Phase I Report to NIAC for
The Aragoscope:
Ultra-High Resolution Imaging at Low Cost

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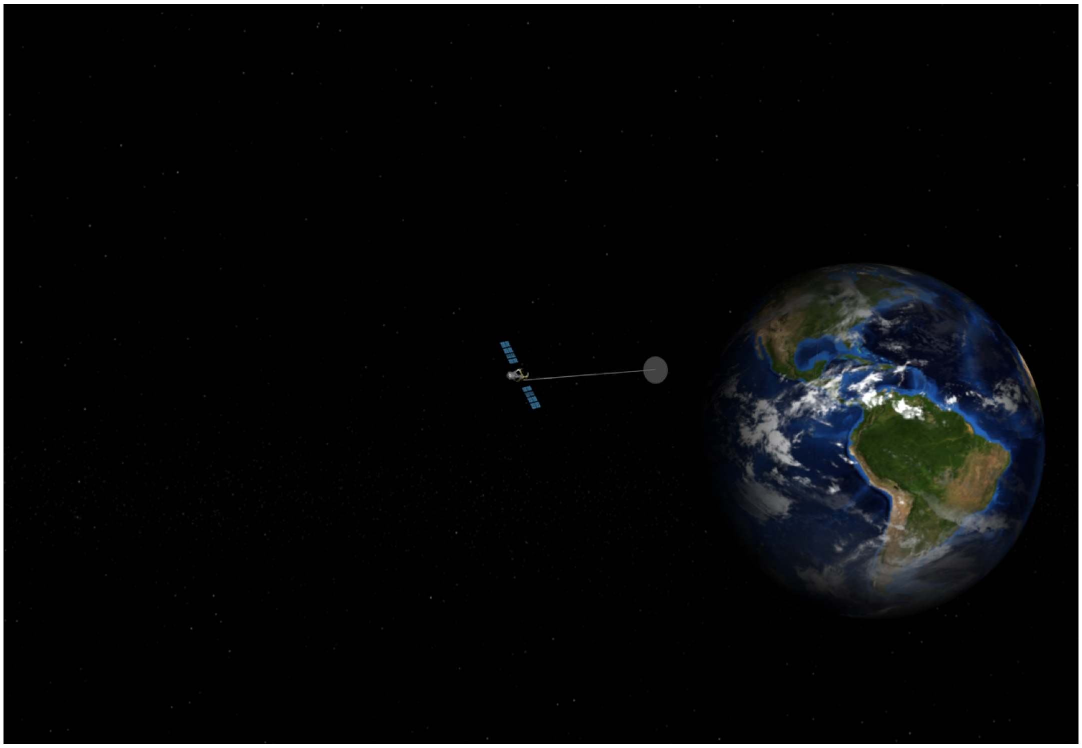
Abstract

The Aragoscope is a concept for building giant telescopes in space in a practical and affordable manner. They can be used to view outward into space to perform astronomy with unprecedented resolution - hundreds or even thousands of times finer than the Hubble Space Telescope. Or, they can be used to look down at the Earth with unprecedented clarity from the high stable perch afforded by Geosynchronous Orbit. The Aragoscope is based on very light, deployable optics that can maintain diffraction limited performance despite their large diameters by use of binary diffractive optics. In this report we show that 80% of the way through the Phase I study the Aragoscope remains an attractive concept. We have identified all the major components of the system and shown that there are no show-stoppers.



An Aragoscope in Geosynchronous orbit looking down.

I. Introduction

As actors like to say, "Drama is easy, comedy is hard." Well in astronomy, Spectroscopy is easy, Interferometry is hard. Heterodyne receivers let radio interferometers surpass the Rayleigh limit of single dish telescopes, taking resolutions of arcminutes and degrees into the microarcsecond regime. Sadly, the same tricks do not work at higher energies. Climbing the three orders of magnitude from ALMA's sub-mm band to the optical, where key tracers of life on exoplanets are plentiful, will require a new approach. Ground-based optical interferometers such as the Very Large Telescope and Magdalena Ridge Interferometers rely on finicky delay lines, making the architecture impractical and expensive for space flight or for larger-scale implementation.

We seek a practical approach to space-based optical interferometry, the only viable way to break the leisurely climb in resolution from incrementally-larger observatories. Modern large optical telescopes are, in a sense, interferometers: they use several to many mirror segments with constant path length to the focal plane to build a large aperture without needing cost-prohibitive monolithic mirrors. Interferometry gurus will point out that even a traditional monolithic telescope is just an interferometer with a filled *uv*-plane out to its edge. Consequentially, it is a well-known trick of sophomore physics that an obscuration of a small part of a telescope's aperture dims the image but does not reduce its resolution. A ring-shaped primary mirror loses only collecting area, not resolution.

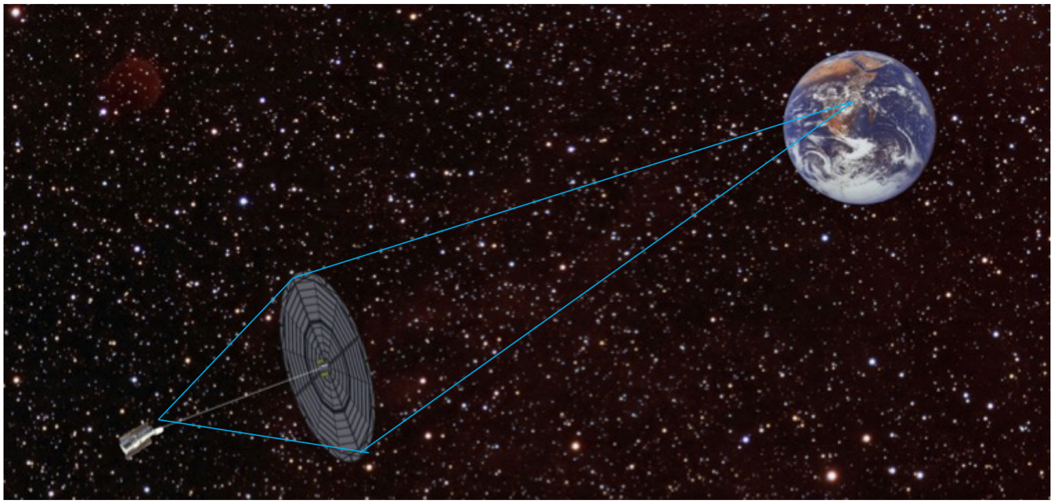


Figure 1: To first order the Aragoscope is an opaque disk with light diffracting around the edge and collected by a telescope that contains wavefront correctors to create an image.

The Aragoscope (Figure 1) study looks at that ring as the future of orbital optical astronomy. And in fact it goes a step further, as geometric optics can be replaced by diffractive optics for a ring-shaped telescope: an occulting disc will diffract light around its edges, behaving similarly to a ring lens and giving resolution proportional to its diameter. The Aragoscope study looks at the capabilities of a telescope with an occulting disk as its primary optic, with light diffracted from a distant source (astronomical or terrestrial) around its edge and focused along the optical axis to a detector on the opposite side. With relative ease and with launch and telescope technologies available today, Hubble's successor could achieve sub-milliarcsecond resolution – over a factor of 100 better than today's state of the art.

This Aragoscope study is the next in a line of NIAC studies that challenge the resolution limit problem. It is well recognized that, since the time of Galileo, the sensitivity limit of our visible light observatories has improved by a factor of over a billion, while our spatial resolution has improved by over a factor of ten. (Yes, just ten. Not ten million or ten thousand, just ten.) Imagine the discoveries that are going to be made when we start to match our sensitivity with clarity. So of course NIAC, with its sights set on breakthroughs, wants to solve this problem.

In our first NIAC study (1999-2002), we studied X-ray Interferometry under the title of MAXIM, the Micro-Arcsecond X-ray Imaging Mission. The original concept adapted grazing incidence optics to steer x-rays without losing their diffraction-limited wavefronts. The NIAC study found an architecture that minimized positioning tolerances but still relied upon formation flying of independent optics to mix beams in phase. It was an interferometer. While there was great interest (at the time) in the existence proof of an instrument that could resolve the event horizons of black holes, it became clear in just a couple of years that the architecture was sufficiently expensive and risky that it would not be developed within the current culture of risk and cost minimization for large missions.

Our second NIAC study (2004-2007) led to the Starshade concept for observing exoplanets. The goal was to improve telescope contrast by orders of magnitude by reducing diffracted light with an external flower-shaped occulter flown in formation with a telescope. The NIAC study found an architecture that creates destructive interference of starlight while preserving photons from nearby sources, allowing observation of planets ~10^{10} times dimmer than their host stars. This solution, or one based heavily upon it, is very likely to be adopted by NASA in the near future.

The fates of our previous NIAC studies, which both produced viable architectures but only one of which is likely to be implemented, taught us a practical lesson. We have found that the requirements of the starshade are more in line with NASA's capabilities than are the requirements of space interferometers. Deploying a large, low areal density shape and maintaining an optical axis against the sky is substantially easier than holding individual spacecraft in position and alignment sufficiently well to create stable, mixed optical beams. Furthermore, a structure provides an optic that samples all azimuthal angles simultaneously. From these considerations was born the Aragoscope concept.

The Aragoscope is a hybrid of diffractive and geometric optics, coupling a diffractive occulter with a geometric telescope. There is no historical experience on which to base our study. Many of the basic concepts are poorly understood, and it is the prime goal of the Phase I study to resolve those issues. In particular, there were issues of low effective collecting area and point spread function. The architecture that supports the optical elements is more straightforward, but still challenging. The creation of any spacecraft of over 100m in size is always a challenge in terms of mass and cost, but this is a solvable engineering challenge that will be addressed more thoroughly in Phase II.

We have resolved the main questions about area and resolution and are confident that the concept is viable. Laboratory optical tests have shown that the basis of the idea is sound. Practical questions, such as tolerances, field of view, and proper mission concept have been addressed only at the broadest levels and are still outstanding.

We finish this report with a visit to three exciting missions that could be enabled by this concept. 1) An Aragoscope parked in geosynchronous orbit, providing continuous, high resolution imaging of the ground below. 2) A similar scope pointing outward to study the stars, and 3) a MAXIM – an x-ray version of the Aragoscope that could potentially resolve black holes at the sub-microarcsecond level and enable the direct imaging of event horizons.

II. Conceptual Development

At the core of understanding a new telescope architecture are questions of image formation, collecting area, and the tolerances that allow it to work. The central part of the Phase I effort was to understand and resolve image formation and collecting area issues.

A. Image Formation

To reinvent the telescope half way between an interferometer and a telescope, we need to understand the nature of image formation at a basic level. Every optic, interferometric or not, creates its image through the superposition of wavelets. In a full aperture lens, the wavelets come from all points in the aperture, and across a circle with uniform intensity, the wavelets sum to create an Airy disk distribution in the focal plane. In an interferometer, the wavelets are individually summed, each representing a point in the frequency domain usually referred to as the *uv*-plane.

1. Direct Formation

A simple disk creates the Spot of Arago on the optical axis, where all light coming around the edge reaches the same point with equal path length. But all wavelets are approaching the focal plane at the same conical angle, thereby sampling a ring in the *uv*-plane. By use of Fresnel's Equation, we can calculate that this creates a point spread function that is distributed as J_0^2 instead of the $(J_1/r)^2$ of the Airy disk. Thus the contrast is poorer in the vicinity of the focus.

While the collecting area of the direct Spot is tiny, it has the remarkable property of always being in focus at the diffraction limit because, rather than being a focusing optic, the image is an interference pattern formed where path lengths are equal (*n.b.*, along the optical axis). Unfortunately, the same property that makes a small spot and high resolution is also responsible for an effective area that is so small that we cannot use it directly for any reasonable observation.

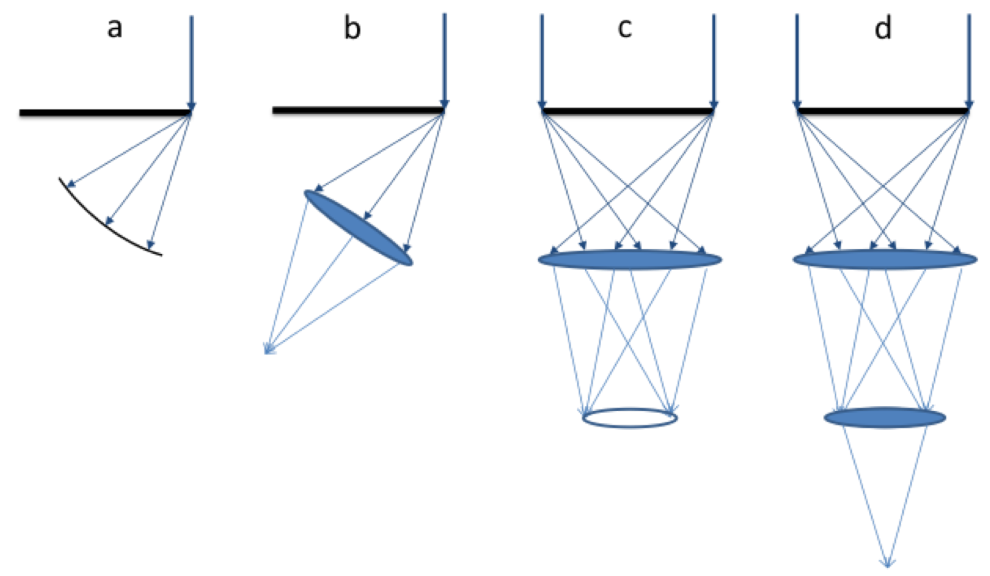


Figure 2: In panel (a) light impinges on one side of an obscuration and diffracts around the edge. The electric field is uniform and in phase along an arc. Panel (b) shows that placing a lens there will focus the light to a point. Panel (c) shows that a lens can focus light from the perimeter of the entire disk to a ring focus with uniform phase. In panel (d) a lens reimages the ring to a point, forming an image.

2. Role of the Axicon

When the light diffracting around a disk reaches the focal plane, the only place where all the light is in phase is on the optic axis. There it constructively interferes to create the Spot of Arago as shown in Figure 2a. By adding focusing optics, we can change from a pure interferometer and increase the collecting area. When a lens is placed near the focal plane, the light from the disk is reimaged into a ring focus. If we wish to bring a ring into a point focus, properly scaled to the detector, we must use an axicon, as shown schematically in Figure 2c. In essence, the axicon takes the ring aberration of the disk back out of the image.

B. Collecting Area

In our proposal we were not precise about the effective collecting area to be expected. The review panel flagged this as a major concern to the resolved in Phase I. We have done that. The answer was not the best or the worst possibility, but rather in the middle.

1. Theory of Collecting Area

The Spot of Arago as generated on the optical axis of a disk has a surface brightness equal to the unimpeded flux and diffraction limited resolution. The width of the Spot is $f\lambda$ where f is the focal ratio of the disk. That, in turn, makes the collecting area of the Spot just $A=f^2\lambda^2$. For an f/10 system operating in the visible band, the collecting area would then be in the vicinity of 25 square microns, way too small to be of use.

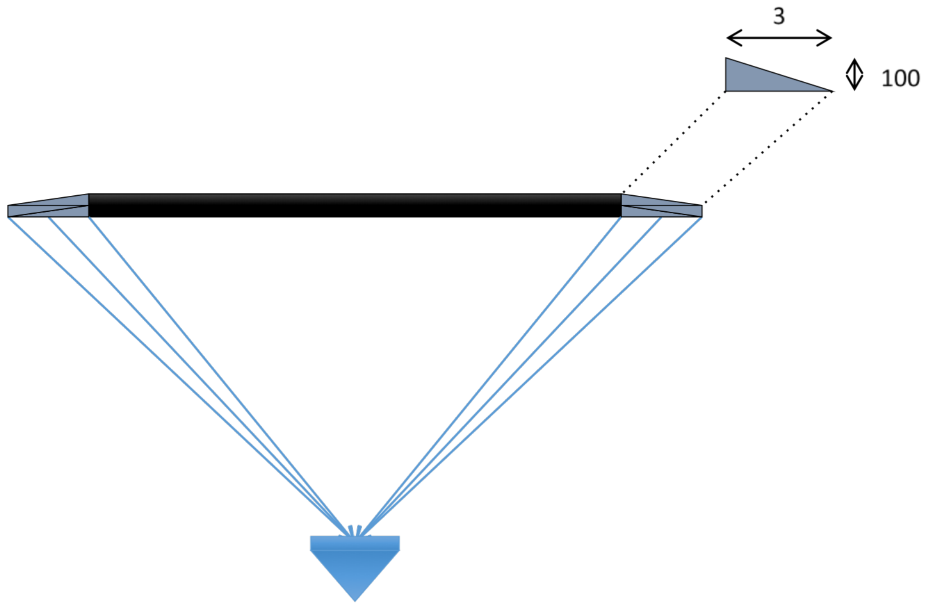


Figure 3: One simple way to increase collecting area is to widen the size of the first half zone by inserting thin prisms that compensate for the pathlength differences across a range of disk radius.

In the proposal we discussed the use of a focal plane lens to gather light off the Spot of Arago to increase the collecting area. That lens would focus the diffracted light to a ring, greatly increasing the collecting area. The light would then be refocused to a point with the use of an axicon. We speculated that the collecting area would rise to equal that of the collecting optic, but this turned out not to be the case.

Instead, the lens gathers a collecting area equal to the area of the first Fresnel half zone around the disk. Thus the effective collecting area rises to $A=2\pi Rf\lambda$. So, the collecting area of a single diffracting ring around the edge of a 100m diameter, f/10 Aragoscope rises to about $3cm^2$ - still too small for most applications.

Luckily, as we pointed out in our proposal, we can have (many) more than one diffracting ring in an Aragoscope and thus build it up to the needed collecting area. We discuss three approaches to acquiring multiple diffracting rings, with the goal of finding one that has a viable effective area, maintains the extraordinary resolution of the Aragoscope, and is still a deployable architecture with existing technology. There still may be a way to increase area down at the focal plane, as well. If Phase II is funded we will study these mission architectures in much greater depth.

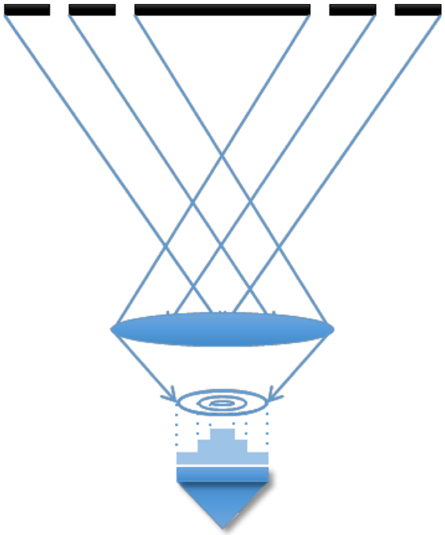


Figure 4: Multiple rings can provide additional collecting area. But if the rings are in a plane, then the different path lengths must be zeroed out in the focal plane.

2. Phased Rings

All of these will be studied in more detail as options in Phase II.

a) Prisms

The easiest approach to understand is the use of prisms around the edge. See Figure 3. Glass delays the phase of the light passing through it in proportion to its thickness and index of refraction. Thus a prism can be arranged to compensate for the greater path length to the focal plane farther from the axis to maintain the Aragoscope's interferometric qualities, while the axial rather than point-like focus of the occulter precludes chromatic aberration. Prisms, in effect, widen the Fresnel half zone to the radial width of the prism. The collecting area of the Aragoscope is the collecting area of the prisms, just as one intuitively expects.

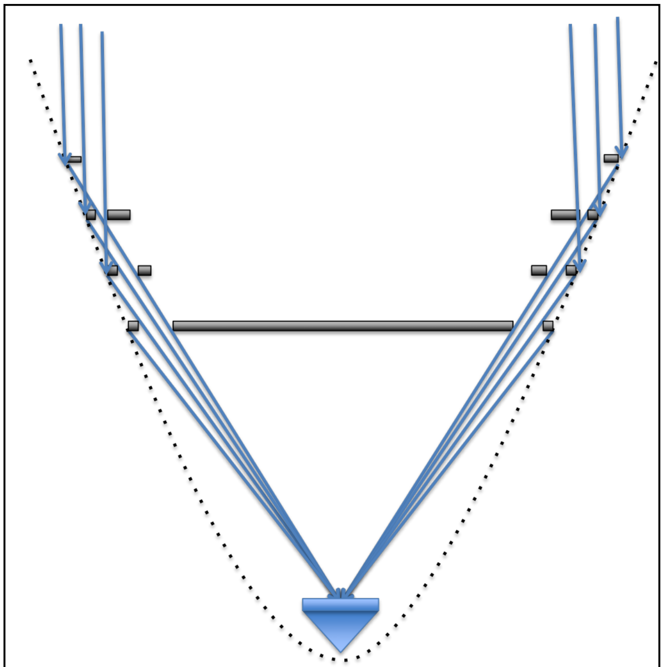


Figure 5: It is possible to arrange concentric rings that provide a constant path to the focal plane. They lie along the surface of a grazing incidence parabola as shown schematically here.

If an Aragoscope is ringed with prisms of width r in the radial direction then the area rises to A= 2πRr. If the prisms are 10cm wide on a 100m Aragoscope, then the collecting area becomes 60m^2, comparable to the collecting area of a 10m telescope like Keck. This is satisfactory for most observations of the both the Earth and the Heavens.

It should be noted that we will have to minimize the thickness of the prisms. If they average just 1cm in thickness, then their total volume would be 0.6m^3, and the mass would be in excess of a ton.

b) Multiple Rings with corrector

We do not have to use refractive or reflective optics. Figure 4 shows multiple diffractive rings spread around the disk. Each of these rings arrives at the focal plane and can be reimaged into an image of concentric rings. As long as the rings are optically separated at the focal plane, then optical path differences may be inserted and the rings refocused to a coherent point with large collecting area. The requirement of optical separation in the focal plane may spread the rings across too much radius and thus drive the mass high. This needs further study. Additionally, the mounting structures necessary to support multiple rings with tight tolerances might excessively perturb the wavefronts.

c) Rings at graze

There is a geometry that allows multiple rings to be in phase without a corrector. If the rings are placed along a grazing incidence paraboloid as shown in Figure 5, the pathlengths to the focal plane are all the same. The difficulty is that surface on which they are mounted rapidly becomes quite long, adding support structures and complexity. This option will also need additional study.

C. Tolerancing

The key to just about any space mission is to design it with directly achievable tolerances that will not push on the state of the art. We believe the Aragoscope provides just such a capability with today's state of aerospace engineering.

Table 1: Top Level Aragoscope Assembly Tolerances
Table assumes a 100m, f/10 system, operating at 0.5µm in the visible band. Positions are given in millimeters and angles in arcseconds.

		Position radial	Position azimuthal	Angle radial	Angle azimuthal
System Pointing	Stability			10	.1
	Knowledge			1	.0003
Disk Structure	Stability	10	10	100	100
	Knowledge	.001	.001	10	1
Optical Arcs	Stability	.001	.01	100	10
	Knowledge	.0003	.003	10	1
Focal Plane Assembly	Stability	1	1	10	100
	Knowledge	.0003	.003	.1	1
Focal Plane Elements	Stability	.0003	.003	.1	1

In Table 1 we present the top level tolerance table for a 100m Aragoscope. Each set of tolerances is broken into "knowledge" and "stability". Some missions, like the Hubble Space Telescope, rely on an entirely stable system; segmented telescopes rely on knowledge of position and the ability to feedback corrections to the alignment of the components. In the table we provide the full range of position and angle error that is allowed under stability while knowledge is the level of information needed to correct the components.

III. Lab Testing

The use of an axicon to clean up the focal plane image and increase the collecting area over the Spot of Arago is a new component of the concept under study. There are major new subtleties about the behavior of the optical element in its role mid-way between pure diffractive and pure geometric optics. As such we purchased an axicon (Edmund Optics part #83-787), made a disk, and tested its behavior in the lab. We found that the point spread function was tighter at the core when compared to an Airy disk, but had wider wings. Imaging using only the outer ring appears to create an acceptable point spread function for most applications.

The experiment setup is shown schematically in Figure 6. It consists of an expanded red laser beam diffracting around a 3-cm circular disk, located 8 meters in front of an optics bench (shown in Figure 7). We tested a number of combinations of optics in the geometric shadow of the disk. The diffraction patterns were recorded with the sensor of a Nikon DSLR camera (with no lens attached). The three optical assemblies we emphasized were (components listed in order along the optical train): disk-camera, disk-axicon-camera, and disk-lens-axicon-lens-camera.

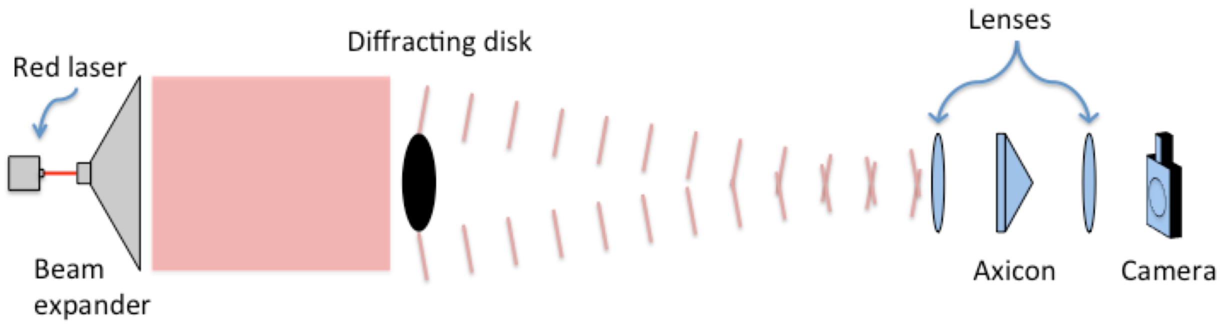


Figure 6: Schematic of experimental setup in the lab.

Images of the diffraction patterns for the camera and axicon-camera are shown in Figure 8. The three bright regions (120 degrees apart) in the first bright ring are due to diffraction by the disk's support wires. The main results are shown in Figures 9 and 10. Figure 9 shows the relative intensity as a function of radial distance for the three different optical setups. These were obtained by taking an azimuthal average of the diffraction image centered on the core of the PSF. Also shown for comparison is the Airy disk intensity profile, which is the well-known diffraction pattern of a circular aperture, and a J_0^2 intensity profile (J_0 is the zeroth order Bessel function of the first kind), which is the resultant diffraction pattern in the geometric shadow of an opaque disk. Figure 9 shows the encircled energy as a function of radial distance for the three different optical setups, along with that of the Airy disk and J_0^2 patterns for comparison.

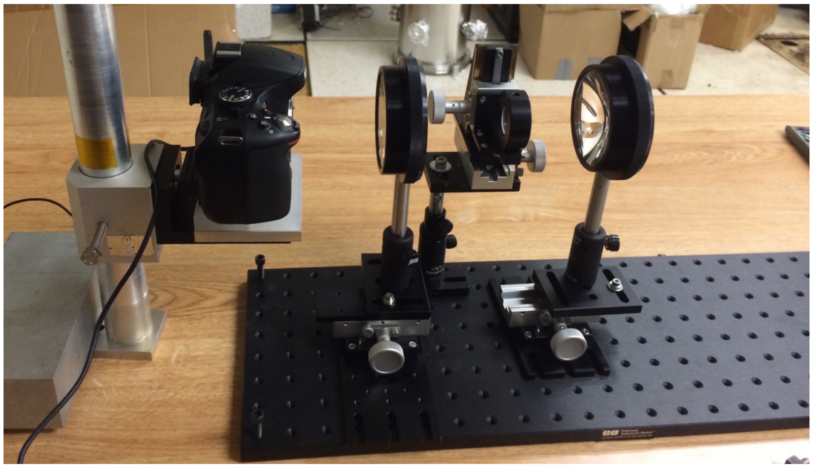
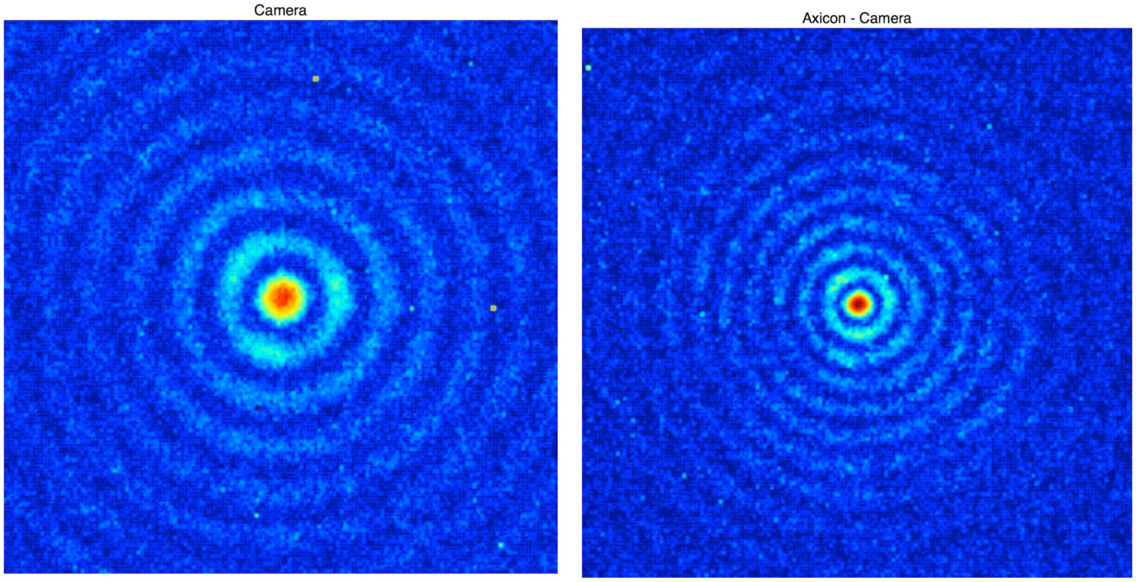


Figure 7: Lens-Axicon-Lens-Camera setup on the optics bench located in the geometric shadow of the disk



(a) **(b)**

Figure 8: Diffraction patterns recorded for **(a)** the disk-camera setup and **(b)** the disk-axicon-camera setup.

The diffracting disk produces a tighter core PSF than that of a typical lens of the same size. The axicon brings the core even narrower still, with the first zero of the diffraction pattern roughly 2 and 4 times closer than that of the J_0^2 and the Airy patterns, respectively. However, as indicated by the encircled energies in Figure 10, the wings of the disk's diffraction pattern are much slower to decay than that of the Airy pattern. While the Airy pattern has > 85% of its power in its core, the disk contains only 8%. This results in a diffuse background being introduced into the image.

We believe that this PSF can be substantially improved with additional diffracting elements other than the pure ring. This is a high priority for the next parts of the study.

IV. System Architecture

A. Systems

A space telescope system has a number of technical areas that must all work in concert. Many of those are quite standard for the Aragoscope and do not need significant development. First we list the main systems and identify which need special attention. Then we go back through those key areas individually.

a) Optics and detectors

The detectors needed for the Aragoscope are standard, and no development or study is needed at this point. The optics, of course, are new and key to the concept. They have been at the center of the Phase I study and will continue to evolve as we define the architecture further.

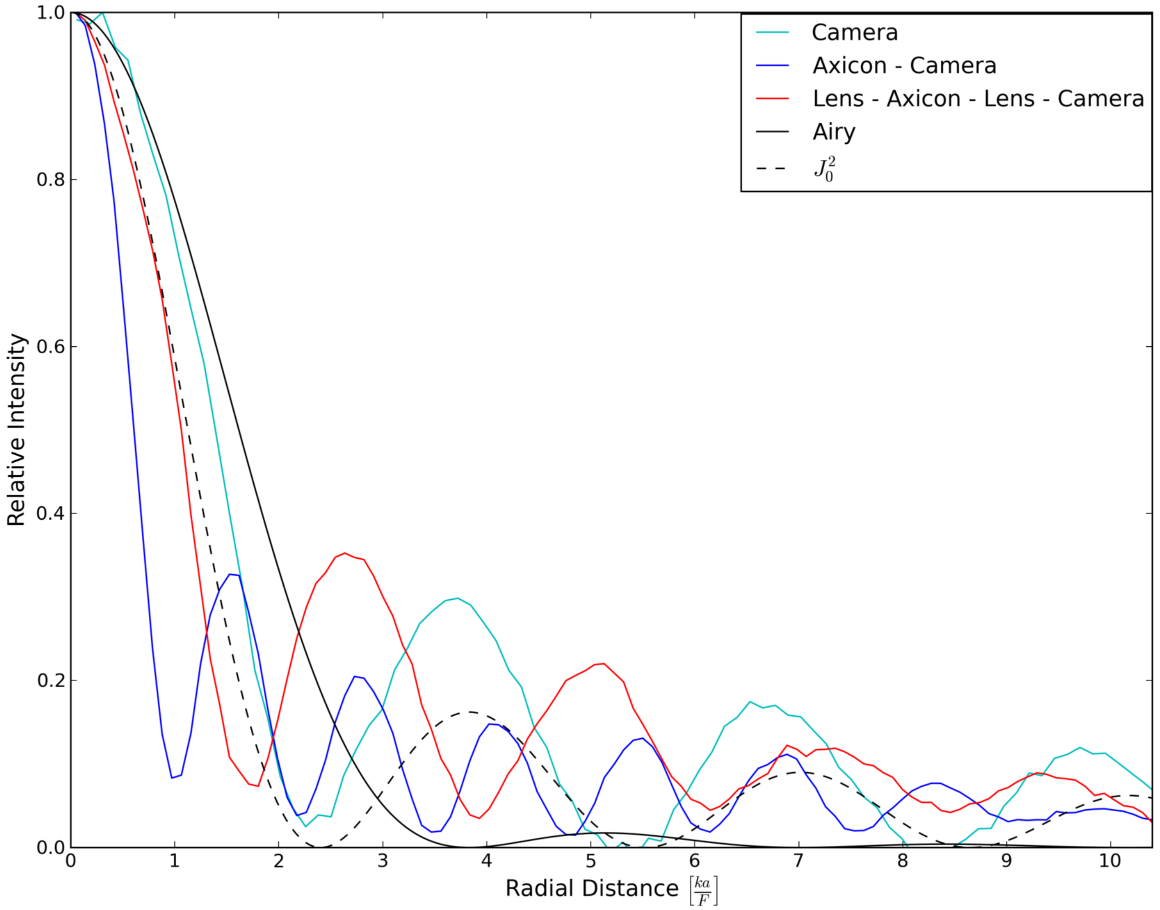


Figure 9: Lab measurements of relative intensity vs radial distance for the three optical arrangements. Shown for comparison is an Airy disk and J_0^2 intensity profile. Radial distance is normalized by wavenumber *k,* occulter radius *a,* and disk-optics separation *F.*

b) Structure and Thermal Control

The mechanical structure is a key element of the Aragoscope and has been looked at in Phase I. Thermal control is not expected to be problematic. Both will be revisited in the Phase II studies of increased collecting area, which add complexity to the overall structure.

c) Command and Data Handling

There are no special needs for the Aragoscope in these areas.

d) Pointing

All high resolution telescopes have pointing issues. The Aragoscope is no exception but is well within the state of the art.

e) Power

There are no special needs for the Aragoscope in this area.

f) Launch and Operations

There are no special needs for the Aragoscope in these areas. But we do revisit this below in a little more detail.

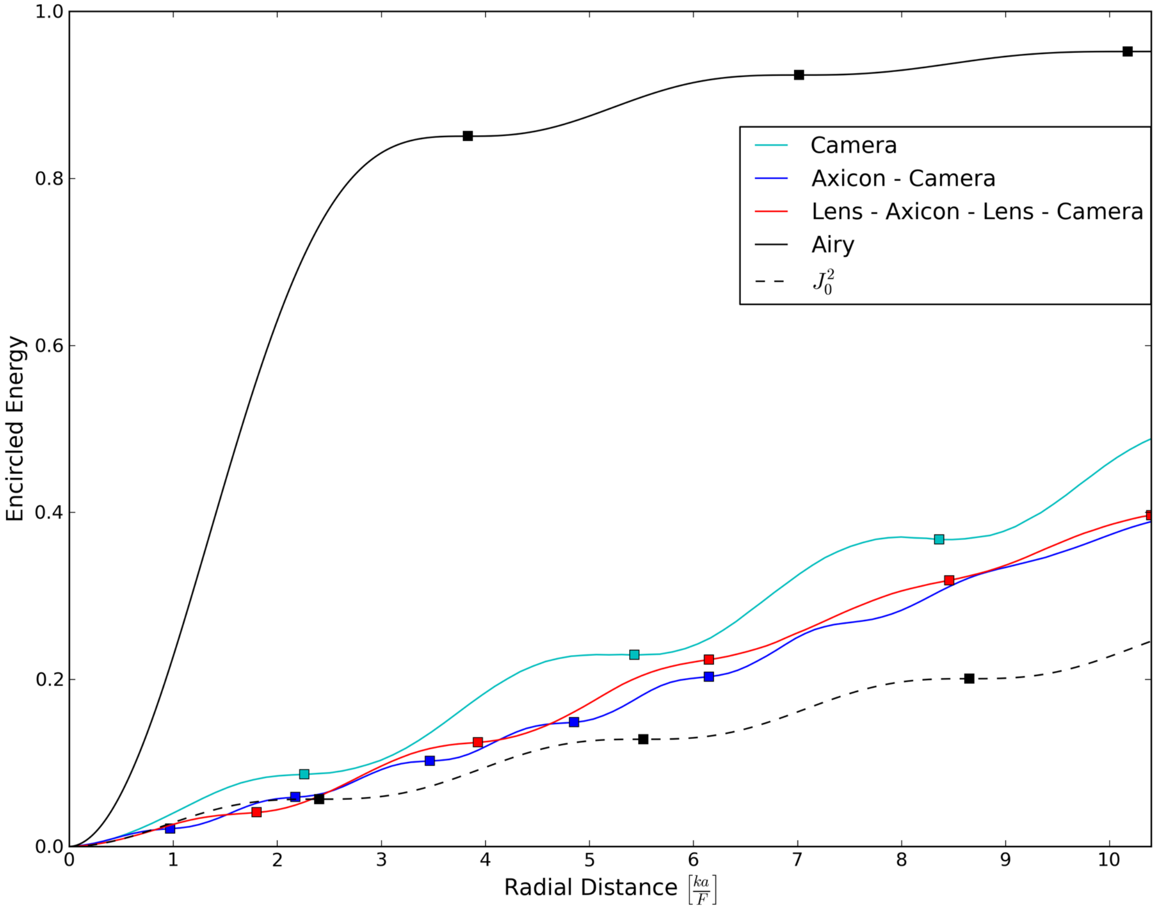


Figure 10: Lab measurements of the encircled energy vs radial distance for the three optical arrangements. Shown for comparison are the encircled energies for an Airy disk and J_0^2 intensity profile. The squares mark the radial distance of the dark rings for each profile.

g) Cost and Schedule

Keeping the cost under control is key to the success of the Aragoscope. After all, if cost is not a concern, we can just launch a 100 m traditional telescope to eliminate our collecting area concerns. But achieving any fidelity on the cost will have to wait until Phase II when the system is more fully defined. However, based on our ten years of experience with starshades, we expect that the cost will be in the range of what NASA usually budgets for flagship missions.

B. Optics

The primary optic of the Aragoscope is the disk and the diffractive and refractive elements mounted on it. This is discussed below.

At the focal plane, however, is an optical system that collects the light from the primary disk, optically corrects it and re-focuses it into an image. The detectors required are identical to those used on other space missions and do not need further study or development at this point.

There are conventional mirrors and lenses in the focal plane assembly. These are fabricated at tolerances normal for diffraction-limited optics and, while expensive, are within the state of the art. Components are at TRL 8 or 9.

There is at least one non-standard optic element in the focal plane assembly. The axicon is used to render the ring focus created by the disk into a point focus. Axicons are available as catalog items, mostly used for laser applications that convert point foci into ring foci. Indeed, it has been pointed out that ring diffracting optics can be considered an axicon (McLeod, J., *JOSA,* 44, 8, 1954). So the use of an axicon in the focal plane is natural. We obtained an axicon for this study and report on our lab studies of it in section III of this report. So, while this is not a normal element for an observatory, it is well within the state of the art and can definitely be obtained for flight.

None of the optics are beyond the current capabilities of optical fabrication.

C. Structure

The structure can be divided into three parts: The disk, the focal plane, and the connecting structure. All parts must meet the alignment and stability requirements of the system.

1. Disk/Ring

The key to the Aragoscope is the primary disk. To first order the disk is a black circle outlined on the sky. The light diffracts around the edge to be collected at a focal plane. The shape of that circle must be maintained to the tolerances in Table 1.

a) Ring vs Disk

The vast majority of the area of the disk is not being utilized by the system. So, when viewing deep space, the design can shift to a ring shape, allowing light to pass through the center unimpeded. Any residual light can be baffled out near the focal plane. This greatly reduces the amount of mass needed, since even a few mils of plastic across a 100m disk adds up to tons of material.

When viewing the Earth, however, there is a huge flux of unwanted light coming through the center of the ring. It is too much to allow into the telescope where it will scatter and ruin the high resolution image. One can still use a ring, reducing the size and mass of the disk by inserting a baffle in front of the telescope as shown in Figure 11.

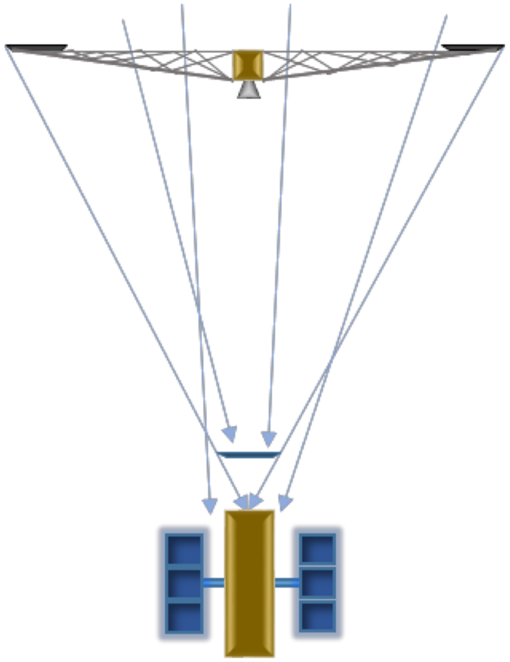


Figure 11: The opaque disk can be replaced by an opaque ring greatly reducing the mass of opaque material needed across the diameter. Light that comes through the center of the ring can be stopped by a much smaller baffle in the focal plane assembly.

b) Metrology Net

As Table 1 shows, the positioning of the diffracting elements must be held to microns. That tight level of control is problematic across hundreds of meters of low mass structure in space. There will be a laser-based optical web across the disk and from the disk to the focal plane. This “metrology net” (see Figure 12) will measure the relative separations of key points around the system and precision actuators will correct any errors. That, in essence, makes this an adaptive optic. And, while the distances are larger than the many AOTs on the ground, the speed is much lower, being driven by thermal drifts rather than twinkle of the atmosphere, making it more of an active optic than an adaptive one if it were terrestrial. This technology exists and can be adapted to the needs of the Aragoscope.

c) Segmentation

The ring is huge, so the optical elements will naturally be segmented as they are in all modern, large telescopes. We envision that the ring will be broken into roughly one meter optical segments, each of which will be positioned by actuators, informed by the metrology net as shown schematically in Figure 12.

d) Deployable

The Aragoscope is too big to be launched in its operational configuration, so it must be folded and then deployed once in orbit. As we did for the starshades, we have consulted with Northrop-Grumman Aerospace Systems (NGAS) on the feasibility of this deployment. NGAS is the world's leader in space deployables, having launched over 2000 such items without a single failure. They are confident that the Aragoscope can be deployed in orbit remotely or robotically to the required tolerances. Of course, as the size increases, so does the difficulty.

The deployment in space is one of the key issues driving the practicality and cost of the Aragoscope. While the principles are sound, and we are confident that we can succeed at some level, study needed to quantify those trades is beyond the scope of a NIAC Phase I, so will have to await a more in-depth study in Phase II.

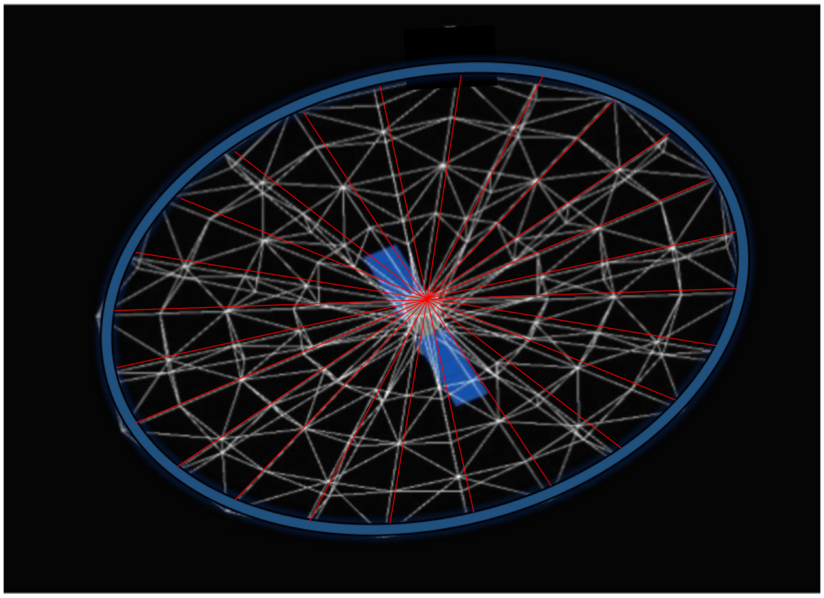


Figure 12: The optical elements are mounted on stable arc substrates, notionally a meter long each. Laser beams from the center measure the position of each arc to submicron precision. Actuators are used to bring each arc into alignment. This is, effectively, a segmented mirror like Keck or JWST. Truss structure in this diagram courtesy of TUI.

e) Space Assembly

It is now the 21st Century and it is surprising to many of us that the world's space programs are still so expensive that nothing can be assembled in space. Indeed, NIAC is addressing space assembly and manufacturing. We believe that space assembly will become routine in the next twenty years, maybe in time to be applied to the Aragoscope. As such, we will consider in-orbit robotic assembly options in our Phase II study.

2. Connecting Structure

For a typical Aragoscope, we are looking at a 100m, f/10 disk. That places the focal plane assembly one kilometer away from the primary diffracting element. Somehow that assembly must be held in position along the optic axis of the large disk.

a) Truss

Conventional telescopes connect their focal planes to their telescopes through use of a mechanical structure. As separations become great, the structures naturally become longer and increase in mass. Very light, deployable structures have flow as best exemplified by NuStar. However, NuStar's bench was only 10m long, not even in the same ballpark as the 1km required for an Aragoscope.

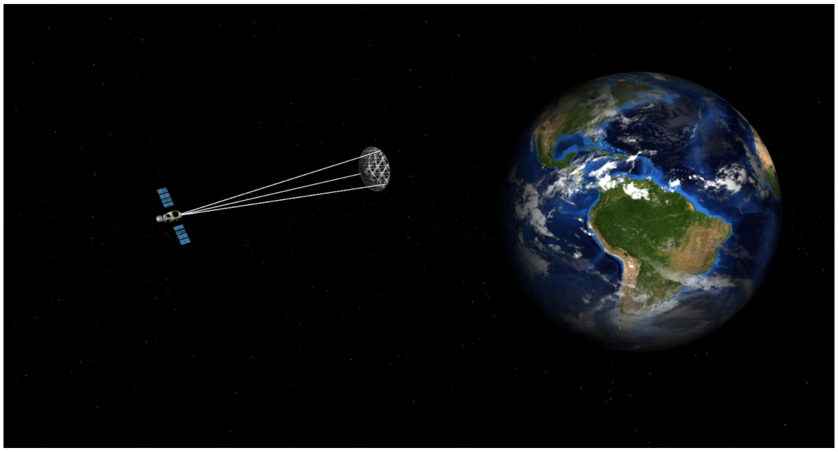


Figure 13: The Aragoscope can be built with either a triple truss or triple tether to ease holding the focal plane assembly in place.

Originally we did not think that 1km trusses were realistic. Then we attended the NIAC Symposium in January 2015. Dr Hoyt of Tethers Unlimited gave a talk about some work they were doing on ultra-light yet stiff space structures like trusses. While these can be deployed, the exciting possibility of assembly in space (rather than deployment) was presented. We contacted Dr Hoyt afterward and verified that such a structure is realistic. We plan to involve TUI in our Phase II study.

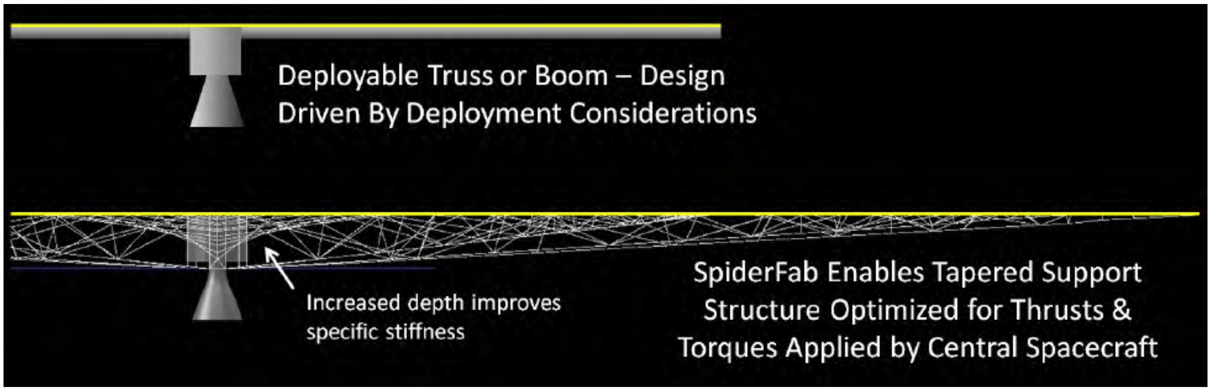


Figure 14: The structure can be conventional boom-deployed as shown above. Alternatively, the ultra-light truss structures under development at Tethers Unlimited Inc., appear the best route for the future. *(Robert P. Hoyt, et al., SpiderFab: An Architecture for Self-Fabricating Space Systems, American Institute of Aeronautics and Astronautics, 2013)*

b) Tether

Tethers have been proposed and even implemented for mechanical structures kilometers in length. The connecting structure of an Aragoscope could be three tethers, as long as the pointing is such that gravity gradients maintain a tension on the cables and the focal plane does not drift toward the primary disk. While under tension, position can be adjusted and maintained by reeling in and releasing the tethers. It seems to us that tethers are the best option currently available, but it comes with some viewing constraints that have not yet been quantified.

c) Formation Flying

There comes a point where the focal plane assembly is simply too far away from the primary disk to be attached mechanically. That is certainly the case for a MAXIM application where the separation can be several thousand kilometers or more. Then, the focal plane assembly will have to maintain position based on formation flying sensing and position-keeping techniques. The level of tolerances required has been contemplated by NASA for a number of missions and it is concluded to be possible and on the general path to capabilities for the future. However, it is difficult and to be avoided if possible as evidenced by the fact that NASA has never implemented one of these missions.

d) Just a Ring

An alternative that needs study could be to move the focal plane assembly back into the plane of the ring. That completely solves the problem of the long connecting structure. But it comes at a cost. Specifically, each beamlet must be sent to the center via a reflection to bend the light 90 degrees. There it is bent again to create a final beam by the process known as pupil densification. Each reflection is on the order of five times tighter position tolerance on the mirrors. While the metrology net is easily capable of sensing the errors, there may be some cost to the stability of the system. The tradeoff between no long structure to the focal plane and easier stability has no obvious answer and must be studied in more depth.

3. Focal Plane

We assume that the focal plane instrumentation will be fully assembled, integrated and tested on the ground. The focal plane assembly will be launched as a single piece and attached to one end of the connecting structure during deployment.

D. Pointing

1. Target Acquisition

There are $5x10^{17}$ square milliarcseconds in the sky. Talk about a needle in a haystack! And to make matters worse, everything is moving around on that scale. So target acquisition will have to happen through a process of successive approximations.

We have all had the pleasure of Google Earth. By successive approximations, homing in by an order of magnitude per step, we can move from a view of an entire hemisphere to a view of our home in a matter of seconds. We will have to use the same approach for the fine-pointing of the Aragoscope.

Today's startrackers will get us to about one arcsecond pointing, which is 200m from GEO. That is about the size of the field of view at full resolution. So a single, intermediate image, taken with a meter-class finder scope would suffice to bring the target into the field of view on the second image. It is thus likely that people will be involved in the target acquisition phase of an observation.

2. Holding on Target

All imaging systems must have a pointing system. This is a particularly important subsystem and must be satisfactorily designed if the Aragoscope is to achieve its potential.

The white light interferometer that the Hubble Space Telescope (HST) uses provides a 0.007" error signal that is used to stabilize the pointing to well below the 0.100" resolution of the system. We would like to achieve sub-milliarcsecond resolution on the sky, so we need to significantly improve on HST. But luckily, the baseline for a device like that on HST increases along with our required resolution. So, to first order, we can copy the HST design for astronomical imaging.

For this level of pointing stability, we need to reference to either the target itself or something close by. If we are observing the sky, that nearby object will most likely be a star. The best approach appears to be that of HST. In a white-light interferometer with a baseline across the disk of the Aragoscope, the fringes will have angular scale similar to the resolution of the telescope. Then, observation of a bright, nearby star will allow centroiding an order of magnitude or more below the fringes and thus provide a stability signal sufficient to avoid any noticeable smearing.

If we are observing the Earth, then that reference needs to be on the Earth in some way. Here we must deal not just with drifts in attitude, but also with drifts in position. The orbits at GEO are not perfectly stable. We have looked at two approaches.

First, we could create a network of lasers spread around the Earth and pointed at the Aragoscope. These could be used as fiducial points and provide the telescope a stable reference grid. But cloud cover and the need to maintain a laser system is not a very attractive alternative.

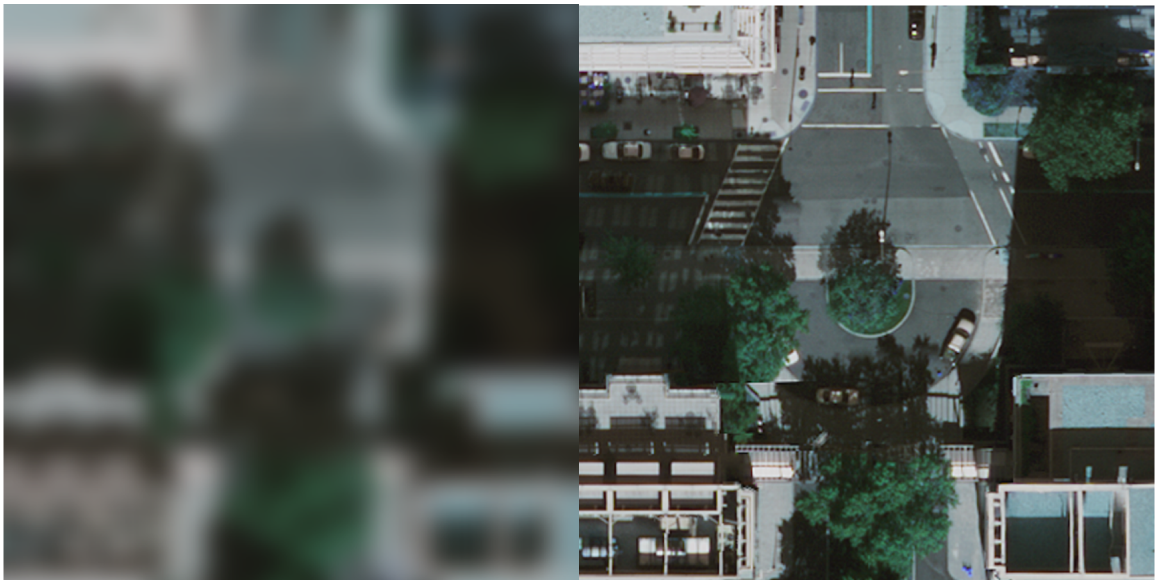
So our second idea is to view a piece of real-estate nearby that has strongly contrasting surface features. The telescope could take quick images and monitor drift in that way.

The error signal so generated will go back into the pointing control of the system. Major drifts will require a pointing adjustment through gyros or jets.

Minor drifts (i.e. significantly smaller than the field of view) can be handled in a simpler way. HST was designed in the 1970s when detectors needed long exposures, so the pointing had to be held stable with respect to the target. But Chandra, taking advantage of the low noise of x-ray detectors allows the pointing to drift, and aspect information is used to correct the image after the fact. Today's visible light detectors now can match the x-ray detectors of the 1980s. Fast readout detectors with essentially zero dark noise or readout noise are available. So real-time correction of the drift is now not only possible, but quite straightforward.

E. Launch and Deployment

Launch should be achievable in a single large rocket. By restricting ourselves to a ring the mass is minimized and a 100m diameter deployable Aragoscope should be launchable with today's large rockets. Of course, there are many realities to be detailed. This is just a ballpark estimate based on extrapolation from detailed starshade studies.



(a) **(b)**

Figure 15: Image of the intersection of 3rd St and E St, Washington, DC (NASA HQ) blurred to the resolution of a telescope operating at geosynchronous orbit for **(a)** a 2.4-m Hubble class telescope and **(b)** a 100-m Aragoscope.

Similarly, deployment once in orbit can be based on starshade studies. Northrop Grumman, the world's most experienced builder of large space deployables, has taken a look at the Aragoscope requirements and feel they are well within their current capabilities.

Of course we hope that soon NASA will have the capability to ferry the parts up separately and assemble and test in space without an automated deployment. Such a process would greatly lower cost and risk by allowing overall simplification of the system.

V. Three Example Missions

In this section we give three examples of possible missions based on the Aragoscope concept. It is not surprising that the 100m to 1km assumed diameters leads to some revolutionary new capabilities.

A. Geo Imager

As many of us learned from reading Tom Clancy novels, high resolution reconnaissance satellites operate from low Earth orbit (LEO). These satellites are screaming around the Earth in 90 minute orbits at altitudes of a few hundred miles that occasionally take them over a desired target area. This lack of continuity of observation is obviously less than ideal for many kinds of observations. A Hubble-class telescope at 400km distance provides 20cm of resolution - about what we see on Google Earth. The twinkle of the atmosphere as light travels upward and into space limits seeing at somewhere in vicinity of a few centimeters.

The obvious place to park a reconnaissance satellite is in geosynchronous orbit (GEO) where it would be able to view a substantial portion of a hemisphere and would not be moving relative to the ground. But GEO is 35,786km above sea level, representing a factor of 100 increase in distance, and limiting ground resolution to 20meters. While there are satellites in GEO with 20m resolution, one would like to improve that resolution and the only way is through increased telescope diameter to beat down the diffraction limit.

This is a prime application for the Aragoscope. Increasing the telescope diameter to 100m would reinstate the 20cm resolution that we enjoy from LEO. Such a telescope would be able to look at any point on a hemisphere of the Earth at any time and continue observing as long as is necessary for the application. One would be able to search a mountainous area for a lost Boy Scout in minutes. One

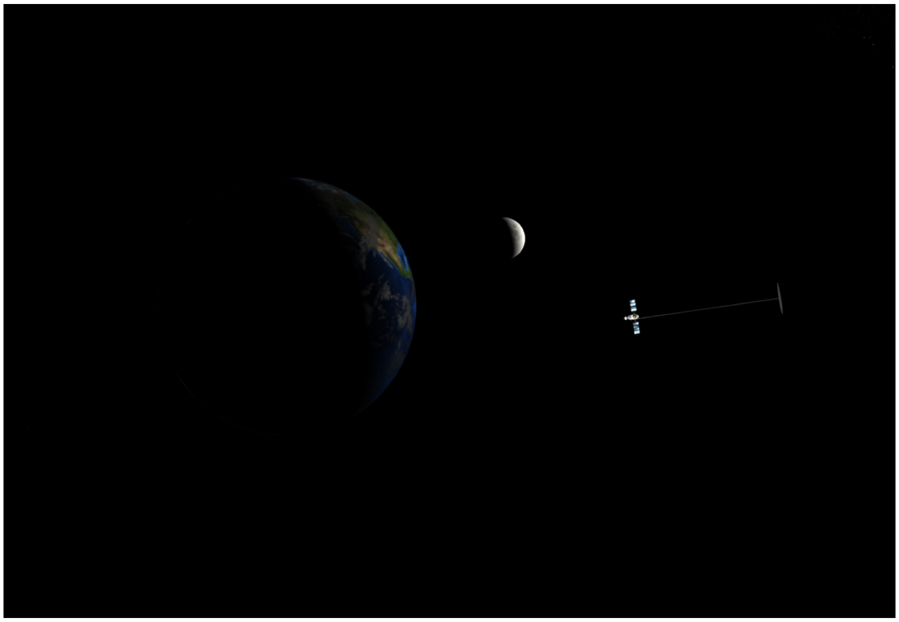


Figure 16: An Aragoscope looking outward toward the stars.

could follow a suspicious truck as it wends through traffic. One could perform a census of endangered species. The list of applications is endless.

In Figure 15 we show an image of NASA Headquarters as seen from GEO with both a Hubble-class telescope and a 100m Aragoscope. The value is obvious.

B. Astro Imager

Now take the same 100m telescope and point it at the sky. We would gain the same factor of 100 in resolution, approaching one milliarcsecond and entering a new regime of astronomical imaging. But for the purposes of this study we have increased the notional size of our astronomical Aragoscope to one kilometer diameter – roughly where we see the limit on space structures for the foreseeable future.

With 1000m diameter, the resolution on the sky would be diffraction limited at 100 micro-arcseconds. This would give us 70 resolution elements across the stellar disk of Alpha Centauri, showing starspots. But, of course, the whole world is excited about the ongoing discoveries of exoplanets. A one kilometer Aragoscope, matched with a comparable sized starshade would allow unprecedented resolution of planetary systems. What is often unappreciated about imaging of exoplanets is that the sensitivity is often background limited. That is, the zodiacal and exozodiacal light create a background against which very faint planets must be detected. Even with a 4m diameter space-based telescope, the diffraction limit of the telescope in the visible allows the Earth at ten parsecs (which is 30th magnitude!) to be the same brightness as the local zodiacal light alone, leaving anything fainter or more distant undetectable.

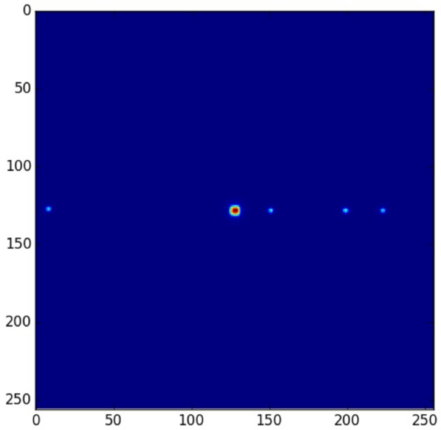


Figure 17: Simulation of a 1km diameter Aragoscope observation of the planet Jupiter from a distance of seven parsecs. The Galilean moons are clearly visible and we are starting to resolve the disk of the planet.

As an example of the power of the Aragoscope we simulate viewing our own Jupiter from a distance of ten parsecs, protected from the glare of the central star by a starshade. In Figure 17 the Galilean Moons are visible and the disk of the planet is just barely resolved. Such a telescope would bring the study of external planetary systems close to that with which we viewed our home system before the beginning of space science.

C. Maxim

The Chandra Observatory is the standard against which all x-ray telescopes are measured. Launched over fifteen years ago, it features one arcsecond imaging of the sky and collecting area of about 1000cm^2 at a cost of over $400,000,000 for the optics alone. But in the visible band, these capabilities can be purchased for under $1000 in an amateur-class telescope. That's how difficult x-ray optics are. High resolution is very difficult to achieve.

Ironically, because of the very short wavelengths of x-rays, the diffraction limit is much easier to overcome. It is the quality of the mirrors that is limiting our resolution. So a purely diffractive telescope could solve the problem of x-ray astronomy and open up a truly astonishing new capability.

If our goal is to image the event horizons of the giant black holes in the center of Active Galactic Nuclei, we will need a primary Aragoscope disk about one kilometer in diameter. However, we need only about 1000cm^2 of effective area to capture the signal from blobs of plasma spiraling into the hole.

The visible light Aragoscopes can operate at f/10 because we can mechanically maintain a circular profile to 5 micron tolerance as discussed elsewhere in this report. But once the wavelength of light falls to 2nm from 500nm, the needed cleanliness at f/10 is no longer feasible. The solution is to back way off with the focal plane.

Assume a 1km diameter disk and move the focal plane 20,000km away. That makes the first Fresnel half zone have a width of 40microns, which is achievable circularity. Around a 1km circle, that zone has an area of 1200cm^2.

Design of an x-ray axicon is an interesting challenge. We have noted that a Wolter telescope can be naturally adapted to become an axicon by adding an axial tilt to the grazing incidence surface. The quality should not have to be diffraction limited since the boost in resolution already happened at the disk.

Pointing to better than a millionth of an arcsecond has never been attempted. Right now, we see the best possible solution is to use the same disk as a visible light Aragoscope at an f/10 distance. Centroiding the visible light image of the AGN to 0.4% of the diffraction limit would allow sending a position signal to the much more distant x-ray focal plane. So there appear to be solutions to the most difficult challenges. Clearly this is very challenging, but at least it's not completely crazy.

Figure 18: This is the image of an active AGN black hole from the movie *Interstellar*. If this black hole were to be the giant black hole in the center of M87 at 15Mpc, it would take about 100nanoarcsecond resolution to capture this image. That would require a 1km Aragoscope.

Just as the search for Earths and signs of life on them is the premier piece of science in the visible band, the imaging of event horizons is a piece of science and exploration that would excite scientists and non-scientists alike around the world. Consider the recent movie *Interstellar* wherein the heroine does a close orbit around a black hole and the hero actually falls in. In Figure 18 we reproduce some artwork from that movie showing an artist's conception of what that accretion disk would look like, based on the calculations of Kip Thorne and others.

An Aragoscope has the long term potential to capture that image without waiting for five dimensional beings to put a wormhole near Saturn.

VI. The No-Cost Extension Period

When we started writing this document we had envisioned it as a final report on our Phase I efforts. But as the document came together we realized that there were important areas of study that were incomplete. We did not feel comfortable with the level of quantitative analysis that had been completed, and as a result, the direction an optimal design should take was too undefined. So we decided that the best course of action was to delay the submission of the Final Report until next year.

We have used the additional time to come to terms with the practicality of the Aragoscope. While it is clear that the Aragoscope has great potential, there were a variety of solutions to the collecting area problem and no one of them stood out as obvious. So we have looked, instead, at the most likely architecture that could be implemented by NASA in the foreseeable future. And that means Starshades.

Starshades are now, ten years after the end of their NIAC study, becoming the odds-on favorite for the next exoplanet mission. A starshade involved a large diffractive optic that can formation fly with a telescope. As such, converting a starshade to a high resolution imager is the most likely path to an Aragoscope. One could easily envision apertures in the starshade that could be opened when imaging mode was desired. A full ring on a 50m diameter starshade would give resolution of two milliarcseconds, which is fifty times better than Hubble. A single ring could give 6cm^2 of effective area and a 100x100 resolution element image in a 2.4m telescope like WFIRST. This would allow unique new images on bright targets.

But, of course, one would like more collecting area. This can be achieved by opening multiple rings on different Fresnel zones. This would cause some chromatic diffraction rings, but those can be handled in the data analysis. Since the collecting area would rise as the number of rings squared, even a dozen rings could put one in reach of fainter and more interesting targets.

In summary, we feel a study of a limited Aragoscope on a starshade to improve the return of the mission is worth a study. At this time we expect to propose such an architecture study for Phase II at the next opportunity.