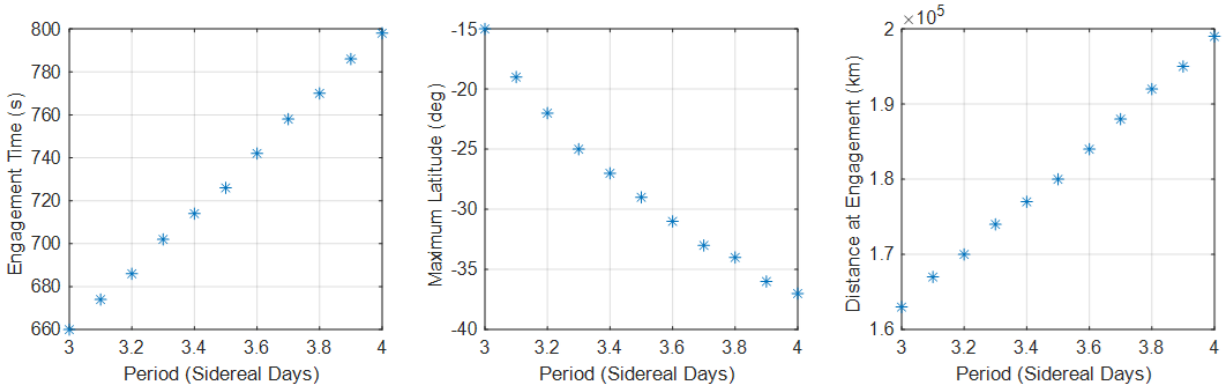

Fig 11 (Left: Orbit period in Sidereal days vs. maximum engagement time associated with the highest feasible latitude for the given orbit period. (Middle) Orbit period in sidereal days vs. highest feasible latitude. (Right) Orbit period in sidereal days vs. distance from ground station to beacon at engagement.

of the ground station. At that point, instead of having hundreds of seconds on the target, we have less than a minute, making those orbits infeasible for this application. Therefore, the lowest engagement time that still meets requirements will be about 650 seconds.

4 Discussion

Two possible orbits have been presented in the results section which represent a range of possible times on target and days between engagement opportunities. In order to select the orbit to be used for this mission, a preliminary design will need to be done to determine which orbit characteristics are most important.

A longer engagement time can be achieved by increasing the distance at engagement and/or increasing the orbit period. Additionally, the latitude of the ground station has a significant effect on the time on target. At latitudes further from the equator, the ground station has a lower velocity since the rotation of the Earth is constant for all latitudes but the distance from the axis of rotation is not. Therefore, at higher latitudes, the time on target can be higher but the orbit must have a slower velocity at observation, requiring a longer time period between observations. For the 800s

orbit, a latitude of -37.6° was chosen. If the ground station is at a higher latitude than this, more than 4 days may be required for the time between engagement opportunities. At a lower latitude, the engagement time will be shorter. For instance, for the same orbit at a latitude of -25°, the engagement time will be 740s (the value of R must be reduced to about 197,000 km to make the orbit possible). On the other hand, an orbit with 3.3 days between engagements would not be possible at -37.6° latitude which is why that orbit is assumes a latitude of -25°.

If the 800s orbit is used, the Earth-based site would need to be in Chile, Argentina, Australia, or New Zealand to be at the required latitude. Note that the latitude is a range, and so latitudes slightly closer to the equator will also work. As they get much closer to the equator, by several degrees, there will be a loss in engagement time of at least 10-20 seconds.

With a latitude of -25°, the shortest period between engagements is 3.3 days. However, if the latitude requirement is slightly relaxed, an orbit with a period of three days could be designed to meet all the other requirements. This orbit would require an Earth-based site at a latitude of -10°.

In addition to the latitude, there are other considerations to take into account when selecting a final orbit. Both the orbits presented are within 50 km of the 1000km perigee requirement, so any orbit selected should be checked to ensure that it meets the requirement. Additionally, if the requirement is relaxed to 900 km or so, a slightly longer (5-10 seconds) engagement time could be possible.

5 Summary and Future Work

A range of highly elliptical orbits can be designed to meet all requirements for the breakthrough starshot mission. Two of those orbits have been presented in this paper as examples of the type of orbit that can be selected for the mission.

Overall, the major trade off with this orbit design is between engagement time and days between engagements. The latitude of the site will also have a significant impact on what engagement times are possible. The two orbits presented represent two ends of the spectrum of what type of orbits are available, with one giving an engagement time of 800s and 4 days between opportunities, and the other giving an engagement time of 700s and 3.3 days between engagements. It was found that orbits shorter than 3.3 days cannot meet orbit requirements, specifically the perigee requirement. The same is true for Earth based sites with latitudes south of -40°.

Past work has looked at using hybrid ground and space missions to meet goals that neither could achieve alone. Using a hybrid mission for breakthrough Starshot will provide a laser reference source in an orbit creating small angular separation to the line of propagation for the Starshot laser to limit anisoplanatism, while providing enough separation to avoid sail-beacon impacts or illumination of the beacon from the propulsion beam. Combined with the effects of focal anisoplanatism from cone angle differences the beacon can provide the means to measure and correct fluctuations in the optical path differences due to atmospheric and mechanical turbulence. In this paper, we have shown that having a laser reference beacon in this type of orbit is feasible.

A Preliminary Design will need to be completed before the final orbit for Breakthrough Starshot can be selected. In the orbital requirements, several ranges were given with desired and required times, and the range of orbits presented represents a trade off between those values. Future work on this project should be done to determine the impact of different engagement times. sail mass, sail speed, laser cost, optics cost and battery cost each affect the resulting cost-optimized array diameter, power and launch duration.

6 Acknowledgments

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7 Biographies

Author biographies are not available.

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