White light demonstration of one hundred parts per billion irradiance suppression in air by new starshade occulters

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ABSTRACT

A new mission concept for the direct imaging of exo-solar planets called the New Worlds Observer (NWO) has been proposed. The concept involves flying a meter-class space telescope in formation with a newly-conceived, specially-shaped, deployable star-occulting shade several meters across at a separation of some tens of thousands of kilometers. The telescope would make its observations from behind the starshade in a volume of high suppression of incident irradiance from the star around which planets orbit. The required level of irradiance suppression created by the starshade for an efficacious mission is of order 0.1 to 10 parts per billion in broadband light. This paper discusses the experimental setup developed to accurately measure the suppression ratio of irradiance produced at the null position behind candidate starshade forms to these levels. It also presents results of broadband measurements which demonstrated suppression levels of just under 100 parts per billion in air using the Sun as a light source. Analytical modeling of spatial irradiance distributions surrounding the null are presented and compared with photographs of irradiance captured in situ behind candidate starshades.

Keywords: starshade, occulter, irradiance suppression, New Worlds Observer, extra-solar planets, exo-planets

1. INTRODUCTION AND TEST OBJECTIVES

Light occulters of new shapes have been conceived which provide significant regions of space in their geometric shadows in which very deep suppression of irradiance occurs, even in broadband light. Dubbed starshades, these occulters would hopefully provide a means to suppress light from a star so that planets around that star (exo-planets) could be directly imaged by a space telescope of modest size and quality. Suppression levels of at least eight orders of magnitude with goals of ten would be required for direct imaging of Earth-like planets at a distance of 10 parsecs.

As proof-of-principle for a proposed new mission called the New Worlds Observer (NWO), tests have been conducted in the laboratory at the Center for Astrophysics and Space Astronomy (CASA) at the University of Colorado to determine how deep a suppression of broadband irradiance in the plane of the starshade itself can be achieved in the geometric shadow of the starshade using scaled-down devices. The objective of the tests described here was to build small, anatomically-correct starshades of candidate shapes, expose them to a beam of light like that from a star, and measure the suppression of irradiance to levels as low as one tenth of a part per billion.

2. CONSIDERATIONS FOR TEST CONFIGURATION

2.1 Test Layout

A simplified layout of a suitable test configuration is shown in Figure 1. Light from a source passes through a small aperture some distance from the starshade, simulating a star. The greater the distance from the aperture to the starshade, the more plane-wave-like is the light reaching the starshade. Also, the smaller the entrance aperture, the smaller the apparent angular extent of the source and thus the more star-like it is. The starshade is suspended in the beam some distance from the source by as little structure as possible to prevent that structure from diffracting or scattering light into the irradiance null behind the starshade. A scanning photometer in the observation plane on the other side of the starshade from the source measures the irradiance pattern in that plane.

A dark tunnel created by erecting a frame of PVC pipe covered with two layers of 150 micron thick, black, sheet polyethylene blocked external stray light from spoiling the measurement and enclosed the measurement volume, allowing dust particles which would scatter light into the photometer and spoil the null to settle out over time. In the facility available for the experiment, the total distance from the entrance aperture to the photometer within the dark tunnel was roughly 42 m. The internal height and width of the tunnel were 2 m and 1.8 meters, respectively. Distances from entrance aperture to starshade ranging from 23 m to 34 m were used with corresponding distance from the starshade to the detector of 19 m to 8 m, respectively. For those source distances, a 1 mm pinhole had an angular extent of roughly 6 – 9 arcseconds.

2.2 Measurement Feasibility: Photometric Flux Budget

It is immediately obvious that measuring optical flux at a part per billion level of some incident flux requires both a very intense light source and a very sensitive light detector. To determine whether a system which would accurately measure irradiance over ten decades of dynamic range would be feasible, we developed a flux budget in which it was convenient to explore that dynamic range using the properties of the brightest, most readily available, broadband light source – the Sun – and those of the most sensitive type of optical detector – a photon counting photomultiplier tube (PMT) as a baseline. A photon counting system already in hand with a PMT having a bi-alkali photocathode (most sensitive to near UV, blue, and green light) would be used in this study.

We start by estimating how much solar flux within the spectral response range of our PMT we can expect to come through our system's entrance aperture, assumed for now to be a 1 mm^2 pinhole. The mean bolometric flux from the Sun – assumed to be a 6000 K blackbody – outside the Earth's atmosphere is roughly 1.35×10^3 W/m^2. This is our starting point for estimating what irradiance will actually be measurable in the plane of the starshade.

Using the Planck radiation formula[1] to estimate what fraction of that bolometric energy is within the spectral band of our measurement (350 nm, limited by the building's windows, and 550 nm, limited by the long wavelength spectral response of the PMT's photocathode), we calculate that 25% of the exo-atmosphere solar flux or 3.3×10^2 W/m^2 is within our measurement passband. We must further de-rate this value by the transmission of the atmosphere over that passband as well as by the estimated transmission of the building's windows and our feed optics. To be conservative in our budget, let us suppose that only 30% of that available flux makes it through the atmosphere, through the building window, is reflected off of our three flat fold mirrors and passes through our entrance aperture. This means that the irradiance at our entrance aperture is about 100 W/m^2, and a paltry 1×10^{-4} W will pass through our 1 mm^2 aperture within our measurement passband.

At a distance from the pinhole to the photometer of 42 m, and considering the divergence angle of light from the Sun passing through the pinhole (~9 mrad), the area covered by our 0.1 mW of energy is a circle roughly 0.37 m in diameter having an area of about 1.1×10^5 mm^2, giving an irradiance at the starshade of 1×10^{-9} W/mm^2. If the aperture in front of our photometer has an area of roughly 4 mm^2, then the photometer will collect 4×10^{-9} J/s when it looks directly at the Sun through the 1 mm^2 entrance aperture. The typical photon energy in our passband is about 3 eV or 4.8×10^{-19} J, so the photometer collects approximately 8×10^9 photons per second.

The typical quantum efficiency of our PMT over the measurement passband is roughly 0.2, so that the highest count rate we can expect to register is of the order of 1.6×10^9 counts per second using the apertures we have assumed. If we were to increase the size of our entrance aperture to 3 mm in diameter and the size of our detector aperture to 6.3 mm^2, we would boost that signal to about 2.3×10^{10} counts per second. This implies that if the photometer were positioned in the null of the starshade and that null were 10^{10} deep, then we would have a signal of 2.3 counts per second which would be difficult to measure meaningfully over the 200/s dark count rate of our photon counting system. Meanwhile, we can distinguish between the PMT's dark count rate and a measured limiting count rate of about 240/s (40/s above the dark rate) with a signal-to-noise ratio of unity. So, we should be able to barely measure an irradiance suppression ratio of 20×10^{-10} with an integration time of one second or 2×10^{-10} with an integration time of ten seconds. If the null were only 10^8 deep, then we would have a signal of 230 counts per second above dark which is readily measurable with our photon counting system.

For the sake of measurement linearity with our photon-counting system, we would like to limit our peak count rate to roughly 1.5 x 10^5/second. Therefore, when the photometer is looking directly at the entrance aperture with the starshade in the way, we require a neutral density attenuator in front of the PMT with a transmission of about 1 x 10^{-5}.

2.3 Stray Light Suppression

Even the slightest amount of stray light can spoil a measurement of irradiance suppression at the 0.1 parts per billion. For this reason, control of stray light in the setup is paramount in importance. While the design of the photometer itself is chiefly responsible for stray light control (discussed in Section 3.2), there are a couple of obvious measures taken in the layout of the measurement setup which helped to control stray or re-entrant light. The dark tunnel constructed of black sheet plastic is well oversized compared to the size of the naturally diverging beam of sunlight traveling down its length, there is essentially no structure for the beam to reflect off of. Light striking the source side of the starshade is specularly reflected back into that incident hemisphere and is dumped in the black tent material out of the direct view of the photometer.

3. APPARATUS

3.1 Heliostat

The Sun makes an ideal light source for these measurements for several reasons. Fundamentally, it is the most intense, – and in Colorado, one of the most reliable – sources of broadband light available with a spectral emission well-matched to the spectral sensitivity of the photometer PMT's bi-alkali photocathode. When passed through a small pinhole aperture, the natural divergence angle of the Sun's light (roughly f/110) obviates the use of baffles to prevent stray light in the setup. Simply letting the light beam propagate in an open tunnel results in no scattering edges being directly illuminated within view of the photometer.

In order to use the Sun as a source to make measurements which take the better part of an hour to complete, however, a heliostat which tracks the Sun and feeds its light continuously to the experiment is required. We constructed a heliostat by retrofitting a commercially-available, motorized, fork-mounted telescope with a flat folding mirror in place of the telescope tube to guide the Sun's light along a fixed vector direction, replicating the existing mechanical interfaces on each side of the mount's declination axis. Additional, fixed, fold mirrors were used to steer the light through the pinhole at the entrance to our dark tunnel.

Figure 2 shows the telescope mount and a solid model of the cradle which holds the plane of the flat fold mirror so that it contains the mount's declination axis and is centered on mount's right ascension axis. Figure 3 shows the completed heliostat folding Sunlight to the first fixed fold mirror. The heliostat is placed as close as can be to the window and is azimuthally oriented due celestial South as well as possible. The default drive rate of the heliostat which is sidereal is close enough to the solar rate that only occasional tweaks to heliostat tracking are required during the time needed to make even a detailed raster map of irradiance behind the starshade. A user may slew and make fine adjustments to tracking by pressing or tapping up/down and left/right buttons on a pendant control. The direction of sunlight passing through the illumination system is maintained by the proper tracking of the Sun by the heliostat.

A small pickoff mirror is placed adjacent to the entrance pinhole outside the tent, and the sunlight it picks off is folded twice so that it propagates along the tent's length outside the tent to a screen at the operator's station. This allows the operator to adjust tracking during a raster scan of irradiance with the pendant control attached to the heliostat using a long extension cable. The pattern of sunlight on the screen is essentially identical to that at the detector assembly inside the tent except that there is no starshade in the beam outside the tent. A baffled, silicon photodiode located at the center of the pattern stares back into the Sun beam to monitor and record the flux over time. Each photometer reading is normalized to the available sun flux at the time the reading was made.

3.2 Photometer

Figure 4 is solid model rendering illustrating the anatomy of the photometer. The main elements of the photometer are the large beam dump with small entrance aperture, an iris which limits the photometer's view volume, a motorized wheel containing calibrated neutral density filters, a photomultiplier tube (PMT), and a motorized X-Y stage. The top edge of the light dump was hinged so that it could be lifter and propped up, and a thermo-electrically cooled CCD camera could image the starshade and its support wires as well as the photometer's view volume from the location of the irradiance null. The treatment of image data obtained with the camera is described in Section 6.

The two axis, X-Y stage driven by stepper motors have 150 mm of travel and 0.025 mm resolution in each axis and is arranged to allow the entire photon-counting photometer to be raster-scanned through the irradiance null behind the starshade in a plane parallel to gravity. The entire photometer assembly was mounted on a stand adjustable in height, transverse position, pitch and yaw to allow boresighting of the photometer's line of sight with the starshade and the entrance aperture before measurements commenced.

The beam dump consisted of a pyramidal cavity with a pyramidal cone emanting from its center and sticking out a few cm in front of the cavity. The cavity was oversized to accept the entire beam from the Sun regardless of the photometer's scan position. All surfaces (inner and outer) surfaces of beam dump are covered with self-adhesive, black flocked paper. The pyramidal foil piece on the front of the beam dump has its tip cut off to create a square entrance aperture roughly 2.5 mm square. That piece is the farthest forward part of the detector assembly so that light which does not pass through the aperture specularly reflects into the beam dump and undergoes at least two diffuse reflections inside the steep walls of the black cavity.

Once the light has passed through the photometer's entrance aperture, it passes through a second aperture sized to create an acceptance cone which when projected to the plane of the starshade, covered an area about four times the diameter of the starshade. This aperture limited the volume of air and dust particles which could errantly scatter light into the photometer while assuring that the entire starshade would be in view at any scan position. Any light passing through both apertures was assumed to be valid flux coming from the starshade or its supporting wires. A wheel of calibrated, neutral density attenuators was placed immediately behind the internal aperture to adjust the count rate in the photometer.

3.3 Starshade Mounting

A wooden frame mount was built to support the starshade under test. Each starshade was suspended from the frame in the Sun beam from three 80 micron diameter, nichrome wires. The frame was large enough to allow great clearance for the Sun beam (Figure 5). The frame also allowed adjustability of the position of the starshade within the frame, including the clocking angle of support wires so that the projection of the wires could pass through the sharp tips of these petal-shaped occulters.

3.4 Automated Instrumentation

A system block diagram of the measurement instrumentation is shown in Figure 6. The stepping motor controllers, the digital voltmeter, and the frequency counter are all controlled with a PC. A silicon photodiode read out by an optical power meter is located adjacent to the entrance pinhole to the measurement system. Its purpose is to monitor the real time flux level from the Sun associated with measured PMT counts at each position in the irradiance map. It produces a voltage proportional to incident flux that is logged by the digital voltmeter.

Light levels incident on the photometer at any moment were maintained in a range where count rates were as high as possible for optimized counting statistics but below some value above which the risk of pulse pile-up – resulting in non-linearity – would occur. This was achieved through software interchange of the selection of neutral density filters in a motorized wheel just in front of the PMT inside the light dump. At each stop of the XY stage, the PC initiates an integration of counts from the PMT and logs the counts before moving to the next position. If the counts are outside of high or low flux limits, the PC commands a change of beam attenuators to either decrease or increase counts, respectively, for the current position before moving to the next position.

The neutral density filters were calibrated in situ in a measurement which not only established their broadband transmission relative to one another with the Sun as a light source and the PMT as the detector, but with a wide range of light levels which permitted the establishment of the range of count rates which would ensure linearity. Measurements of flux recorded at each raster scan position using the pulse counter were tagged with time, date, available Sun flux, photometer integration time, and attenuator selection so that a properly normalized map of irradiance could later be re-constructed.

4. TEST ARTICLES

The best starshades we tested for New Worlds Observer were made by NIST/Boulder using deep reactive ion etching (DRIE) of a silicon wafer. Two starshades were tested – one with 42 petals and one with 16 petals. The first test article was about 25 mm tip-to-tip (two times the r_2 dimension in Figure 7). This delicate test article was supported in the light beam by very fine wires clamped to a small puck bonded to the back of the starshade (Figure 8). Each starshade was coated with opaquely coated with aluminum to make sure that the shade was truly opaque so that any sort of leakage would not spoil the measurement. The mathematical form of the petals is discussed in another paper at this conference.[2]

5. TEST RESULTS

The highest, raw suppression ratio measured under the best of conditions was about 8 x 10^{-7} using a Si starshade having 16 petals. Metal starshades made by electroforming performed at the few times 10^{-6} level. It is believed that their shapes were not as well controlled as their Si counterparts as their petal shapes were composed of a small number of line segments instead of smoothly varying curves.

There are numerous sources of stray light which can spoil the null including: a) light glinting off of starshade support structure, wires, etc.; b) light glinting off of dust attached to the starshade; c) light scattering off of aerosol within the view volume of the photometer; d) light diffracting around broken tips or valleys or defective edges of starshade petals; e) light bouncing off of the source side of the starshade to structures within view of the photometer; f) light escaping the light trap on the photometer and scattering off the back of the starshade and starshade support structure; g) light from the diffuse sky component surrounding the Sun and illuminating things within view of the photometer.

Photos taken with the CCD camera stationed at the null location reveal from where and in what proportion light which the photometer detected at that location came from for at least some of these listed items. A careful accounting of the image brightness from things like dust particles along petal edges, glints from particles and defects along starshade support wires, and diffracting around obviously broken petal tips allow a more favorable suppression value to be derived as we can surmise how much light collected by the photometer came from defects which would not have otherwise contributed to spoiling the null signal in the photometer. After accounting for defects and contamination, a suppression value of just under 1 x 10^{-7} or 100 parts per billion was realized for the 16 petal Silicon starshade. This level of suppression is referred to the detector plane in this experimental arrangement. The suppression is nearly a factor of 2.3 more promising if referred to the plane of the starshade, as irradiance falls of as $(1/\text{distance from the source})^2$ in this arrangement. On station in flight, incident irradiance from a star at the starshade and at the telescope would be essentially the same.

The signal detected in the null carried an uncertainty of approximately 3%. The uncertainty of the attenuation value used when the photometer stares directly at the Sun beam is approximately 10%. The estimated uncertainty in the accounting for flux seen by the photometer from defects and contamination is approximately 30%. So, the estimated rms uncertainty of the measured suppression ratio is roughly 30% .

It is believed that the suppression level measured at CASA was limited by scatter of sunlight by illuminated aerosols within the view volume of the photometer. Although, the signal to noise ratio of the CCD camera imagery is insufficient to quantify this diffuse effect, one can place one's dark-adapted eye in the location of null and look back at the starshade and see the glowing aerosol column illuminated by the expanding cone of the Sun's light. This visual observation motivated the adaptation of the experimental setup to a long vacuum tank at the National Center for Atmospheric Research (NCAR) in Boulder, CO to repeat these measurements in the absence of aerosol scattering. These studies are going on as of this writing.

6. CONCLUSIONS

High fidelity miniatures of new candidate starshade shapes have been fabricated. A measurement system has been developed having the capability to measure suppression of irradiance in the null behind a starshade of roughly one part per billion. Candidate starshade were found to perform to levels of around 100 parts per billion in air when immersed in broadband light from the Sun.

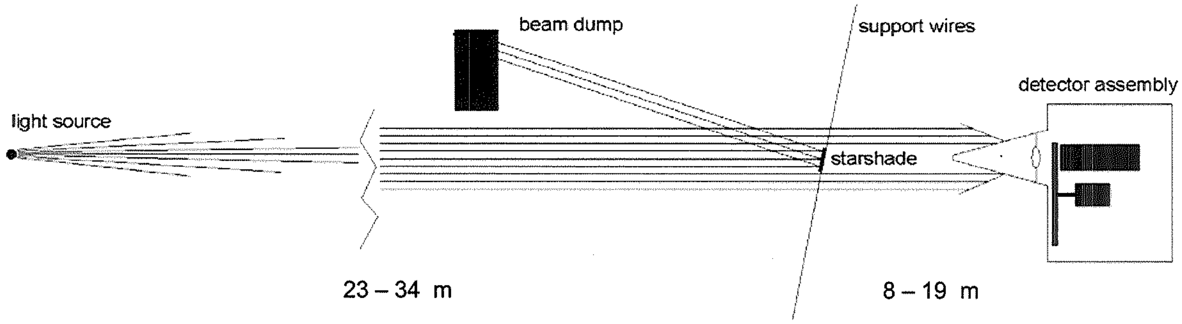

Figure 1 – basic layout of test configuration for measuring irradiance suppression in geometric shadow of starshade occulters (null)

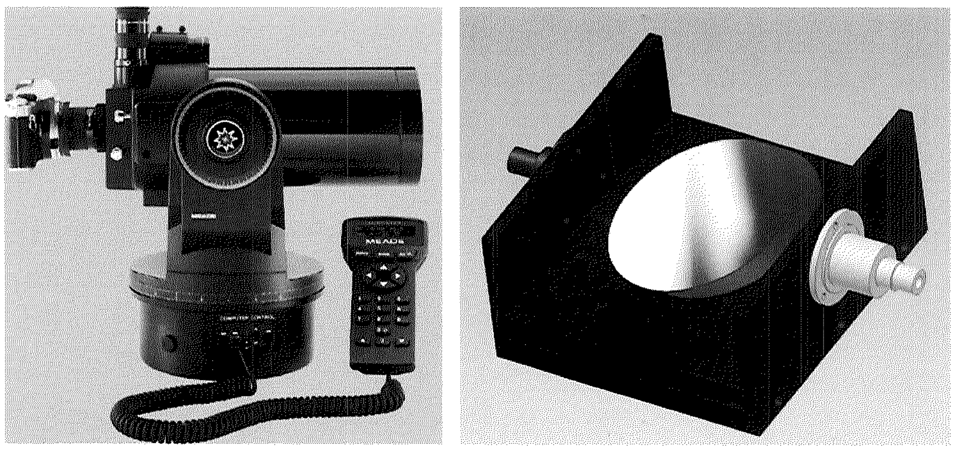

Figure 2 – L) Commercial, motorized telescope with control pendant; during measurements, pendant is extended to a remote location using an ordinary ethernet cable with RJ-45 connectors at each end; external DC power is fed to the drive unit using the connector just right of the pendant connection; R) solid model of cradle built to go between telescope forks replicating the mechanical shaft features of the original telescope assembly (removed); the plane of the flat elliptically shaped mirror is adjusted so that the declination axis passes through that plane; it is also positioned so that the polar axis passes through aperture center

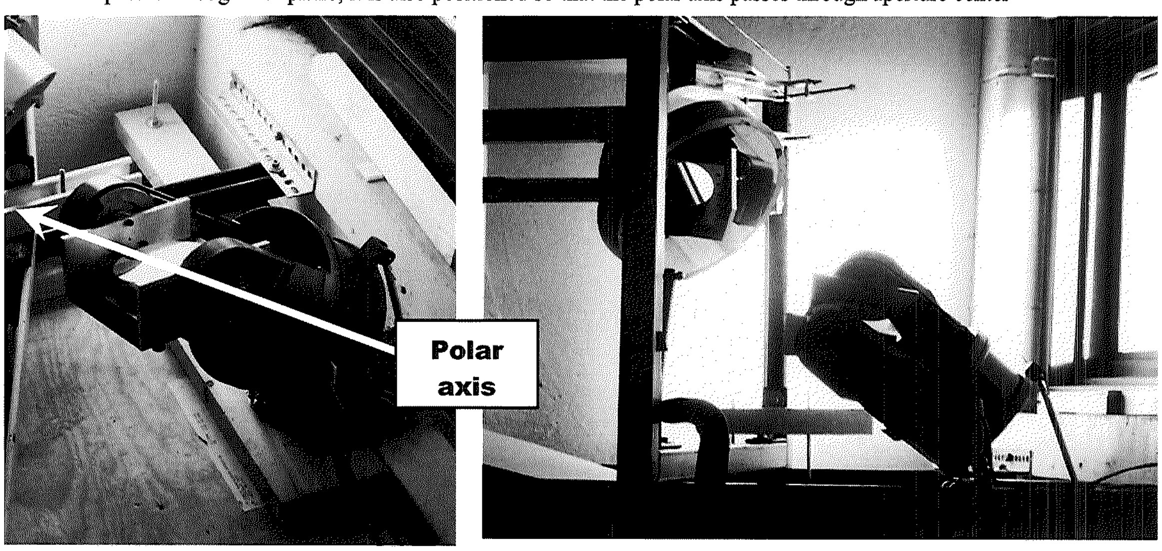

Figure 3 – L) completed heliostat assembly built from commercial motorized telescope mounted in front of a South facing window; R) large flat mirror M2, suspended from a steel frame folds beam from heliostat down and toward entrance aperture to dark tunnel

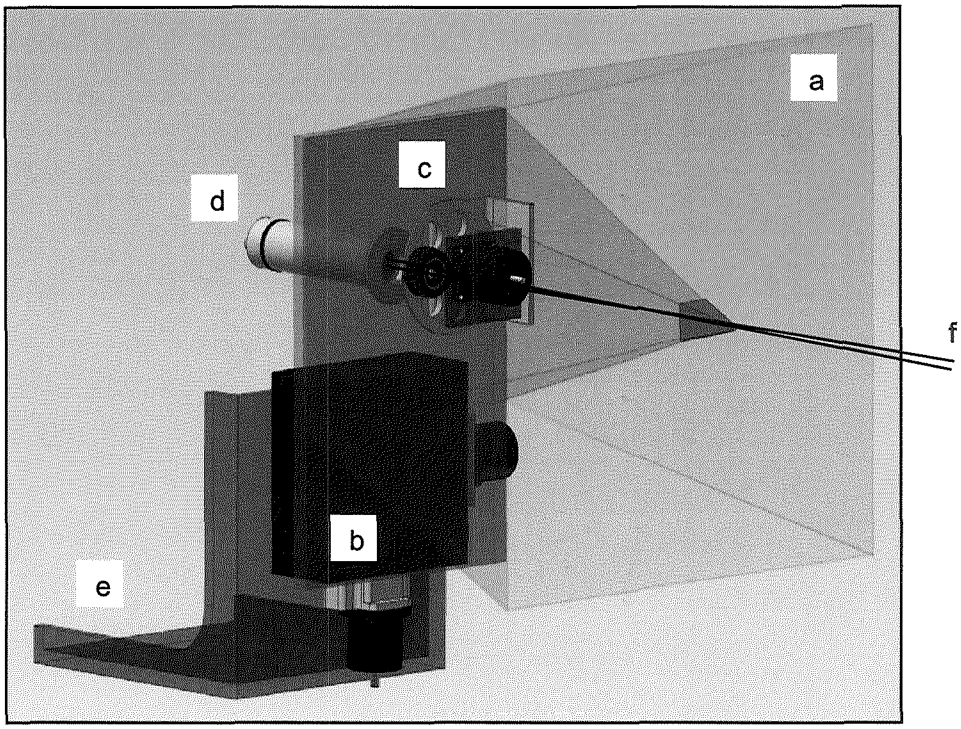

Figure 4 – solid model of photometer assembly: a) light dump (transparent grey pyramidal cavity) with pyramidal aluminum foil entrance aperture tip (black rays crossing at tip define acceptance cone of photometer); b) stepping motor driven X-Y stage (solid black attached to right angle support bracket) moves entire photometer in a plane parallel to gravity; c) motorized, detented attenuator wheel (grey) and iris assembly inside light dump in front of d) pulse counting photomultiplier tube (PMT) (light grey cylinder); X-Y translation stage has 150 mm of travel; e) support bracket; f) black rays depict photometer's angular acceptance

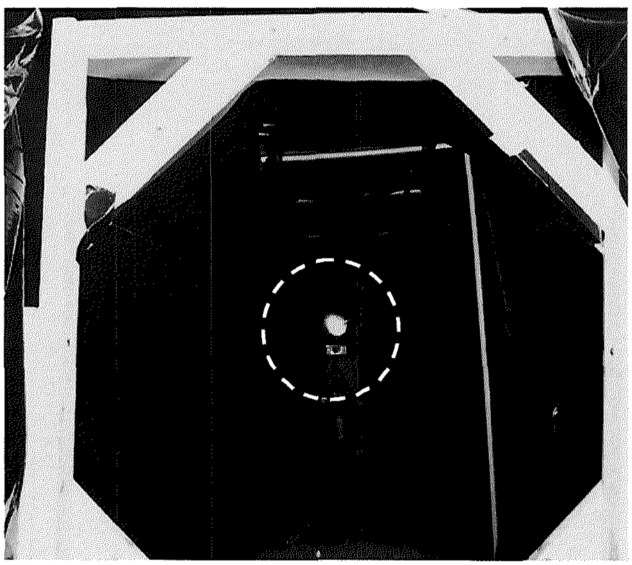

Figure 5 – starshade suspended in beam path by three, fine nichrome wires from custom-built, adjustable wooden support frame; beam diameter from Sun at starshade is indicated by dotted circle

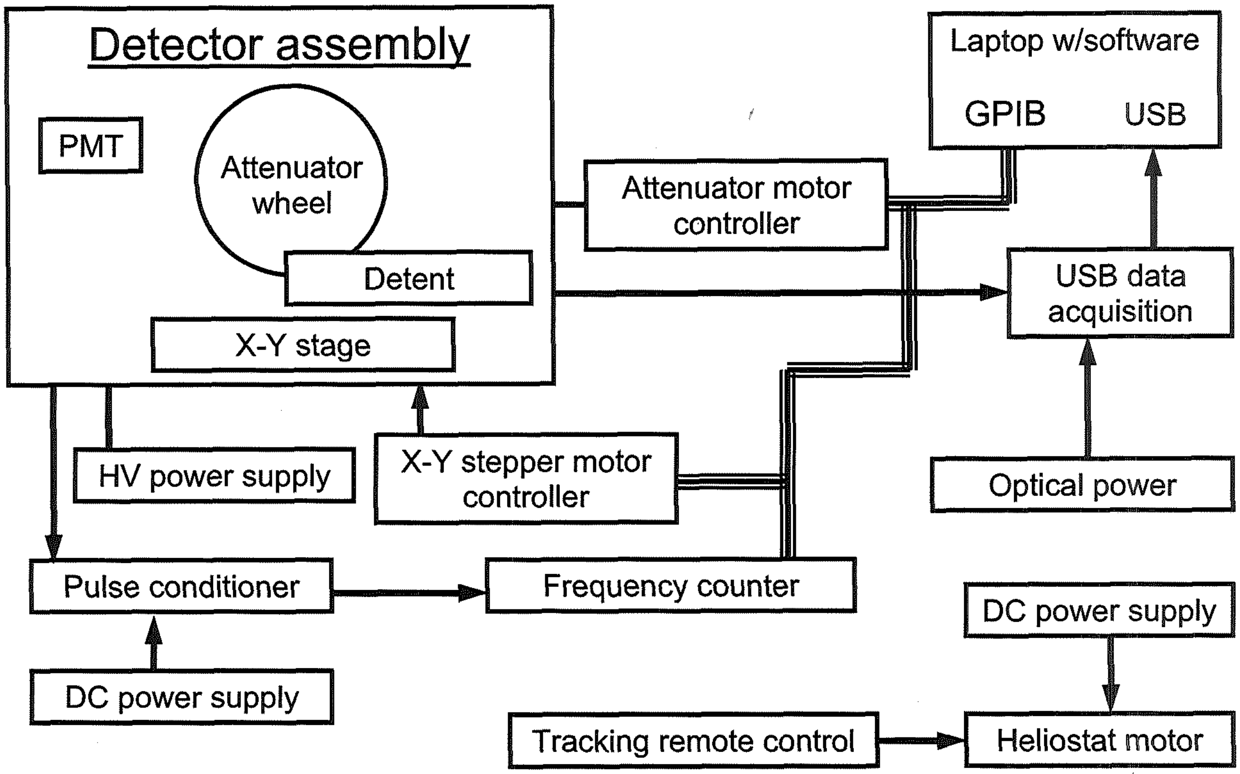

Figure 6 – instrumentation block diagram for starshade irradiance mapping

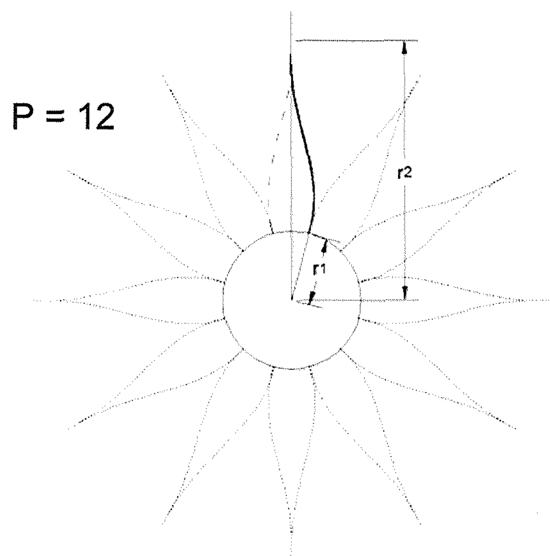

Figure 7 – sketch of test article illustrating sizes r1 and r2, distance from center to beginning of petals and distance from center to tips of petals, respectively

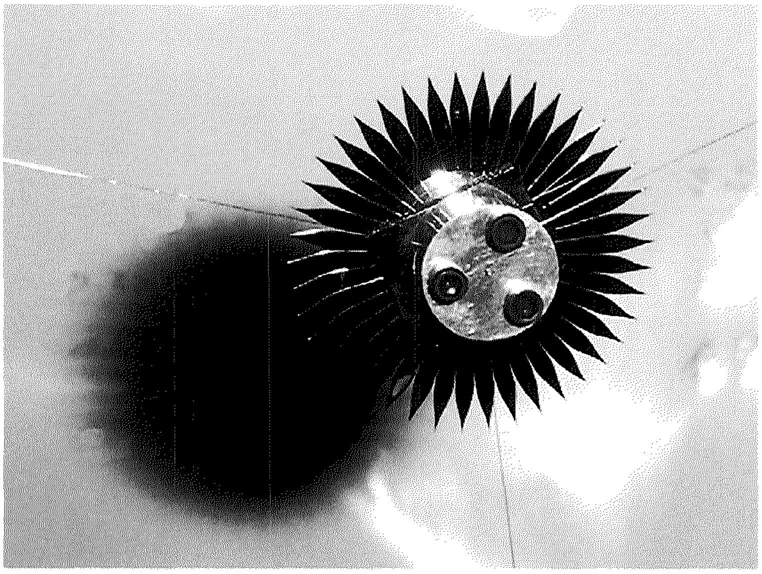

Figure 8 – 42 petal Si starshade supported by fine fires clamped to a puck bonded to the back of the starshade

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