

# Astronomical telescope with holographic primary objective

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## ABSTRACT

A dual dispersion telescope with a plane grating primary objective was previously disclosed that can overcome intrinsic chromatic aberration of dispersive optics while allowing for unprecedented features such as million object spectroscopy, extraordinary étendue, flat primary objective with a relaxed figure tolerance, gossamer membrane substrate stowable as an unsegmented roll inside a delivery vehicle, and extensibility past 100 meter aperture at optical wavelengths. The novel design meets many criteria for space deployment. Other embodiments are suitable for airborne platforms as well as terrestrial and lunar sites. One problem with this novel telescope is that the grazing exodus configuration necessary to achieve a large aperture is traded for throughput efficiency. Now we show how the hologram of a point source used in place of the primary objective plane grating can improve efficiency by lowering the diffraction angle below grazing exodus. An intermediate refractive element is used to compensate for wavelength dependent focal lengths of the holographic primary objective.

**Keywords:** holography, telescope, dispersion, astronomy, spectroscopy

## 1. INTRODUCTION

Telescopes with diffraction optical element or holographic optical element primary objectives could overcome some obstacles facing the deployment of large aperture space telescopes. For the past decade we have examined architectures that exploited grazing exodus configurations of primary objective diffraction gratings that lend themselves to ribbon-shaped primary objectives.<sup>1-10</sup> We have shown that the surface figure tolerances for such primaries are remarkably forgiving, fostering speculation that tension structures with areal mass of less than 1 kilogram/sq. meter can be achieved.

Related diffractive telescope primaries have been disclosed that are based on photon sieve optics.<sup>11,12</sup> Unlike our grazing exodus designs that diffract sideways, photon sieve designs presume axial focusing like lenses. With our designs or the photon sieve two problems are evident: throughput efficiency and chromatic aberration.

### 1.1 The Dittoscope

As originally disclosed, our grazing exodus design, dubbed the “Dittoscope,” cannot suffer significantly from lateral chromatic aberration *per se*, because the instrument is intrinsically dispersive. This immunity to chromatic aberration is possible, because the broad chromatic dispersion of a dispersive diffraction grating primary is exploited rather than suppressed. A double dispersion optical train segregates each source in the field-of-view by wavelength. Observations are made by scanning sequentially over resolved sources to assemble spectrograms temporally.

However, with the original Dittoscope design there is a trade-off with efficiency, because diffraction efficiency is minimal at grazing exodus, that is, angles  $>88^\circ$  that are subtended between the primary objective grating surface normal to the secondary telescope. While it is true that as the angle of diffraction increases, the allowable length of the primary objective increases exponentially, increasing flux collection, grating efficiency decreases and arrives at zero efficiency precisely when the primary has no limit to its length at the grazing angle of  $90^\circ$ .

Loss of efficiency is not a show-stopper for a grazing exodus design, because the potential increase in primary objective area runs ahead of losses due to decreased efficiency. In Fig. 1 we show the predicted efficiency of a 555.5 nm reflection grating with a groove depth of 280 nm for grazing angles subtended from  $90^\circ$  to  $85^\circ$ . We also predict that grazing exodus is highly polarizing with the losses in the electric transverse wave reducing the average polarization by half. Even more dramatic are predicted overall losses - regardless of polarization - since the efficiency drops to zero at  $90^\circ$ .

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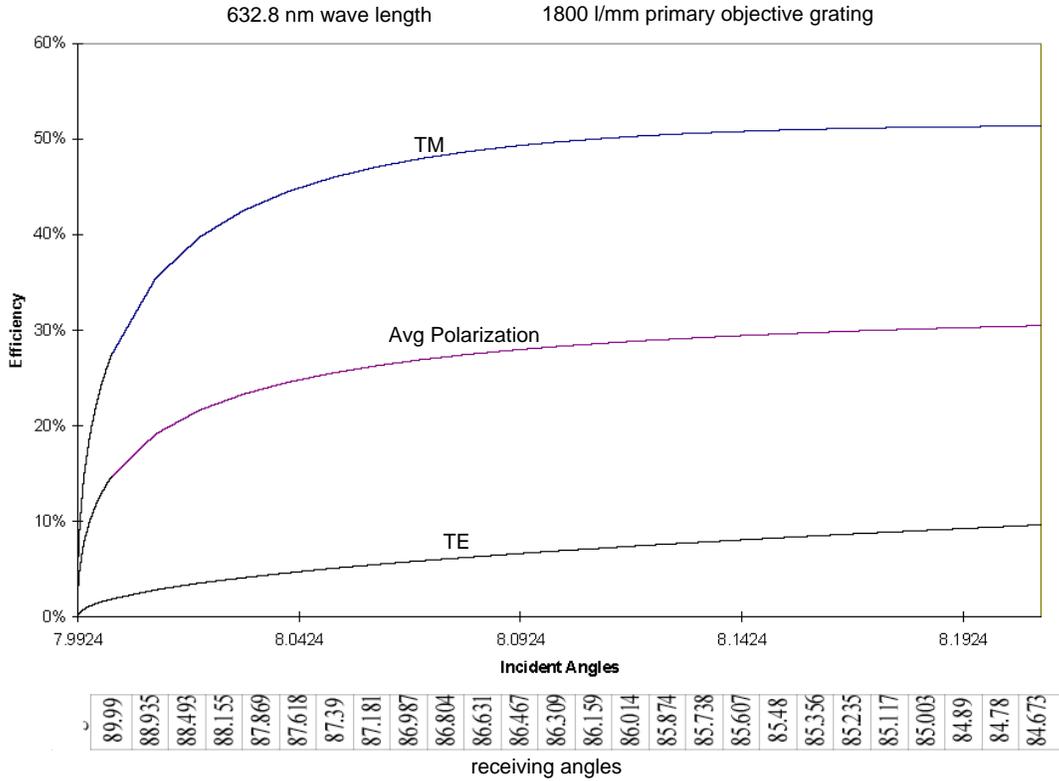


Figure 1. PCGrate® prediction of the HeNe line near grazing exodus for a 555.5 nm Primary Objective Grating

The maximum length  $L$  of a Primary Objective Grating (POG) is determined by the receiving angle  $r$  and the diameter of the secondary mirror  $D$ , Fig. 2. The dependency is

$$L = \frac{D}{\cos(r)} \quad (1)$$

Telescope magnification derives from Eq. (1). To identify the parameters, consider how grating length  $L$  grows with the angle of grazing exodus  $r$  for a fixed diameter  $D$  of secondary mirror, as illustrated in Fig. 2. In the example graph of Fig. 3, the secondary mirror is modeled to be 2 meters. Kilometer scale length for a POG can be achieved at grazing exodus of 89.881°.

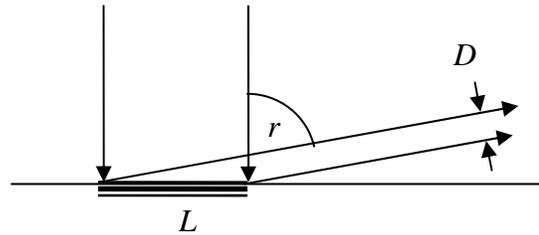


Figure 2. POG length  $L$ , mirror dia.  $D$  and  $r$ .

We define the effective efficiency  $e_f$  as the product of POG length  $L$  and the efficiency,  $e$ , divided by the mirror diameter  $D$ . This can be understood as the monochromatic flux ratio between the POG as the collecting aperture and a telescope of diameter  $D$ .

$$e_f = \frac{eL}{D} \quad (2)$$

It might seem that lowering of efficiency by pushing the grazing exodus to maximize length would defeat the goal of increasing flux collection. However, the available flux keeps growing. As shown in the graph of Fig. 4, even while efficiency drops toward zero, gain keeps growing. Despite the efficiency loss with increases in grazing angle, the benefit of increasing POG length is not overridden.

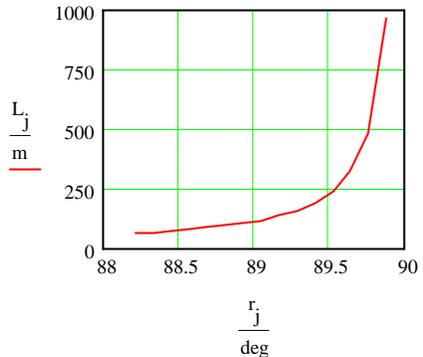


Figure 3. Length  $L$  vs grazing angle  $r$

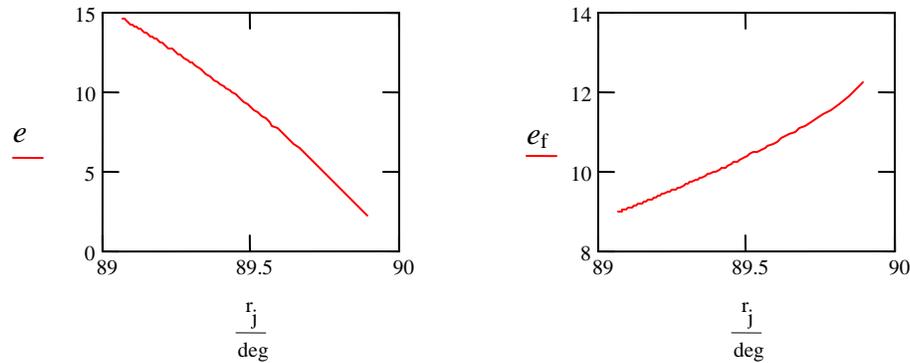


Figure 4. Comparison of loss of efficiency with continuing gain as function of grazing angle

### 1.2 Fixed pitch POG

As originally proposed, the Dittoscope concept assumed a fixed pitch POG, i.e., a plane grating. A benefit included simplicity of fabrication. Strips of diffraction grating are routinely manufactured by roll embossing, and kilometer scale lengths at 2 meter width are commercially available today. A cylindrical roll of the diffraction grating primary objective is compatible with payload bays of conventional lift vehicles.

Research can be scheduled with reasonable confidence notwithstanding an architecture with this degree of novelty. The specification of a secondary that is nothing more than a conventional spectrographic telescope also allows for a direct demonstration of the concept. If the mirror of the secondary telescope was in the two meter class, the mirror would also conform to lift vehicle fairing dimensions. Such space telescopes, including the Hubble, have been deployed over the past decades. Know-how for that component, an astronomical spectrographic telescope, is at a high level of practice. Conceptual ground testing would require little more than pointing an existing telescope at the ground along either an east or a west orientation at a POG placed parallel to the ground at a grazing angle.

Plane gratings with sinusoidal grooves are bilaterally symmetrical. Radiation is received in two directions but inversely by wavelength as per Fig. 5. Spectrographic telescopes can be placed on either end of the POG thereby doubling flux collection. The temporal assembly of spectrograms allows for each source to be seen twice, each at a separate time. For terrestrial installations, the dual reception allows for corroboration of flux intensity, because the lack of a match suggests variations in atmospheric absorption due to limits in seeing. This cross-correlation is a useful means of error detection.

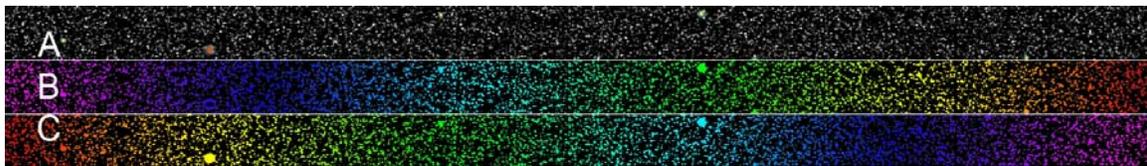


Figure 5. Star field A is acquired by opposed mirrors in reverse spectral sequences B and C

In space deployment, ballast provided by secondaries at the *extrema* contributes to spacecraft inertial stability, Fig. 6.

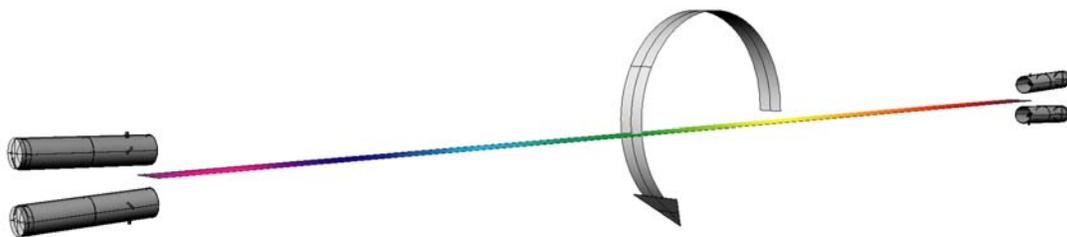


Figure 6. "The Boloscope," a rotating platform with two-sided POG, illustrated with symmetrical secondaries

## 2. PRIMARY OBJECTIVE HOLOGRAM

A motivation for using the grazing exodus configuration in a plane grating objective version of the Dittoscope is to maximize POG length. The increased area offers greater collection, and the increased length improves angular resolving power. With projects for extremely large telescopes aimed at apertures of 30 meters as well as some deferred projects that flirted with 50 and 100 meters, the arrival of primaries at this scale has been targeted by astronomical instrument builders. Early disclosures of the Dittoscope also emphasized the unprecedented apertures that could be achieved. On the ground a Dittoscope using a secondary collector on scale with today's 10 meter mirrors, kilometer-scale POGs are reasonable to contemplate. In space, a 100 meter class geostationary earth science telescope can be foreseen.

The loss of efficiency at grazing angles, however, gives rise to consideration of large POGs made from holograms that can focus. With the benefit in ray convergence provided by a focusing primary, kilometer scale designs with receiving angles lower than grazing angles can be considered. One can surmise from the predictions shown in Figure 1 that efficiency will more than double as the angles of diffraction drop below  $89^\circ$  to  $80^\circ$ .

Diffraction gratings with curved rules and variable pitch can focus monochromatic light. Holography can be used to fabricate such diffractive optical elements. When Gabor conceived of holography it was with a wavefront that was self referential along a common axis. As demonstrated by Leith and Upatnieks, splitting a coherent source into off-axis reference and object beams overcomes an occlusion liability that seemed to limit Gabor's holography to transparent objects. In a related manner, the use of co-axial diffractive optics in primary objective telescope design, as typified by photon sieves, faces an intrinsic zero-order suppression issue, because, no matter how slight, the zero-order is on the same axis as the focused first-order image. The Dittoscope reconstructs first-order images off-axis to the side of the primary, and the zero-order transmits itself on-axis, so the two orders do not mix. That said, both photon sieves and a Dittoscope which uses a holographic primary objective share wavelength-specific focusing. Achieving a polychromatic gamut requires a secondary that accommodates chromatic aberration. The problem is addressed in Section 3.

### 2.1 Variable pitch POG

A plane grating can be realized holographically through the interference of two plane waves. We begin modeling our holographic POG by using sources at infinity. A central wavelength  $\lambda$  is chosen, and a receiving angle  $r$  is fixed. The incident angle  $i$  for the central wavelength  $\lambda$  is presumed to be at the zenith or  $0^\circ$ . The pitch  $p$  of the grating can be determined for first-order diffraction by the Grating Equation:

$$p = \frac{\lambda}{\sin(r) + \sin(i)} \quad (3)$$

By way of example, if the central wavelength  $\lambda$  is 550 nm and the receiving angle  $r$  is to be  $80^\circ$ , then the plane grating pitch  $p$  would be 558.485 nm or 1.791 lines per  $\mu\text{m}$ .

Fabrication of a primary objective holographic optical element (POHOE) can be realized by selecting two beam angles. One is at the first-order angle of reconstruction  $r$ , the receiving angle. The other can be determined as a function of the wavelength of the incident radiation. As illustrated in Fig. 7, if the receiving angle  $r$  is  $80^\circ$  and if radiation at 550 nm is incident at  $0^\circ$ , then a focusing grating can be fabricated if a plane wave of 405 nm is incident at  $-15.04818^\circ$ . We know this from the Grating Equation, because according to Eq. (3) we calculate that  $p = 558.48464$  nm for  $\lambda = 550$  nm  $i = 0^\circ$  and  $r = 80^\circ$ . Knowing  $p$  for the central wavelength, we then determine  $i$  for 405 nm by solving Eq. (3).

$$i = \arcsin\left[\frac{p \sin(r) - \lambda}{p}\right] \quad (4)$$

A plane grating can be made by the interference of two coherent plane waves of wavelength  $\lambda$  at  $i_1$  and  $i_2$  where  $i_2 = r$ . If a laser was available with a wavelength of 550 nm, then  $i_1$  would be  $0^\circ$ . With a 405 nm laser,  $i_1$  is  $-15.04818^\circ$ .

An advantage to holographic fabrication is the ability to produce a variable pitch POHOE capable of focusing. If  $i_1$  remains a plane wave but  $i_2$  is finitely spherical, the focal length along the receiving angle  $r$  is proportional to the distance of the source of illumination to the holographic plate along the axis formed by angle  $i_2$ . The construct along this axis follows the ratio of  $\tan(i_2)$ .

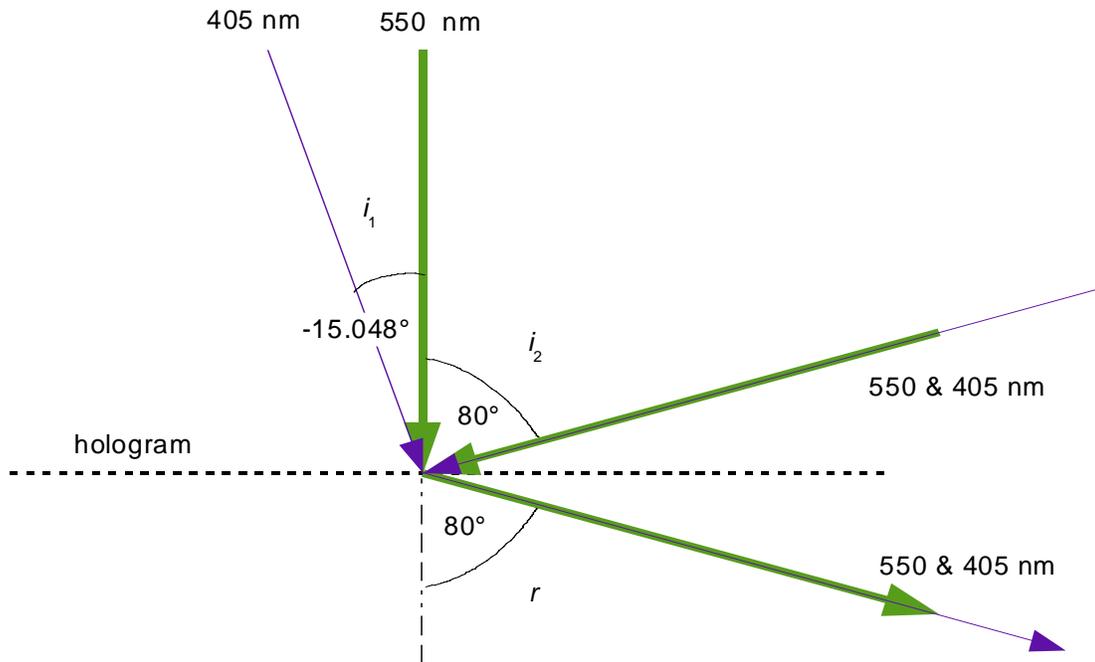


Figure 7. Construction of a hologram with 405 nm laser illumination to focus incident from angle  $i$  at receiving angle  $r$

## 2.2 Zemax model

Here we concern ourselves with the optical train up to the secondary slit of the Dittoscope. It remains to model the secondary spectrograph which might possibly take the form of an echelle or a multiple fiber fed matrix. The challenge in using a POHOE is focusing polychromatic radiation at a slit ahead of the spectrograph

We have shown that with a plane POG it is possible to differentiate wavelength as a function of the angle of incidence with a level of precision proportional to the width of a spectrograph slit. With POGs at 100 meter scale, the resolving power of a Dittoscope is theoretically within a milliarcsecond.<sup>13</sup> A Zemax rendering of a Dittoscope is in Fig. 8. The POG was modeled at a length of 400 m, the parabolic mirror (on left) is at an angle of grazing exodus of  $88^\circ$  with a 16m diameter, and the slit at the focal point of the mirror is 2 mm. The slit maps back into the sky at approximately  $0.0003^\circ$ .

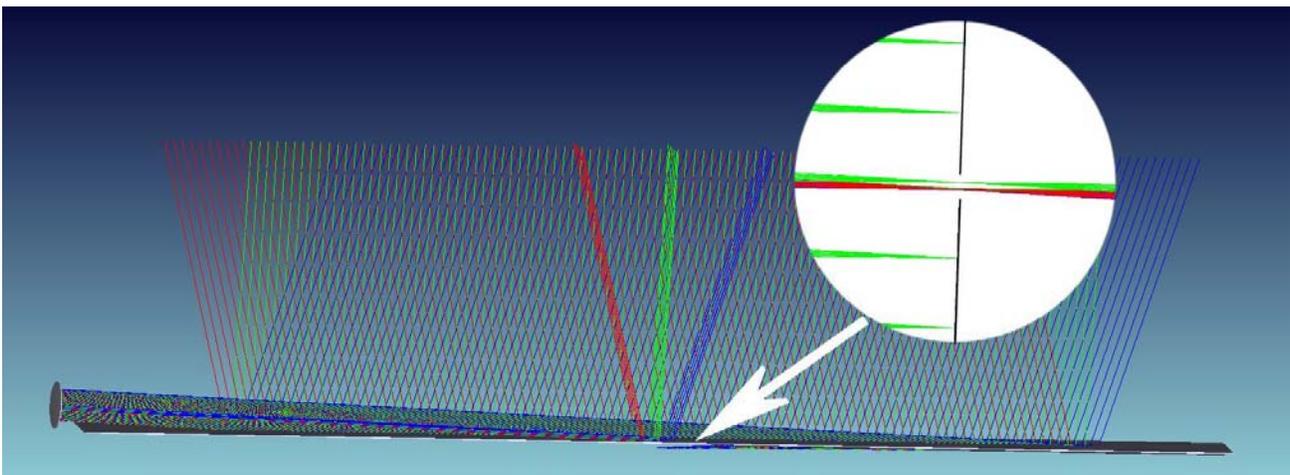


Figure 8. Dittoscope with 400 m POG. The highly magnified insert shows 3 cm detail of slit at focal point of the parabolic mirror.

A holographic POG can be modeled in theory as a 50 meter POHOE of fixed pitch by placing both sources at a great distance. The output of the POHOE is a redirected plane wave in the first-order. A parabolic mirror then focuses the wave to a slit. In the example of Fig. 8, the size of the mirror for a 50 meter primary at  $80^\circ$  is 20 meters, as opposed to the 16 meter mirror for a 400 meter POG at  $88^\circ$ . A move off grazing exodus shortens the POG and grows the mirror.

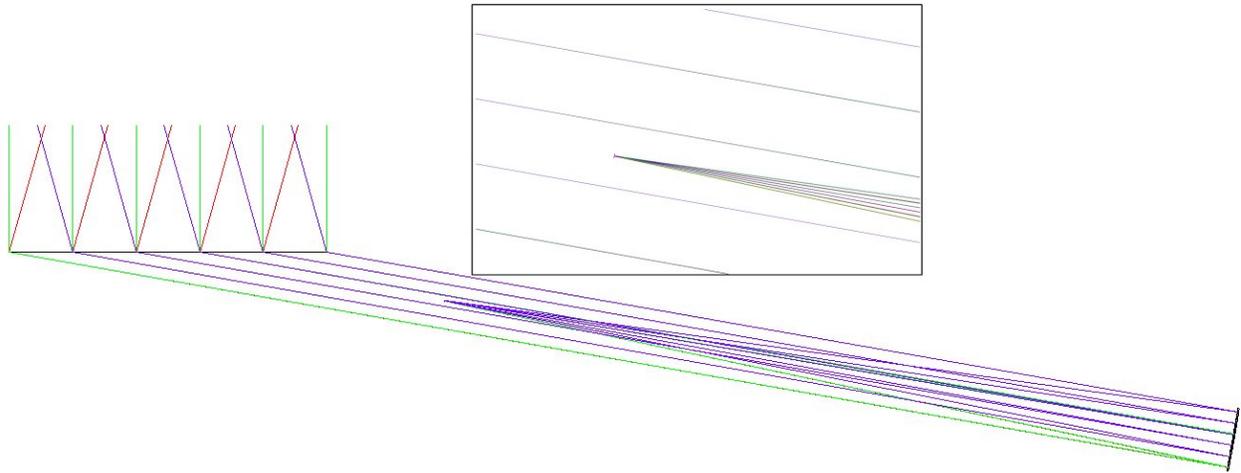


Figure 9. A Zemax model of a plane grating made by holographic methods. Inset detail shows convergence at what would be a slit.

However, rather than shorten the primary and grow the mirror diameter to permit diffraction angles other than grazing exodus the POHOE model shown in Fig. 10 can have a variable pitch that focuses to a point. Creation of the model was based on a 405 nm laser. Interference was of a plane wave at  $-15.04818^\circ$  with a spherical wave at  $80^\circ$  originating at an  $(x,y,z)$  point  $(0,567.1,100)$  meters above the 100 m length hologram surface. Each wavelength has a different focal point.

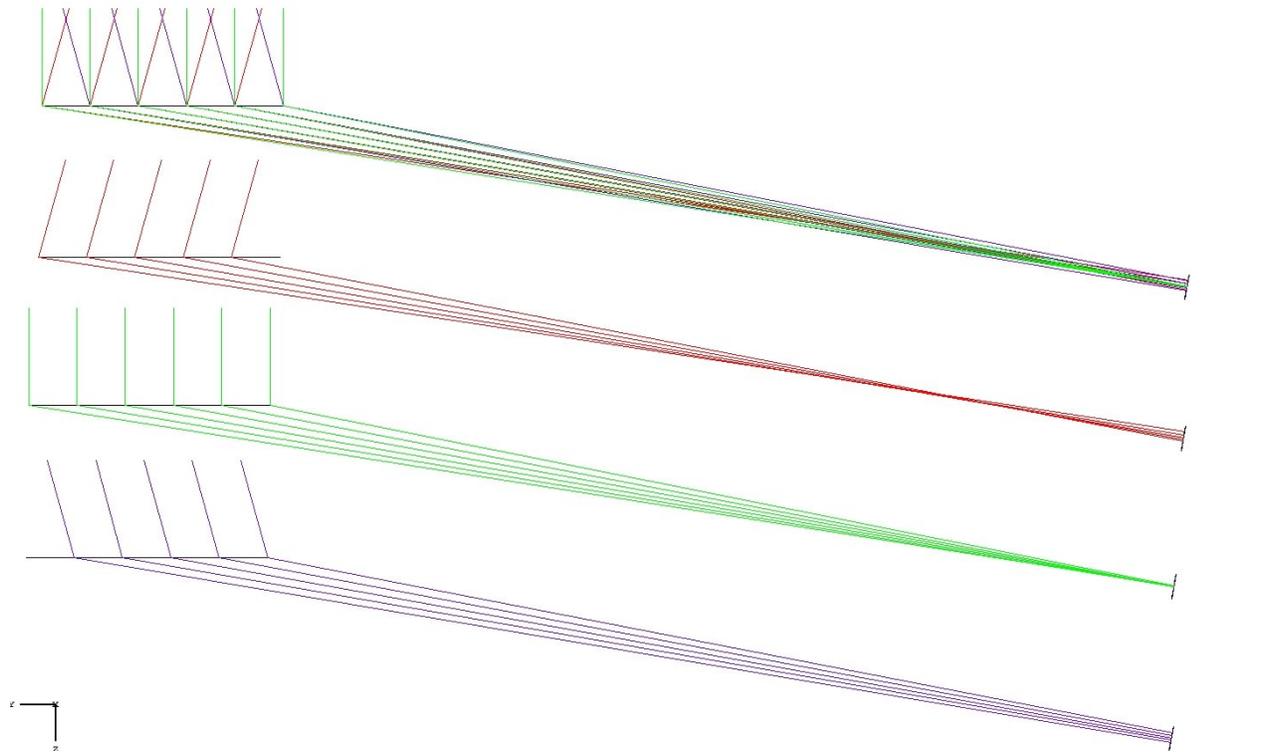


Figure 10. Plane wave radiation at 400 nm, 550 nm and 700 nm incident on a POHOE centered at 550 nm. The resulting focal lengths are shown in combination on the top and in three examples of decreasing wavelength below..

### 3. CORRECTION OF FOCUS

The angle of dispersion is proportional to wavelength in diffraction and inversely proportional to wavelength in refraction. In the former instance, red is bent more than blue, and the latter, blue more than red. The phenomenon was noted by Rittenhouse in his seminal publication describing diffraction gratings.<sup>14</sup> Rittenhouse cites Newton who described the colors of diffraction fringes and reported these observations in his *Optiks*.

Achromats that counter the chromatic dispersions of refractive with diffractive optical elements are widely studied and have entered the commercial market. These are thought of as refractive lenses with diffractive chromatic correction. The primary objective is a refractive lens and a diffractive element corrects the aberration.

However, when the primary objective is a hologram, the problem of chromatic aberration correction sets a strongly aberrant primary against weaker dispersion in the inversely dispersive secondary. To overcome this, Anderson and Tullson have used a correction optic that uses a diffraction grating inside of a double reflector chamber.<sup>15</sup>

Another approach to overcome the strong chromatic aberration of diffractive optical elements would be to use long focal lengths in the POHOE and shorter ones in a secondary refractive element.

#### 3.1 Plastic lens

Plastics have relatively high index of dispersion and might be used in a POHOE telescope secondary for correction of chromatic aberration. An example of dispersion by a plastic lens is shown in Fig. 11. The central blue disk is ringed by colors of increasing wavelength which have proportionately lower angles of dispersion.

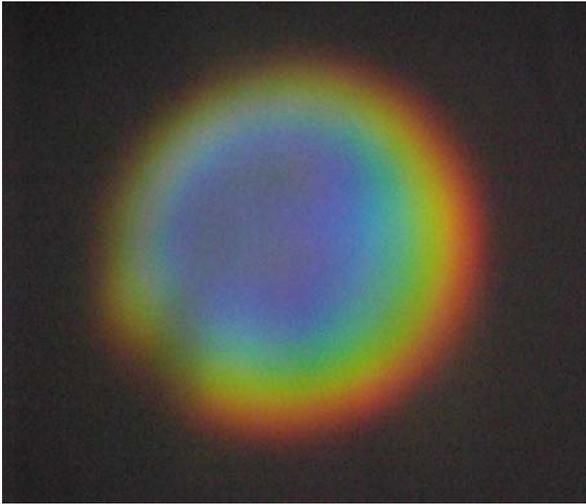


Figure 11. Dispersion by a plastic lens

We modeled a short focal length lens in Polystyrene found in the Zemax<sup>®</sup> miscellaneous glass catalog. The choice of the focal length is driven by the need to maximize the chromatic aberration of the lens, quite the reverse of the motivation behind the very long focal lengths in refractive astronomical telescopes of the nineteenth and earlier centuries. Those long tubes have bestowed a stereotype on telescopes of this type. The length was not so much to increase magnification as to decrease chromatic aberration. A short focal length introduces pronounced aberration.

In the Zemax<sup>®</sup> model, Fig. 12, the POHOE is 80 meters in length. The effective focal length at 405 nm is 575.89 meters. Angle  $i_2 = 80^\circ$  where the constructive spherical wave originates at (0, 567.1, 100) meters. The plastic lens is placed at 290 meters from the center of the POHOE inclined at  $80^\circ$  relative to the POHOE surface normal. It is 6 m in diameter with a focal length of 9 m at 405 nm.

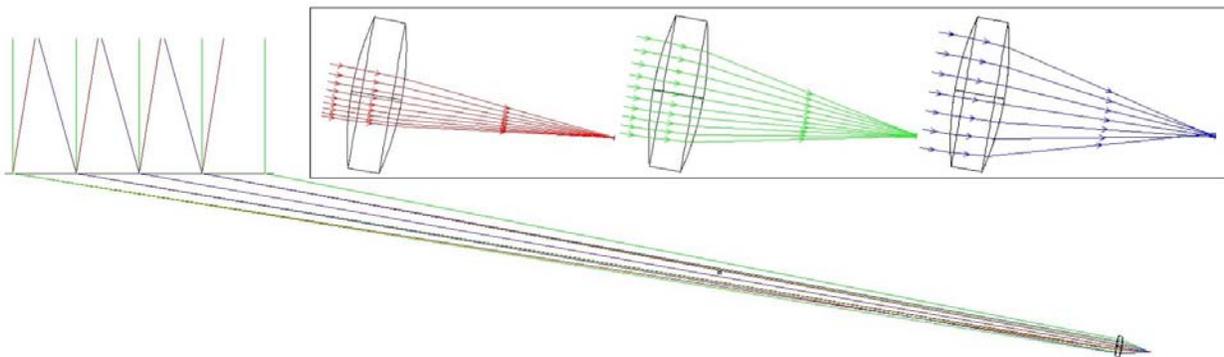


Figure 12. POHOE of focal length 576 m with plastic lens of focal length 9 m to correct chromatic aberration. Insert shows lens.

### 3.2 Reduction-to-Practice

The surface figure of the lens, the consistency of the refractive medium, and the line spacing of the POHOE will affect performance of the telescope. These critical tolerances remain to be investigated.

The fabrication of plastic lenses promises to be a challenge, but there may be glass substitutes. A Zemax catalog item, BASF55 was highly effective when substituted in the model. The *in situ* performance of large glass elements has not been much pursued since refractive telescopes were largely abandoned 100 years ago. It would be interesting to revive their study in this context.

It is anticipated that if the POHOE is made by the interference of coherent waves, far-field performance will be determined by coherence in the near-field. For example, an 80 meter POHOE would lose coherence in the far-field if fabricated by a laser with less than 80 meters coherence in the near-field. Solid state diode lasers are now commercially available with the specification of 100 m coherence, but complicating factors of noise, power and stability must be evaluated. Holographic elements can be segmented and assembled piecemeal into a larger structure. Alignment of POHOE segments into a final assembly is a process sometimes called “shimming” which can be done under laser auto-collimation. Assembled holographic masters can be used to print a continuous gossamer membrane roll. A roll made from assembled segments could be held to a coherence length of each segment.

It may be possible to maintain active control of POHOE dimensions since a membrane can be dynamically adjusted. One method is the use of photonic plastics that are addressed by an external laser.<sup>16</sup> This method or mechanical pistons similar to contemporary practice with adaptive optics could be used to achieve optimized performance of the POHOE. The corrective lens, on the other hand, is rigid, and it must be installed within the working specifications or the instrument will be taken out-of-line for fine adjustment to its surfaces.

## 4. APPLICATIONS

Survey telescopes that read out directly in spectrograms are a design goal for such reflector primary projects as HETDEX.<sup>17</sup> Designs that achieve large numbers of spectrograms through multiple fibers bear some similarity to a fully implemented Dittoscope, because with each fiber added to a Dittoscope gains it more flux, but a Dittoscope is the only telescope that reports a spectrogram for every object in its field-of-view as its native format. A single spectrograph on a Dittoscope will report all spectra of all resolved stars over a single observation cycle. This unique multiple object spectroscopy capability is one of several features that set it apart from other telescope designs.

Installations of the Dittoscope have been published that include ground-, aerial- and space-based. A variant suitable for the lunar equator is detailed in a *Report* to the NASA Institute for Advanced Concepts.<sup>18</sup> On the ground, the low wind resistance and subterranean secondary offer a valuable alternative to ELT designs that face significant turbulence and temperature differential issues in their huge above-ground enclosures. Aerial embodiments of the Dittoscope compare favorably against NASA’s long delayed SOFIA, because a Dittoscope primary objective grating could be integrated into the airframe, preserving the aerodynamics of the airplane and maintaining uniform pressure inside the fuselage holding the optics. In space deployment, a flat gossamer membrane is transportable in any length as a roll plastic, overcoming one of the most daunting restrictions on primary objective aperture size: the packaging for transport. A Dittoscope with a secondary that can be inserted into orbit as an integral unit of two meters or more, primary apertures of 150 meters are realizable. This size for a primary optical surface has been unobtainable with segmented mirror primary designs. A geostationary 100 meter scale telescope would have utility both in astronomy and in earth science/surveillance.

A speculative design proposes a geostationary POG primary with a ground-based secondary.<sup>19</sup> In order for this design to work, the ground station mirror would have to be on the order of 100 meters, notwithstanding the terrestrial mirror would not have to pivot and could be built in a passive static pose. However, a POHOE at geostationary would offer an advantage over a POG, because a very slight focusing capability could deliver the ray bundle to a far more modest terrestrial site secondary collector.

## CONCLUSION

A design for a dispersive primary objective telescope can use a plane diffraction grating at grazing exodus angles, but there is a trade-off in efficiency. We propose a primary objective holographic element that does not require a grazing angle. The POHOE can focus, but it is wavelength-selective. A chromatic correction can be made by using a refractive lens in the secondary. Refraction disperses at angles inversely proportional to wavelength, and this phenomenon ameliorates the pronounced chromatic aberration of the primary objective hologram.

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