

Final Report

Phase II Study

THE MOST

The High Étendue Multiple Object Spectrographic Telescope

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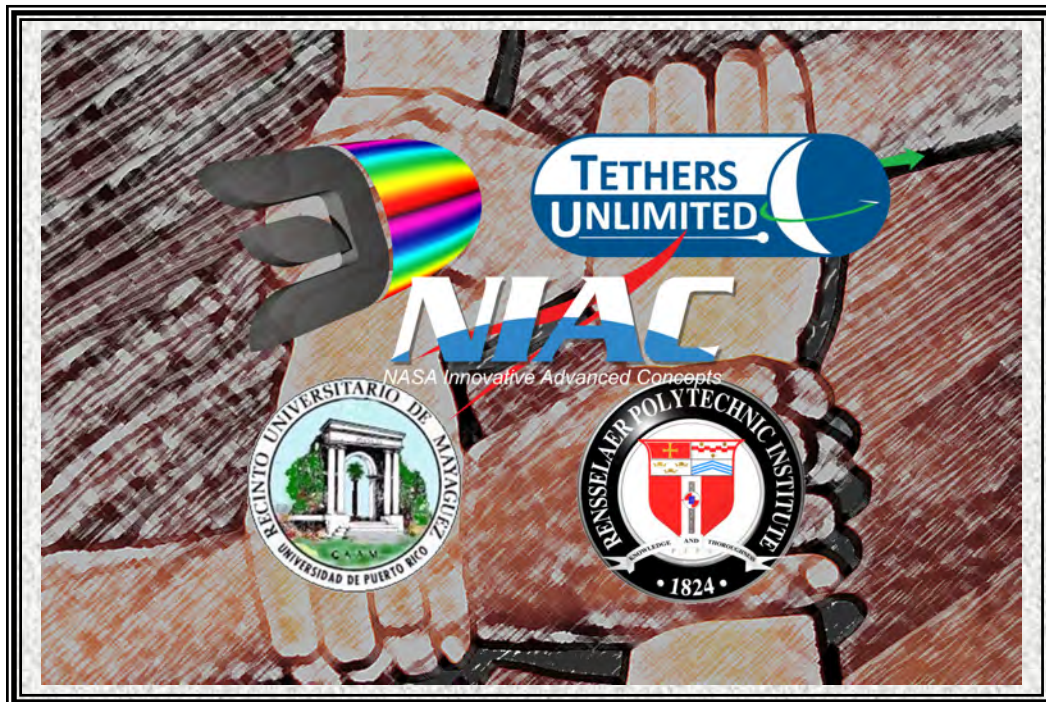


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List of Abbreviations and Acronyms

AO	Adaptive Optics
CTE	Coefficient of Thermal Expansion
DLP	Digital Light Processor
DOE	Diffractive Optical Element
FoV	Field of View
HOE	Holographic Optical Element
HZ	Habitable Zone
mas	milliarcsecond
μm	Micron (micrometer)
MOS	Multiple Object Spectroscopy
NEO	Near-Earth Object
POG	Primary Objective Grating
PSF	Point Spread Function
RV	Radial Velocity
TIR	Total Internal Reflection
TUI	Tethers Unlimited Inc.
VPG	Volume Phase Gratings

Section 1 Introduction

The goal of the present research is to investigate the potential for astronomical observation using a telescope architecture that places a diffraction grating at the primary aperture.

The notion of a primary objective grating (POG) has been in the literature for well more than a century when gratings supplanted prisms as a disperser placed in front of a telescope's optical chain. Gratings offered a practical benefit in aperture size, because only massive prisms could potentially offer comparable resolution. However, while POGs may offer a benefit in resolution they introduce the limitation of ambiguities that arise when higher-order spectra and spectra of proximate objects overlap. These ambiguities forced a preference for coarse gratings with limited angles of diffraction that restrict resolution in resulting spectrograms. Slitless spectroscopy with a similar issue of overlapping spectra can found in some contemporary telescopes, because of the simplicity of the optical chain. The typical secondary optics use hybrid refractive and diffractive elements called grisms.¹ Solar spectroscopy, where there is a single highly dominant object in the field-of-view, also has seen occasional use of POG telescope for spectra of the corona during eclipses.

Our POG optics are traceable to Newton, During the years 1665-1670, as he experimented with mirror telescopes that overcame endemic chromatic aberration found in lenses, he also experimented with prisms which quite to the contrary are intrinsically chromatic. In these experiments with refractive prisms he was interested not in astronomy but in the composition of white light. He showed that what our eyes perceive as “white” light is a superimposition of monochromatic elements. These experiments were accomplished by using two prisms where the primary generated a spectrum (a term he coined) and a secondary prism that redispersed a monochrome ray from the first prism. Figure 1. He demonstrated that no further dispersion into a broader spectrum occurred. It is important to our investigation that in one of his experiments he swiveled the primary prism and noticed that behind the secondary prism a change in colors at varying positions was seen across the image plane.²

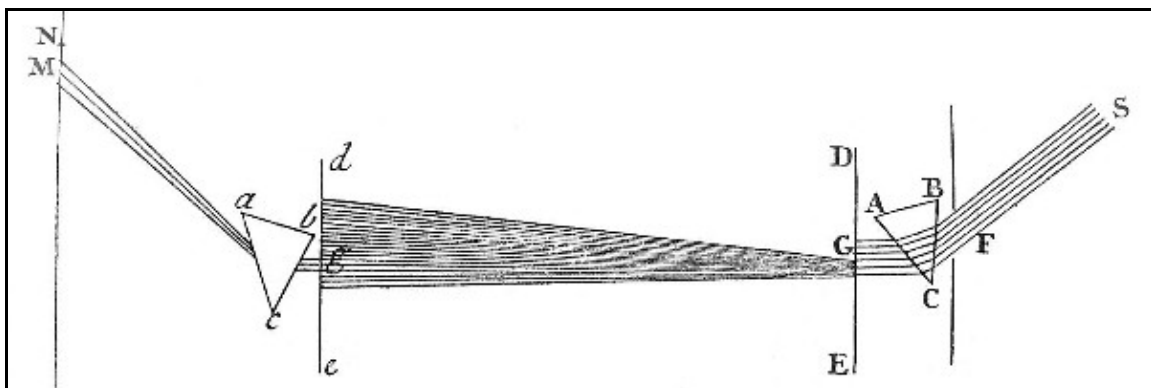


Fig. 1 The Dual Prism Experiment first published *Opticks* 30 years after the bench experiment

Newton had no reason to speculate on the utility of these observed variations in the spectrum as they applied to astronomical observations, but in 1819, Joseph von Fraunhofer discovered varying intensities in light from the Sun that were wavelength

dependent. These lines of intensity variation now bear his name. It turned out that stars also generate Fraunhofer lines from their absorption and emission lines caused by the same species of hot plasma found in the Sun. At this point the spectrograph that Newton used became a significant astronomical instrument.

Other than with POG telescopes, the spectrograph was located in the final portion of the optical chain of lens and mirror telescopes. An achromatic mirror telescope makes little distinction between the infinitesimal points of light that constitute stars. However, when magnified into their constituent wavelengths, spectrographic astronomical data can be used to determine star composition, age, direction of movement, rate of movement, and distance from the observer. These data are enormously important beyond the basic achromatic brightness and spatial astrometrical data provided by mirrors alone.

At the turn of this century, I asked a rhetorical question: Why not gather spectrographic data at the largest optical element, the primary objective, rather than to perform the spectroscopic observation as a final step in the optical chain? Historically, the overlapping images of stars when spread into their constituent spectra cause ambiguities between proximate objects, as mentioned above. A mitigation is found in the dual dispersion that Newton had used, albeit to a completely different purpose. Newton was so impressed with his experiment that he elevated it above others in his seminal text *Opticks* by referring to it as “The Crucial Experiment,” and it is widely regarded as in the top 10 physics experiments in the history of science. Now we add Newton’s dual dispersion experiment to applications in astronomical telemetry pioneered by Fraunhofer.

To understand the resulting telescope, consider the diagram of Figure 2.

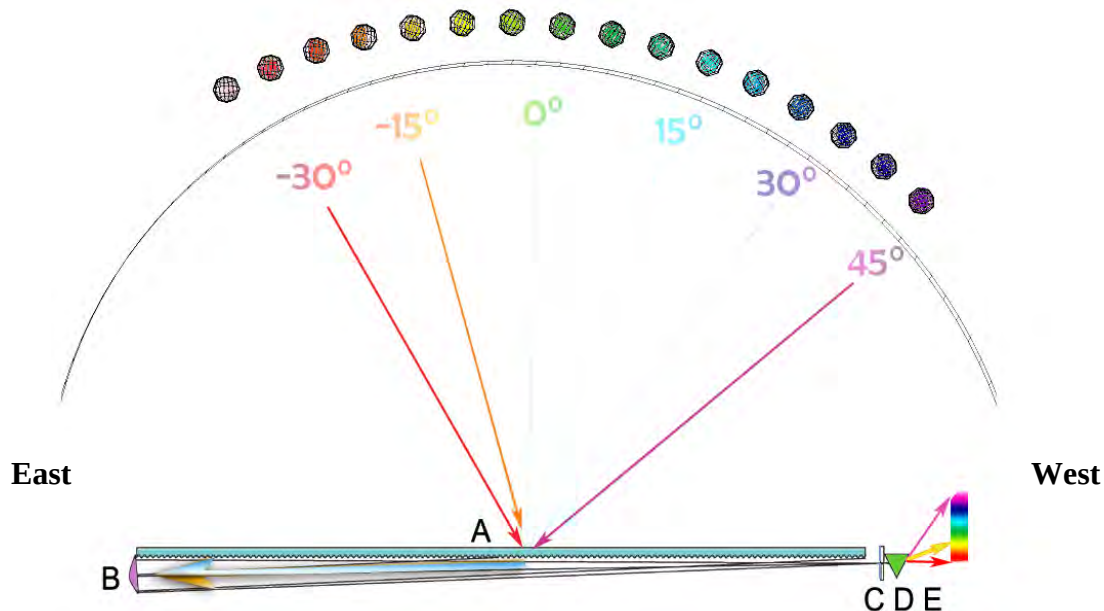


Fig. 2 Plane waves are diffracted by grating **A** at grazing exodus to secondary parabolic mirror **B**. Light is focused on slit **C**. A secondary disperser, **D** separates out all the visible objects as spectrum **E**. Three distinct angles -30°, -15° and 45° are illustrated in bold lines, but an entire line of stars is covered. In the course of an observational drift scan cycle, spectrograms are taken over all wavelengths in the free spectral range for all stars as a series of temporal snapshots at image plane **E**. A ground-based version acquires a line of right ascension. In space, the telescope can drift or be rotated like a radar antenna.

When a POG is used as the aperture in front of a conventional spectrographic telescope, the problem of superimposed diffraction higher-orders remains. Shorter wavelength bands encroach on longer wavelengths. The overlap is far less pronounced between the first- and second-orders, the only orders visible with gratings where the pitch is shorter than the central wavelength of the dispersed light. These high frequency gratings operate almost exclusively in the first-order band. If the secondary spectrographic telescope acquires dispersed light from a sub-wavelength POG at an angle of diffraction approaching 90° , what we call an angle of grazing exodus, the dispersed light is forced almost entirely into the first-order, expanding the free spectral range to its maximum breadth. In the grazing exodus configuration, masking the encroaching second-order becomes a matter of baffles which could include a band blocking short wave filter at the extremities of the Field-of-View (FoV). At the same time, the FoV of the secondary telescope can now encompass a lengthy POG. The larger effective telescope aperture is in one dimension along the considerable POG length. The result is an anamorphic magnification that increases the resolution of the telescope in the same dimension as the resulting spectrograms. The increase in power is analogous to a mechanical lever which gains in force as the lever length is extended. One might say, "Give me a POG long enough, and I show you the end of the universe."

These peculiar features and others that emerged as the dual dispersion architecture was investigated in our research recommend the novel configuration of optical elements for certain applications where contemporary astronomy has been placing increasing emphasis, in particular, in extremely high resolution spectrographic sky surveys. An additional feature that merits study is a significant lessening of aerial mass that inhibits launch of large apertures in space. The mass of a diffraction grating is almost entirely invested in the weight of its substrate, since the optically active portion of the grating is microns in thickness. Gratings can be flat membrane materials which facilitates their storage for launch in cylindrical rolls. A kilometer length roll of narrow grating material can be held in two hands. This novel physical embodiment has the potential to alter space telescope designs going into the 21st century.

This Report documents a three year research project that studied the POG telescope concept. It included a bench model which empirically confirmed several key features of the concept. We worked with the Department of Physics, Applied Physics and Astronomy for this experiment where the bench resides. Without the help and support of RPI and particularly Prof. Heidi Newberg, this project would not have come to fruition, and the P.I. acknowledges her contribution and that of her students.

Tom Ditto
Sept 3, 2022

Section 2 Work Plan

In our applications for a NIAC Phase II we projected a work plan that would result in a bench experiment testing key parameters of performance leading to TRL-2. See Figure 1.

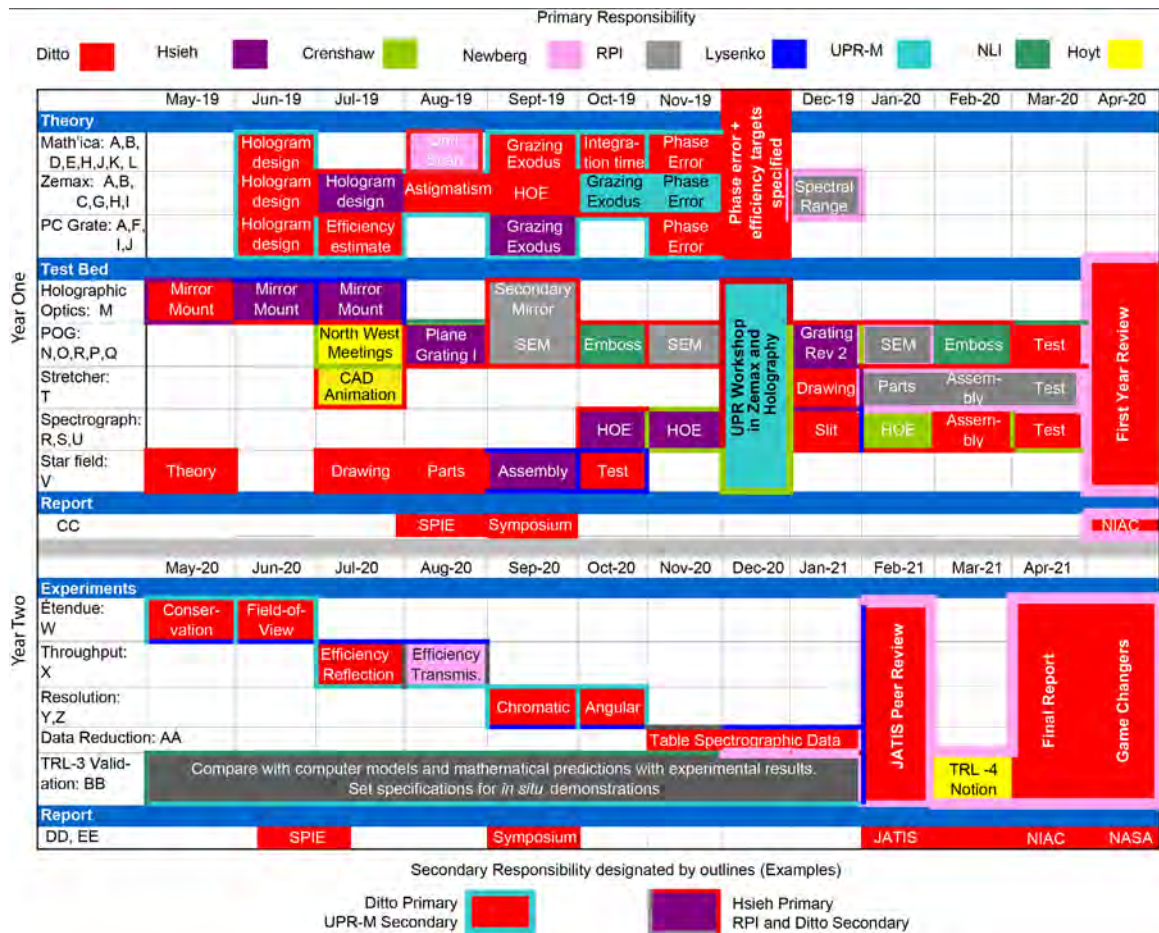


Fig. 2.1 Phase II Work Plan submitted 2019

Alphabetical designations of Phase II components listed on the left hand column were:

- Trade of POG efficiency vs. magnification at grazing (PC Grate, Zemax & Mathcad)
- Trade of spectral vs. angular resolution (Zemax & Mathcad)
- Trade of secondary mirror dia., aspect ratio, astigmatism and focal length (Zemax)
- Optimization of quantity of MOS – compare to échelle (Mathcad)
- Optimization of time domain integration to acquire faint objects (Mathcad)
- Optimization of pitch depth & blaze of the POG (PCGrate)
- Optimization of higher-order suppression baffle (Zemax)
- Characterize zero-order suppression and free spectral range (Mathcad and Zemax)
- Comparison of reflection vs. transmission POG (PC Grate & Zemax)
- Error budget for pitch coherence & “Shim” error budget (Mathcad & PC Grate)
- Error budgets for secondary spectrographs in RV and BAO measurements (Mathcad)
- Systematics from stitching, stochastic, and periodic errors in plane gratings (Mathcad)

Bench

- M. Mount our remaining 750 mm dia. mirror (RPI)
- N. Fabricate 600 mm POG master by holographic recording (3DeWitt)
- O. Test pitch depth vs. prediction (RPI EML)
- P. Replicate POG on plastic ribbon (New Light Industries)
- Q. Test membrane POG rule geometry (RPI Electron Microscopy Lab)
- R. Fabricate Spectrograph HOE on glass (3DeWitt and UPR)
- S. Replicate Spectrograph HOE on glass (New Light Industries (NLI))
- T. POG stretcher (3DeWitt)
- U. Mount spectrograph HOE (3DeWitt)
- V. “Star” generator (RPI)

Predictions from theory will be bench tested (year two) in a laboratory at RPI.

- W. Test of POG conservation of étendue in comparison with mirror telescopes
- X. Test of overall throughput and specific diffraction optic efficiencies
- Y. Test angular resolution in two dimensions for reflection and refractive POGs
- Z. Test spectral resolution as a function of grating length and pitch error
- AA. Test data reduction protocols and develop a standardized algorithm
- BB. Evaluate at TRL-3 in anticipation of in situ TRL-4 low fidelity breadboard

Our preferred publication venue is SPIE. We had three abstracts filed as of Jan 2019 for a special joint session at the SPIE Annual Conference in San Diego in August 2019 for (1) Innovative Space Telescopes, (2) Detection of Exoplanets, and (3) Optical Testing

- CC. 2019 SPIE Astronomical Optics and Instrumentation
 - DD. 2020 SPIE Symposium on Astronomical Telescopes and Instrumentation
 - EE. SPIE *Journal of Astronomical Telescopes, Instruments, and Systems* (JATIS)
- Also on the calendar were the annual NIAC Symposia.

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Scheduled Task A is reported in Section 4 of this Report.

Task B eventuated in a Phase I proposal, *Ghost*, which optimizes efficiency of a POG by viewing it from a distance. The Zemax model it uses appears here in Section 6.

Task C led to detailed study of mirror field-of-view detailed here in Section 6 – DICER

Task D is reported here in Section 6 under embodiments: Ground - THE MOST

Task E appears under Section 6, Airborne.

Task F is touched on in Section 4. (We did not purchase PC Grate, because our gratings will not be metalized).

Task G is covered in Section 4

Task I is covered in Section 4

Task K is integrated into the proposed study, *Ghost*, Section 6

Tasks J and L were left undone.

Tasks M-V were carried out and are reported in Section 3

At the conclusion of this *Report* in a Personal Note we will detail how two medical crises, Covid 19 and a bout with cancer, interfered with strict conformity with our schedule. The hiatus prevented carrying out Tasks W – BB.

Tasks CC, DD, and EE were carried out with ongoing SPIE presentations and publications made possible in part through virtual participation in conferences. This Report incorporates elements of those publications which are linked in a Bibliography.

As a Visiting Researcher at RPI, the P.I., Thomas Ditto, was on campus where his interaction was with Professor Heidi Jo Newberg and her students, notably undergraduates Hunter Rouillard and Makayla Wahaus. Our collaboration led to the SPIE conference paper, “Scale Model of a Dual Dispersion Primary Objective Grating Telescope.” Dr. Newberg made the presentation at the SPIE Annual Conference in San Diego in August 2019, and she also presented our joint research at the September 2019 NIAC Symposium where Ditto delivered a presentation on a NIAC Phase I, DUET, that was concurrent. Also at RPI, Visiting Researcher, Dr. Mei-Li Hsieh established a holographic bench for fabrication of HOE components in the laboratory of Dr. Shawn Yu Lin. Dr. Hsieh used a Zemax workstation set up by Ditto to model these optics. At this point, RPI had two laboratories that participated, one housing the Scale Model of THE MOST and the other in the Center for Industrial Innovation under the administration of Dr. Yu Lin. It has since added a third laboratory, the Newberg Laser Lab, explicitly for holography.

Collaboration with the University of Puerto Rico – Mayaguez began in November 2019 with an undergraduate, Diego Gutierrez Villarreal, who was tasked with Zemax models of the opposed mirrors in THE MOST. This investigation was aimed at the development of a novel coronagraph, BLOC – The Bifurcated Light Optical Coronagraph as reported in Section 6. Subsequently at RPI a related bifurcated mirror ground-based embodiment of THE MOST called TWO – Trip Wire Optics was pursued. Subsequent to that a self-nulling exoplanet telescope, DICER - The Diffractive Interfero Coronagraph Exoplanet Resolver which was invented by Dr. Newberg and her PhD advisee, Leaf Swordy. As these three innovations, detailed in Section 6, postdated the work plan for THE MOST, they are not explicit in the original calendar but advanced under this round of NIAC funding.

Scheduled tasks M and V spanned the entire two year work period. Initial CAD drawings were rendered early on, as planned. The task of ordering machinable metal was carried at RPI where the materials were delivered. The light engine for the experimental mirror was designed by the P.I. who ordered the components. These were delivered for assembly at RPI’s facilities. In addition to the light engine, a plasma lamp was brought into service as the light source. An SPIE paper describing the project was delivered at the 2022 SPIE Astronomical Telescopes and Instrumentation Conference by Leaf Swordy whose PhD work is on a variant of POG telescope.

Scheduled task N, the fabrication of a grazing incidence plane grating was undertaken as planned by M. Melissa Crenshaw and T. D. Ditto at the 3DeWitt laboratory in Cairo, NY in a month-long effort. The bench included a mirror that was newly recoated in Ithaca, NY in September 2019. (Taking advantage of travel to deliver the mirror, Ditto was able to give a talk at Cornell’s Sagan Institute where he introduced his observation strategy to locate Earth analog exoplanets. Being nearby, Ditto also visited Corning, NY initiating a discussion of using Willow Glass as the grating substrate.)

An experiment in developing a grazing exodus capable grating was not successful, and we remain in theoretical territory. This forestalled production of primary objective gratings as anticipated in Scheduled tasks O-U.. We looked to suppliers and found meter scale surface relief gratings were available from Plymouth Labs in Massachusetts. We had not budgeted the purchase price, but that option is on the table for future projects. The experiment did lead to an experiment using Total Internal Reflection at grazing, and that experiment is reported in Section 3. This led to a novel method of index of refraction engineering which we disclose in Section 4. The newly instituted Newberg Laser Lab can serve as the site where the novel grazing exodus grating will be studied.

Teams assembled for this project included university cohorts from Rensselaer Polytechnic Institute (RPI) and the University of Puerto Rico – Mayaguez. These collaborations drew from their Departments of Physics. After completion of their undergraduate assignment on this project, two of the students proceeded to their B.S. degrees at RPI. A graduate student has been admitted to the PhD program at RPI.

Section 3 The Bench Model and Analysis

In pursuit of empirical demonstration of THE MOST, an optical bench model was built at the RPI Department of Physics, Applied Physics and Astronomy. As illustrated in Figure 3.1, a breadboard with a 6 x 2 foot form factor was outfitted with 1) broadband (incandescent) and fixed (laser) wavelength star simulators 2) a reflection POG 3) a 12 inch parabolic mirror 4) a fiber fed spectrometer under computer control.

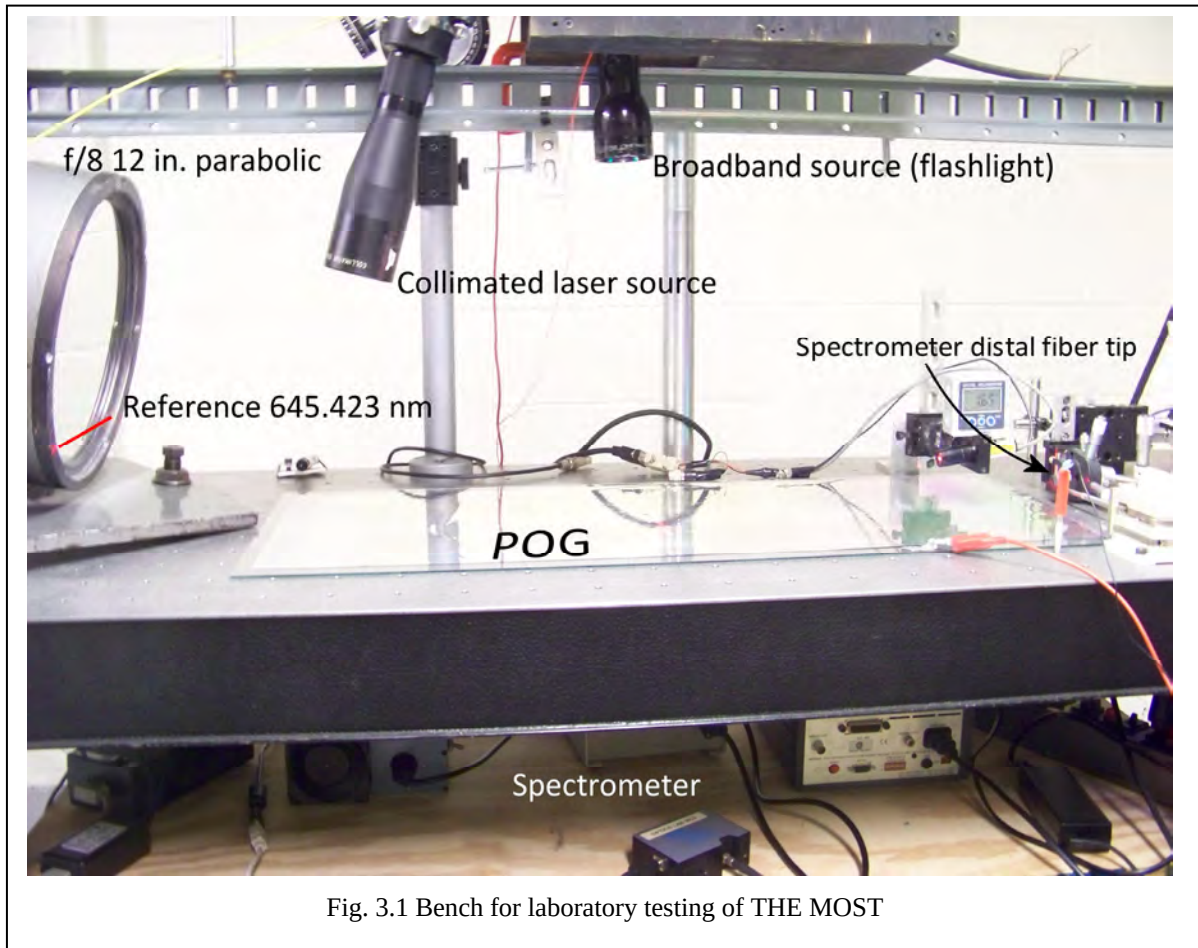


Fig. 3.1 Bench for laboratory testing of THE MOST

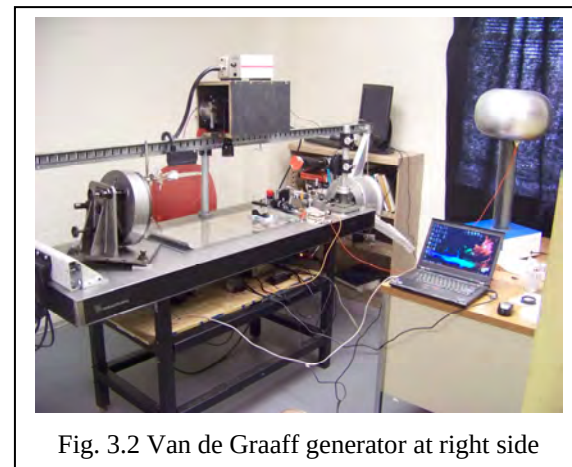


Fig. 3.2 Van de Graaff generator at right side

As seen in Figure 3.2, this laboratory also had a van de Graaff generator which was used to create a 400K V potential between the metal bench and the reflection POG. A 1/16th inch thick pane of window glass was used to form a dielectric resulting in adhesion of the thin membrane POG to the table mass. The goal was to flatter the plastic to optical quality. The grating flattened but exhibited small bubbles, and the surface was not to optical quality.

Preparation of the grating is shown. Figure 3.3, from SPIE disclosure August 2019.³

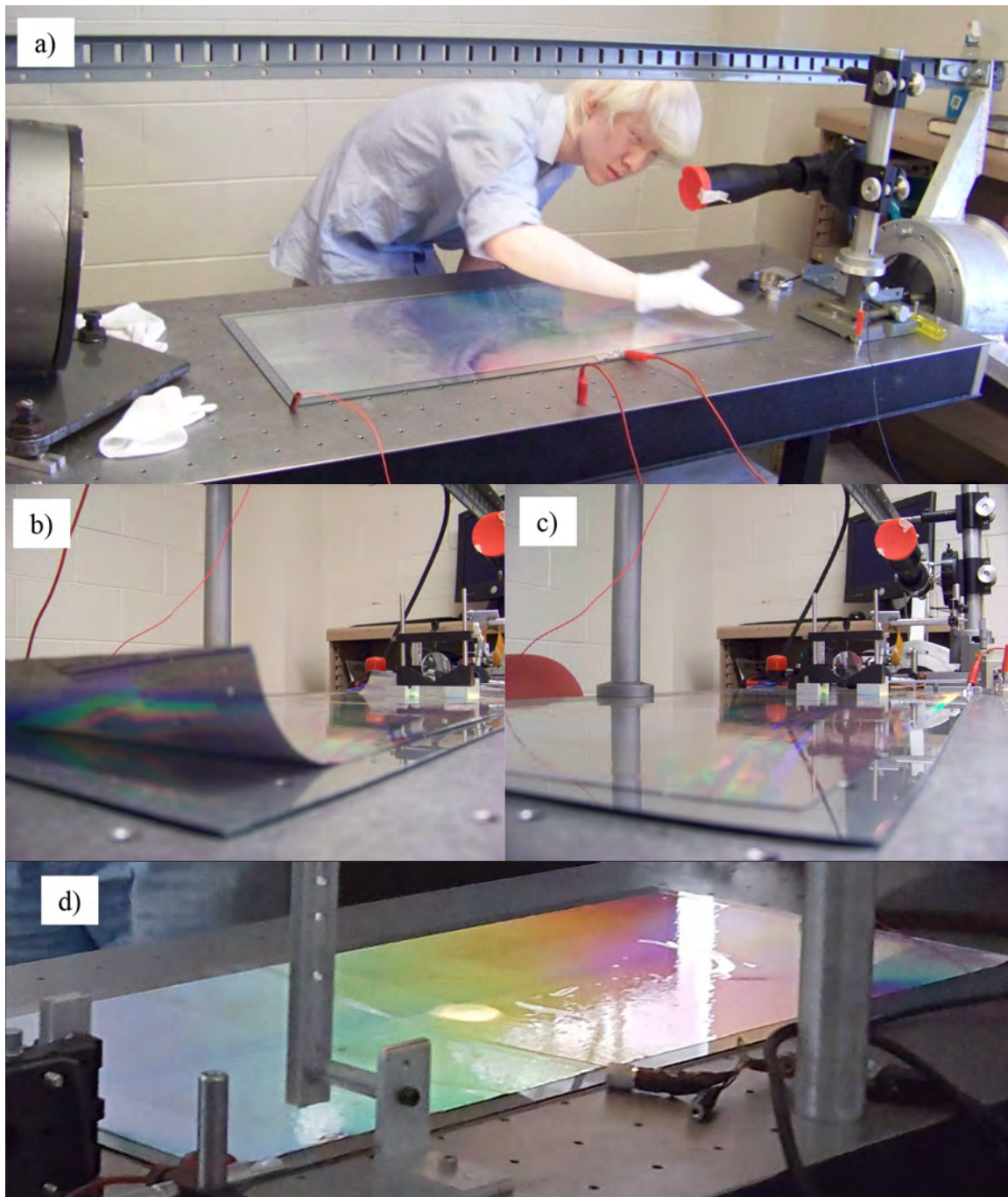


Figure 3.3. Electrostatic flattening of decorative holographic grating. a) The decorative holographic grating is placed on a float glass plate and charged with a Van De Graff generator. b) Before charging, the grating is curled. c) After charging the grating is flattened due to electrostatic attraction to the optical bench. d) However, after flattening very large bubbles persisted in the grating material, at a level that was unacceptable for astronomical observations. The white circle in the center of the grating shows the spot size of the flashlight light source.

Despite the uneven surface, the reference laser line at 645 nm was seen at the image plane of the secondary spectrometer as a fine line, Figure 3.4.

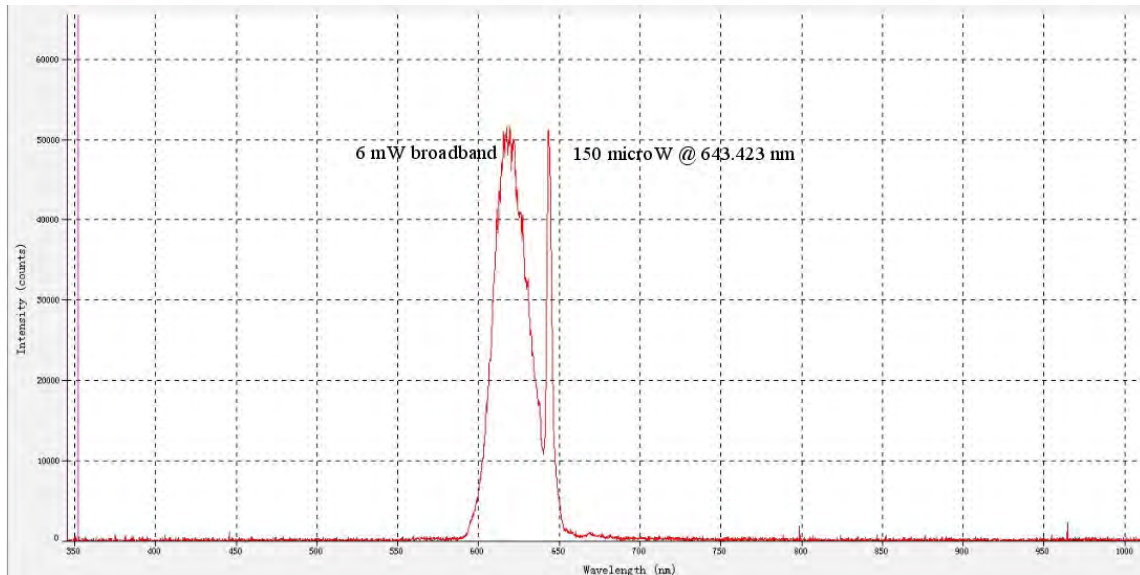


Fig. 3.4 Spectrogram comparing broadband and laser line at nearly common diffraction angles.

The broadening of the incandescent line is traceable to its source, a garden variety flashlight with an elliptical mirror that focuses a filament. This intrinsic error in the wavefront is a near-field phenomenon caused by defocus at the parabolic secondary mirror. Nonetheless, other than an anomaly at zero degrees where the flashlight was reflected into itself by the silvered POG, the basic concept that a secondary disperser will segregate wavefronts dispersed by the POG by their wavelengths as a function of their angles of incidence upon the POG was demonstrated conclusively, Fig. 3.5.

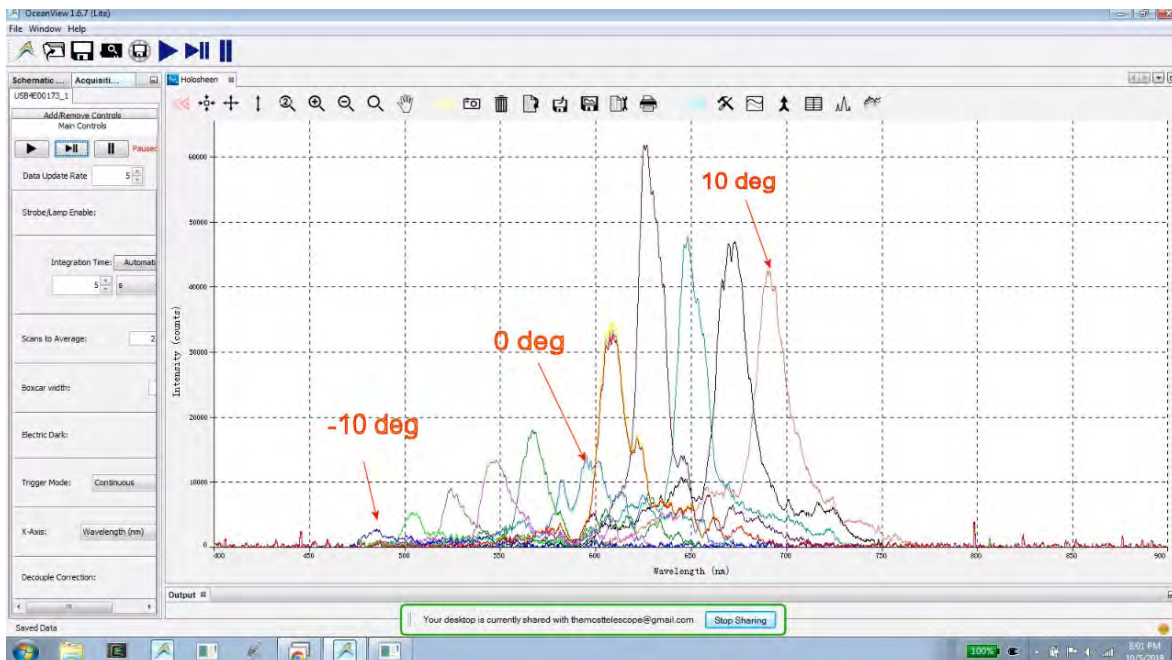


Fig 3.5 Simulated transit of a star over 20° using an ordinary flashlight as the source

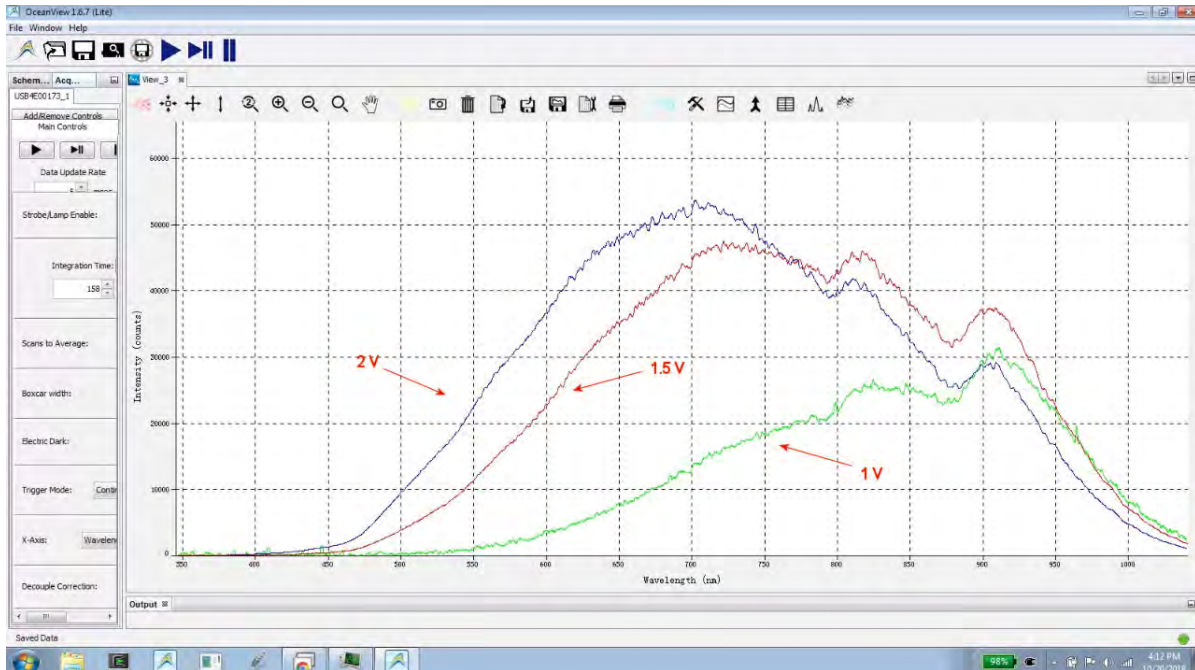


Fig. 3.6 Power distribution of incandescent source over 3 discrete supply voltages

Change in flux of the incandescent bulb, Figure 3.6, explains the changes of intensity in Figure 3.5. The nominal 2 V supply voltage pushed the incandescent furthest into the visible. Fortunately our spectrometer was able to record into the infrared. The effect of the xenon doping is evident in increased flux around 810 nm and 900 nm.

The experiment of Fig. 3.5 was repeated with collimated light, Figure 3.7..

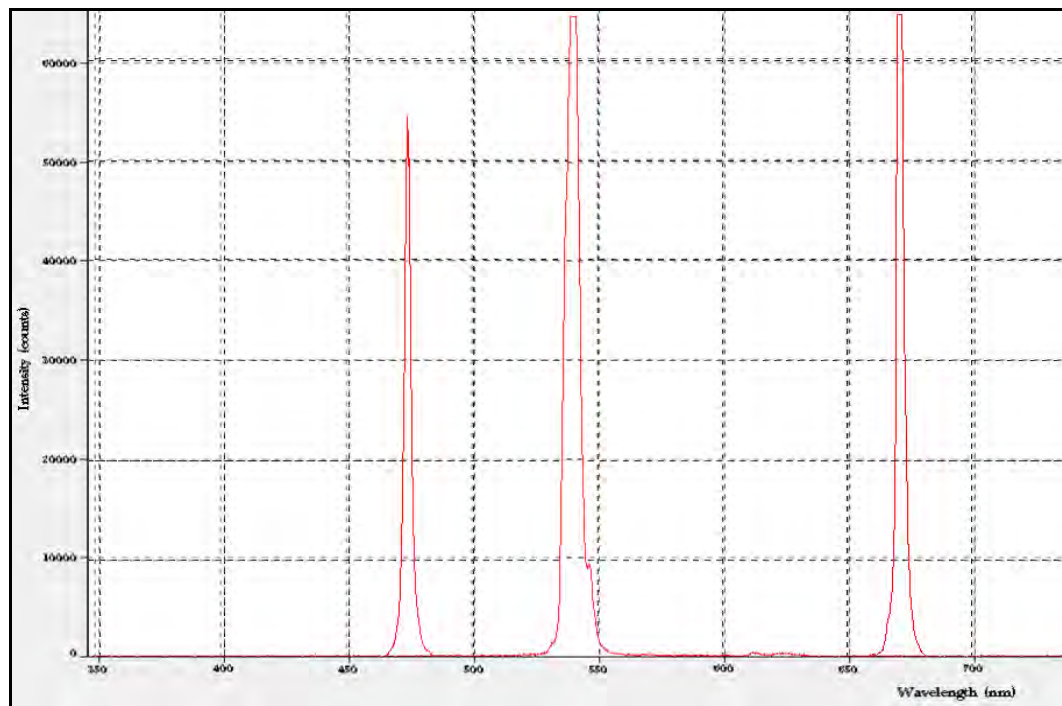


Fig. 3.7 Simulated transit of a star using three bands of collimated light as the source

A “star generator” reported below provided the incident wavefronts which were broadband and collimated. Nominal red, green and blue wavelengths were recorded in this experiment, but the fundamental principal of correlation of angle to wavelength was demonstrated.

As expected, the spectral lines in the experiment of figure 3.7 are considerably sharpened. This result was achieved with an uneven grating. To demonstrate how poor the grating figure was, we looked at its zero-order image by projection a laser line a grazing angle that was equivalent to the grazing angle used to record spectra.

To characterize the zero-order distortion, a laser line was projected on to the grating surface at grazing incidence, approximately the angle at which first-order diffracted light would be redirected during an observation of the sky. The setup is shown in the schematically annotated photograph, Figure 3.8. The resulting caustics after reflection were photographed, Figure 3.9.

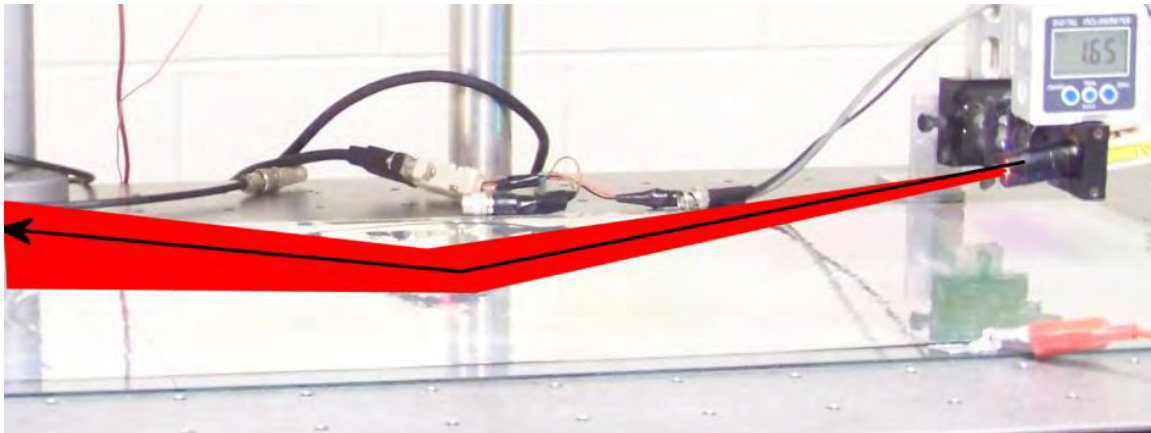


Fig. 3.8 Stripe laser projection on Holosheen POG reflected at grazing incidence

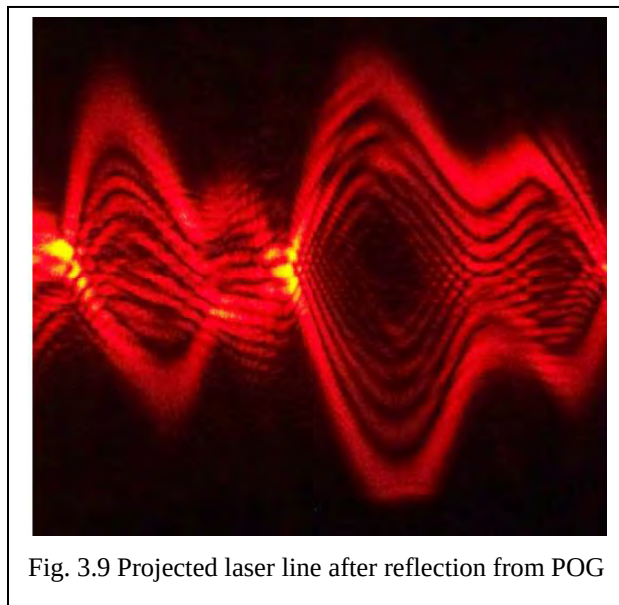


Fig. 3.9 Projected laser line after reflection from POG

The caustics span a significant range of angles and amplitudes. The surface figure tolerances for POGs differ remarkably from reflection surfaces. Reflection has been extensively characterized in the literature, and the diffraction limit is understood to be reached with sub-wavelength error tolerances. Typically, a diffraction limited mirror is presumed to hold its figure at $\lambda/4$ or better. On the other hand, the diffraction image is formed by a completely different process than reflection. We have predicted that nothing would ever be gained by maintaining a sub-wavelength surface figure. The inexpensive decorative

grating has served to further empirically demonstrate this distinction.

A conventionally ruled glass substrate 4 x 4 cm blazed plane grating with an 1180 line/mm ruling was tested on the bench for comparison. Typically such gratings are on float glass. Reflection the zero-order did not exhibit caustics. Performance in the first-order was consistent with the performance of the uneven grating, Figure 3.5. The asymmetric shape of the first-order response was probably due to the groove blaze.



Figure 3.10. Conventionally ruled 4 cm × 4 cm, 1180 line/mm grating ruled on float glass (left). The center image shows the zero-order (reflected) 1 mm spot of a laser, which does not show the caustic patterns seen in Figure 3.9. The right panel shows the shape of the profile of the first-order spot size.

A blaze is specified to increase throughput in a selected diffraction order. Our plastic decorative grating was presumed to have a symmetrical sinusoidal surface relief. We measured an approximate throughput for the plastic grating and 10° exodus angle using a Newport 1830-C photometer with a detector that was 1 cm². Because both the collimated laser beam and the first order diffraction spot were larger than the photometer, we focused the light onto the photometer with a magnifying glass. The photometer detected 9.7μW in the collimated beam from the source, and 0.4μW facing the same direction but moved out of the beam. We then placed the photometer in front of the fiber aperture. We detected 1.5μW at the first order diffraction spot, with 0.2μW when the light from the source was blocked. The spot size of the light that was diffracted in first order was very large, presumably due to the extremely non-flat grating. Assuming that the spot size would be placed inside the fiber with better optics, the throughput of the grating would be 1.3μW / 9.3μW = 14%. If blazed, we estimate that the grating could have reached 20%.

Multiple diffraction orders, most notably the zero-order, reduce the flux available to the secondary sensor. Increasing efficiency became a focus of this research, and we offer a prospective solution that could increase efficiency to 50% at grazing exodus in Section 6.

After the bench experiment, a Zemax model was created to characterize this type of installation, Figure 3.11. In this model, which is not explicit to our lab but generalized for study, the POG is 37.5 cm with a surface relief groove pitch of 625 nm. The exemplary traced wavelengths are 615.5 nm and 406.66 nm. Their respective angles of incidence measured from the zenith are 0° and 19.52°. The slit is modeled as a distal fiber tip diameter of 0.15 mm. We do not have a Zemax model of the OceanOptics miniature spectrometers used in our experiments, so rays terminate at a sink. The secondary mirror is modeled without surface aberrations, ie., it is “perfect” and was given a 250 mm diameter.

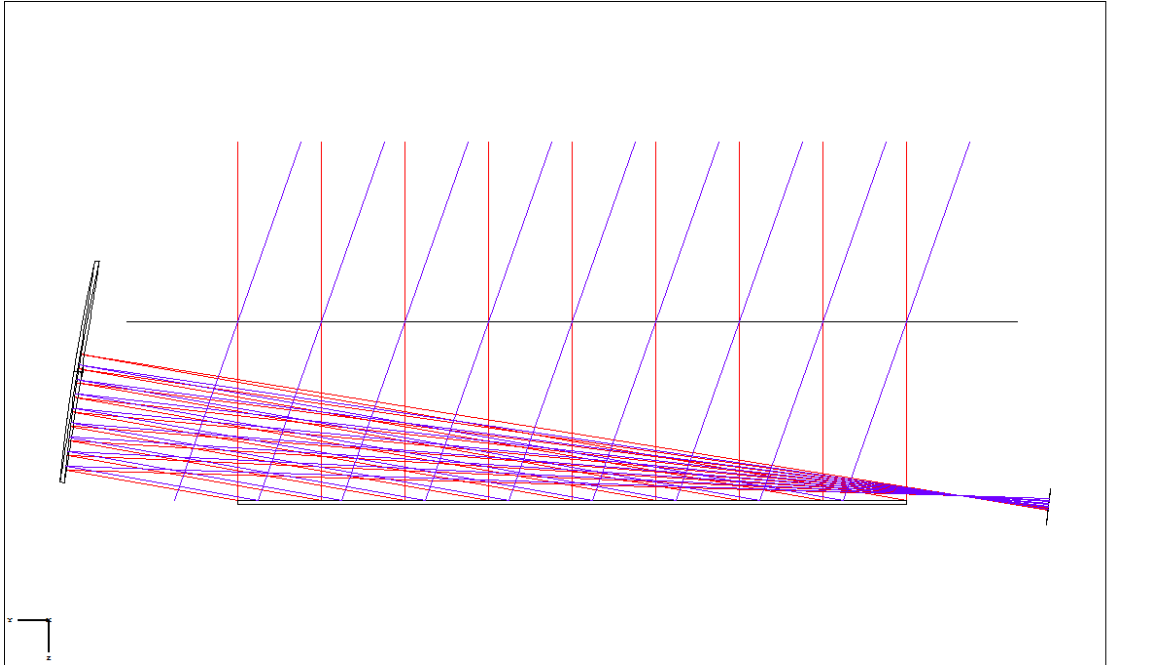


Fig. 3.12 Bench experiment in Zemax

In order to better understand the three dimensional character of the wavefront propagating from a circular diameter mirror and a plane grating, an analysis was conducted. An analysis of the loss by vignetting is made by the diagram of Figure 3.13.

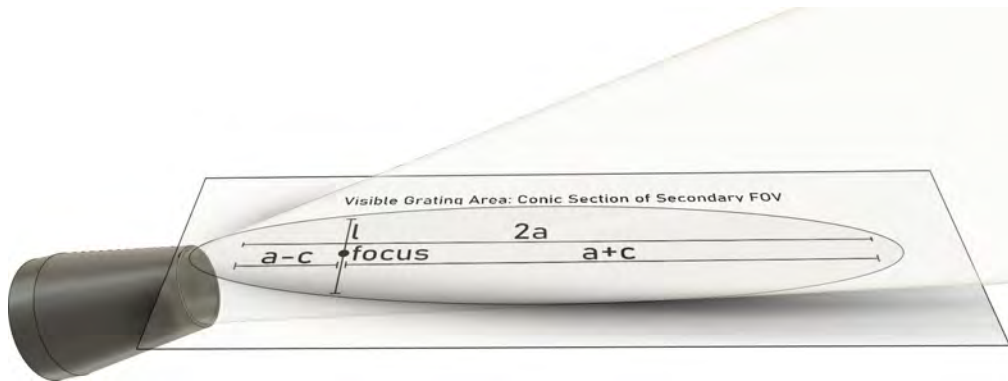


Fig. 3.13 The conical section formed at the intersection of a POG and the FoV of a circular mirror

In Figure 3.13 the secondary focusing element field of view is exaggerated in order to demonstrate that total collection area is truly a conic section. It is seen from the figure that the major axis is determined solely from the secondary aperture diameter and field of view, and the angle at which the secondary aperture axis intersects the grating.

The conic section area depicted in Figure 3.13 is the total area visible to the secondary focusing element. One of the foci of the ellipse of visible grating area is identified by the intersection of the secondary focusing element optical axis with the grating surface. With one of the foci determined, geometrical properties of the visible grating area such as the linear eccentricity c , semi-major axis a , and semi-latus rectum l can be derived from

trigonometric calculations. The ellipse of visible grating area is determined by the semi-major axis and semi-latus rectum. These are given in terms of central exodus angle θ_E , secondary focusing element diameter D , and secondary field of view ϕ_{FOV}

$$a = \frac{D}{2} \left(\sin(\pi/2 - \theta_E) + \frac{\cos(\pi/2 - \theta_E)}{\tan(\pi/2 - \theta_E - \phi_{FOV}/2)} \right)$$

$$l = \frac{D}{2} \left(1 + \frac{\tan(\phi_{FOV}/2)}{\tan(\pi/2 - \theta_E)} \right)$$

With these quantities in hand, we can determine the semi-minor axis b and subsequently the total conic area A :

$$b = \sqrt{l * a}, \quad A = \pi * a * b$$

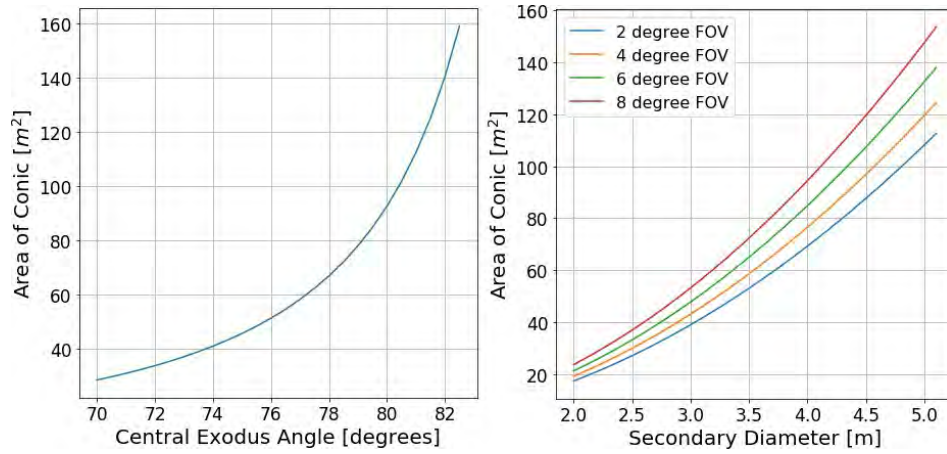


Fig. 3.14 Total grating area visible to the secondary focusing element (left) and constrained (right)

Figure 3.14 illustrates the scaling relationships of total conic area with the central exodus angle received by the secondary, as well as the diameter and FOV of the secondary focusing element.

Figure 3.15 illustrates the linear grating dimensions (Width (a) and length (b)) required to contain inscribed ellipse of visible grating area; shown as a function of the secondary focusing element diameter and field of view. In both panels of the figure, central exodus angle is constrained to 70 degrees.

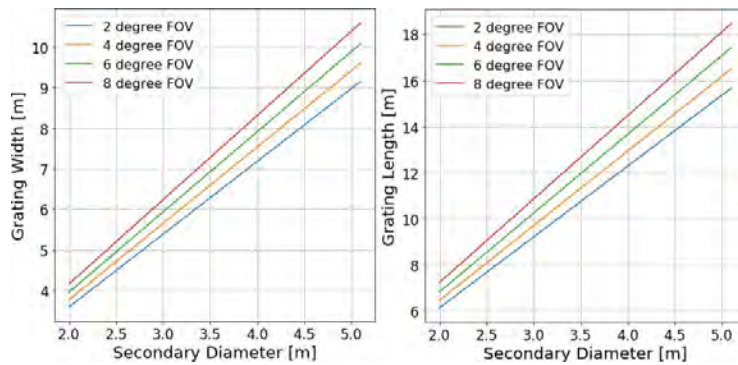


Fig. 3.15 Grating width and length calculated as a function of secondary FoV

Additionally, the vignetting caused by the conical intersection of a mirror secondary with the POG is affected by wavelength. Not all photons of a single wavelength or of a narrow wavelength band appear at the secondary for any angle of incidence. The phenomenon is illustrated in Figure 3.16 made at a 70° angle of grazing exodus.

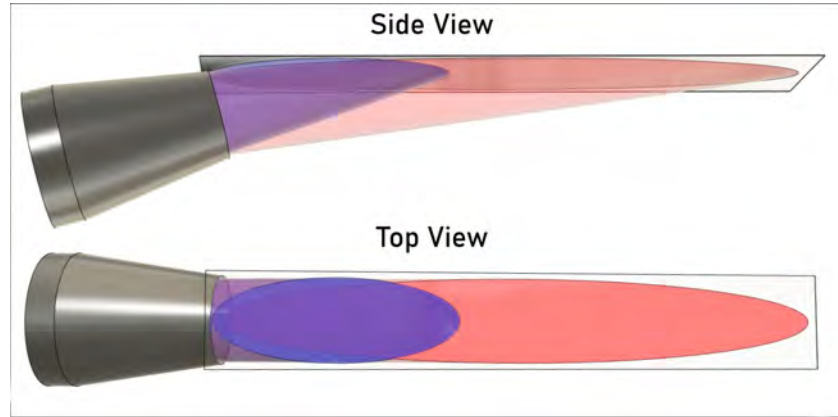


Fig. 3.16

As the bandwidth in the secondary spectrometer narrows, the footprint on the POG bucket shrinks and shifts for any particular wavelength. These are factors that limited flux sensitivity of our laboratory model that used an off-the-shelf circular mirror and suggests a rectangular form factor for the secondary mirror in future reductions to practice.

The star simulation of Figure 3.7 above was made using a customized plane wave source called The Star Generator. Built around a 30 inch F/10 $\lambda/5$ parabolic mirror, it replaced the dodgy flashlight used for broad band sources.

The test fixture concept is shown in Figure 3.17. A light engine is mounted behind the mirror bore hole. It targets a DLP Digital Light Processor. The image on the DLP is reflected into the parabolic mirror which collimates it as it reflected toward the bench supporting a POG.

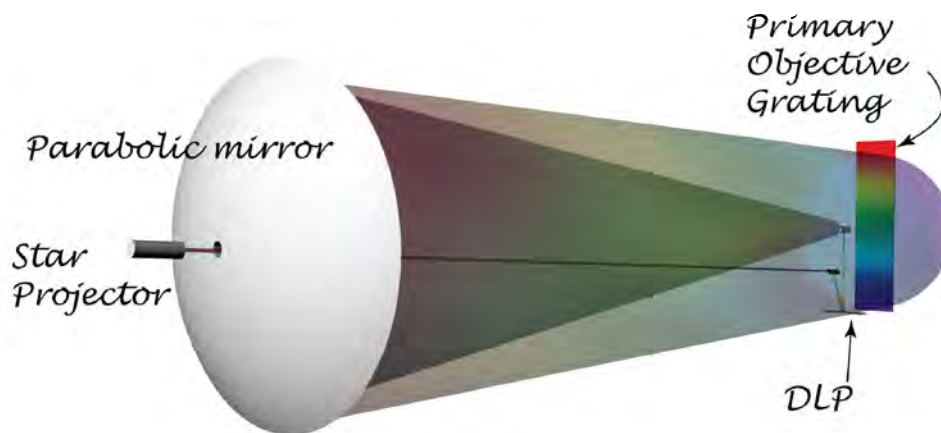


Fig. 3.17 CAD render of the Star Generator concept

To face the Star Generator, the breadboard holding the POG was rotated 90°, Figure 3.18.

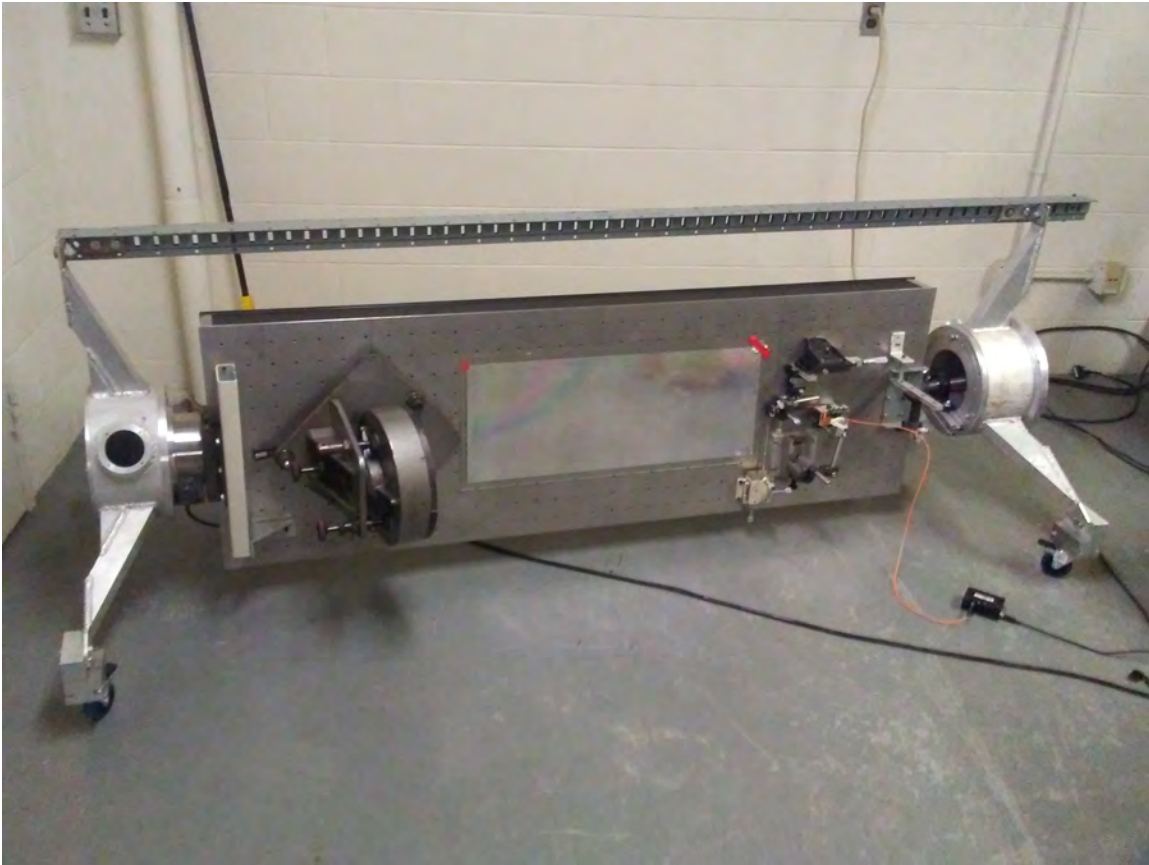


Fig. 3.18 Breadboard of Figures 3.1 and 3.2 after 90° rotation. POG loosely attached before experiments

The image on the DLP was adapted from a laser projection art piece by Fred Berkhout. As exhibited in an Amsterdam's art gallery, Melkweg, as shown in Figure 3.19. As modified for this experiment by the P.I., the “seed” images included one in Figure 3.20.



Fig 3.19 Laser stars by Fred Berkhout

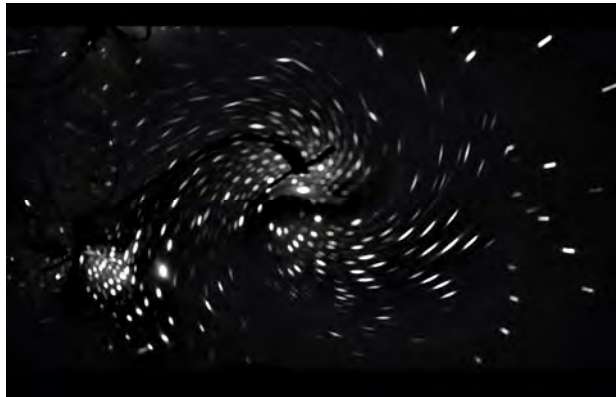


Fig. 3.20 Computer processed version of Berkhout stars

The Star Generator places a point-like source in the focal plane of a 30 inch parabolic mirror which is akin to running a large telescope in reverse. A large-aperture telescope, when exposed to a plane wave that is spatially coherent on the length scale of the primary diameter, will produce a tiny diffraction limited Point Spread Function (PSF) in the focal

plane. Conversely, a point source or pinhole placed in the focal plane of a telescope will result in the emission of a highly coherent wavefront from the telescope aperture. The degree of wavefront uniformity after collimation can be estimated by calculating the diffraction limit, and Plate-Scale, of the 30 in (0.762 m) parabolic mirror.

The diffraction limit of a circular aperture is:

$$\theta = 1.22 \frac{\lambda}{D}$$

where λ is the wavelength in question, D is the telescope mirror (or aperture) diameter, and θ is the diffraction-limited angular resolution in radians. Setting the mirror diameter to 0.762 m and choosing a wavelength of 1 μm , we obtain a diffraction limit of 1.6×10^{-6} radians, or ≈ 0.33 arcseconds.

In the focal plane of a telescope, the linear scaling of distance with the angular position of objects in the field of view (the plate-scale) is defined as:

$$\text{Plate Scale} = \frac{206265}{f} \text{ arcsec/m}$$

Where f is the focal length of the primary mirror, and 206,265 is the number of arcseconds in one radian. With the 10 ft (3.05 m) focal length of the 30 inch mirror currently used in the Star Generator, we obtain a plate-scale of $\approx 67,672$ arcseconds per meter, resulting in our 0.33 arcsecond diffraction-limited PSF having a size of $\approx 4.9 \mu\text{m}$ in the focal plane. This implies that a perfectly spatially-coherent 1 μm plane wave incident on the 30 in parabolic mirror, results in a 5 μm PSF in the focal plane. Conversely, if a pinhole with a physical extent of 5 μm is placed in the focal plane of the mirror, a highly spatially-coherent plane wave is produced after collimation by the mirror. The previous example was worked for the case of 1 μm light so that the diffraction limit of the collimator approximately matched the size of a single mirror in the DLP array. If the same setup is used for shorter wavelengths (i.e. visible light), the spatial coherence is limited by the physical size of each DLP pixel. In this case a smaller primary mirror can be used with no degradation of the wavefront coherence, up until the diffraction limit of the mirror is approximately equal to the DLP pixel size for the wavelength range of interest. Alternatively, a DLP with a smaller micro-mirror size could be employed, if available.

There are approximately 2 million mirrors comprising the DLP micro-mirror array. In the typical application of DLP for video projection technology, each mirror in the array acts as a single pixel on the screen of a television or projector. The two state tip-tilt control of each mirror allows for light to be directed either towards the screen, or to a light sink or 'dump'. In a similar manner, we oriented the DLP so that incident light was directed either towards the 30 in collimator, or elsewhere in the room, Figure 3.21. A video rate digitized image can be projected from the micro-mirror surface as in the example of, Figure 3.22. The DLP mirror configuration is controlled in the exact same manner as in a typical application of DLP (e.g. HDMI connection to a laptop. In fact, the DLP chipset currently implemented in the lab was re-purposed from a rear-projection television.

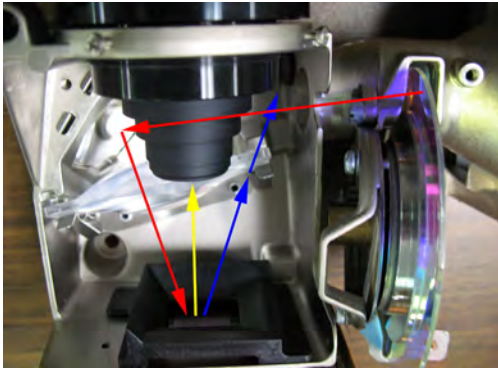


Fig. 3.21 Light path of TV DLP showing input (red), projection (yellow) and dump (blue)



Fig. 3.22 Exemplary image from our experiment taken directly from the DLP surface

Control of the DLP via standard video connections allows for complex scenes (i.e. dense star fields) to be conveyed to the DLP array as slides. The Star Generator can therefore simulate highly complex light fields featuring over 2 million point-like objects. This arrangement is potentially beneficial to any research requiring complex-scene analysis of experimental optics in a highly controlled environment.

With full control of the DLP array established, and a light source of the desired nature incident on the DLP, all that remained is to place the DLP at the focal point of the primary. Ideally, the DLP should obscure the collimated beam as little as possible. In our current assembly, the DLP is directed to the focal point via a small mirror, Figure 3.23. The achromatic nature of DLP allows for virtually any light source to be used. The current setup employs a xenon High Intensity Discharge (HID) lamp in order to simulate the ionized-plasma spectrum of stars. Other light sources, such as diffused lasers, can be used if a narrow-bandwidth applications are needed. Our current research of primary objective gratings may require many lasers in a variety of wavelengths to be incident on the DLP. This can be achieved by the use of multiple beam combiners to achieve a light source composed of many narrow-band sources (Figure 3.24).

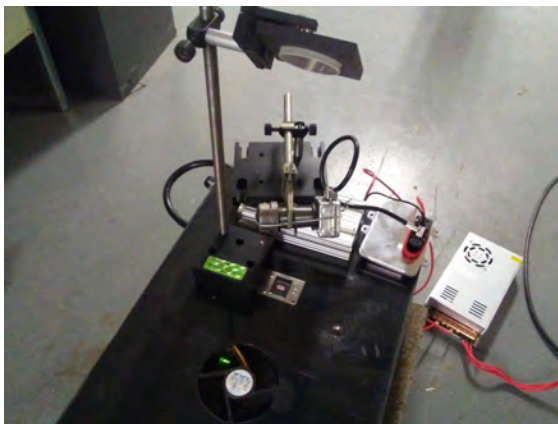


Fig. 3.23 DLP and HID assembly. Top down (left) Front facing (right)

The 30 in parabolic reflector used is shown in Figure 3.22. The CAD exploded view used in its construction is shown in Figure 2.23.

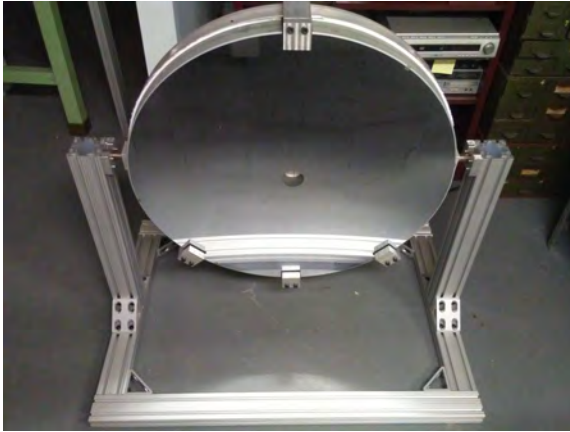


Fig. 2.22 The 30 in collimating mirror on swivel mount

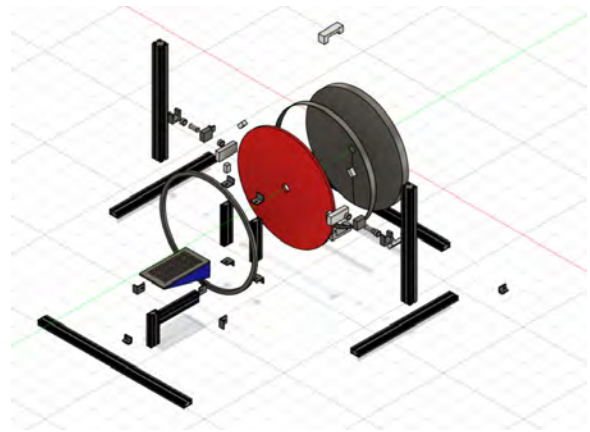


Fig. 2.23 CAD for the Star Generator mirror mount



Fig. 2.24 Projecting the DLP with no image on the table

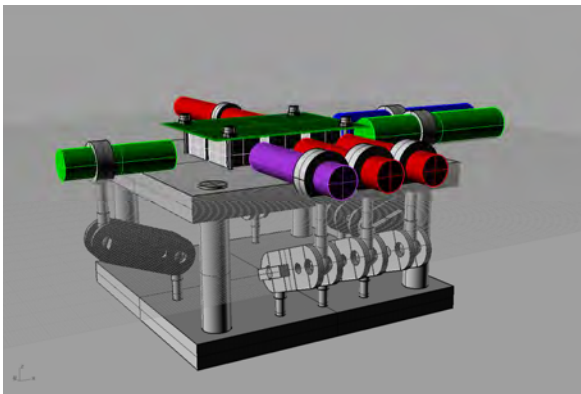


Fig. 3.25 CAD model of a light engine with seven pointing lasers using a six prism combiner

The mirror is supported by an adjustable mount. A central borehole allows for placement of the laser light engine, Figure 3.23, or other optics behind the mirror, although the borehole is not employed in the results reported here. The achromatic nature of DLP allows for virtually any light source to be used. “First light” where the collimator was projected on breadboard is shown in Figure 3.24.

Other light sources, such as diffused lasers, can be used if a narrow-bandwidth application is needed. Our current research of primary objective gratings may require many lasers in a variety of wavelengths to be incident on the DLP. The choice of garden variety pointing lasers was made to take advantage of their multi-mode operation which exhibits resonances at different temporal modes. These peaks and nodes are similar in frequency variations to Fraunhofer lines. The performance of the POG will be examined at these fine lines as well as from the broadband of the xenon HID which was used in the measurements of Figure 3.7.

The Light Engine is a work-in-progress, as is the newly instituted Newberg Laser Lab which has a 5 x 10 foot vibration isolated breadboard with a 5 W single mode argon-ion laser suitable for holography. It is a wet lab with a sink for photographic emulsions. Figure 3.26.



Fig. 3.26 Holography facility under development at RPI

Section 4. POG and Grazing Exodus

The longer the lever, the greater the force on the short side of the fulcrum. Anamorphic magnification using a POG is analogous. As the receiving angle of the secondary approaches the plane of the grating, the length of the POG may grow exponentially and yet remain fully in the FoV of the secondary mirror. The leverage was described in the seminal presentation of the eponymous Dittoscope⁴ at the 2002 SPIE Astronomical Telescope and Instrumentation Conference. If a ribbon grating is viewed at an angle r of diffraction, then for a secondary mirror of diameter D length L grows exponentially as the angle of diffraction approaches 90° , Figure 4.1.

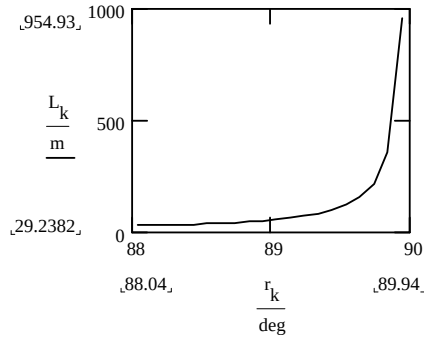


Fig 4.1 Grating length vs grazing angle with a one meter aperture D . Units in meters

$$L = D \frac{\tan(r)}{\sin(r)}$$

With a lever, greater force on the short side of the fulcrum has the tradeoff that the distances of travel are unequal such that a force on the long side increases force on the short side by increasing travel on the long side. With a POG a similar trade is that efficiency decreases as magnification increases. The secondary mirror diameter is proportional to the integration time

at the slit of the secondary spectrometer. Photons are lost as the integration time lessens. The size of the secondary mirror is somewhat equivalent to the allowable travel on the long arm of a lever. This is not to say that a lever is not clever. They built the pyramids. We will examine optimization of the inevitable trades that fall out of POG optics.

If the POG is a surface relief type diffraction grating, then efficiency is lost in proportion to an increase in POG length. The culprit is groove depth, see Figure 4.2. For a wave to be reradiated toward the secondary mirror, the portion of the groove that is visible from the vantage of the secondary mirror must be above the peak of adjacent grooves. At grazing exodus angles, blaze geometry flattens. An alternative is sinusoidal or triangular grooves that radiate in both directions. The use of dual opposed secondary mirrors doubles photon capture, but zero-order loss also increases at the same time, reducing efficiency in the $\pm$ first-orders. The overall losses result in virtually no gain in photon collection, regardless of POG length. In fact, infinite POG length = no photons.

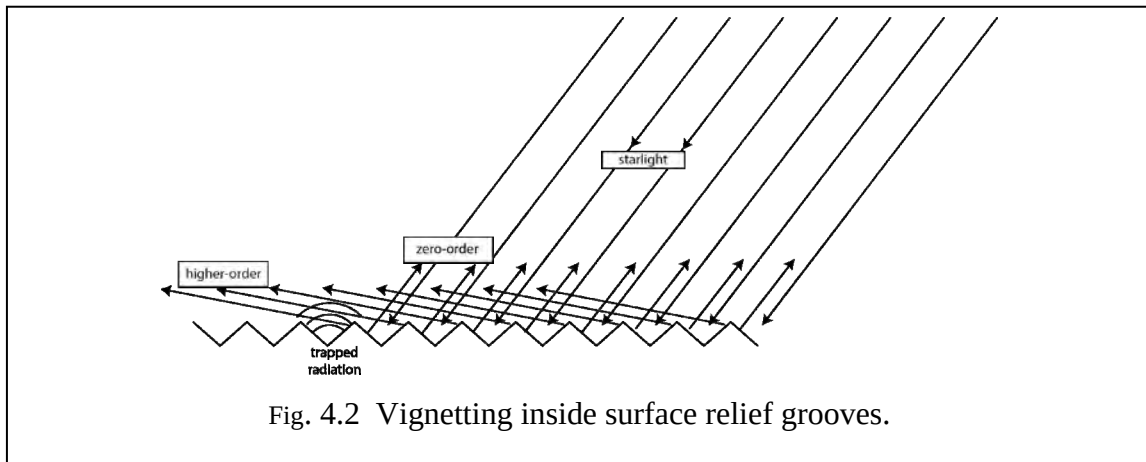


Fig. 4.2 Vignetting inside surface relief grooves.

This conundrum led to our investigation of a holographic emulsion type of POG such as exemplified by volume phase gratings (VPG).⁵ These emulsions such as dichromate gel are typically are thicker than 10 μm . That would recommend a dichromate VPG for a POG except that dichromate is hygroscopic requiring a seal under glass to prevent water absorption. The resulting glass sandwich precludes a grazing option, since diffracted light is trapped by total internal reflection (TIR) in either the substrate or the seal glass. However, dichromate gel would not absorb water in the vacuum of space. hence it would be a candidate for future research beyond Phase II, so we opted to experiment in our laboratory with silver halide emulsions which were readily available and could serve as a model. It has been shown that silver halide gelatin can be converted into dichromate plates.⁶ The emulsion side does permit diffracted light to escape at grazing.

One means for fabrication of a silver halide plane grating calls for two coherent plane waves superimposed at a film plane. The angles of superimposition at exposure of the plate are comparable to the implementation of the POG, that is, a beam from the sky diffracted at a grazing angle. In our lab we had a 30 inch $\lambda/5$ mirror. Fully illuminated from a spatial filter at its focal length of 10 ft, it produces a plane wave which can be split into the reference and object beams. A film holder was placed at 23° off the axis of the plane wave which served as the grazing beam. A 10^{th} wave flat was positioned to redirect

the mirror plane wave reflection to a plate 50° off the surface normal, Figures 4.3 (a & b).

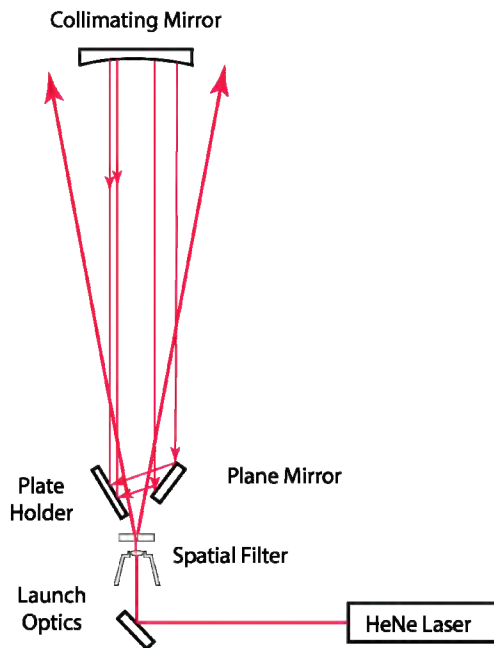


Fig. 4.3 (a) Schematic of recording setup

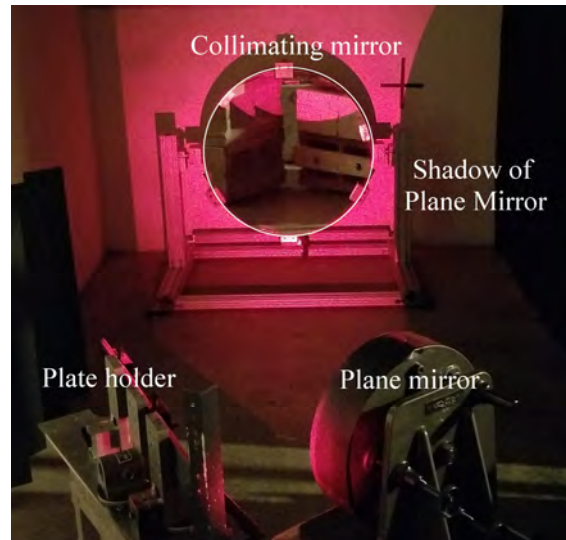


Fig 4.3 (b) Laboratory installation for recording

Recording at grazing below 5° (as the POG is contemplated for service) was not possible. The beam from the collimating mirror would have been attenuated by surface reflection. Even the selected 23° angle was problematic, not only due to attenuation but also from reflection from the emulsion surface. When the resulting hologram was tested for performance, a further complication emerged due to internal reflections from the back of the plate that produced tell tale “wood grain” textures caused by phase interference. An anti-halation black was then used to coat the plate.

Test holographic plates were made for a reference $45^\circ \times 45^\circ$ exposure and the $23^\circ \times 50^\circ$ for a model grazing POG. Incident light levels as measured directly into the incident illumination are shown in Figure 4.4.

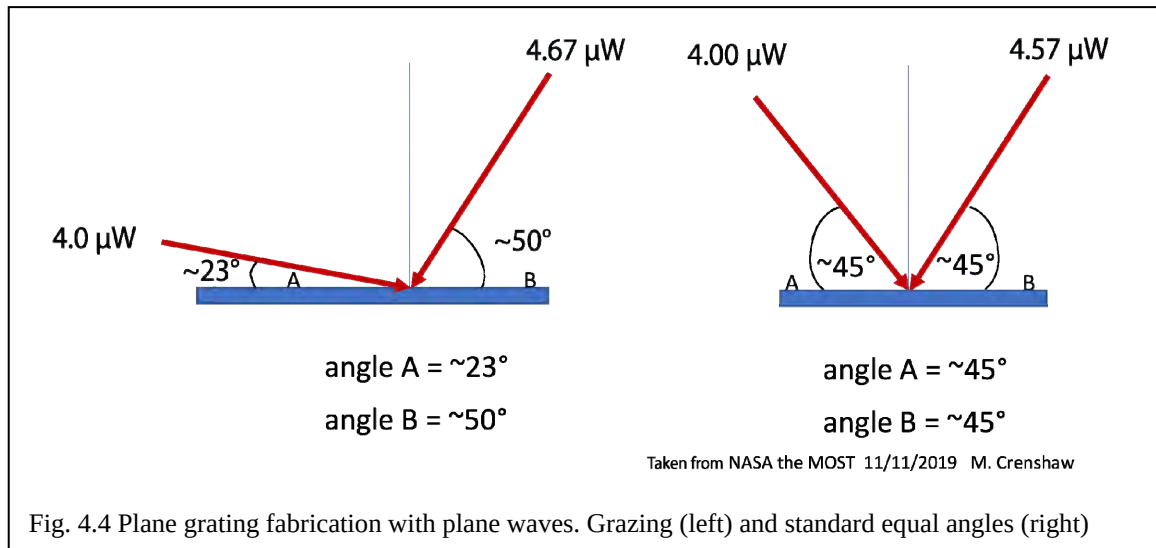


Fig. 4.4 Plane grating fabrication with plane waves. Grazing (left) and standard equal angles (right)

We used PGF 01 fine grain silver halide plates which resolve 3000 lines/mm. In addition to silver halide, we used LitiHolo polymer, but integration times were too brief to leave a useable exposure. Detailed *Laboratory Notes* for the materials and the fabrication processes of these gratings, as prepared by M. Melissa Crenshaw, appear in Appendix 1.

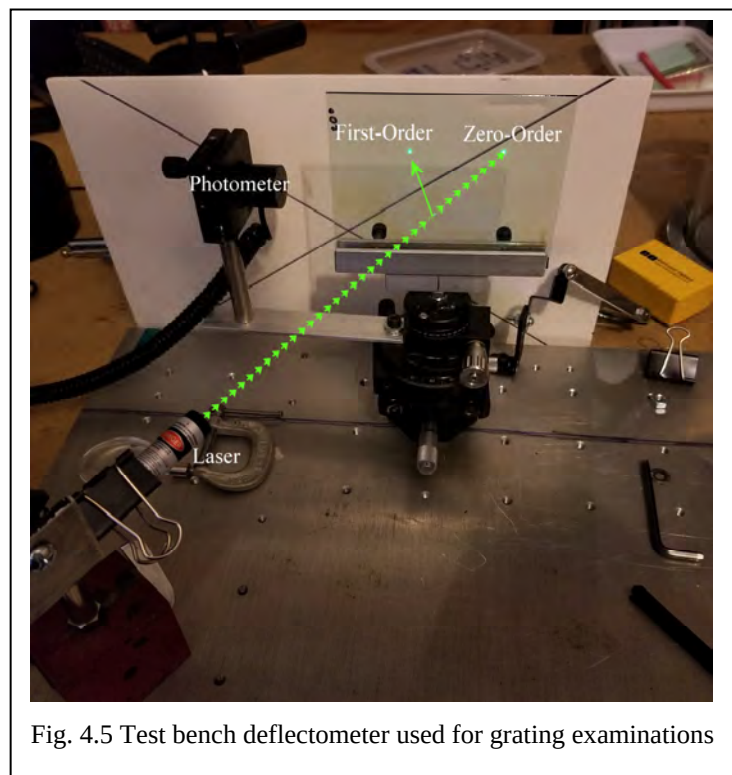


Fig. 4.5 Test bench deflectometer used for grating examinations

Samples from the exposures were tested for performance by James Drake and Victoria Wisniewski from RPI's undergraduate program in physics under the supervision of Prof. Heidi Newberg. They confirmed that the standard grating performed nominally. They confirmed that its pitch was 2000 lines/mm. Using a deflectometer constructed in-house by Fred Berkhout and the P.I. illustrated in Fig. 4.5 measurements were taken to establish the variation in angle of incidence and angle of diffraction as well as the relative change in the intensity of the incident and diffracted beams. A schematic representation of

the deflectometer bench is shown in Figure 4.6 and graphs of the intensity readings are shown in Figure 4.7.

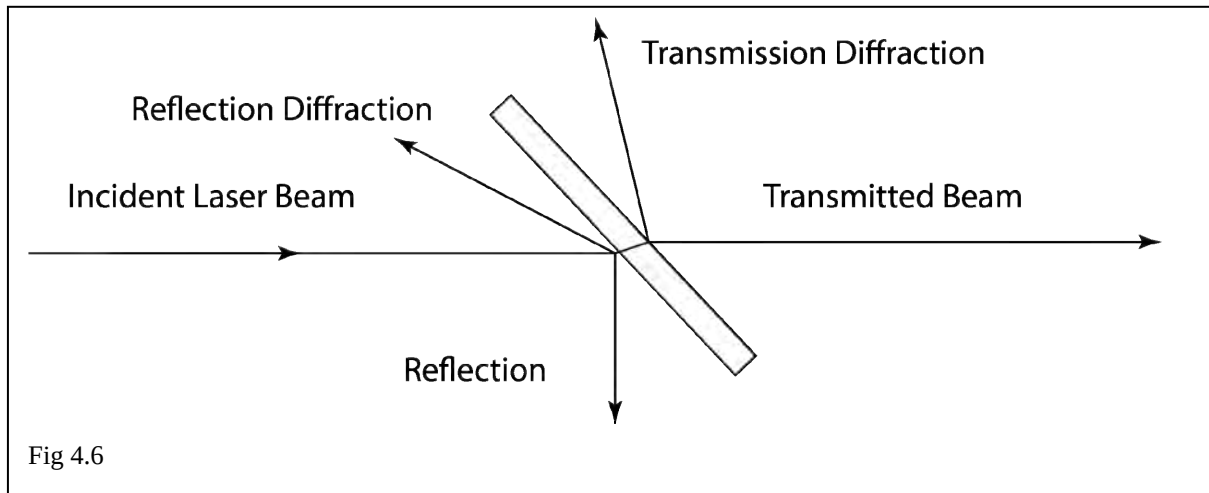


Fig 4.6

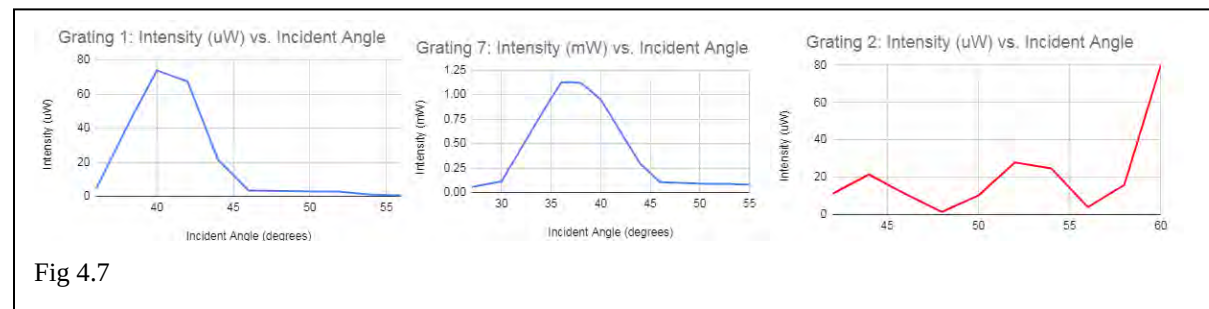


Fig 4.7

Angles are measured from the grating surface normal. Efficiency of two samples of gratings exposed at equal reference and first-order diffraction angles peaked at 37° and 40°. Shrinkage of the emulsion in development caused variations from exposure angles. The POG (Grating 2 in red) exhibited an anomalous series of spikes that are attributable to a wavefront that is trapped inside the plate that produces a pattern of internal reflections. Measurements were halted at 60° where the incident beam reflects. A follow-up experiment investigated the phenomenon, Figure 4.8. The behavior was caused by skips between the top and bottom of the holographic plate caused by internal reflections within the plate. Multiple reflections were controlled by adjustment of plate inclination.

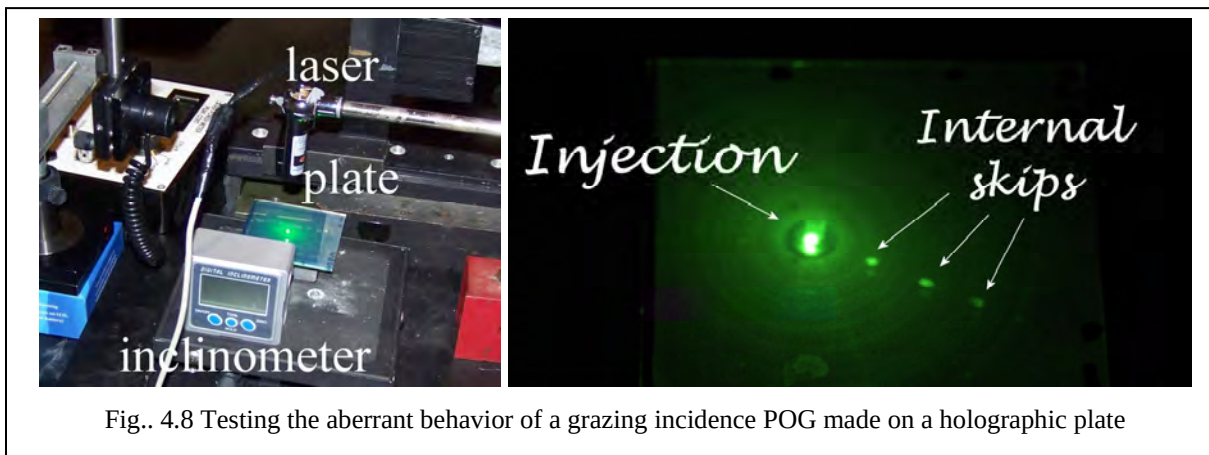


Fig.. 4.8 Testing the aberrant behavior of a grazing incidence POG made on a holographic plate

The thickness of the plate, ~ 3 mm, plays a role in the internal reflection phenomenon. A thinner plate such as the substrate for LitiHolo,⁷ a polymer, recommended itself, but it was not as sensitive as silver halide, and our attempt at production of a POG sample with the LitiHolo product failed to produce a working exposure at 5 minutes integration time. In an experiment, not directly related to this project, we were able to demonstrate a serviceable DOE in LitiHolo at 30 minutes exposure time instead of the 5 minutes we allowed ourselves in our POG series of experiments. That success spoke to the robust vibration damping of the 3DeWitt laboratory bench, but as NIAC funding had ended, we lost access to our rented laboratory (the studio of the late Rudie Berkhout) in April 2022. Fortunately, by this time, RPI had instituted a new laboratory explicitly for our research with a 5 W argon-ion laser that can fabricate on LitiHolo film in fractions of the exposure time required for the 20 mW HeNe used in this experiment. We hope to continue this experiment at the RPI facility, Newberg Laser Lab.

Our experiment confirmed that at grazing exodus plates develop so-called “wood grain” textures from light trapped inside the substrate. The answer to the problem rests with index matching fluids that surround the plate. Derived from xylene “wet gate” optical printers from the era of photographic motion picture film and edge lit holography, the process exploits a liquid with nearly the same refractive index value as glass and film substrates. As a result laser light exits the plate at the site where the wavefront from the exposing radiation would otherwise be trapped. In a proposed experiment, Figure 4.9, the plate is illuminated along the plate axis. The return reflection would set up a standing wave at $\frac{1}{2}$ the wavelength of the illumination. The wood grain effect would be neutralized by the index matching fluid. The allowable error in the lateral offset between Mirrors 1 & 2 is sub-wavelength, but this is a challenge routinely met in Michelson interferometry.

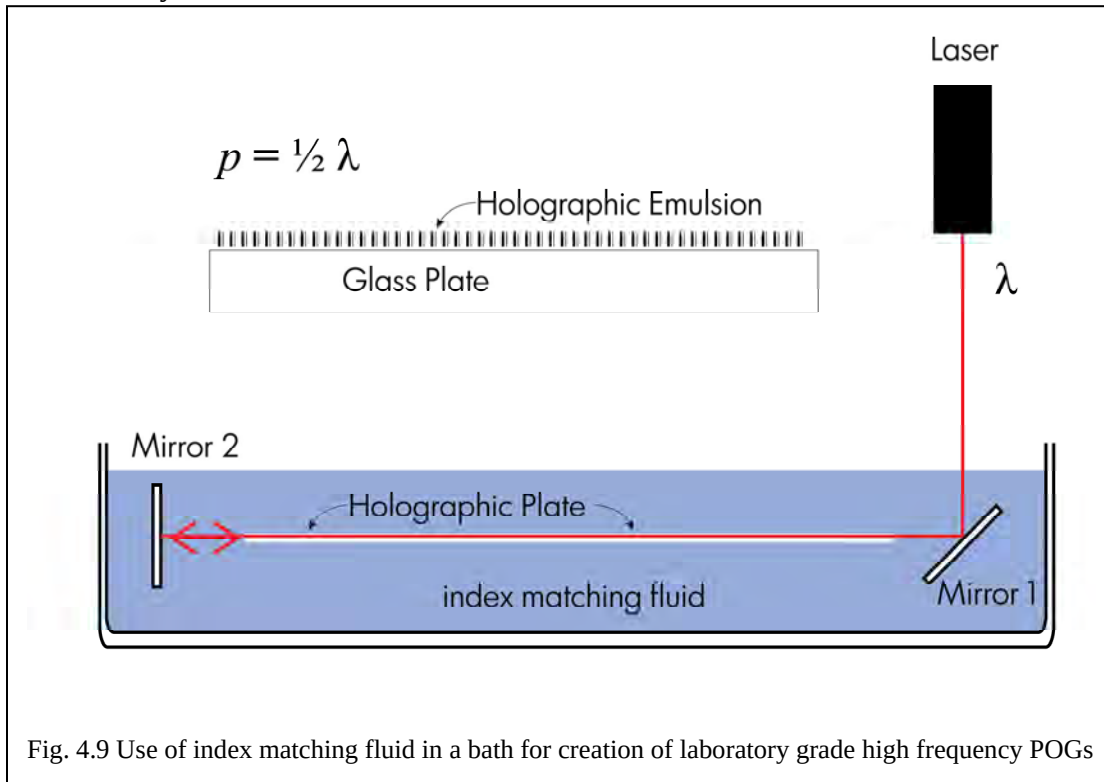


Fig. 4.9 Use of index matching fluid in a bath for creation of laboratory grade high frequency POGs

Overcoming internal and external reflections on the POG in fabrication does not address the same phenomena as they occur in astronomical telescope observation where a shallow grazing exodus angle is requisite to achieve leverage from long POGs. A high frequency DOE POG alone does not necessarily direct radiation into the secondary at grazing.

Our current thinking is that fabrication should follow reflection holographic procedure where the object and reference beams are on opposite sides of the recording emulsion. Exposure is made using opposed plane waves intersecting the plate at angle θ illustrated in Figure 4.10 . The resulting fringes are parallel planes separated by the illumination laser wavelength divided by two.

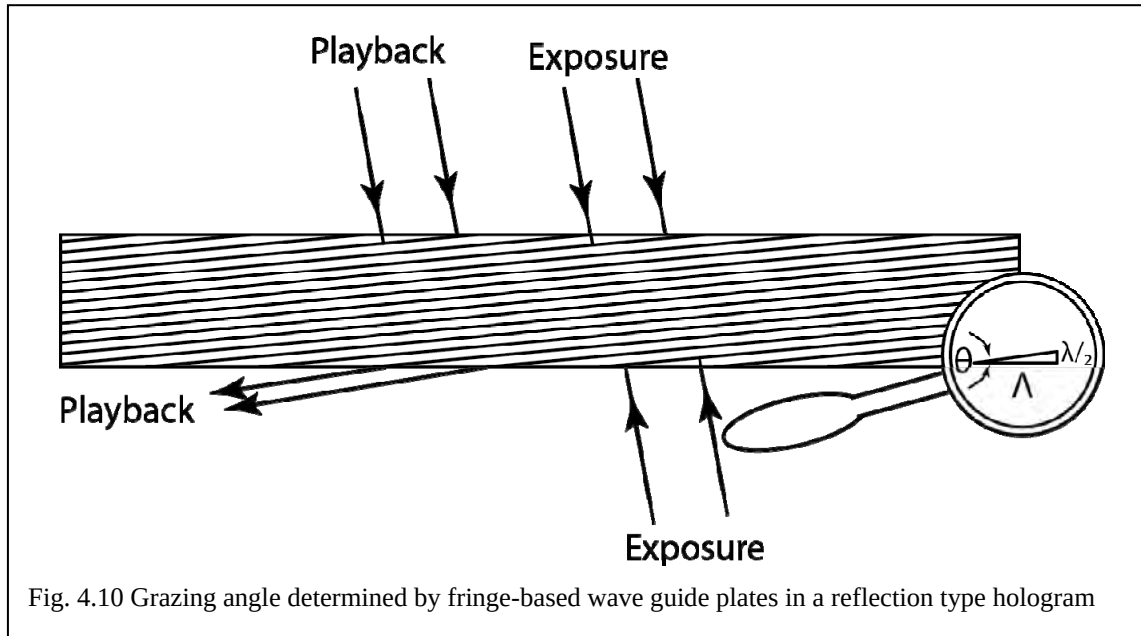


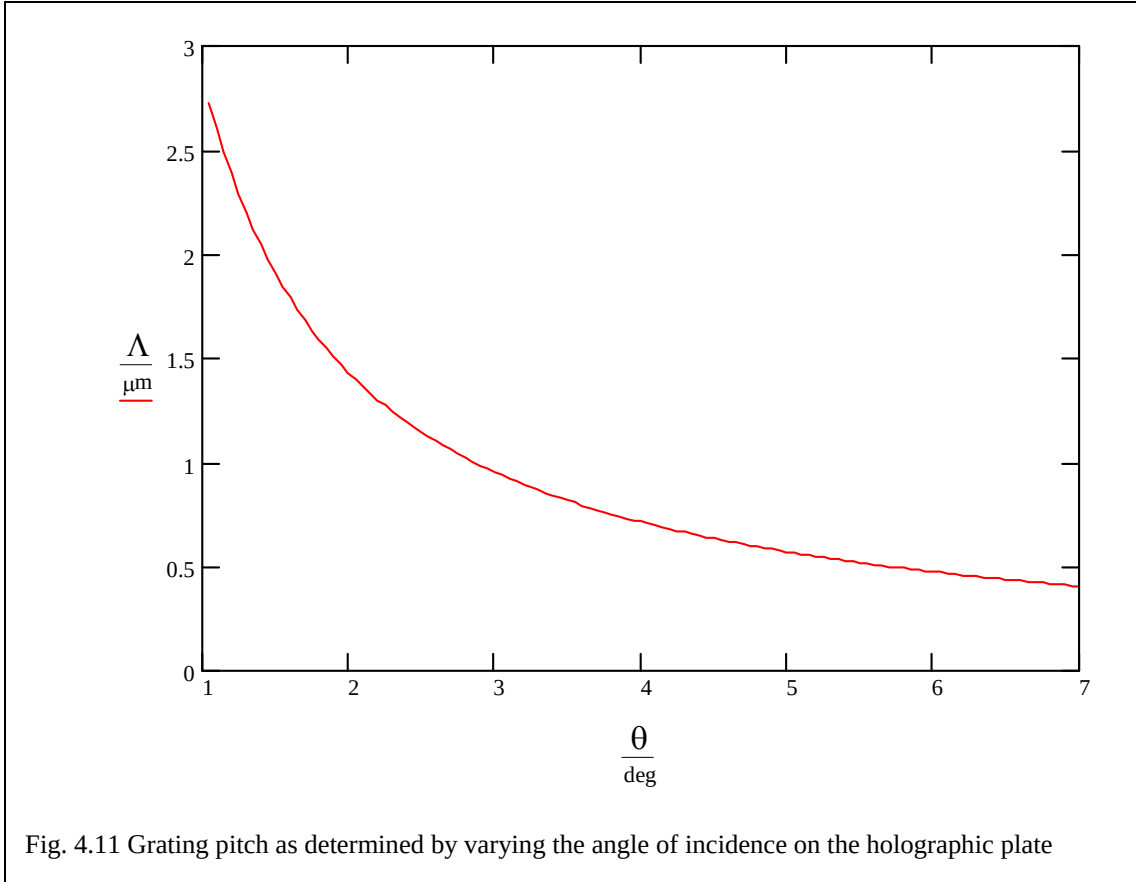
Fig. 4.10 Grazing angle determined by fringe-based wave guide plates in a reflection type hologram

Unlike edge lit reflection holography, here the diffracted light is channeled out from the parallel fringes at a preferred grazing angle θ . Edge lit holograms must achieve the reverse where the illumination must enter the plate at a prohibitive angle that induces the reflection that must be defeated with index matching plates. A notable distinction in our application is that the escaping light diffracted to the grazing angle appears along the playback surface with a period Λ , which is significantly longer than a reflection hologram playback which occurs at wavelength. λ The downshift shift can be predicted based on a triangle seen under the “magnifier” on the lower right in Figure 4.10.

$$\Lambda = \frac{\lambda}{\tan(\theta)}$$

As $\theta \rightarrow 0^\circ$ where grazing leverage is greatest, $\Lambda \rightarrow \infty$, so we are faced with a similar dependency as with the loss of efficiency illustrated schematically in Figure 4.2 for surface relief gratings, but in this dependency, the pitch becomes infinite. While this fabrication technique cannot achieve an infinite grating length note that, if a hologram is fabricated at a short wavelength, it will result in a grating of longer pitch.

By way of imagined example, in Figure 4.11 we show a grating made at extreme-UV of 50 nm that results in a grating with a pitch of 500 nm at a grazing exodus angle of about 6° in the visible spectrum band. With a pitch of 1.5 μm, this fabrication would enjoy a grazing angle of 2° and cover the Earth's near-IR window. We will discuss this application in Section 6.



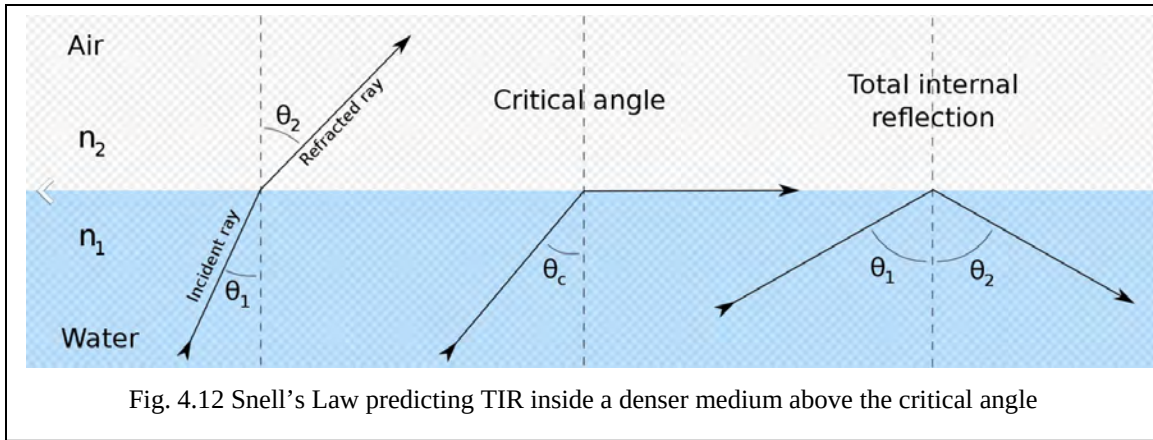
In phase holograms such as is typical with holographic emulsion, fringes are variations in the index of refraction. Think of each fringe pair as a waveguide resulting in a wavefront at grazing that is propagated at the angle of the fringes relative to the surface normal.

Where the waveguides intersect at the grating surface with the exterior medium, Snell's law applies

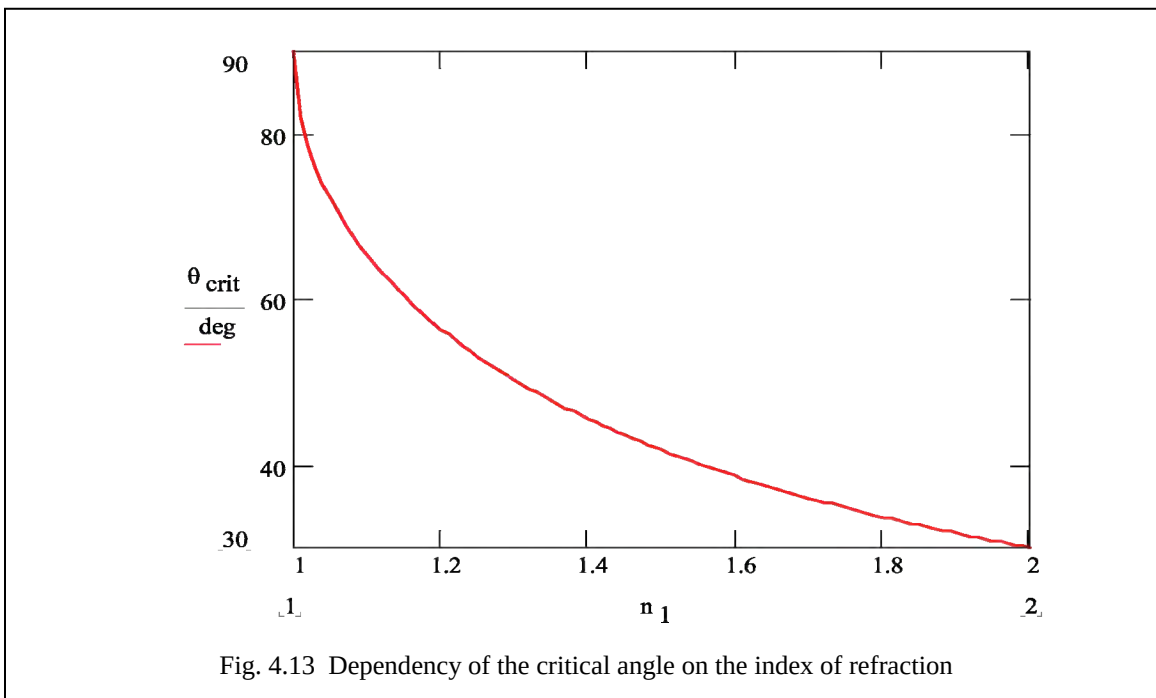
$$\sin(\theta_1) = \frac{n_1}{n_2} \sin(\theta_2)$$

where the first surface is n_1 and the second surface is n_2 , further bending the wavefront closer to the grating surface. The parameters are illustrated in Figure 4.12 (taken from Wikipedia).⁸ The critical angle of 90° where $\sin(\theta) = 1$ can be known from

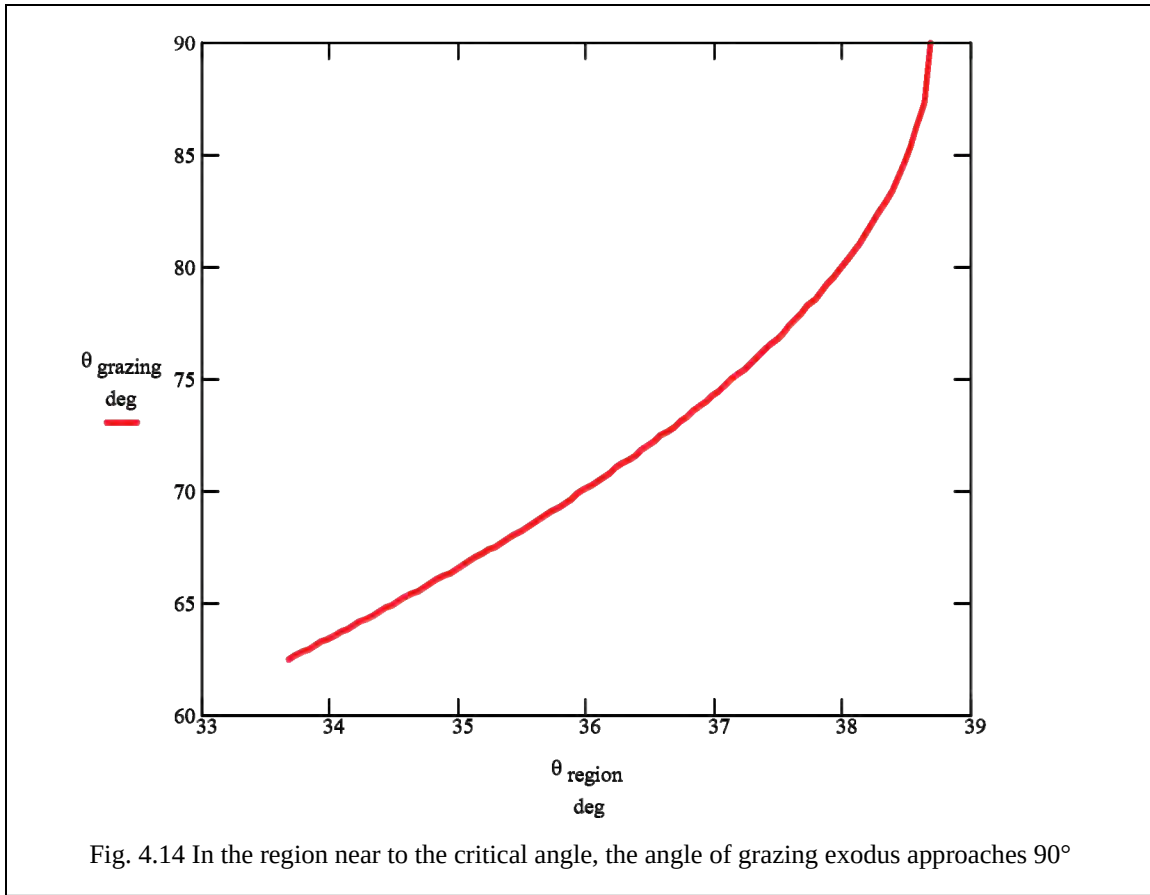
$$\theta_{critical} = \arcsin\left(\frac{n_2}{n_1} \sin(\theta_2)\right) = \arcsin\left(\frac{n_2}{n_1}\right)$$



Refraction indices of holographic emulsions and glass substrates are typically $n = 1.6$. A variety of optical coatings can be used to raise or lower these indices. If the wavefront is escaping into a vacuum $n = 1$. Air is $n = 1.003$. We compare the critical angles for light refracting into a vacuum from materials with indices of refraction in Figure 4.13 .

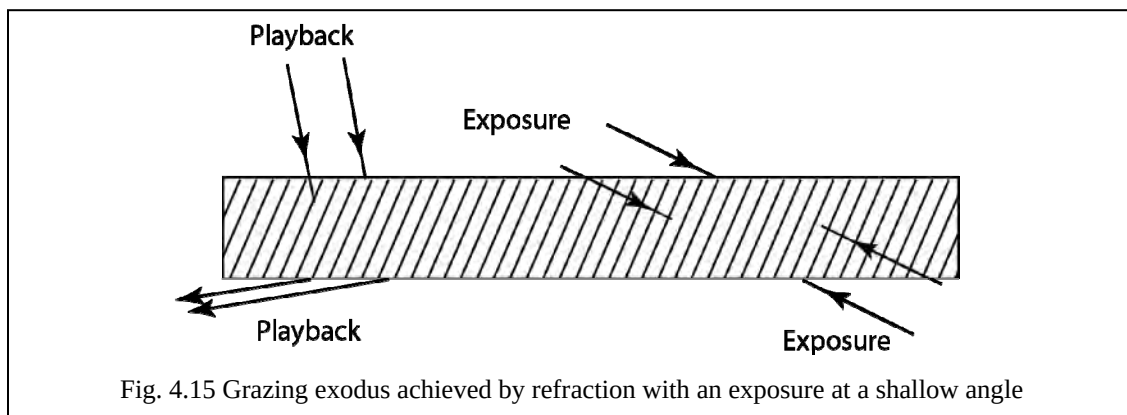


Grazing angles just shy of the critical angle are in the realm of grazing exodus angles that produce the greatest leverage of anamorphic magnification just so long as $\theta_1 > \theta_{critical}$. In Figure 4.10 playback from the source illumination is subject to refraction between the emulsion and the open air (in laboratory settings) and a vacuum (in space). We can see from this example that internal fringes at angles above approximately 40° will be trapped by TIR in a POG fabricated in the manner sketched in Figure 4.12. The precise angle of a POG with an index of refraction of 1.6 is 38.682° . We will use this as an example. The dependency is shown in Figure 4.14 .

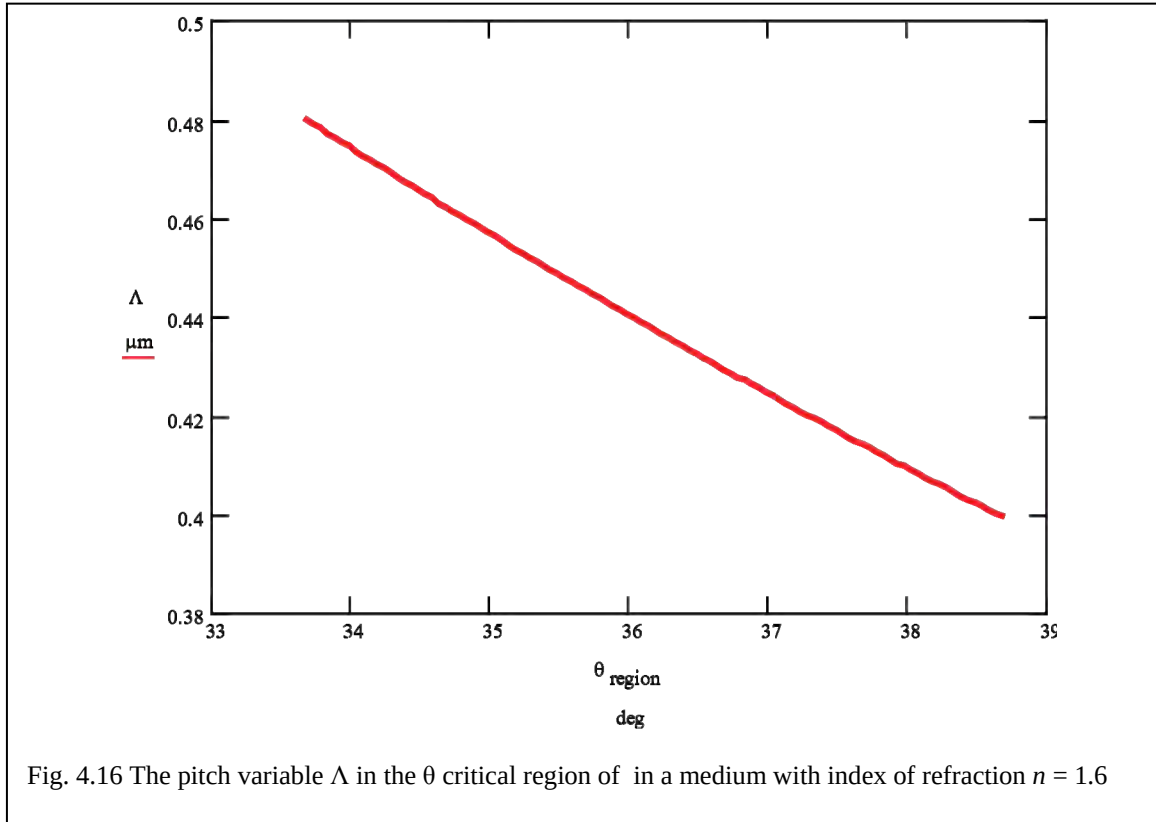


This dependency shows that if we use holographic emulsions as we approach the critical angle, grazing angles approaching 90° at the playback can be achieved using the index of refraction, providing extraordinary leverage, permitting extremely long ribbon POGs.

Compare Figure 4.15 with Figure 4.10. The fringes are more closely spaced because refraction is factored into the model of the grating. As a result, the fabrication can be made with lasers of longer wavelengths similar to those contemplated for the recording of Figure 4.9, putting a physical embodiment into the realm of possibility, unlike the model of Figures 4.10 and 4.11 which requires a notional 50 nm single mode laser.



For example, using a 320 nm laser which is in a band now serviced by laser diodes, the relationship of Figure 4.16 shows that on a substrate like holographic film with $n = 1.6$ the grating pitch Λ is in the realm of the visible. The angle of grazing exodus, $\rightarrow 90^\circ$ has $\Lambda = 400$ nm, the edge of the near-UV, a band inaccessible without the refraction effect.



Because exposure angles are also affected by the indices of refraction, fabrication may require index matching fluid as per the diagram of Figure 4.9 to avoid wood grain features and possible losses of incident laser light through reflection.

Note that surface waves are along an insulator substrate such as glass, plastic, or any gelatin with an refraction index waveguide. There are no coupling phenomena as with metalized mirrors. Glass is a suitable substrate for a transmission POG and is recommended for THE MOST, if feasible.

Corning and Schott offer flexible glass substrates with low CTE and uniform transparency across the visible spectrum which are both desirable features for the POG and HOE components. We investigated Corning Willow Glass, Tables 1 & 2, Figure 4.17

Sheets		Rolls
Sizes	Up to 1100 mm x 1200 mm	Up to 1.3 m wide and 300 m long
Composition	Alkali-free Borosilicate	
Packaging	Flat Box / Interleaf	Rolls/Edge tab/Leader/Trailer/Interleaf
Thickness	100 μm and 200 μm	100 μm and 200 μm

Table 1 Corning Willow Glass Spec Sheet 2019

Metric Unit	Nominal Values	Bulk Properties
g/cc	2.56	Density
$\times 10^{-7}/^{\circ}\text{C}$	34.6	CTE (0°C to 300°C)
GPa	78.7	Young's Modulus
-	0.23	Poisson Ratio
$^{\circ}\text{C}$	725	Strain Point
$^{\circ}\text{C}$	781	Annealing Point
-	5.95	Dielectric Constant ($k=E_o/E$)
Ra (nm)	< 0.5	Surface Roughness
Rpv (nm)	< 20	
mm	100 μm = 90 mm	Minimum bend radius for curved design*
	200 μm = 180 mm	
$\text{g}/\text{m}^2/\text{day}$	Below Detection Limits	Water Vapor Transmission Rate (WVTR)
2000 g load 15 second dwell time	588	Hardness

Table 2 Corning Willow Glass Spec Sheet 2019

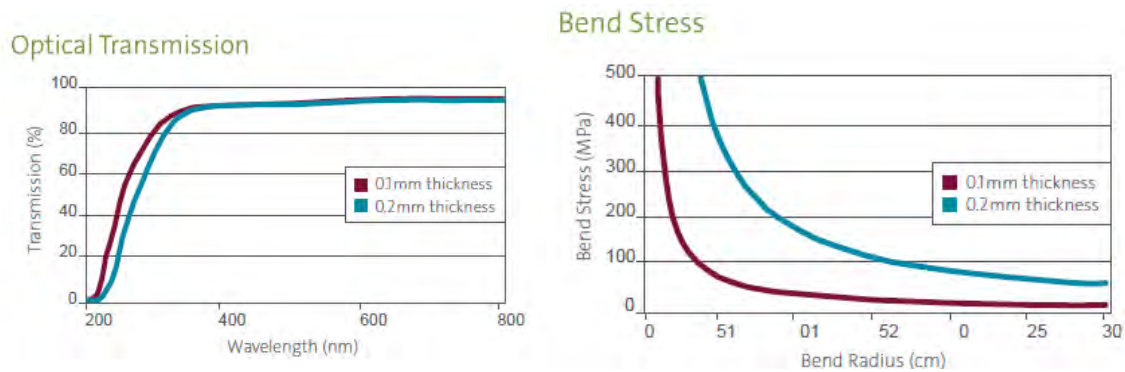


Fig. 4.17 Corning Willow Glass Spec Sheet 2019

We visited the home base in Corning, NY. Samples of Willow Glass were sent to us for inspection. While the folding dimension is flexible, the posterior is not. The 100 μm thick substrate can catastrophically shatter under stress or shock. This defect remains to be addressed. All the optical parameters needed for our application were otherwise in conformity to our preconditions for an optimal substrate. Alternatives are plastics that have poor transmission bandwidth characteristics. While plastics would be suitable for aluminum coating in reflection mode, the POG would be required to hold a sub-wavelength flat figure to deal with the posterior image. It is far preferable to utilize transmission diffractive optics.

We understand that Corning research on fusion glass is central to their operation, since their glass of similar manufacture, Gorilla Glass, that does not shatter is used in display screen manufacture. Finding the right combination of flexibility with strength would permit Corning to compete with Schott which presently has supplied flexible screen



Fig. 4.18 Willow Glass forming rollers

glasses to the cell phone market. The Corning company is geographically close to us, so we would like to maintain a working relationship with them. It is not simply about the glass. The processes to coat the grating with photo sensitive emulsion requires that we collaborate on their roll press, Figure 4.18. Likewise

the proximity of the legacy Eastman Kodak facilities in Rochester, NY could play a role.

Looking again at the grazing angle needed for leverage, the first-order free spectral range is optimized. The collapse of the free spectral range at angles of diffraction below grazing introduces ambiguities in overlapping higher-orders. The dependency is described by solving the diffraction equation for the allowable angle of incidence i in radians.

$$i = \arcsin\left(\left(\frac{n\lambda}{p}\right) - \sin\left(\frac{\pi}{2} - r\right)\right)$$

where r is for the grazing angle

THE MOST is constrained in bandwidth by the free spectral range of the POG's 1st order

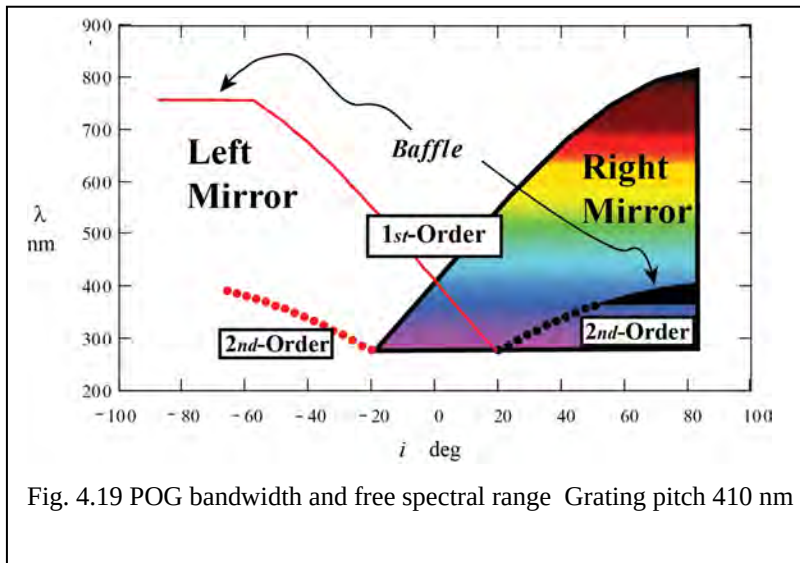


Fig. 4.19 POG bandwidth and free spectral range Grating pitch 410 nm

as subtended over incident angles i from 0° to 90° longitude, i.e.. from horizon to zenith. The remainder of the spectrum competes with the 2nd-order which appears at the horizon and partially penetrates into one side of the sky. An exemplary calculation for opposed mirrors is graphed in degrees, Figure 4.19. The infiltration of the 2nd order occurs at 400 nm

or at half the longest wavelength in the free spectral range.

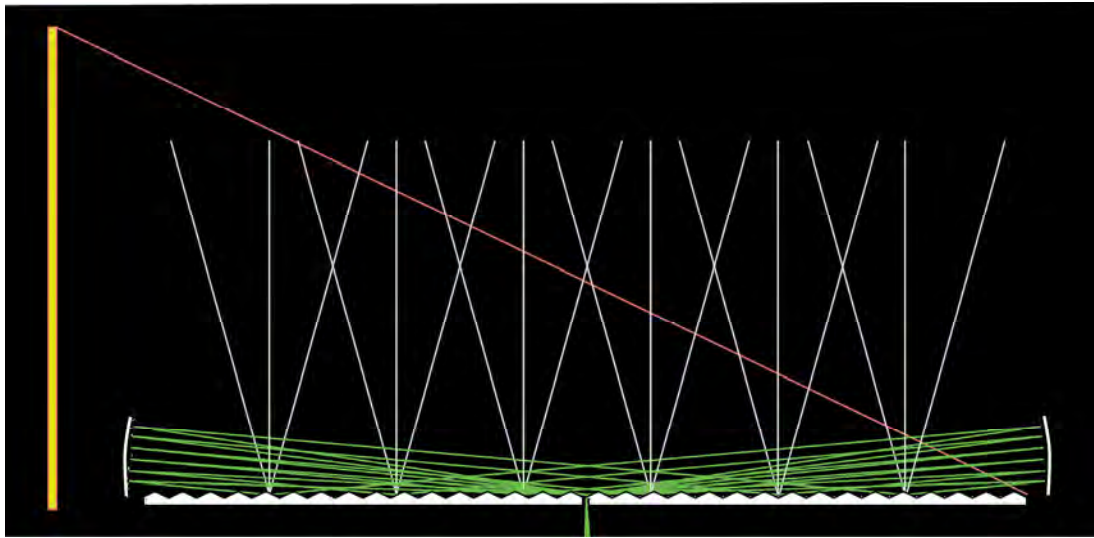


Fig. 4.20 Dual secondaries share a common POG. Baffle on left side.

The 2nd-order can be blocked using a baffle. A dual mirror configuration is used in a Zemax model Figure 4.20. The baffle will occlude the 2nd order on one mirror and the longer wavelengths on the other mirror. The 2nd order can be subtracted out from a non-occluded spectrum, and the missing portion of the 1st order can be filled in. Dual mirrors also double photon collection and provide redundancy for calibration purposes. The baffle is an added complication not studied in our model of THE MOST in Section 5. We contemplate using frequency selective band block filters in the sensors as an alternative to shadow casting baffles.

Section 5. The High Étendue Multiple Object Space Telescope - THE MOST

In the literature and with the guidance of the 2020 *Decadal Survey* space telescopes for the coming decade are to be confined to an aperture limited to ≈ 8 m, because logistics of cost vs. performance favor mirrors that remain in the present bracket of JWST, 6.5 m. However, in a private conversation with a proponent of this mirror diameter ceiling, Phil Stahl, we were told that this constraint does not apply to our novel POG telescope, and he encouraged NIAC to continue taking chances with this high risk/high payoff study.

The differences make all the difference. We have shown on the bench in Section 3 that a POG has a relaxed figure tolerance. The empirical demonstration follows in the wake of a mathematical model first disclosed in 2002 that made the prediction. That is not all, because a POG can also be flat, as compared with legacy mirrors and lenses. It is their shape as well as their tight figure tolerances and substrate mass that contribute to their cost and limited apertures in foreseeable space applications.

THE MOST is a space telescope. A model taken from Zemax, Figure 5.1, has served as the base design prior to this NIAC Phase II project.

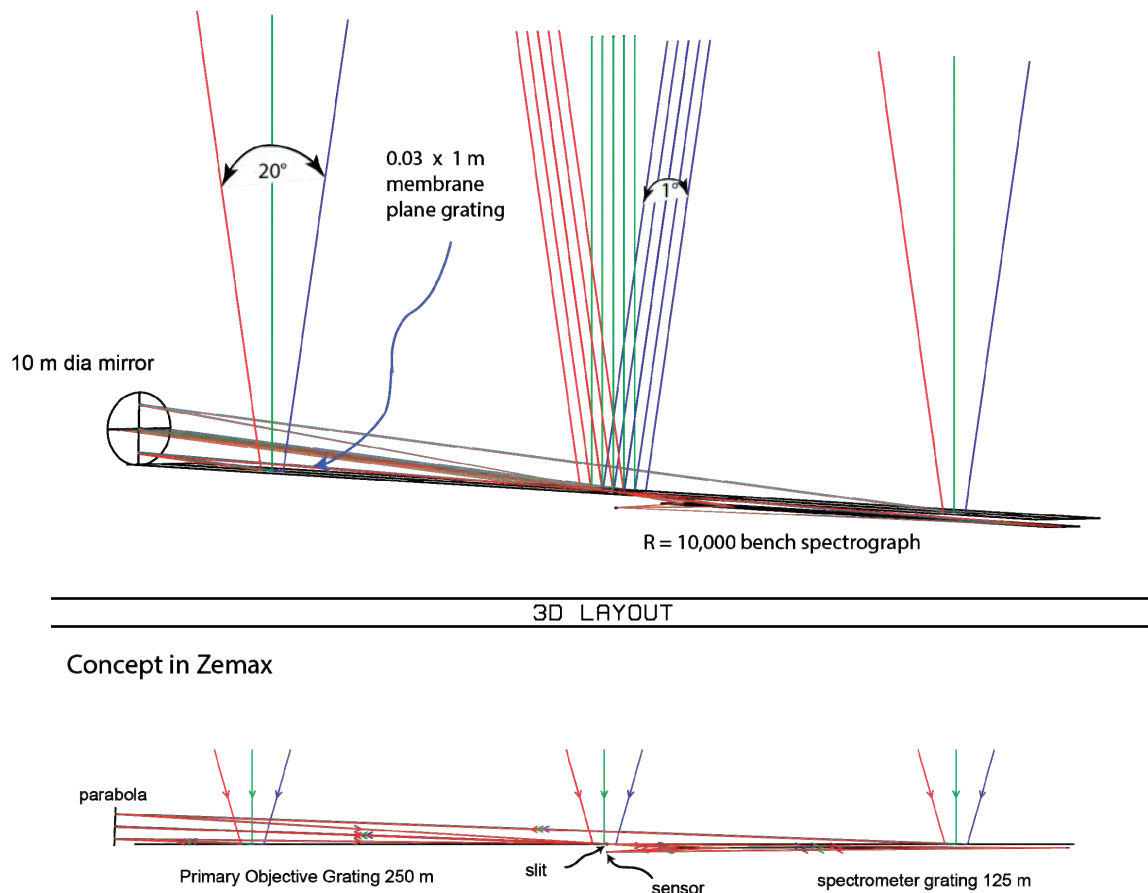


Fig. 5.1 Model of Zemax submitted in prior proposals by 3DeWitt and TUI

Distinguishing features are the long POG which one can think of as a lever where magnification is the ratio of the length of the grating vs. to the diameter of the secondary mirror. The ultimate magnification ratio is taken from the size of the sensor. Either way, there is astronomical magnification. Another feature that distinguishes the POG telescope

is the secondary spectrometer with disambiguates the overlapping images by correlating angle on the sky with wavelength as resolved in the spectrometer.

The aperture in the diffraction dimension where magnification of spectra takes place is the easiest to launch. Kilometer scale ribbon membrane gratings are conveniently stowed on rollers to be deployed in orbit for assembly by robotic agents. For astronomy, the 10 m mirror can be stowed as a sliver form factor. The more challenging dimension is the oblique lateral dimension. Magnification in the oblique is provided solely by the secondary mirror. If the secondary mirror's size faces the same limits as imposed by *Decadal Survey* specification, it resolves less at a narrower oblique field-of view than along the considerable length of the POG.

Guidance for stowage of a 10 m oblique dimension is illustrated in Figure 5.2.

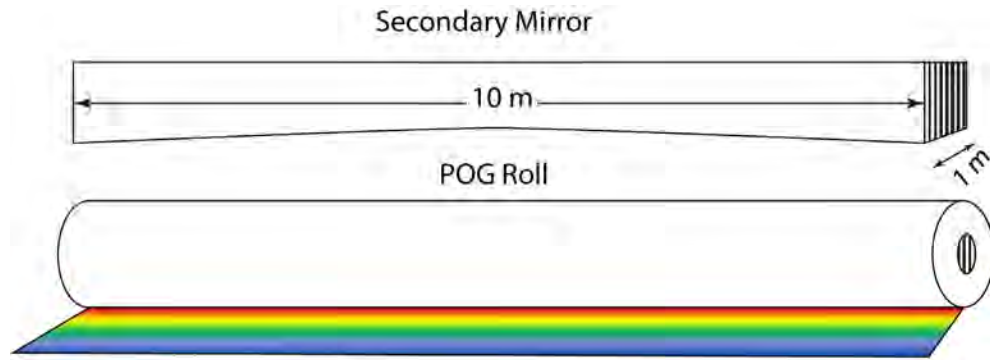


Fig. 5.2 For stowage, membrane optics roll up and secondary mirror is a “sliver”

Cylindrical roll POG packaging for insertion conforms to delivery vehicle dimensions. The wrap required to hit 300 m length can be calculated by the approximation of

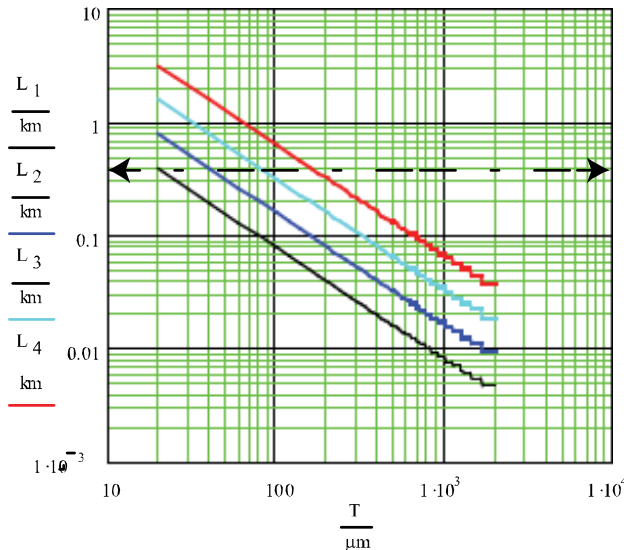


Fig. 5.3 Stowable lengths of membrane
Roll OD = 0.25 , 0.5 , 1 , 2 m
Lengths of 300 m are marked with arrow

$$L = \sum_{n=0}^N \pi(OD - nT)$$

OD is the outside diameter
 T is membrane thickness
 N is the number of wraps

$$N = \frac{OD - ID}{T}$$

Diameters are shown in Figure 5.3. Drum storage during transport offers optical surface protection without significant mechanical or weight overhead. The tensioning frame are mechanical and launch weight problems addressed by SpiderFab®. TUI holds patents and practice on robotic assembly in space after NIAC and DARPA development.

The bench experiments of Section 3 were run using an off-the-shelf decorative grating that operates in the reflection mode, but as illustrated in Figure 3.9 the performance of a reflection film as an optical surface is not of any utility, because in the oblique direction it would have to hold to sub-wavelength mirror tolerances. To resolve in both the diffracted and non-diffracted directions, it is more practical to use transmission gratings in astronomical telescope designs. We have a model in Zemax that incorporates the transmission mode, Figure 5.4. Detail of the transmission POG is shown in Fig. 5.5.

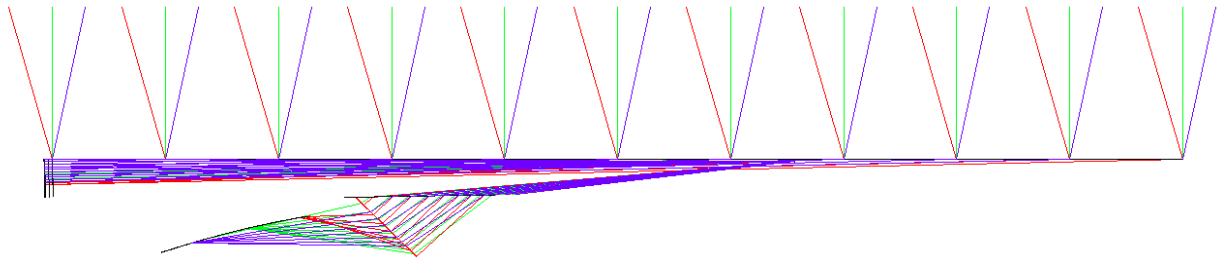


Fig. 5.4 Zemax model (rev 49) of THE MOST based on use of transmission POG

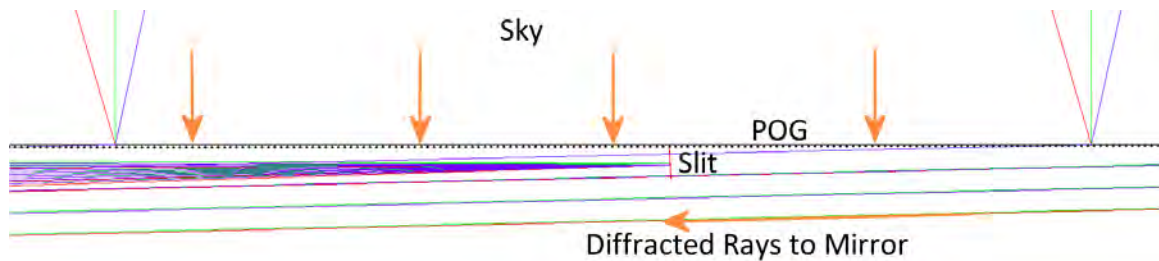


Fig. 5.5 Transmission POG detail up to the Slit aperture

This latest model has details of the secondary that remain under study, but the POG, the secondary mirror, the second disperser and a sensor bar of considerable length are basic to the design and were our guidance for the 2021 renders made by TUI. A 3D rendering with annotations appears in Figure 5.6, seen full scale on the following page.

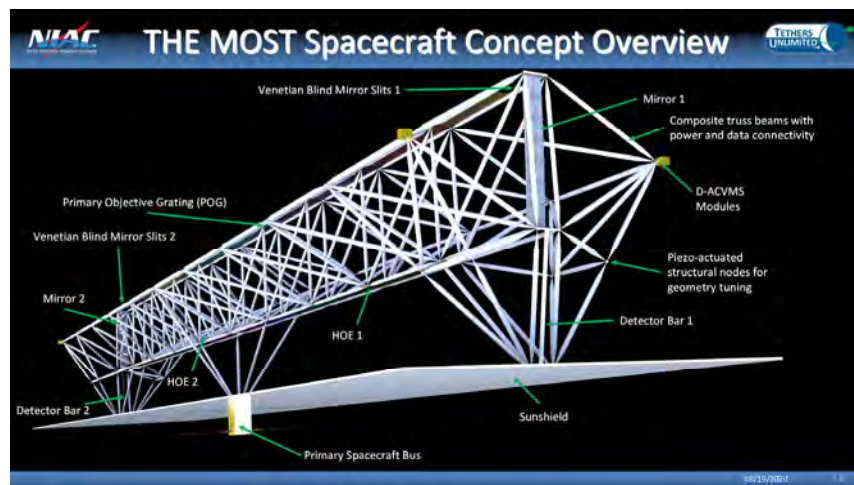
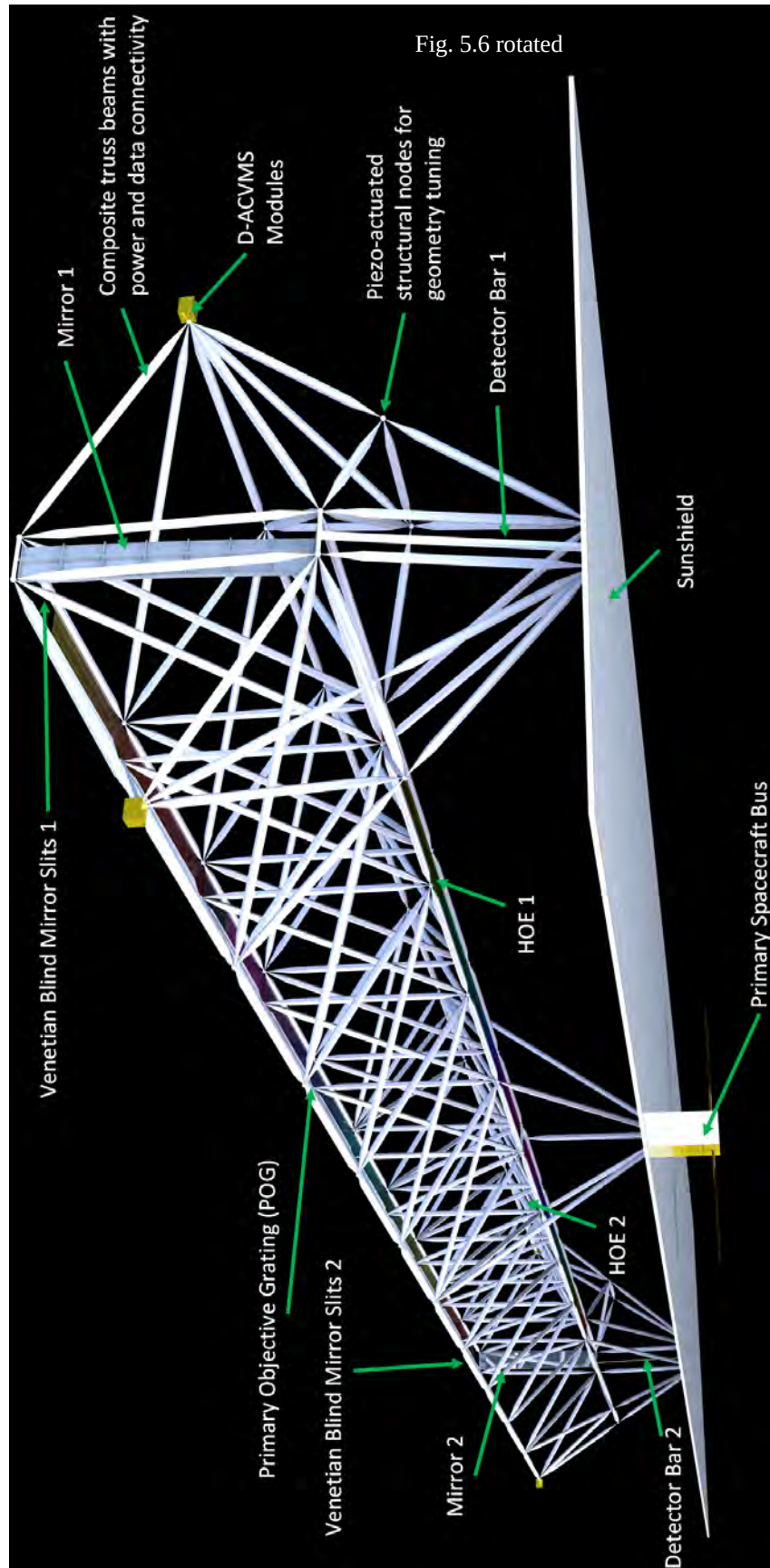


Fig. 5.6 100 m transmission POG version of THE MOST with annotation



The POG appears on the superior structure in the rendering Figure 5.6, viewed as it is being deployed from rollers removed from stowage, Figure 5.7.



Fig. 5.7 Installation of a 100 m POG from stowed cylinders

The design has dual secondaries, because the POG diffracts in both directions. This symmetrical configuration doubles throughput by selecting opposite bands for the image of the sky. What is blue for a star on one side is red on the other side. Their error bars have a differential measurement. The opposed mirrors are annotated in Figure 5.8

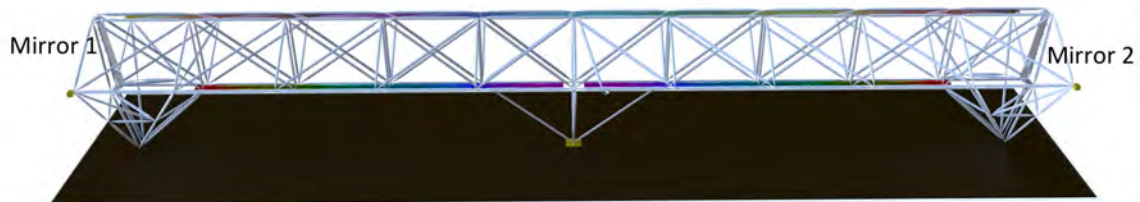


Fig. 5.8 Dual sliver shaped mirrors collect $\pm$ first-order diffraction images

The slit concept we are exploring uses narrow mirror segments to redirect the focused rays to the secondary spectrometer, Figure 5.9.

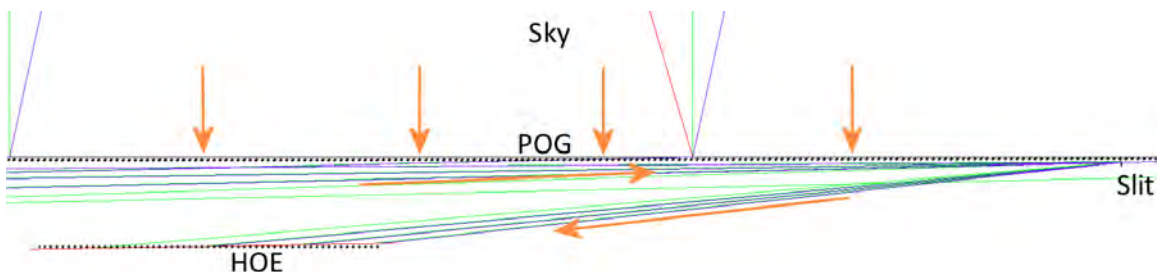


Fig. 5.9 The “slit” is a mirror, motorized to control integration time as stars transit

Motorizing the mirrors permits scanning backwards on wavelength bands to increase integration time. Multiple motorized mirrors increase the total flux available within the tracked bands up to the allowable bandwidth of an observation. The nominal resolution of a 100 m POG is 200,000,000 with a slit of the narrowest width, a value so immense that it should be padded it down, because so few photons are available at such high resolution. The trade of Venetian blind slits provides increased photon collection. The Venetian Blind Mirror Slats do the scaling. A Zemax model of the secondary in Figure 5.10 shows two mirrored slits that are combining a common wavelength at the secondary HOE by capturing that wavelength band as it transits across the slit section of the scope.



Fig. 5.10 Slit Slats of the Venetian Blind redirecting the same wavelength onto a common secondary HOE

The secondary spectrometer is based on chirped holographic gratings studied under a NIAC Phase I called HOMES. In that embodiment, the plane waves from the sky were focused as a function of wavelength, somewhat similar to the POG which achieves focus with a parabolic mirror in the secondary. In THE MOST, the secondary HOE serves to collimate the diverging wavefront reradiated at the slit. In effect, the HOE reverses the compression in a compact space where the sky is reconstructed wavelength by wavelength onto long sensor bar. These basic concepts appear in the 2020 TUI rendering, Figure 5.11.

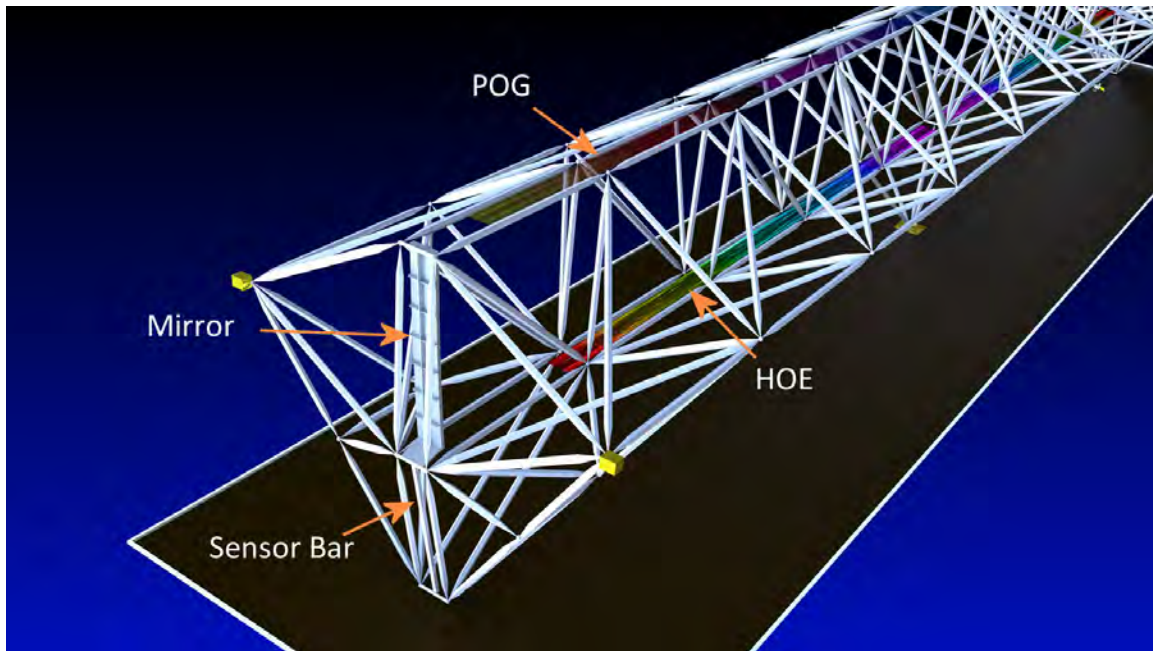


Fig. 5.11 Assembled system seen from one side

The HOE does not form an image on the sensor bar. Zemax modeling led to a tertiary HOE which focuses the light collimated by the first HOE, Figure 5.12

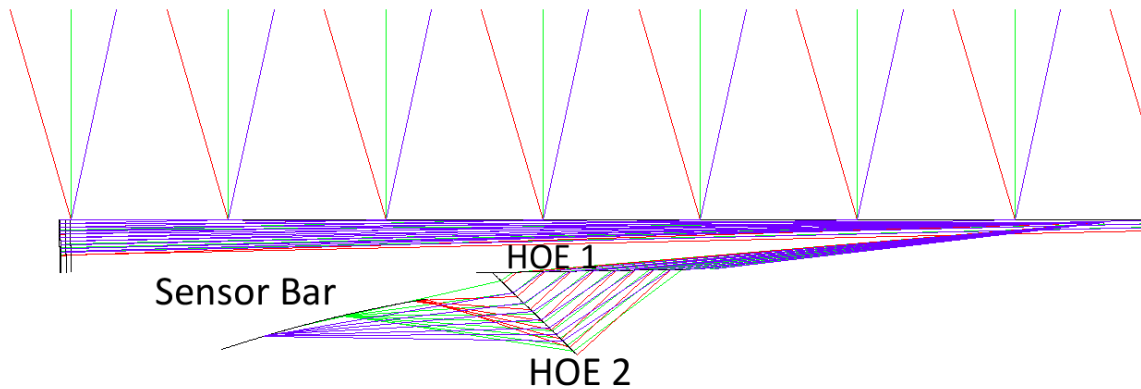


Fig. 5.12 Back end of the optical train with paired HOEs focusing on the sensor bar.

Native diffraction optics alone did not provide a sharp focus nor an on-plane wavefront, After the 2020 TUI renderings we studied a notional spectrograph that include a large mirror, 4 m, in the concept of Figure 5.13. The reflective mirror spectrograph is shown in Figure 5.14

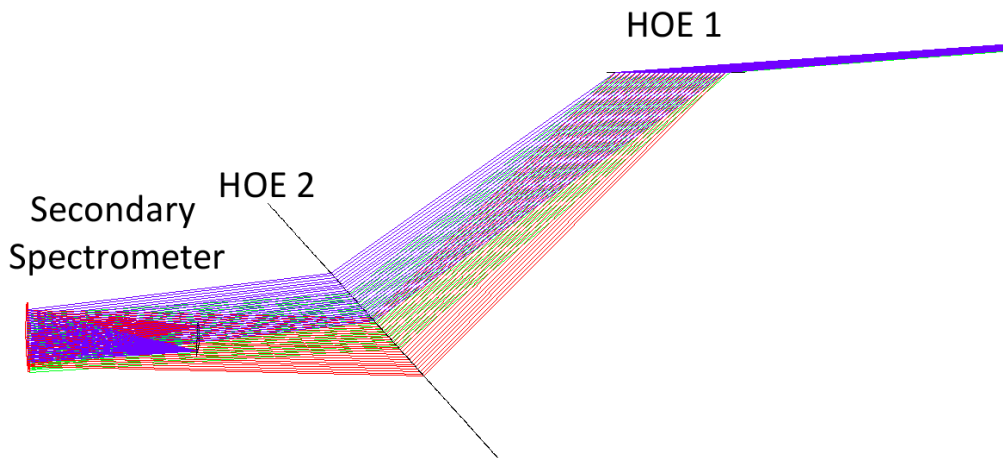


Fig. 5.13 Notional secondary

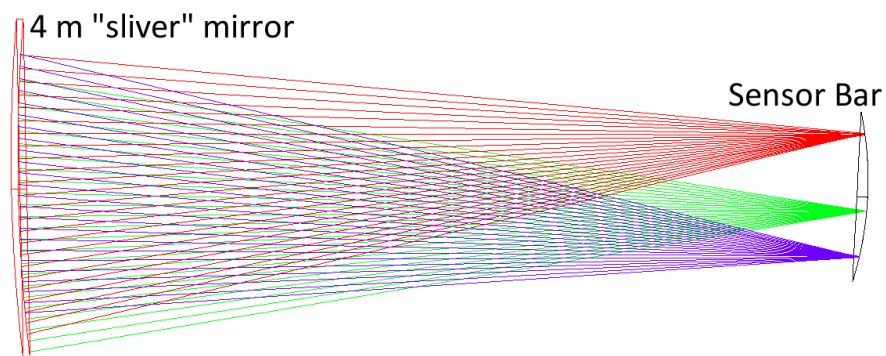


Fig. 5.14 Reflection mirror spectrograph by itself

Spot diagrams are shown in Figure 5.15. Over 2 meters the $45\text{ }\mu\text{m}$ spot of an exemplary wavelength is far short of the $2.3\text{ }\mu\text{m}$ Airy disk. The defocus is in one axis only, the long axis of the 2 m Sensor Bar which if constructed of $45\text{ }\mu\text{m}$ cells would resolve about 40 million - within the expected resolution of the telescope across its free spectral range.

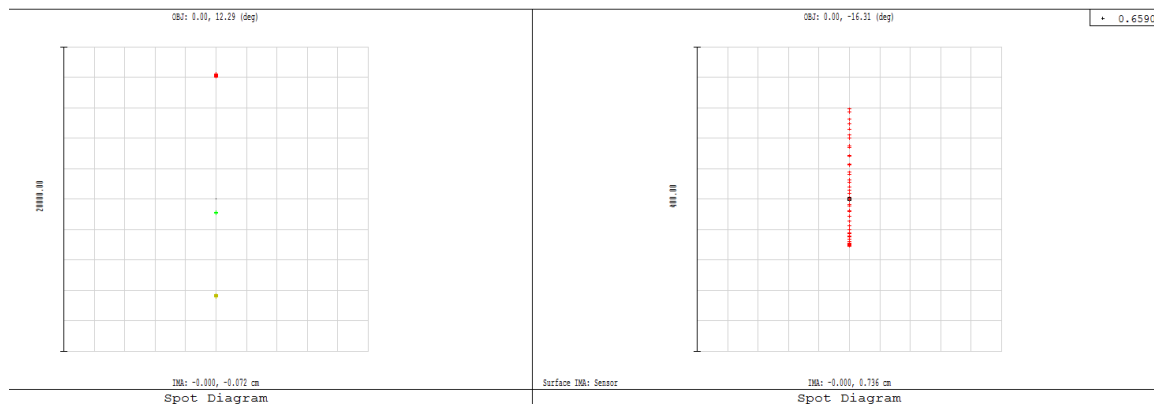


Fig. 5.15 Spot diagram for 3 wavelengths (left) Exemplary wavelength (right)

The additional mirrors in the current secondary design add mass to the 2020 TUI launch package designed for a single heavy lifter, Fig. 5.16.

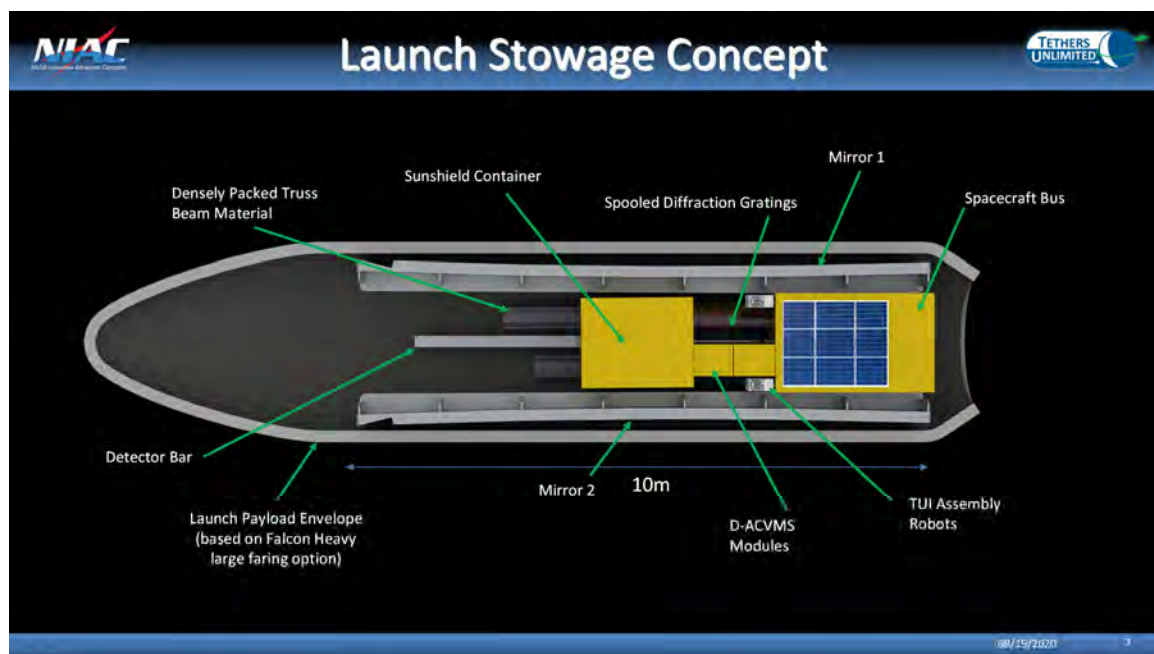


Fig. 5.16 Under the Faring of a Falcon 9 Heavy

This payload would include the robot agents for in-space assembly. The sliver mirrors are compatible with the ratios of width to height typical of this stowage concept. The extra mirrors for the spectrograph present more stowage beyond the original design and are not accommodated in the 2020 assessment.

The launch package did include the material for trusses. The TUI concept for the platform assembly is shown in Figure 5.17 which details a patented concept for stackable beams.

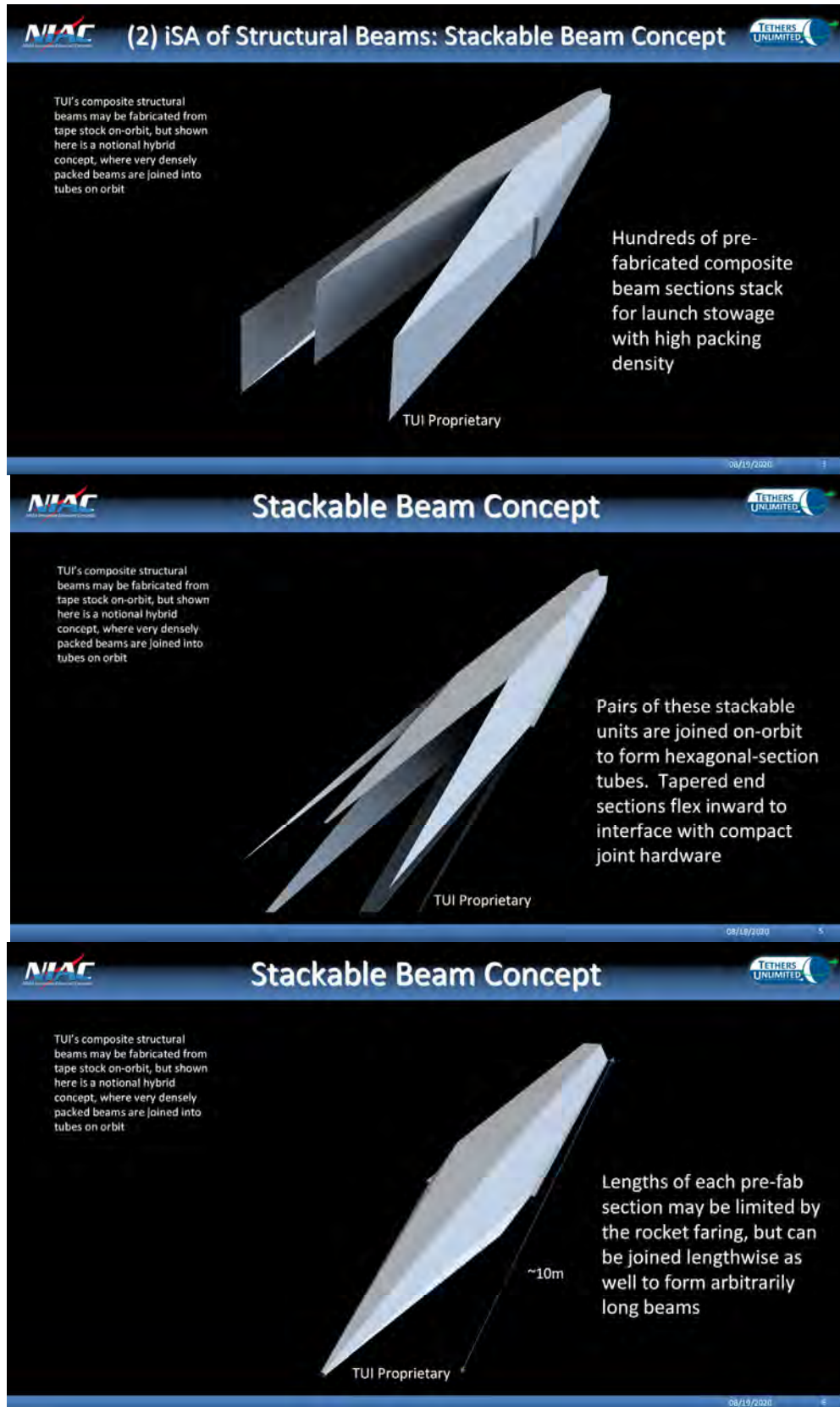


Fig. 5.17 TUI Stackable beams fold into truss segments

Service robots that were in the payload assemble them into THE MOST, Figure 5.18.

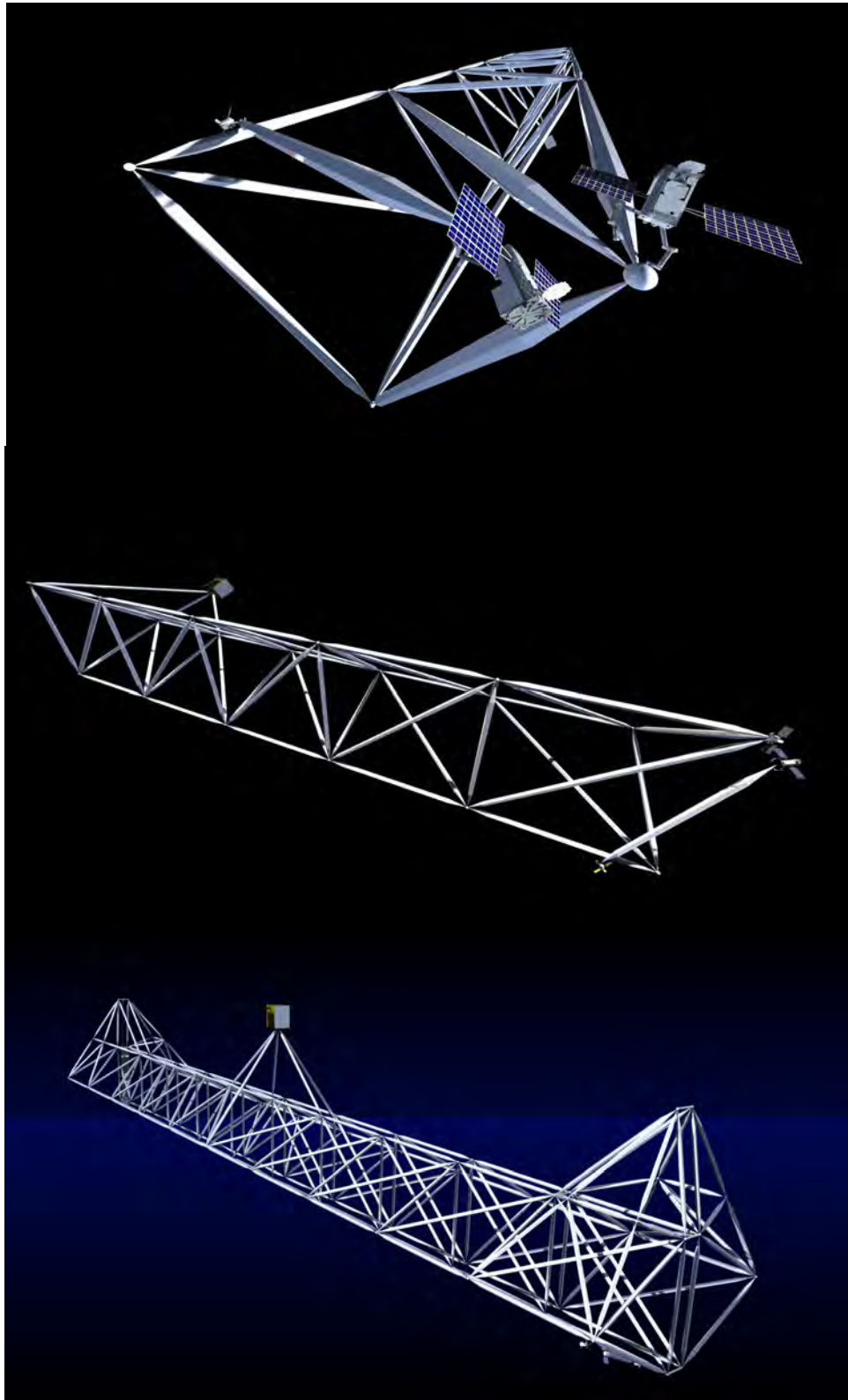


Fig. 5.18 TUI in space assembly process

The sunshield is attached to the base of the telescope, Figure 5.19

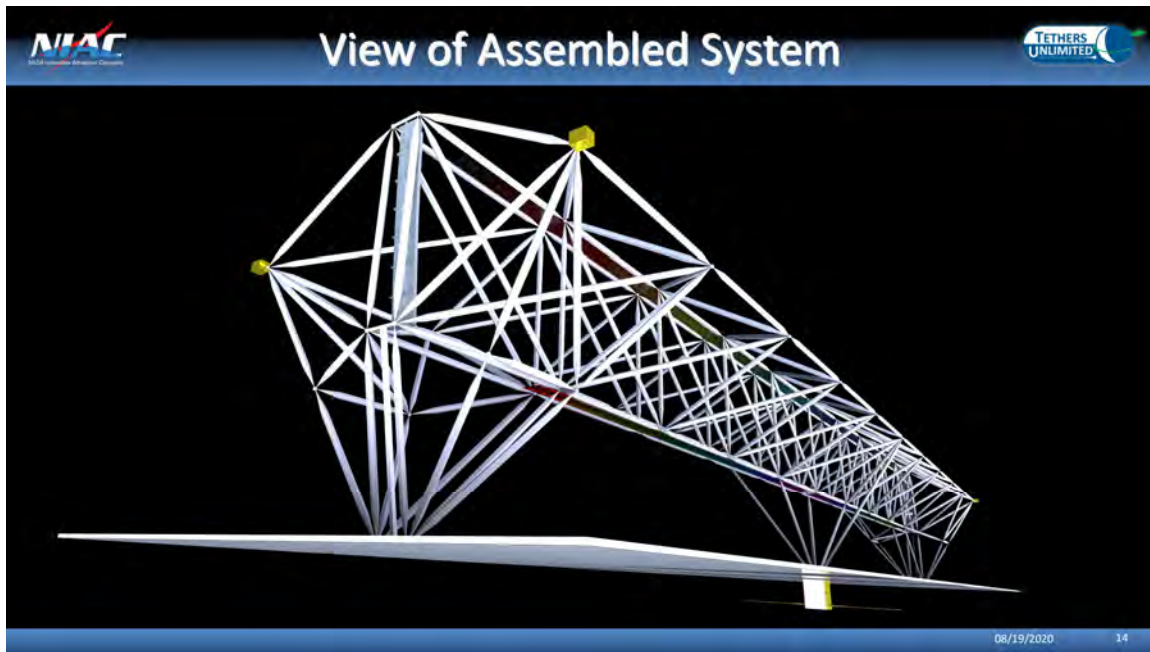


Fig. 5.19

Observations can be made by drift scan from trailing Earth orbit, Fig. 5.20

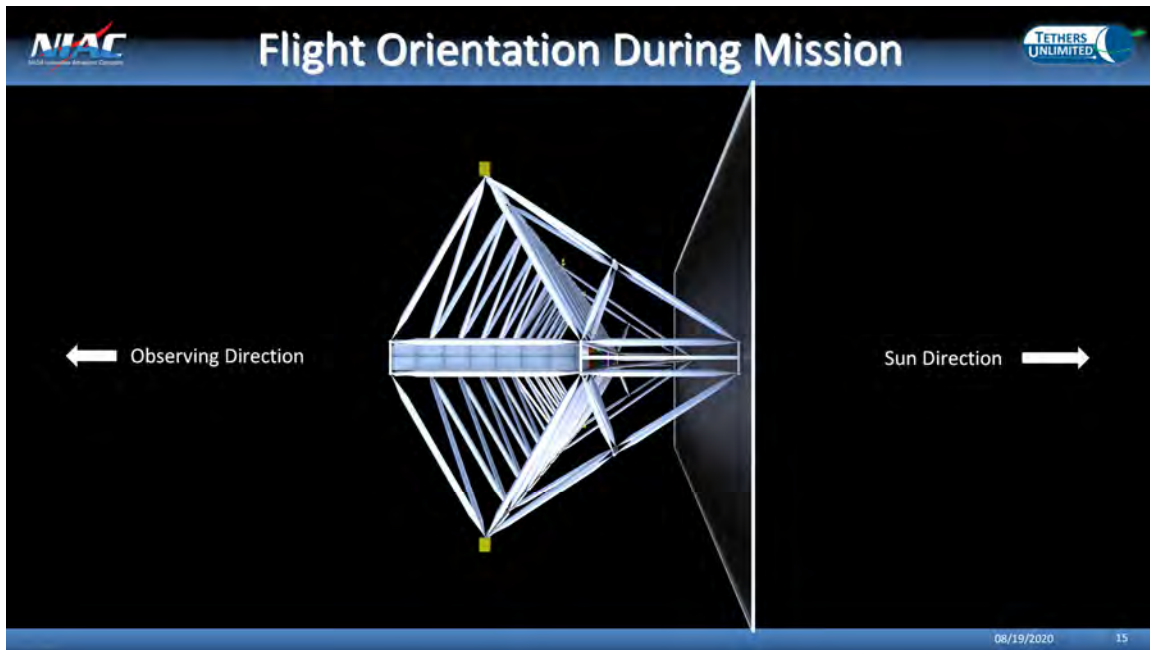


Fig. 5.20 Passive drift scan for survey observations

The truss network will tension the POG and substructures by use of joint management made possible by the use of Piezo-based mechanics which have been under development by TUI for GEO platforms studied for DARPA. Three dimensional force feedback mechanisms are summarized in Figure 5.21.

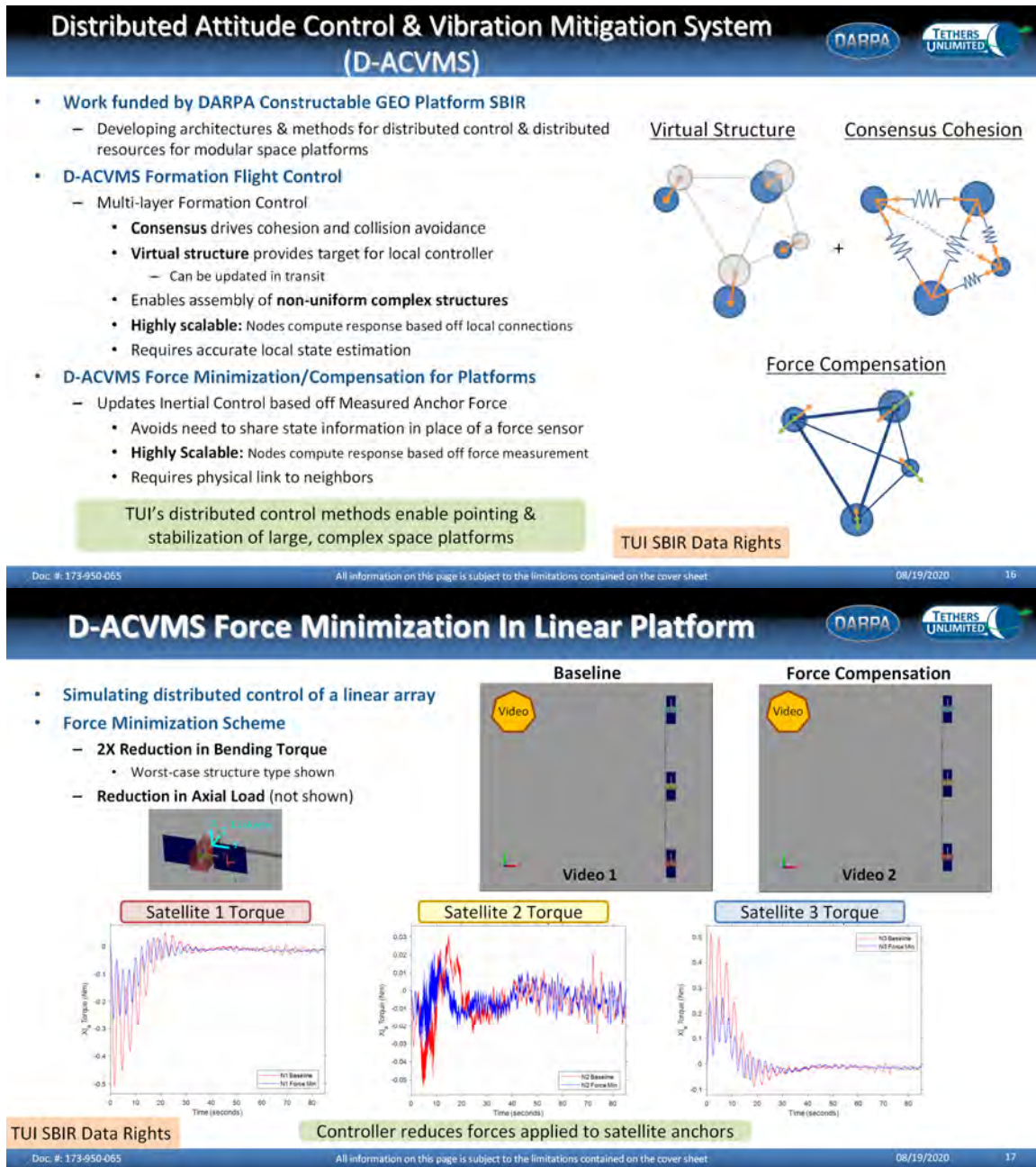


Fig. 5.21

In-space construction is a legacy of NIAC research conducted by Robert Hoyt as a NIAC Fellow. The service robots illustrated are derivative of the SpiderBot concept, which was a 3D printing engine in a service robot for in-space extrusion of trusses. The engine was dubbed The Trusselator and was demonstrated on the ground in 2016. The present concept is an in-orbit factory for manufacturing “2x4’s”, Figure 5.22.



(1) iSM of Structural Beams: MakerSat



- **Goal: Demonstrate in-space manufacture of a 60-ft carbon-fiber boom**
- **Carbon fiber composites have near-zero CTE needed for astronomy platforms**
- **Integrates metrology and in-line verification of beam structural properties**
- **Status: Completed CDR and on-schedule to deliver flight hardware summer 2021**
- **Mission evolved out of NIAC SpiderFab program**

Video courtesy MAXAR



SPIDER and MakerSat on-orbit manufacturing and assembly

MakerSat Demonstrates In-Space Manufacture of the "2-by-4's"
We Need to Build Space Infrastructure

08/19/2020
2

Fig. 5.22 MakerSat

After construction, the telescope must be inserted into a permanent orbit which will be remote from an in-space manufacturing and assembly facility. The option exists to make the insertion first. In that scenario, the assembly and service robots are included in the delivery package and can be a unified module such as the 3D printer SpiderBot. Maintenance of a large space telescope should be assumed in its Concept of Operations, since to abandon an investment in a major astronomical resource for simple want of remedial attention would short change the overall investment.

Propellant expenditure is a factor in attitude control, but with a passive drift scan strategy, such as we propose for THE MOST, on-board expendables can be minimized to occasional resets of reaction wheel inertial control. Solar arrays on the sunlit side will provide all the energy needed for almost all operations, attitude control included.

Solar panels on the sunlit side serve as a sun shield. There is a choice between attached and formation-flown, the former being modeled in Figure 5.20, but if attached, it will be scaled to accommodate the rotation along the diffraction axis that orients the POG. A rigid attachment, as illustrated, is problematic, since at high angles of inclination, one side of the shield would be proportional to the $\tan(\theta)$ where θ is the angle of inclination. This could be ameliorated if an attached sunshield could pivot. We have not modeled the axle. Precision is not required. A pivoted sunshield could have an error budget of 10-20% without failing or becoming a heavy cost burden. Formation-flown solutions may become commonplace in space telescopes going forward. Interferometric planet finders such as LIFE⁹ assume them. However, delivery of collected photovoltaic energy would have to be by microwave or equivalent non-contact transmission, a somewhat problematic additional concern. Pointing reliability when power is transmitted suggests that reliability would have to be proven at 100% over other missions before it should be adopted here.

Section 6 Other Embodiments

POG telescopes have a wide range of possible embodiments. The optics are novel in astronomical telemetry leading to many conceptual implementations on the ground, airborne, in space, hybrid ground/space, and lunar.

Ground

THE MOST was called The Million Object Spectrographic Telescope when presented in 2008, Figure 6.1.. It was conceived as a ground telescope capable of high resolution spectrographic surveys. The POG was posed in an East/West orientation and conducted a staring observation.

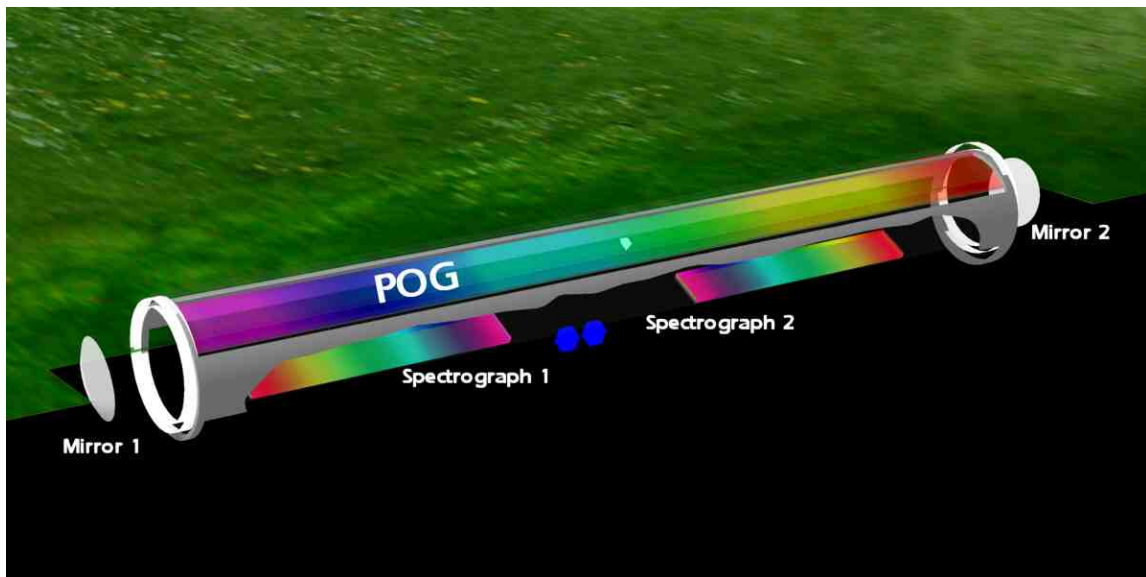


Fig. 6.1 The MOST - One POG serves two secondaries which see the sky inversely with respect to wave length.

In the notional telescope of Figure 6.1, the short side of the telescope can pivot along the

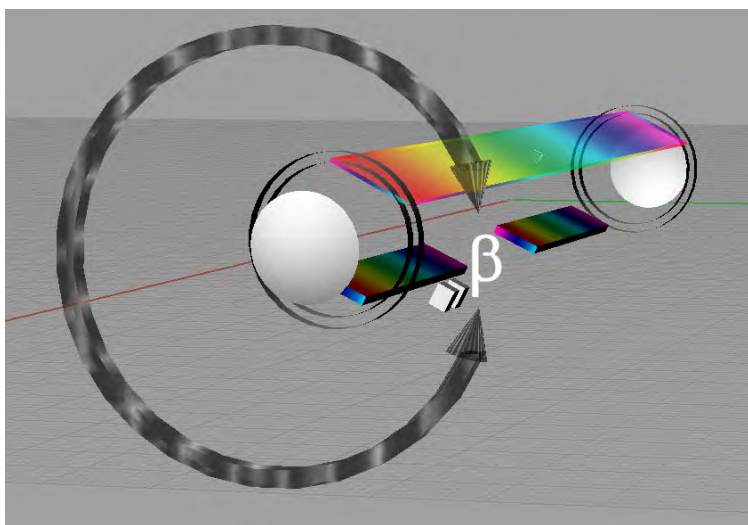


Fig. 6.2 Declination angle β is set along one axis of rotation

long axis, Figure 6.2. There will be data reduction that accounts for the arcs along the Great Circle. Data is acquired as temporal spectrogram, that is, a series of frames like a motion picture film or videotape, Figure 6.3. Within each frame were all of the objects within the free spectral range, each one being decoded at a narrow wavelength band.

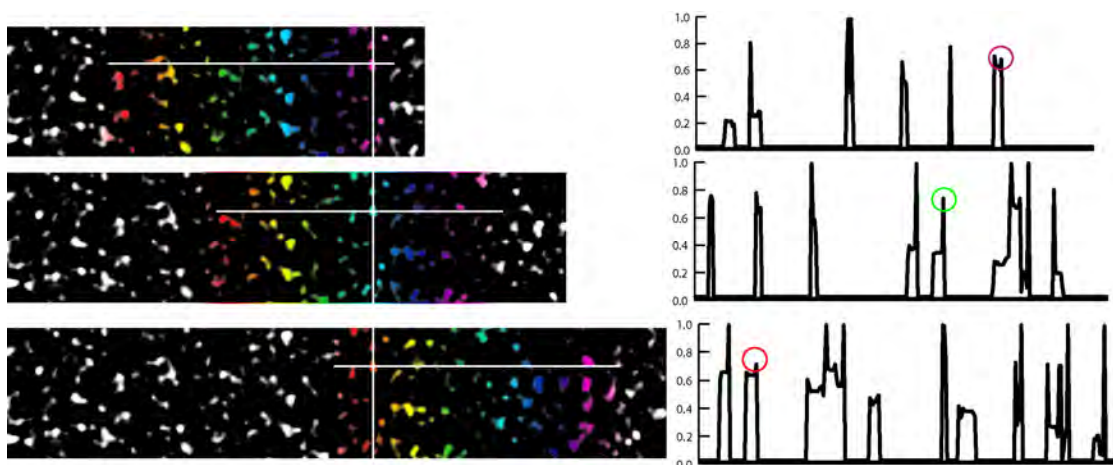


Fig. 6.3 Simulation of three frames - Crosshairs track one star with amplitude of that star at three wavelengths circled above.

A full spectrum is divided by double dispersion into subsets depending on the color and positions of the sources. The simulation subtracts out the continuous spectrum where no sources exist, leaving the examples of one source, two sources, and the night sky itself.

The superimposition of the spectrum with the line of right ascension results in a large number of targets being tracked simultaneously. The data set is time stamped in sidereal time. The line of right ascension is along lines of latitude. Because the field of view in the diffracted axis is uncommonly wide, the data set is suitable for computer processing. The tables contain the wavelength, flux, sidereal time stamp, and latitude as the stars transit.

Calibration of a temporal spectrograph presents a serious obstacle for ground observatories. Variation in atmospheric transparency will cause fluctuations in energy at the receiver. Conventional mirror primary objective telescopes are immune to this problem, because a variation in any one wavelength almost equally affects all others. With a POG, the flux must be normalized, because each wavelength is acquired sequentially over time. It is difficult to monitor local variations, because the angular resolution of the telescope vastly exceeds any auxiliary sighting scope used as a reference. The problem is exacerbated by the wide field of view along the diffraction axis, as much as 40° . While a very wide angle camera might report generalized cloud cover, it would never be able to normalize localized variations that interfere with specific spectra. As a result, atmospheric variations could make the amplitude data unreliable.

One mitigation takes advantage of the symmetry of the telescope. For a plane POG of uniform pitch, mirrors can be placed at both ends, Figure 6.1. In this configuration, there are two symmetrical spectrographs. Spectrograms should be identical but in reversed order and at different times of night for specific wavelengths with the exception of a single unique center wavelength that would be recorded at midnight. Variations in intensity at any wavelength for any object will indicate a fault, likely caused by absorption in the atmosphere. The normalization process could presume that the lesser the two readings exhibits atmospheric absorption. Further correction could be made on the basis of the behavior of adjacent bands. While this does not eliminate error, the redundancy does limit the impact of the errors.

In Figure 6.4 illustrates the opposed spectrograph process. On the top rows are the native broadband spectra from generated by white light posed in opposite sequence as falls out when there are mirrors on opposite sides of a common POG. In the illustration, below each broadband spectrum are extracted simulated white light sources taken at the wavelength band from the exemplary spectrum above them. In the bottom three bands of the illustration is a color image of the sky as visible to the telescope. There are similar extractions illustrated, that is, with the sky sources masking the broadband spectrum.

In operation, the redundancy over the same portion of the sky will provide differential data suitable for the production of error bars. The presumption is that the observation is taken in a drift scan mode of sufficient duration so that objects will have their complete spectral signatures taken clear across the free spectral range. Where the spectrograms are incomplete, a differential measurement cannot be taken.

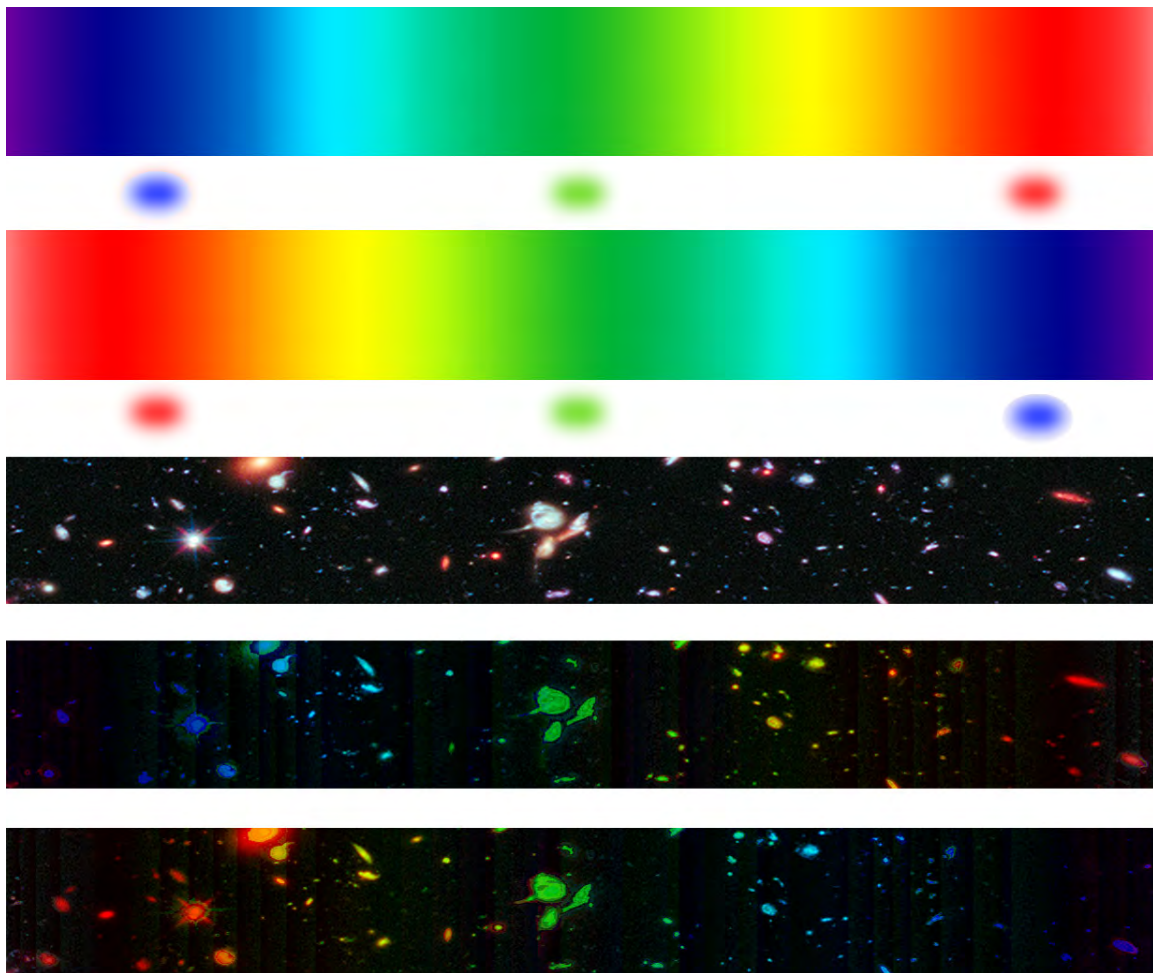


Fig. 6.4 Comparison of spectrographs on opposite sides of THE MOST

Another ground-based version of THE MOST architecture is TWO, Trip Wire Optics. Unlike THE MOST which is an astronomical survey scope, TWO is a surveillance scope with applications in Situational Awareness, a term of art used in tracking satellites and

near-Earth objects (NEOs). To set up the “trip wire” the telescope is oriented not East West, but at alternative angles ϵ to the equator as illustrated in Figure 6.5.

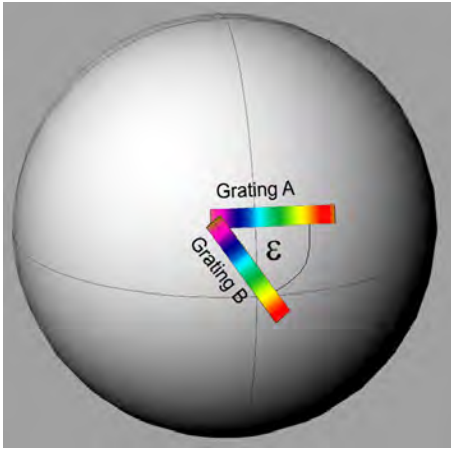


Fig. 6.5 Geographically rotated POGs

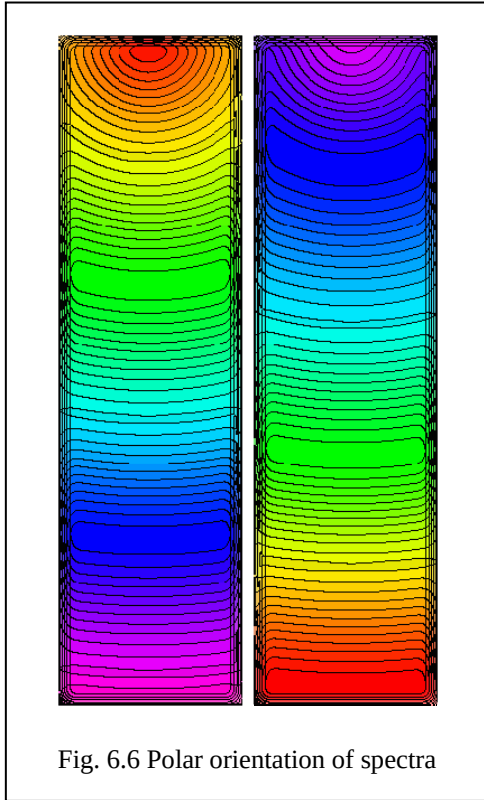


Fig. 6.6 Polar orientation of spectra

An exemplary configuration points the POG in a North South orientation, and the spectrum appears to run from the pole south with bands that are registered with lines of latitude, Figure 6.6. In this orientation, the transit of stars follows the circular path, but satellites crisscross the spectral lines, so that a subtraction from the database of star motion is distinct, and anomalous objects can be isolated for follow-up study with agile pointing telescopes.

We seek an optical design that observes as much of the sky as possible at any given time. NEOs could be observed directly in infrared light or reflected light from the Sun, or they could be observed by occultations of background stars. Either way, we need to survey large areas of the sky to faint magnitudes. The science case does not require that we obtain spectra or observe the NEOS/background stars at any particular wavelength; we must only observe that the NEO is there or that the background star is not.

This science case drives the design of TWO to be somewhat different from THE MOST that is imagined to be spectroscopic survey of the sky in that the grating direction is aligned with longitude lines on the Earth rather than aligned along constant latitude. If the grating is aligned with constant latitude, then we observe a ribbon of the sky that is as wide as the field of view of the secondary telescope and tens of degrees wide (theoretically, the width is set by the grazing angle, the grating spacing and the wavelength range over which the detectors operate) along the direction of right ascension. This classical POG telescope observes each object as it traversed the sky, detecting different wavelength ranges for

each object as a function of time. TWO scans a very large area on the sky, and we are less concerned with full wavelength coverage (except to the extent that a larger wavelength coverage would give us a fainter limiting magnitude). By aligning TWO along constant longitude, we observe a range of declinations that is tens of degrees wide, while at any given time we see a range of right ascensions that is as wide as the field of view of the secondary telescope. As the Earth turns, that wide swath of declinations is scanned in a drift scan mode, one hour of right ascension per hour. This wide field of

view gives us a very large étendue, but will produce a complex focal plane, as the sky will move at different rates and in a curved pattern over tens of degrees of declination.

TWO can be imagined to operate at optical to near infrared wavelengths in the range from $500 < \lambda < 1100$ nm. Since it is useful for the exodus angle from the diffraction grating to be large in the first order, an exemplary grating spacing, Λ , was chosen so that the wavelength in the middle of this range, $\Lambda = 800$ nm, was diffracted into an angle of exodus equal to the central collecting area of the secondary telescope. In this benchmark design, with an angle of exodus fixed at 70° , the grating spacing is 851 nm and then, a wavelength range of $500 < \lambda < 1100$ nm translates to $-21 < \theta < 21^\circ$. Because the edge of this angular range the bandwidth is diminished, the full bandwidth viewable from the secondary telescope is only available in the $-19^\circ < \theta < 19^\circ$ range. Nonetheless, this telescope scans a very swath of sky that is $\approx 40^\circ$ wide, centered on the zenith.

For the ground-based POG telescope, one must consider the effect of the atmosphere on the wavefront that reaches the POG. At sufficient distance, the radiation from a star will form a plane wave that is incident on the Earth. However, the atmosphere will cause wavefront distortions in the light that actually makes it to the POG. Because the POG is expected to be tens or hundreds of meters long, it is much larger than the coherence length in the atmosphere. Therefore, the wavefront distortions will average out over the area of the POG, producing a blurring of the light from a point source that is similar to the Airy disk of a diffraction limited telescope but created instead from shifting diffraction patterns or ‘speckles’ that evolve on timescales of milliseconds.

To understand the effects of atmospheric seeing on the angular resolution of TWO, a simple simulation of atmospheric wavefront distortion was built to verify the seeing Point Spread Function (PSF) predicted by theoretical considerations. The sky was modeled from a contour plot of phase-screen data taken over a 12 x 12 m area on Mauna Kea¹⁰

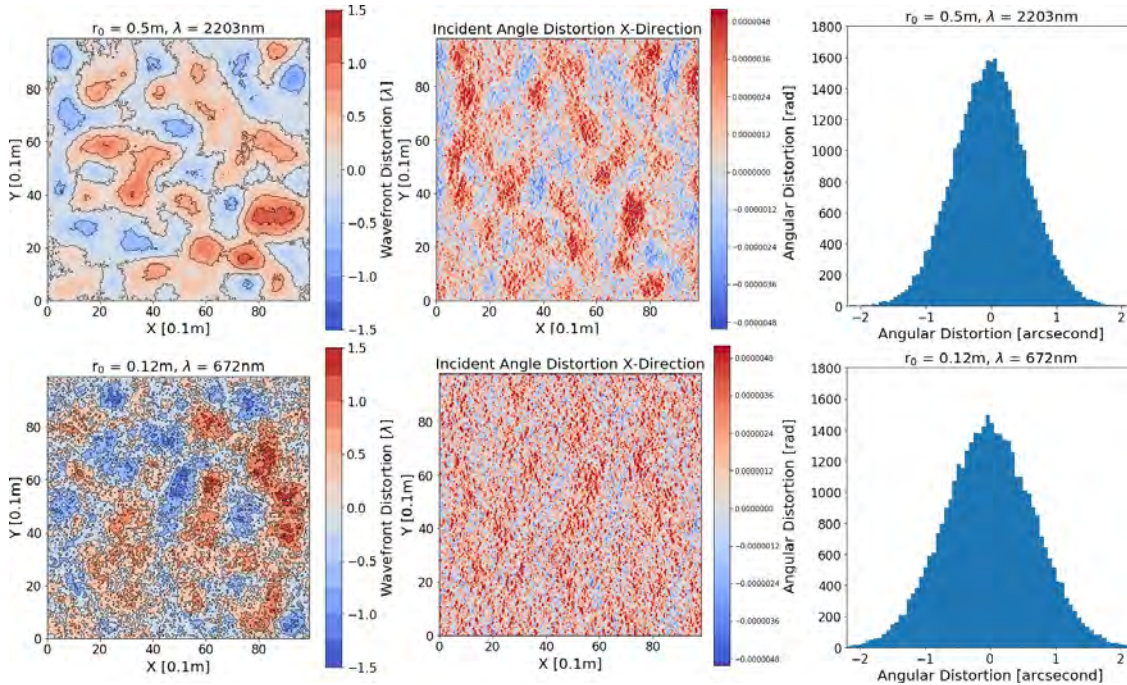


Fig. 6.6 Incident angle distortions generated from simulation data

The histograms of incident-angle distortion shown in Figure 6.6 are equivalent to the distortion incurred by a 1×100 m collector (or any other 100 m^2 primary grating), regardless of the fact that they are calculated from a 10×10 m area; this is due to the isotropic nature of the wavefront distortions. Angular distortion for two simulations of differing coherence length under the same seeing conditions (coherence length is wavelength dependent). Theory dictates a coherence length of 0.5 m and wavelength of 2203 nm (top row) should result in an angular resolution of 0.88 arcseconds, and a coherence length of 0.12 m and wavelength of 672 nm (bottom row) should produce an angular resolution of 1.12 arcseconds. The rightmost plots demonstrate that the resulting angular distortion is highly reasonable and in line with theoretical expectations.

The seeing of, say, $1.5''$ becomes a blurring in the wavelength direction. In the case of our benchmark design, the wavelength blurring is 0.006 nm. The spot size that this produces after light from the secondary telescope focal plane is dispersed with a second grating depends on how effectively the second grating reconstructs the sky. In principle, if the second spectrograph is capable of identifying the wavelength and position of every photon that hits the secondary telescope focal plane that wavelength blurring will turn back into a blurring in angle that is equal to $1.5''$ in the final image. That is because if you detected the wavelength exactly, you would know to within $1.5''$ where the photon originated. This blurring precludes diffraction limited imaging, as it does in all ground-based observations, but does not significantly hamper the performance of TWO.

One consequence of the atmospheric distortion is that it shows that ground-based applications of POG telescopes have relaxed requirements on uniformity of the grating. In order to get high angular resolution, the grating spacing would have to be uniform over the length of the grating to produce a coherent diffraction pattern. The atmosphere already makes coherence over the length of the grating impossible. This opens options, for example, the grating for TWO could be built from individual gratings that are larger than the coherence length. Gratings could be ganged together to cover the whole length and would not have to be precisely aligned. While a precision grating of area 80 m^2 is not commercially available, individual gratings could be ordered to our specifications, Figure 6.7.



Fig. 6.7 Discrete POG modules with ganged laser interferometric alignment masts

Airborne

Ground observations in the terahertz band are constrained by atmospheric water absorption. A stratospheric placement of the POG telescope could follow the same ganged grating approach of figure 6.7 but where the segments are on the dorsal side of an airborne observatory. This would contrast the POG approach to the retired SOFIA which attempted to stabilize a 2.5 m mirror inside the fuselage with a port opened to the flow of exterior air at hundreds of kilometer/hr airspeed.

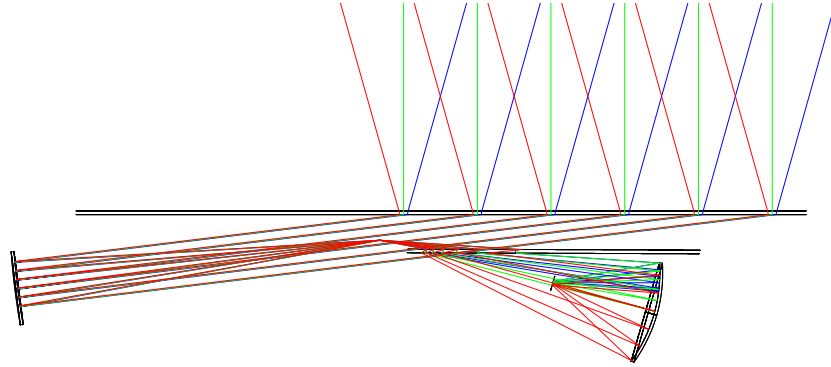


Fig. 6.8 Transmission POG with secondary mirror on left and spectrograph on right.

A transmission grating was modeled in Zemax for use in the visible spectrum, Figure 6.8. It has the advantage that the cabin would be sealed and could be operated with air pressure maintained. A transmission POG would involve a relatively straight forward aircraft modification, Figure 10. The POG segments readily, so the modification is structurally equivalent to putting windows on the roof. The secondary mirror and spectrograph would be housed inside. Operator access would be possible during flight..

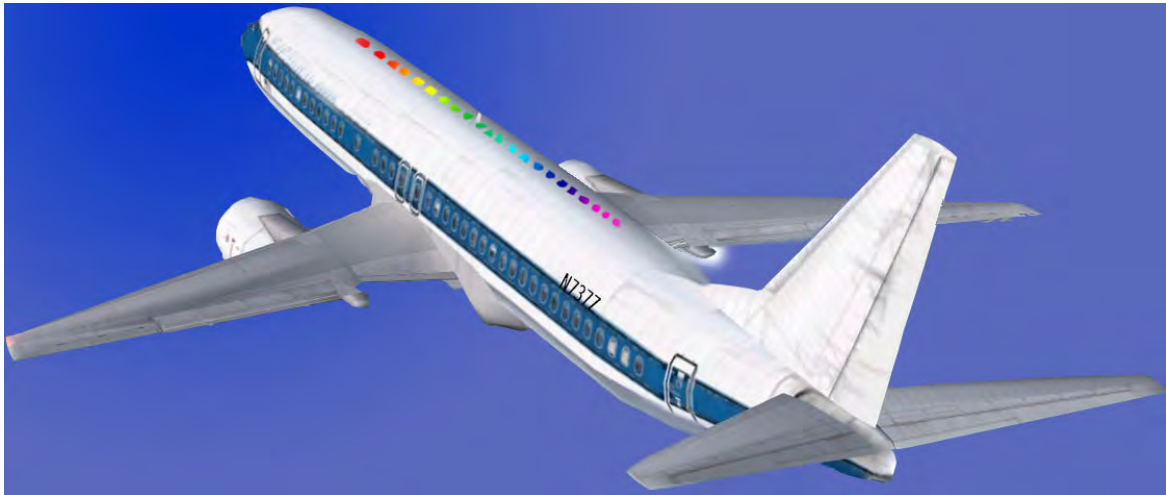


Fig. 6.9 A concept sketch of the exterior of a transmission POG aircraft.

Reflection gratings would require a special aerodynamic roof pod to house the secondary mirror. The POG can be laid out as a continuous strip, since the only penetration into the fuselage is a very narrow slit at the secondary mirror focus. That slit will cost cabin pressure, and the optics might be remotely operated depressurized from behind a cabin bulkhead. .

The use of an aircraft as the platform gives the POG telescope increased flexibility in controlling its integration time. This compares with fixed terrestrial settings where the integration time is inexorably linked to the rate of rotation of the earth. Presuming that the aircraft can be put through a slowly changing and sustained arc, the dwell time on targets can be improved by flying east to west in a convex path or west to east in a concave path. The inverse flight path will effectively increase the FoV over the equivalent period for a terrestrial version of the POG. See Figure 6.10.

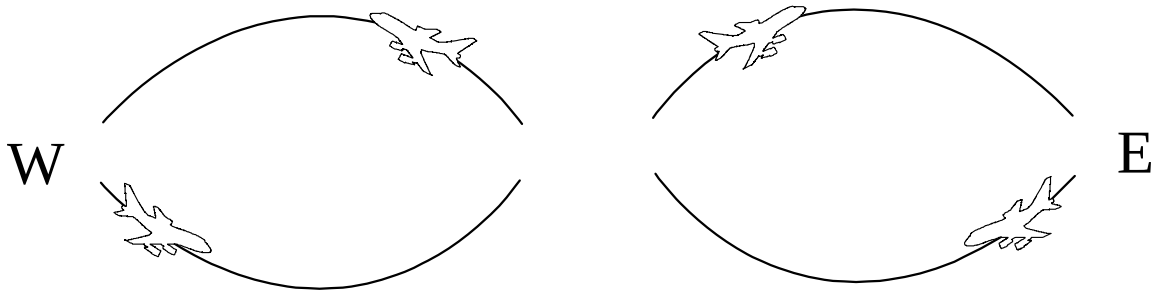


Fig. 6.10 Increased integration time by flight path on the left Increased survey data on right.

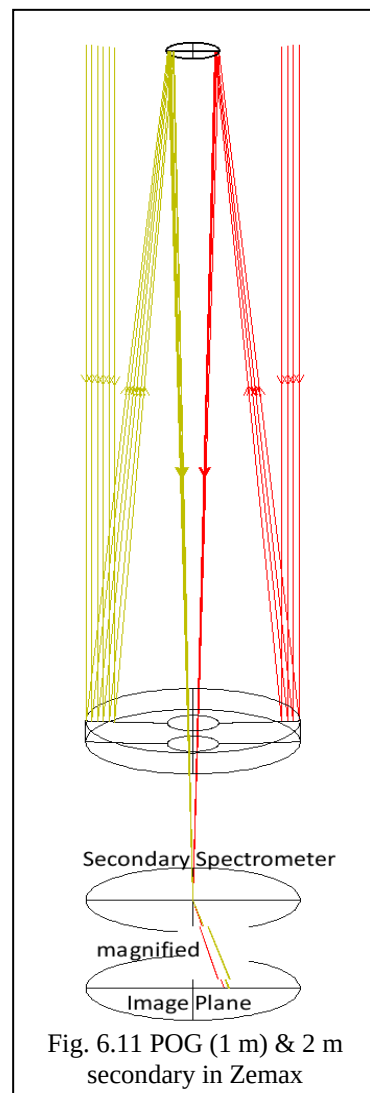
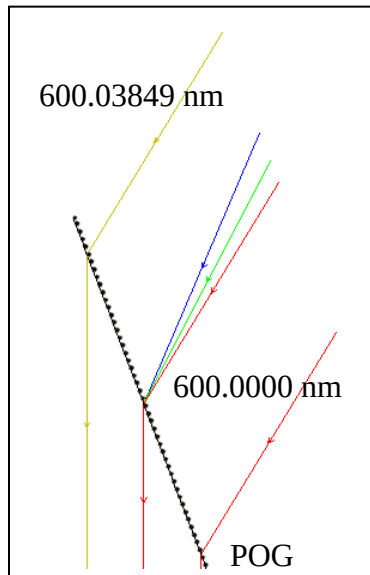
Rotational banking can be used to counteract the latitudinal arc that naturally occurs if a terrestrial POG is pointed north or south off the Great Circle.

Space Based

A space-based variant of the POG telescope was considered in Section 5, but two more significant developments followed. The first of these is a hybrid design where the POG is held in a geostationary orbit for observation from the ground.

Ghost (Geostationary hybrid optical spectrographic telescope), like the NIAC-funded HOEE¹¹, takes advantage of ground telescope infrastructure, leaving NASA to provide only the space-based first element in the optical train. On the back of an envelope it is easy to show that a 10 meter POG has a spectrographic resolving power of 1 million, as can be appreciated from the state of the art in échelle spectroscopy where 10^5 power is achieved with one meter plane gratings. Spectrographic resolution is being improved now at terrestrial observatories, because extreme precision spectroscopy is a target goal of the *Decadal Survey*¹² for radial velocity measurements essential to the process of identifying Earth-like planets by the Doppler shift method. Our approach of a dual dispersion architecture permits high resolution spectrographic surveys.

It is reasonable to ask if ground telescopes can even resolve a POG at GEO - a tiny speck within the field-of-view. Using Zemax to model *Ghost*'s diffractive optics we made a scaled down model, Figure 6.11, where a 1 meter POG is positioned 12 km away from a 2 m mirror telescope. On our "napkin" this would be comparable to *Ghost*. Multiply a 1 m POG by a 500 m POG and 2 m mirror by 5 m to get a Keck. Multiply 12 km by the resulting 2500, and the standoff is in effect 30,000 km. This Zemax model resolves 0.038490 nm at 600 nm. The field of view is 10° and resolution 200 mas. A 500 m *Ghost* would perform 500 x better, 0.000077 nm or 400 μ arcsec, also with 10° field of view. Ground telescopes need merely resolve in arcseconds to acquire *Ghost* - quite normal for star spectroscopy. *Ghost* will provide the primary aperture and hence the resolution and field of view. We plan to use Phase I to calculate the correlation between the POG to spatial and spectral resolution on the ground. Are there enough photons? Can ground

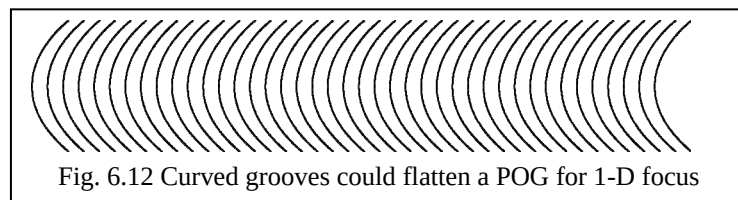


telescopes perform dual dispersion deconvolution to requisite precision? How about survey numbers? These are all questions that must be addressed going forward.

In prior models of POG telescopes where the secondary mirror is near to the POG, we have used shallow grazing exodus angles with a sacrifice in grating efficiency. A long POG viewed at 36,000 km can be seen in its entirety at any angle of diffraction. The exemplary Zemax model diffracts at a relaxed 70° . Note that the field of view is a function of angle of diffraction and can reach 90° at grazing exodus. Optimizing diffraction angle is an ongoing topic.

A *Ghost* POG of 1 km is not prohibited by launch mass, because it weighs as little as 10 gm/m^2 . Long membrane POGs can be made by roll embossing common in decorative gratings. One forward looking problem is in-space assembly of the delivered membrane optics. We have been studying ConOps with another NIAC Fellow, Rob Hoyt, for over a decade. This mission involves a robotic deployment at GEO. *Ghost* brings new challenges to our shared research.

What are diffractive optics with the requisite materials and groove structures that meet this embodiment specifications? A strong leg of our past research has been in holography. Grooves can be curved in one dimension. We plan on fabrication of sample physical POGs, including a flat DOE, Figure 6.12. Holographically fabricated POGs potentially have a huge pay-off in future space telescopes due to low mass. Regardless how *Ghost* turns out, we expect that our study of holography will have a lasting impact in photonics.



Multiple observatories on the ground can share the geostationary *Ghost* resource. GEO footprints cover a third of the Earth's surface, so multiple telescopes can be employed. This will result in collaborative networks using the resource. A consortium of colleagues could

coalesce around a common interest to tell *Ghost* stories. *Ghost* is a mission that has meaning in this context. It can also be used widely by other telescopes simultaneously. Devoting instruments like EXPRES to exoplanet detection would not prevent another telescope from accessing *Ghost* at the same time for Hubble Constant red shift measurements of galaxies, another *Survey* target for observation.¹³ The difference is that exoplanet detection by Doppler shift requires a quality of spectroscopy that is very hard to come by. We have seen productive shared endeavors where radio astronomers assembled black hole portraits by swapping data. Indeed, there could be multiple *Ghosts* with synchronized spectra recorded using a combination of atomic clocks and laser combs – an experiment suitable for infrastructure on the ground as an initial step that may lead to space-based POG telescopes 1 AU apart.

Because it is at GEO, this POG is at a fixed location in the sky. Locked down tracking systems are reminiscent of zenith tubes which can be built at reduced cost for their comparative apertures and enclosures. There is a development path for *Ghost* scopes that exceed practical dimensions of ground observatories where mirror mass, wind mitigation, and precision tracking systems are cost factors that have led to a retreat from some fantastic concepts such as the 100 m OWL and 50 m Euro at the turn of the century. The double dome of TMT is not needed if a porthole holds a fixed gaze at geostationary. There could be a HMT (H as in Hundred) telescope that relied on *Ghost*.

There is a fixation in our Neighborhood of 10 pc as the goal for Earth 2.0, but there are a paltry number of G class stars to study. Doppler shift is not limited by exoplanet albedo. Earth mass stars on distant Sun-like stars can be detected in the HZ simply by Doppler. A survey capability for this search is not anticipated by the *Decadal Survey*, *per se*, but then again, there has never been a survey scope that enjoyed cm/sec radial velocity capability. Imagine if that capability was shared by every precision spectrographic ground telescope.

Extraction of key spectral data of many varieties may be available to major observatories, but additionally a colorful twinkle could be noticeable to anyone. One can anticipate that *Ghost* will become a popular topic in the general population, because its fixed position in the night sky will hold a unique point of reference for small backyard scopes. Depending on *Ghost*'s size, it may even be visible to the naked eye.

A candid appraisal of *Ghost* requires a skeptical outlook and therefore a deep scrub of its possible fatal flaws. The long standoff from GEO to the ground affects the bandwidth of each source being acquired. While the narrowing of bandwidth is exactly what is needed to accommodate high precision spectroscopy, there is photon starvation at the same time that undermines the requisite signal to noise to extract cm/sec Doppler shift. The manner in which transits of target stars pass through their complete spectra when they are in the field of view of the ground telescope is tied to their latitude. Polaris integrates as a source all night long, but being fixed it has virtually no spectral spread. On the equator, thousands of stars can be surveyed in a night, but integration times in the worst case is limited to a few seconds per wavelength band. These parameters must be catalogued in tables that will be used to make a determination informing a future study.

A second development that occurred during Phase II was the use of POGs as the key element in coronagraphy. A narrowband self-nulling spectrograph for star glare rejection, BLOC or Bifurcated Light Optical Coronagraph is an adjunct to dual dispersion types of telescope. Although diffraction gratings work on an interference principle not far removed from interferometry as we know it, in a diffraction grating there are a plurality of re-radiators consisting of thousands to millions of grating grooves. A conventional astral interferometer incorporates few, often only two, re-radiators. It could be surmised that to the extent a diffraction grating differentiates wavelength, it has already accomplished the central function of the interferometer by producing sharp spectra through interference. This can be exploited by a POG telescope.

The distinction between interference from sparse sources such as an astral interferometer and many sources such as a POG deserves scrutiny with regard to the problem of exoplanetary host star nulling, because with a POG the problem can be thought of in very different terms - not as a question of including the widest bandwidth at the null but rather the shortest possible bandwidth notch. A fully developed Dittoscope with a primary in the tens to hundreds of meters along its diffraction axis can resolve the diameter of a star over a wavelength band measured as narrow as thousandths of a nanometer. Conceivably such narrow bands can be far more readily extinguished to a factor of 10⁻¹⁰ or even 10⁻¹², than broader bands sought for exoplanet telemetry as it is being pursued today. In other words, the native output of a diffraction primary permits a “divide and conquer” approach to the problem of parent star nulling.

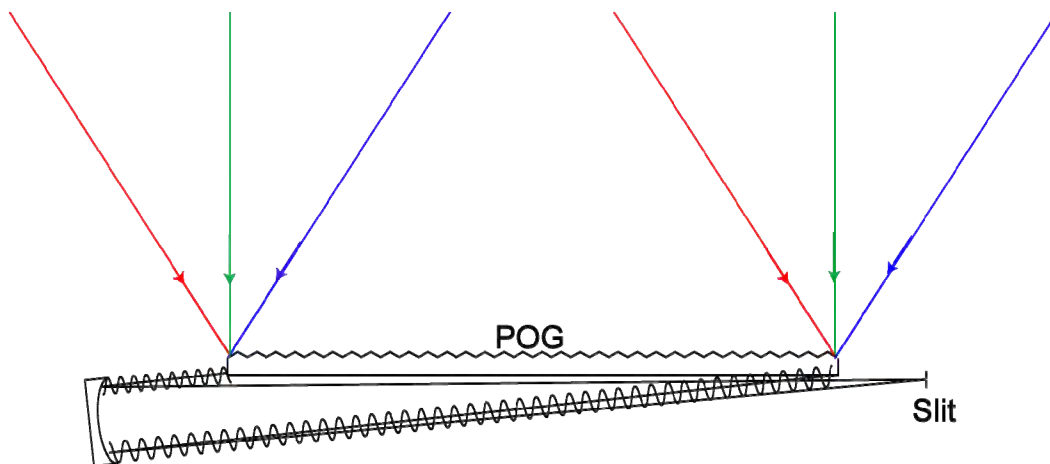


Fig. 6.12. Path lengths from POG to secondary mirror are all unequal, making normal astral interferometry seemingly impossible.

To preserve phase of incident periodic wave radiation, astral interferometric telescopes assume equal path lengths for all rays from the source star to the image plane. This would seemingly rule out interferometry from flat diffraction primaries such as the Dittoscope, because path lengths are intrinsically unequal (Figure 6.12).

Other than a central column perfectly perpendicular to the grating plane (green in Figure 6.12 above), the wave trains arriving at the POG from angles away from the grating plane normal are out of phase with each other. Inside the telescope, the path lengths are also

unequal as they travel from the POG to the secondary parabolic mirror. Only the waves from the mirror to the slit can preserve phase. At the slit of Figure 2 are discrete wavelengths corresponding to stars distributed across the spectrum. A complete spectrum is illustrated schematically in Figure 6.13.

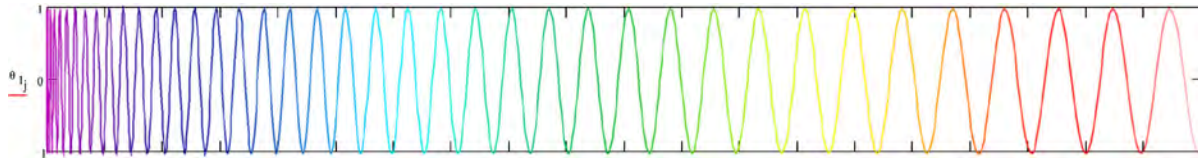


Fig. 6.13. Full bandwidth output of the POG and secondary parabolic mirror of a Dittoscope at the pre-spectrograph slit

The wavelengths focused on the slit are caused by an interference phenomenon. There is an integral multiple wave delay from groove to groove of the POG, the diffraction orders. For a fixed angle of reconstruction of the wavefront, there are specific wavelengths that correspond to specific angles of incidence upon the grating. However, the device is not an interferometer, per se. Figure 2 illustrates the front end of a dual dispersion telescope.

Unequal optical path lengths occur in all flat diffractive optics, for example, the NIAC study of an exoplanet spectrograph, HOMES, which uses a flat holographic optical element (HOE) as its primary objective and the DARPA-funded MOIRE which uses an in-line variation on a Fresnel zone plate.

However, unlike MOIRE which diffracts on-axis like a regular parabolic mirror telescope, the off-axis design of the Dittoscope permits a pair of symmetrically opposed secondary mirrors. Symmetry allows the same POG to be used twice. This has several advantages over a single mirror. With respect to astral interferometry, the two path lengths can be equalized in length before the two mirrors are combined, Figure 6.14..

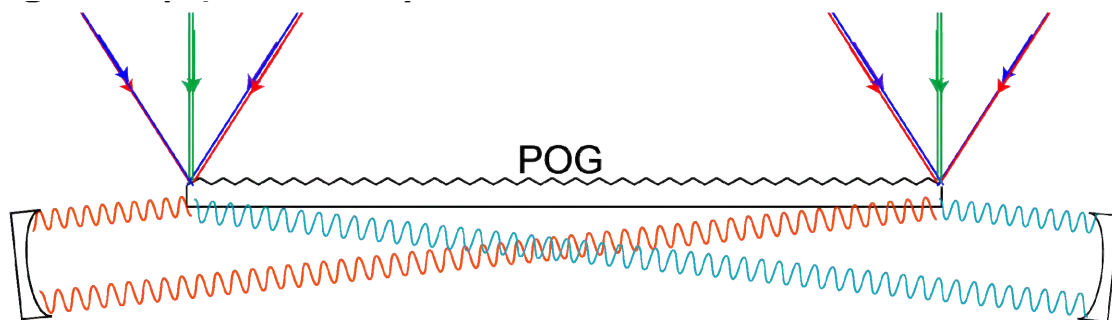


Fig. 6.14. A second mirror placed in an equal and opposite position on the same POG can match the output of the first mirror

The outputs of the two mirrors can now be combined as they are in a dual mirror astral interferometer. A Zemax model of the resulting embodiment is shown in Figure 6.15. This Zemax model is for a 547.9 nm plane wave incident along the grating plane normal with a POG of pitch of 550 nm. The reconstructed plane waves diffract at an angle of 5 deg. of grazing exodus where they can be focused by parabolic mirrors. The combiner is a “magical” double mirror that Zemax allows in multiple configuration mode. If the two

sides are identical except for a half wave difference between the distances of the mirrors to the combiner, at a slit after the combiner, two equal and opposite wave trains are superimposed on an image plane. The symmetrically opposed waves are shown schematically in Figure 6.16.

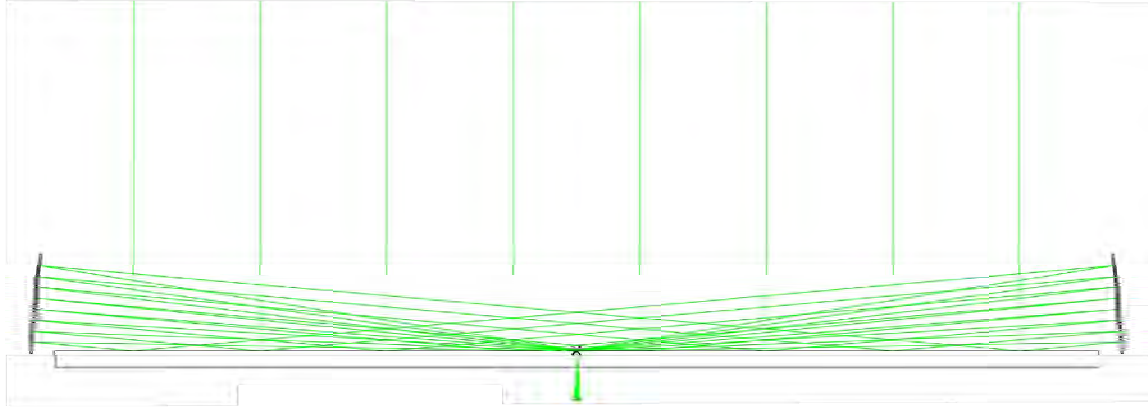


Fig. 6.15 Zemax model of symmetrical mirrors. This POG is modeled in the reflection mode. The incident rays are perpendicular to the grating plane. The pair of foci are combined and sent to a common slit.

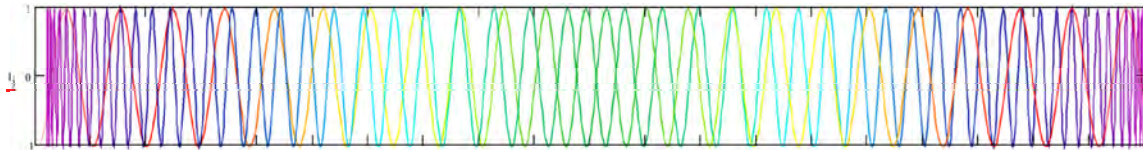


Fig. 6.16. Symmetrical superimposition of two wave trains that are equal and opposite

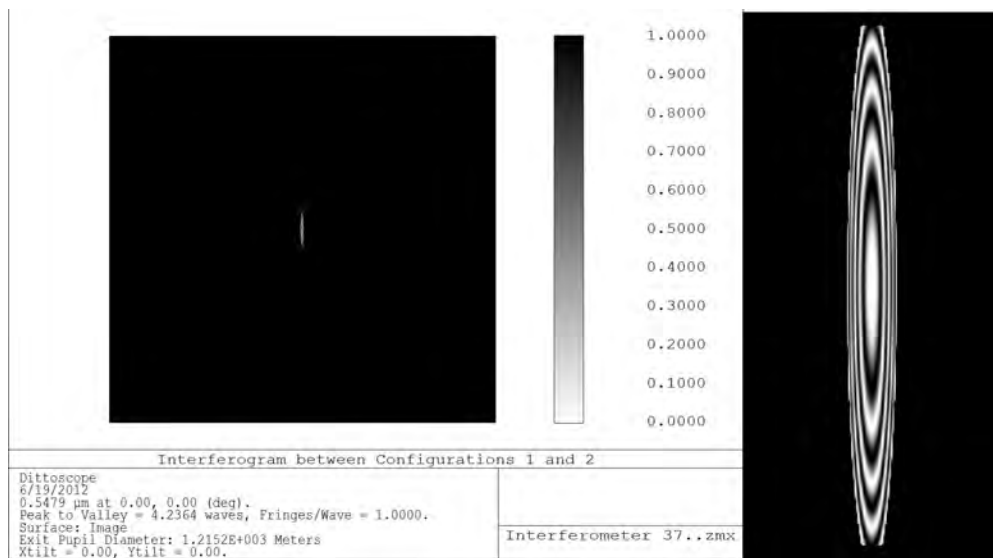


Fig. 6.17 Symmetrical superimposition of two wave trains that are equal and opposite On the left is the image plane with a magnification x 1. The nulled area is magnified on the right hand side by about 15 x

Zemax produced the interferogram of Figure 6.17. At this point neither the depth of the attenuation nor is the region covered by the null has been determined. This nulling method does demonstrate that destructive interference fringing can almost be completely avoided in the region outside of the star's diameter.

In a manner related to BLOC, a coronagraphic method was investigated by members of the RPI team, Heidi Jo Newberg and Leaf Swordy, who were originally tasked with study of THE MOST. Their Diffractive Interfero Coronagraph Exoplanet Resolver (DICER) is a notional concept shown in Figure 6.18. A schematic of the optics is shown in Figure 6.19. By collecting the light with a POG instead of a traditional mirror, DICER substantially reduces the weight of the optical system. Instead of a monolithic telescope with > 20 m diameter, DICER gathers light over two large ≈ 10 m gratings and focuses the diffracted light with two smaller secondary mirrors that are a few meters in diameter. Although 10 m gratings are unusual in astronomy, meter-scale gratings are commercially available today. DICER combines the light from the two secondary mirrors to null the planet's host star light by adapting Achromatic Interfero Coronagraphy (AIC)¹⁴, which has been shown to be capable of dimming the light from the star by a factor of 10^6 .

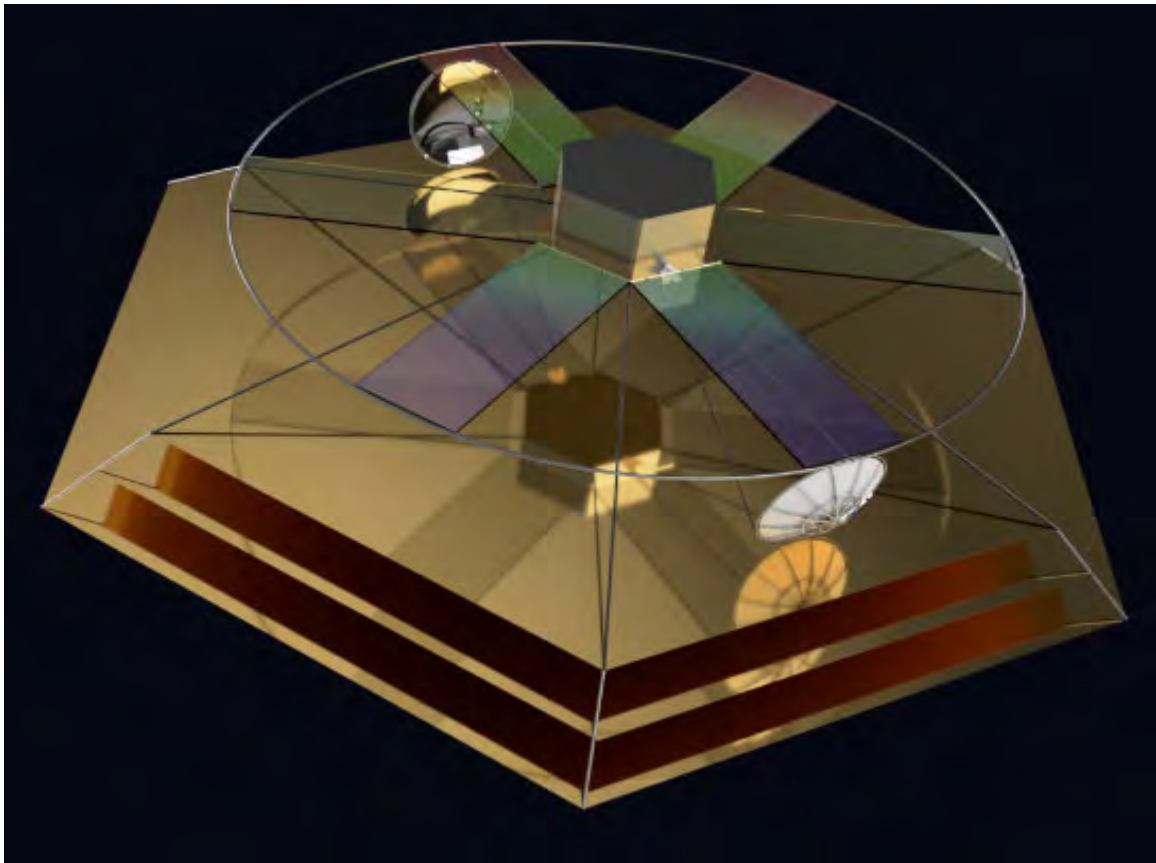


Fig. 6.18. Design concept for an infrared observatory - DICER

DICER collects light in a choice of three POGs (shown in rainbow colors - linearly aligned gratings have the same pitch), which are observed by secondary optics similar to a conventional infrared telescope mirror. The ring rotates to align one of the gratings with the secondary telescope mirrors. Light from the two mirrors is combined in a coronagraph (in central hexagonal box) that nulls the exoplanet's host star, enabling detection of small segments of an exoplanet's emission spectrum.

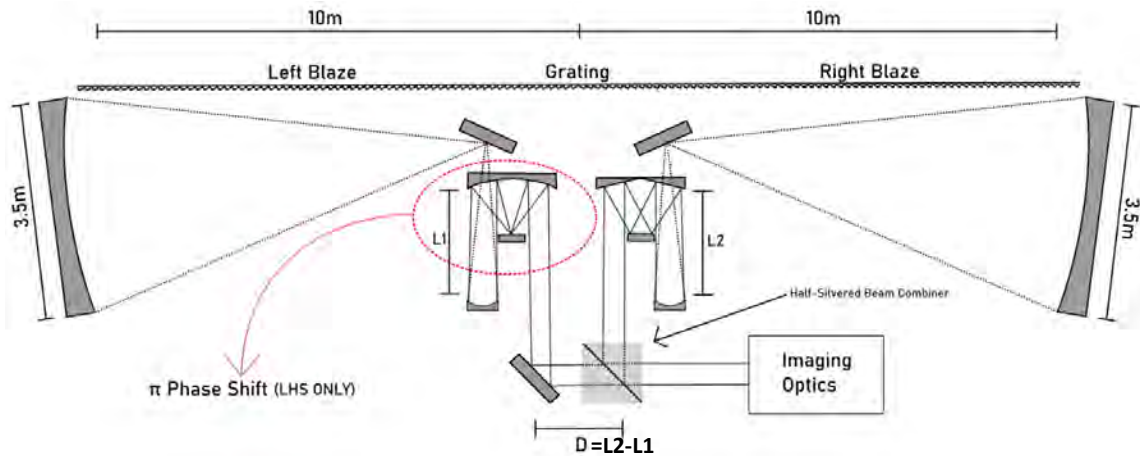


Fig. 6.19. Schematic diagram of the optical system for DICER

Light from a star must come in normal to the grating. The position angle of the planet with respect to the star must be roughly aligned with the long axis of the grating. Diffracted light from each side of the grating, at a wavelength (for example 10 microns) determined by the grating spacing will be captured at $\approx 70^\circ$ exodus angle by the two paraboloid mirrors, and is focused on the interferometer. A phase shift in one side of the interferometer will cause the star light from each side of the grating to exactly null the

other side. Because the planet is slightly offset from normal, the perspective from each side of the interferometer will be slightly different, and the planet will appear in the focal plane as two sources that are at slightly different wavelengths, because the angle of incidence for the planet is on the same side as one mirror and the opposite side for the other mirror.

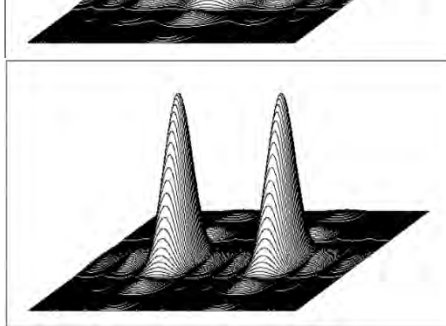


Fig. 6.20. DICER image plane as observed with Zemax. The top panel shows the image of one wavelength of the star, without the interferometer. The lower panel shows that the star is nulled when the interferometer is used so that the planet is imaged at two slightly different positions. Since the actual images will contain a range of wavelengths, the two narrow spectral ranges will not really be separated and will completely overlap.

The optics detect two small pieces of the spectrum (one from each side of the interferometer) of a resolved planet (that is therefore not nulled). These two spectrum segments completely overlap each other, giving us no information about the position of an exoplanet with respect to its host star. The imager detects the sum of the residual light from the nulled host star and from a tiny (≈ 3.8 nm wide) piece of the planet spectrum as one resolution element. Figure 2.20 is the Zemax image plane intensity map and Figure 2.21 is a graphic simulation.

To detect an exoplanet, the planet and its host star must be separated by at least 0.1 arcsec, projected along the grating. (Since the diffraction limit applies to the angular separation of the two images of the exoplanet from each side of the interferometer, the limit is a factor of 2 better than a single 10 m

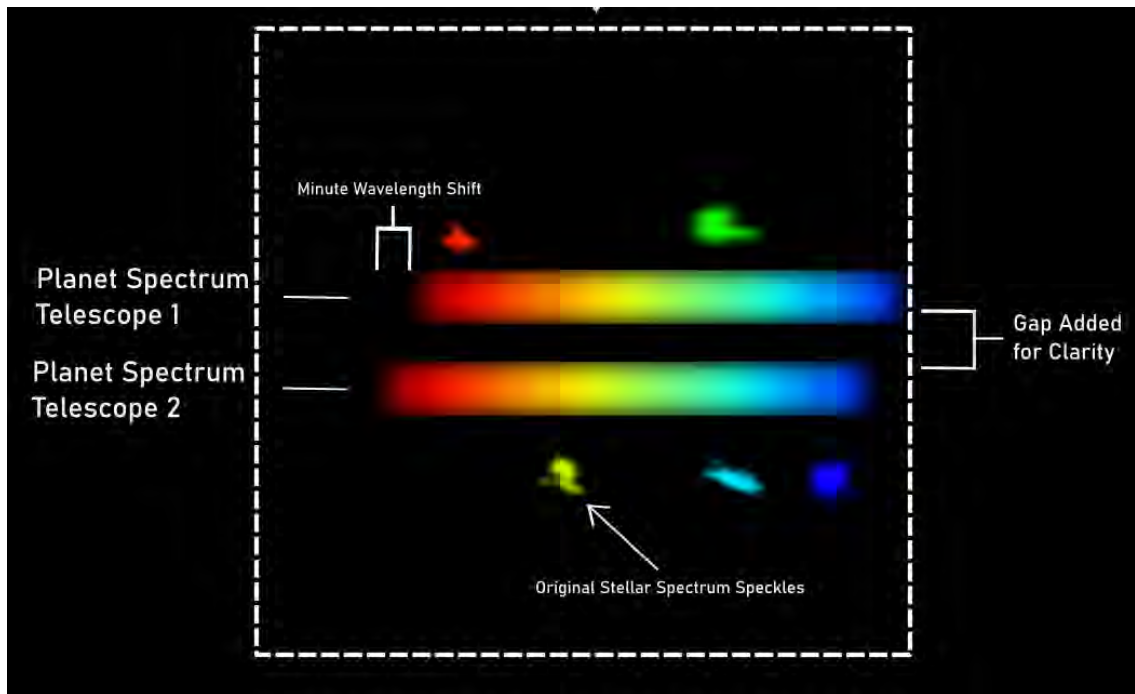


Fig. 6.21 Simulation of DICER image plane with exaggerated separation of overlapping spectra

aperture.) The required alignment of the star-planet position angle and the grating therefore depends on the angular distance between the two bodies (which depends on the distance to the star and the radius of the planet's orbit). If the star-planet angular separation is < 0.1 arcsec in projection, then the planet's flux will be significantly nulled (see Figure 6.23). We will detect most of the flux from the planet if the angular distance between the planet and its host star, projected onto the grating direction, is larger than half the diffraction limit of the grating. No flux is observed if the position angle of the

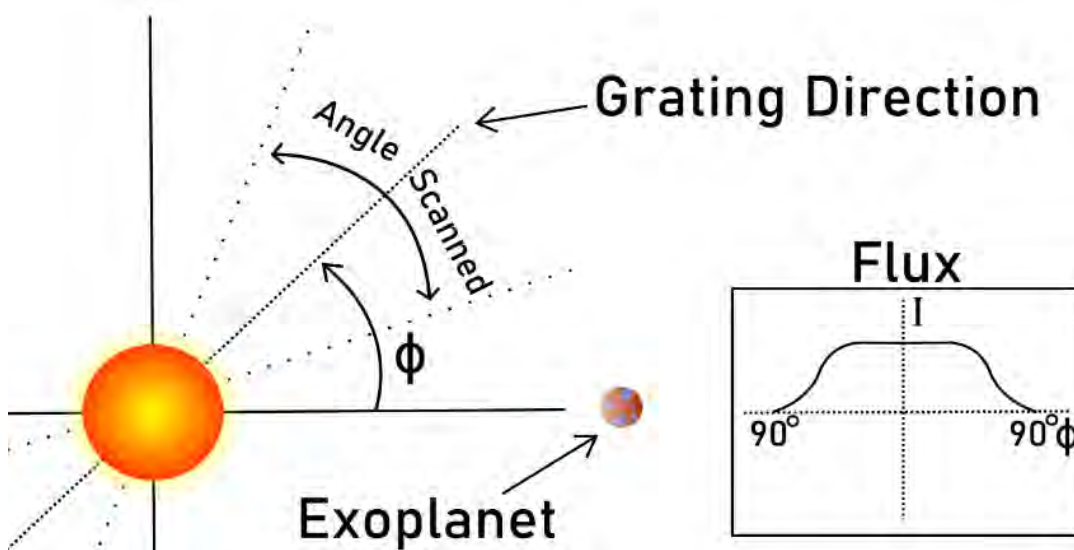


Fig. 6.23 Finding Exoplanets with DICER

planet is perpendicular to the grating direction. The range of ϕ over which the planet is observed depends on its angular distance from the host star. Many planets will produce a signal if they are within 15° of the grating axis, in which case DICER would require up to six pointings to find the planet. Planets in edge-on systems will only be distinguishable from the host star at apocenter. Therefore, we must survey the star several times per target orbital period to find all of the HZ planets. Observation of the positions of the planets over time will determine the orbital periods of any detected planets. Planets that are at least 0.1 arcsec from the host and hot enough to emit at $10\mu\text{m}$ and are preferentially HZ planets.

This method can find most of the HZ planets around the 62 Sun-like (G/K) stars within 10 pc. Because it looks for infrared emission, DICER is very biased towards finding warm planets. Because the planet must be resolved from the star, the technique is biased against finding planets that are too close (thus too hot). Near the survey limit, close-in habitable planets with small angular separations from cool stars will be more difficult to detect. DICER finds planets at any orbital inclination angle to our line-of-sight.

Figure 6.24 shows that the Earth produces ~ 1500 photons per μm per m^2 per hour. If we multiply by the collection area of the gratings ($\approx 50 \text{ m}^2$) and the wavelength range observed (assuming a 0.06° secondary telescope field-of-view we find a bandwidth of $0.0038 \mu\text{m}$), we would expect ≈ 300 photons per hour assuming 100% throughput. Transition-Edge Sensors (TES) are capable of single photon counting down to $20 \mu\text{m}$, giving some confidence that we could detect the light from a distant Earth.

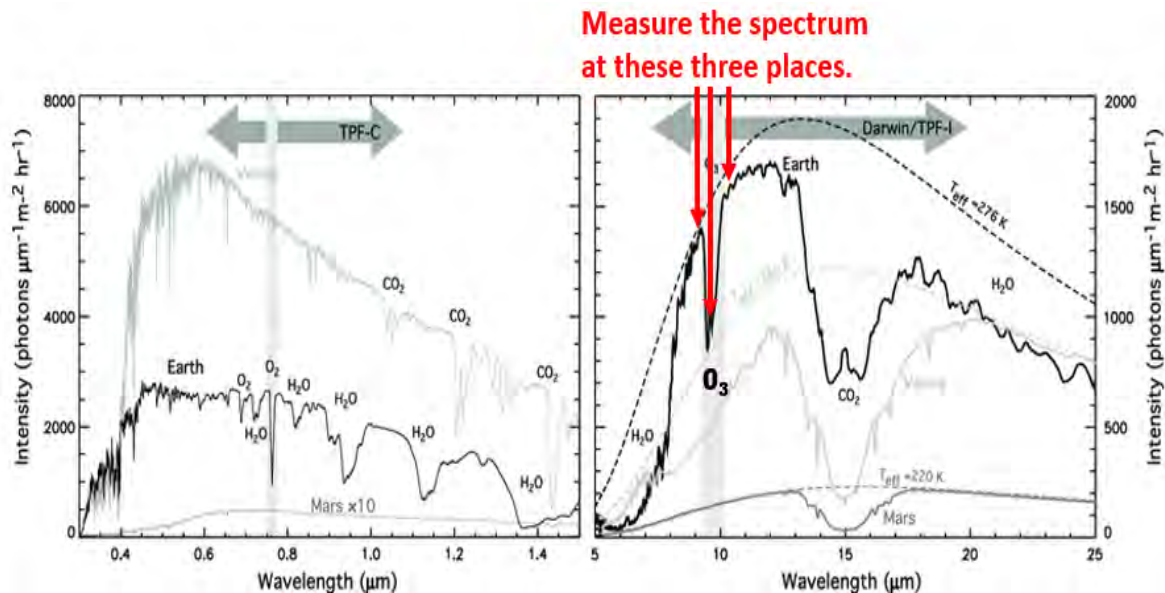
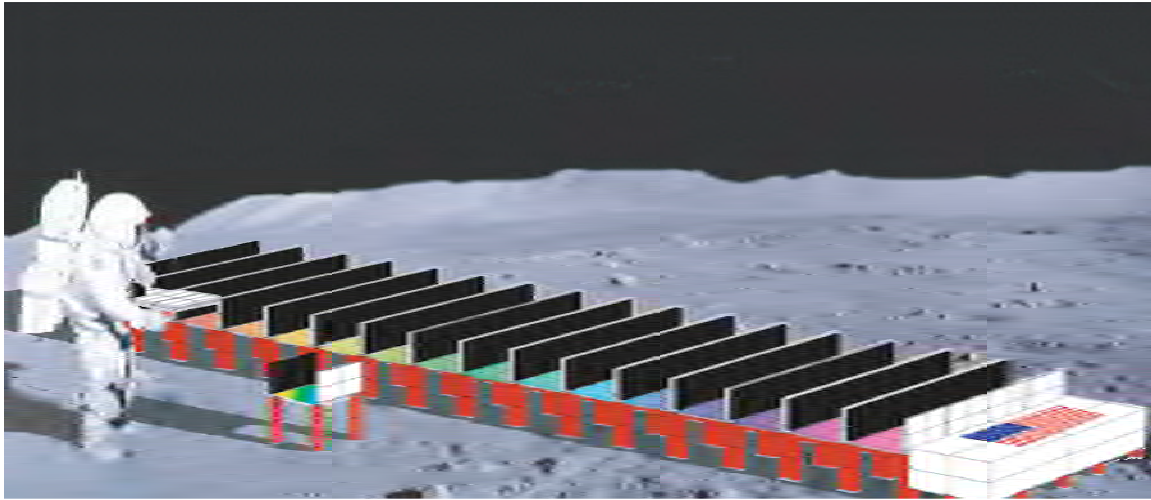


Fig. 6.24. Figure 1 from Selsis et al. (2008)¹⁵ shows the reflection spectrum (left) and emission spectrum (right) of an Earth-like exoplanet (black line) orbiting at a distance of 1 AU from a Sun-like star at 10 pc. The preliminary design concept measures three small ($\approx 3.8 \text{ nm}$ wide) pieces of the spectrum in the center and on each side of the ozone (O_3) absorption line near $10 \mu\text{m}$ as the most important measurements for the detection of life on terrestrial planets in the habitable zone (HZ).

The DICER proof-of-concept design can plausibly measure three small segments of the spectrum around the strong ozone absorption line just shy of 10 microns in the emission spectrum of an Earth-like exoplanet.

Lunar

With the emphasis on the return to the Moon, we can look back to 2006 when introducing a Phase I in Tucson. This embodiment awaits further investigation:



Lunar

Modular & Extensible

- Thin light-weight tiles on skeleton frame
- Grow in scale over multiple missions
- Flat on the regolith - easily built & serviced
- Test first on Earth then deploy to the Moon

Holographic optics

- Tunneling evanescent wave in plate
- Entirely diffractive - no large mirrors
- No moving parts during observations
- Lunar day shut down mode

Efficient in Spectrographic Modes

- Spectra of very faint objects
- No waiting - spectrograms from first light

Equatorial Station

- Ecliptic field-of-view
- Integration periods up to years
- Milky Way structure investigation

Can there be a finer congregation of Fellows? Here I am in Tucson in 2006 with Rob Hoyt, with whom I continue to work, Joe Ritter who lent his name to five SPIE papers, James Roger Prior Angel whose 2002 SPIE conference on Astronomical Telescopes and Instrumentation published my first papers on the POG concept, Mason Peck who went on to become NASA Chief Technologist and has since extended a helping hand from his base in Cornell, and Bob Cassanova who retired to a life in the arts where whence I came.



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Thomas D. Ditto
September 2022

Bibliography

Thomas Ditto, "The Dittoscope," Proc. SPIE 4840, Future Giant Telescopes, (30 January 2003); <https://doi.org/10.1117/12.459878>

Thomas Ditto, "Kilometer-scale primary objective telescope with no moving parts," Proc. SPIE 4837, Large Ground-based Telescopes, (4 February 2003); <https://doi.org/10.1117/12.458208>

Thomas D. Ditto, Jeffrey Foster Friedman, Jeffrey T. Baker, "Kilometer scale primary collector telescope," Proc. SPIE 5578, Photonics North 2004: Photonic Applications in Astronomy, Biomedicine, Imaging, Materials Processing, and Education, (9 December 2004); <https://doi.org/10.1117/12.567574>

Thomas D. Ditto, "Kilometer scale telescope collector deployable in a shuttle payload," Proc. SPIE 5578, Photonics North 2004: Photonic Applications in Astronomy, Biomedicine, Imaging, Materials Processing, and Education, (9 December 2004); <https://doi.org/10.1117/12.606728>

Thomas D. Ditto, Joseph M. Ritter, "10 meter airborne observatory," Proc. SPIE 7014, Ground-based and Airborne Instrumentation for Astronomy II, 70142J (9 July 2008); <https://doi.org/10.1117/12.790261>

Thomas D. Ditto, Joseph M. Ritter, "Ultra low wind resistance enclosure for a 100-m telescope," Proc. SPIE 7012, Ground-based and Airborne Telescopes II, 70123I (10 July 2008); <https://doi.org/10.1117/12.790268>

Thomas D. Ditto, Joseph M. Ritter, "Phase errors in gossamer membrane primary objective gratings," Proc. SPIE 7010, Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter, 70104F (12 July 2008); <https://doi.org/10.1117/12.790222>

Thomas D. Ditto, Joseph M. Ritter, "Million object spectrograph," Proc. SPIE 7018, Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, 70182R (23 July 2008); <https://doi.org/10.1117/12.790244>

Thomas D. Ditto, Joe Ritter, John Valliant, "Working model of a gossamer membrane spectrographic space telescope," Proc. SPIE 7436, UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts IV, 74360H (26 August 2009); <https://doi.org/10.1117/12.826377>

Thomas D. Ditto, Jeffrey F. Friedman, David A. Content, "Astronomical telescope with holographic primary objective," Proc. SPIE 8146, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts V, 814615 (14 September 2011); <https://doi.org/10.1117/12.893141>

Thomas D. Ditto, "Habitable planet finder," Proc. SPIE 8442, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, 84424A (21 September 2012); <https://doi.org/10.1117/12.926343>

Thomas D. Ditto, Sergiy Lysenko, Melissa Crenshaw, "Holographic spectrograph for space telescope," Proc. SPIE 8864, Techniques and Instrumentation for Detection of Exoplanets VI, 88641T (26 September 2013); <https://doi.org/10.1117/12.2024616>

Thomas D. Ditto, Stephen P. McGrew, "HOMES: Holographic Optical Method for Exoplanet Spectroscopy," Proc. SPIE 8864, Techniques and Instrumentation for Detection of Exoplanets VI, 88641S (26 September 2013); <https://doi.org/10.1117/12.2024645>

Thomas D. Ditto, "Conservation of étendue in a primary objective grating telescope," Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91515T (18 July 2014); <https://doi.org/10.1117/12.2055510>

Thomas D. Ditto, "ADDEDPT: apparatus for direct detection of exoplanets by diffractive pupil telemetry," Proc. SPIE 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, 914339 (28 August 2014); <https://doi.org/10.1117/12.2055493>

Thomas D. Ditto, "A new Newtonian architecture," Proc. SPIE 11115, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts IX, 111150I (9 September 2019); <https://doi.org/10.1117/12.2528986>

Thomas D. Ditto, Heidi Jo Newberg, J. Hiroshi Burnette, Hunter Rouillard, Makayla Wahaus, "Scale model of a dual dispersion primary objective grating telescope," Proc. SPIE 11116, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II, 111160A (9 September 2019); <https://doi.org/10.1117/12.2528951>

Thomas D. Ditto, "Self-nulling spectrograph for star glare rejection," Proc. SPIE 11117, Techniques and Instrumentation for Detection of Exoplanets IX, 111171P (9 September 2019); <https://doi.org/10.1117/12.2525524>

Heidi Jo Newberg, Leaf Swordy, Thomas D. Ditto, "Feasibility of NEO detection with a primary objective grating telescope," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 114452I (13 December 2020); <https://doi.org/10.1117/12.2561767>

Mei-Li Hsieh, Thomas D. Ditto, Shawn-Yu Lin, "Experimental demonstration of a Gabor zone-plate hologram for Space Exoplanet Telescope," Proc. SPIE 11451, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV, 114515N (13 December 2020); <https://doi.org/10.1117/12.2561512>

Thomas D. Ditto, Mei-Li Hsieh, Heidi Jo Newberg, Leaf Swordy, Robert Hoyt, Jesse Cushing, "Optical space telescope without mirrors," Proc. SPIE 11443, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, 114431B (13 December 2020); <https://doi.org/10.1117/12.2561673>

Leaf A. Swordy, Heidi Jo Newberg, Thomas Ditto, "The Star Generator: a novel device for optical characterization of large-area primary objective gratings," Proc. SPIE 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V, 121883K (29 August 2022); <https://doi.org/10.1117/12.2630266>

Heidi Jo Newberg, Leaf A. Swordy, "Diffractive interfero coronagraph exoplanet resolver (DICER): detecting and characterizing all Earth-like exoplanets orbiting Sun-like stars within 10 pc," Proc. SPIE 12180, Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, 121805E (27 August 2022); <https://doi.org/10.1117/12.2629487>

¹ Grange & Millard, “Grism developments for space- and ground-based astronomy” (July 2011)

<https://www.spie.org/news/3739-grism-developments-for-space--and-ground-based-astronomy>

² Isaac Newton, *Opticks*, (4th ed 1730), p. 46, <http://www.gutenberg.org/files/33504/33504-h/33504-h.htm>

“Exper. 6. In the middle of two thin Boards I made round holes a third part of an Inch in diameter, and in the Window-shut a much broader hole being made to let into my darkened Chamber a large Beam of the Sun’s Light; I placed a Prism behind the Shut in that beam to refract it towards the opposite Wall, and close behind the Prism I fixed one of the Boards, in such manner that the middle of the refracted Light might pass through the hole made in it, and the rest be intercepted by the Board. Then at the distance of about twelve Feet from the first Board I fixed the other Board in such manner that the middle of the refracted Light which came through the hole in the first Board, and fell upon the opposite Wall, might pass through the hole in this other Board, and the rest being intercepted by the Board might paint upon it the coloured Spectrum of the Sun. And close behind this Board I fixed another Prism to refract the Light which came through the hole. Then I returned speedily to the first Prism, and by turning it slowly to and fro about its Axis, I caused the Image which fell upon the second Board to move up and down upon that Board, that all its parts might successively pass through the hole in that Board and fall upon the Prism behind it. And in the mean time, I noted the places on the opposite Wall to which that Light after its Refraction in the second Prism did pass; and by the difference of the places I found that the Light which being most refracted in the first Prism did go to the blue end of the Image, was again more refracted in the second Prism than the Light which went to the red end of that Image, which proves as well the first Proposition as the second. And this happened whether the Axis of the two Prisms were parallel, or inclined to one another, and to the Horizon in any given Angles.”

³ Thomas D. Ditto, Heidi Jo Newberg, J. Hiroshi Burnette, Hunter Rouillard, and Makayla Wahaus "Scale model of a dual dispersion primary objective grating telescope", *Proc. SPIE 11116, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II*, 111160A (9 September 2019);

<https://doi.org/10.1117/12.2528951>

⁴ Thomas Ditto "The Dittoscope", *Proc. SPIE 4840, Future Giant Telescopes*, (pub. 30 January 2003);

<https://doi.org/10.1117/12.459878>

⁵ <https://wasatchphotonics.com/technologies/volume-phase-holographic-gratings/>

⁶ Stephen P. McGrew, “Color Control in Dichromated Gelatin Reflection Holograms,” (1979)

http://www.nli-ltd.com/publications/color_control.php

⁷ LitiHolo specification, kit_instructions-filmspecs7, <https://www.litiholo.com/hologram-film.html>

⁸ https://en.wikipedia.org/wiki/Snell%27s_law

⁹ <https://life-space-mission.com>

¹⁰ Monnier, J. D., “Optical Interferometry in Astronomy.” arXiv, 2 July 2003 <https://arxiv.org/pdf/astro-ph/0307036.pdf>. (Accessed: June 2020).

¹¹ Hybrid Observatory for Earth-like Exoplanets (HOEE),

https://www.nasa.gov/directorates/spacetech/niac/2022/Hybrid_Observatory_for_Earth_like_Exoplanets/

¹² National Academies of Sciences, Engineering, and Medicine, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, Washington, DC: The National Academies Press, 2021

<https://doi.org/10.17226/26141>

¹³ [2020 Decadal Survey](#) *op. cit.*, pp. 15, 57, 88, 210, 248

¹⁴ Rabbia, Yves, Gay, Jean, and Rivet, Jean-Pierre, “The Achromatic Interfero Coronagraph,” *Comptes Rendus - Physique*, 8(3-4), 385-395 (2007).

¹⁵ Selsis, Franck, Kaltenegger, Lisa, and Paillet, Jimmy, “Terrestrial exoplanets: diversity, habitability and characterization,” *Physica Scripta*, 130, id. 014032 (2008).

The images show the initial optical lay out used in September and near grazing angle tests in November.

Optics set up**Components**

Laser	50 mW HeNe with Etalon
A	main transfer mirror, beam height ~44", aim beam down to launch optic
B	launch optic lowers beam to 24" center working height for components
C	Transfer mirror to Spatial Filter
D	Spatial filter 10X, 15um pin hole
E	30" diameter plano concave collimating mirror, ~ 10' from pin hole in spatial filter
F	12" diameter, optically flat transfer mirror
G	Film plate holder



Components	path length
B-C	launch optic to transfer mirror ~41"
C-D	transfer mirror to spatial filter pin hole 7"
D-E	spatial filter pin hole to large PC mirror ~10'
F-G	center point to center point ~18"

Near grazing angle tests

Component	Angle
F-G	12" mirror to film holder 50° from normal
G	Large parabolic mirror to film holder 20-25° from normal

New equal angle set up, 45° 45° same 10X objective and 15μ pin hole

F-G	12" mirror to film holder 45°
G	Large parabolic mirror to film holder 45°

Same equal angle set up, 45° 45° with 4X objective and 15μ pin hole

F-G	12" mirror to film holder 45°
G	Large parabolic mirror to film holder 45°

NASA November 8-22, 2019
Metering, Recording and Processing

[illegible]

Recording Materials and Processes for this project need to be available in large format film and sensitive to 632 nM laser.

Update 11/22/2019

Silver Halide

ID	Vendor	Special handling	Development	Bleach	Wash/drying
PGF 01 Red sensitive Available on glass or film	Geola http://geola.com/product/pg-01-plates/ <i>Fine-grained red sensitive holographic plates and film designed for reflection or transmission hologram recording. Average grain size is 40nm, resolving power more than 3000 lines/mm, spectral sensitivity range 600-680nm (including 633nm, 647nm).</i>	Store 12-15°C, 65% RH Process > 20°C	SM-6 CW-C2 D-19 - at your own risk is noted on web site.	PBU-Amido rehalogenating A Potassium iodide color shift bath is also shown following the bleach step. Potassium dichromate Reversal bleach	Wetting agent Slow air dry (web site mentions using a wiper blade on wet plates)
	LaserReflections http://www.laserreflections.com/film.html LR does not supply chemicals	Store 40°F RH 30%	SM-6 D-19	PBU-Amido rehalogenating	They refer to Geola for more processing and handling info.
	Integraf https://www.integraf.com/shop/pg-01-holographic-film-plates	No info	JD-2 Devo and Bleach kit JD-3 Devo and Bleach kit	JD-2 Devo and Bleach kit JD-3 Devo and Bleach kit	Wetting agent No other info

NASA Project

M. Crenshaw

2019

Chemicals details

JD2 & JD3 info with packaging

Supplies such as D-19 equivalent can be purchased at B&H in NYC

Info from LaserReflections:

SPECTRUM CHEMICAL	ALFA AESAR	FISHER SCIENTIFIC
Spectrum Chemical 14422 San Pedro Street Gardena, CA 90248 Tel: 310-516-8000 Need to open an account www.spectrumchemical.com	Alfa Aesar 26 Parkridge Rd Ward Hill, MA 01835 Tel: 1-800-343-0860 Need to open account Net 30 www.alfaesar.com	Fisher Scientific To open account call: 1-800-766-7000 Tel: 1-800-343-0860 Need to open an account Net 30 www.fishersci.com
SML-6 Developer Ascorbic Acid Powder USP - 18 gr Sodium Hydroxide Technical - 12 gr Sodium Phosphate Dibasic - 28.4 gr Phenidone - 6 gr Mix in 1 liter of water	A1361 S1302 S1407 P2122 A12089	N/A
PBU-Amidol Bleach Citric Acid - 50 gr Potassium Persulfate - 10 gr Potassium Bromide - 20 gr Cupric Bromide - 1 gr Amidol - 1 gr Mix in 1 liter of water	C1280 P1412 P1320 C1375 D1103	

From Geola web site:

SM-6 Developer	
Sodium Hydroxide	12.0g
Methyl Phenidone	6.0g
Ascorbic Acid	18g
Sodium Phosphate (dibasic)	28.4g
Water	to 1.0L
CW-C2 Developer	
Part A 1 part A + 1 part B	
Catechol	20.0g
Ascorbic Acid	10.0g
Sodium Sulphite (anhydrous)	10.0g
Urea	100.0g
Water	to 1.0L
Part B	
Sodium Carbonate	60.0g
Water	to 1.0L
PBU-Armitol Bleach	
Potassium Persulphate	10.0g
Citric Acid	50.0g
Cupric Bromide	1.0g
Potassium Bromide	20.0g
Armitol	1.0g
Water	to 1.0L
Potassium Iodide Bath	
Potassium Iodide	18.0g
Water	to 1.0L

Table 3: VFP-M and PFG-01

Developers, Bleach and Color shift bath

Photopolymers: no development no bleach

ID	Vendor	Special handling	Other
Liti Photopolymer Product is laminated to glass Film can be removed from the glass substrate	LTI Holographics contact Paul Christie (757)873-6460 www.litholo.com	Storage: Temperature: 55 - 90 degrees F (do not refrigerate), Humidity: 30 - 55% RH Lifetime: 12 month warranty minimum	Substrate: 1.8mm glass, Film thickness: 16 microns, Cover sheet: 60 microns DE Transmission: >90% holographic grating test DE Reflection: >90% holographic mirror test Sensitivity: ~400 - 690 nm Exposure Energy (635nm): 20 mJ/cm ² Exposure Energy (532nm): 30 mJ/cm ² Exposure Energy (450nm): 80 mJ/cm ²
Geola photopolymer GP3C	Geola http://geola.com/product/photopolymer/	High temperatures (above 60°C at the film) should be avoided because they can lead to deformation of the substrate. The unrecut photopolymer film should be stored in the original and sealed container that is used for delivery, whenever possible.	The substrate is a cellulose triacetate film (TAC), and the protective cover is a polyethylene film (PE). The protective cover film can be removed from the photopolymer: 

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		Storage temperature shall be kept at > 15°C and < 25°C. <i>While the recorded film is quite stable, the unrecorded photopolymer film should be protected from light, humidity, heat and foreign materials.</i>	
ZILUX NDA required for further development work	Zilux Contact: Harlan Papert (harlan@ziluxholography.com) http://www.ziluxholography.com/products	No info	Our photopolymer photopolymer was designed for use with BLUE-GREEN lasers (458 to 535 nm) and RED lasers (610 to 660 nm). This is a low cost material designed for substitute the traditional ones. It works by recording a visible reflection hologram. It is further thermally developed in a single process to deliver a reflection hologram with excellent properties. From Papert email: No problem with supply. We do 30cm x 1m or wider. We mass produce rolls for commercial purposes. What wavelengths are you looking for? How much material do you need? Our holograms do not require glass backing.
Bayfol® HX Our Bayfol® HX films are based on RGB light-sensitive photopolymers for the recording of volume holographic optical elements (VHOE).	Bayfol https://solutions.covestro.com/en/brands/bayfol Update 11/12 request sent again. Response on 11/21 sent to Tom. They have a NA headquarters in Pittsburgh PA. They do development work, R&D Samples requested for green and red NOTE: SPIE SPIE 2020 SfCA Expanding possibilities how to apply Bayfol HX® film into recording stacks and optical parts Paper 11306-11	No info	Bayfol® HX comprises a transparent substrate film, a photoreactive layer with adjustable properties and a protective cover film. Key Benefits: Thin and lightweight: Complex optical functions can be recorded in a single thin layer; Highly versatile: Multiple optical functions can be multiplexed in a single thin layer; Fully Transparent: Completely invisible in Off-Bragg conditions; Fits your needs: Tailor-made solutions for B2B customers optionally with technical advisory; Industry ready: Suitable for roll-to-roll industrial recording process. Our customized offer to fit your needs

Personal Note

This research grant was awarded in May 2019. It did not come with any financial support until September. Work began, but the latency in financing required that 3DeWitt borrow from outside sources. We are indebted to the personal loans made by Dr. Heidi Jo Newberg and Sky Dayton. In the first instance, Dr. Newberg's support covered our appearance at the September 2019 NIAC Symposium, and in the latter we were able to muster the physical material needed to launch our research.

In the course of 2020 everyone was faced with the Covid-19 crisis. In the case of the P.I. his work at RPI which had typically involved campus visits five days a week were abruptly stopped, and since March 2020 he has yet to return to campus where restrictions on access require pretesting the day before a week's permission to work. The travel of 120 miles round trip precludes spending one day a week simply to drive up to campus for the test, so he took the option of working in his own laboratory in Cario, NY and occasionally meeting with his RPI colleagues at that location.

In March of 2020, Tom was diagnosed with colorectal cancer and faced three surgeries that spanned nearly four months with another two months required to restore him to a reasonable level of physical health. As of April 2022 the cancer was reported to be in remission.

A handwritten signature in black ink, appearing to read "Tom DeWitt". The signature is fluid and cursive, with the first name "Tom" and last name "DeWitt" clearly distinguishable.