

Working model of a gossamer membrane spectrographic space telescope

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ABSTRACT

The nineteenth century Fraunhofer primary objective grating (POG) telescope has been redesigned with a secondary spectrometer. The POG is embossed on a membrane and placed at an angle of grazing exodus relative to a conventional spectrographic telescope. The result is a new type of telescope that disambiguates overlapping spectra and can capture spectral flux from all objects over its free spectral range, nearly 40°. For space deployment, the ribbon-shaped membrane can be stowed as a cylinder under a rocket fairing for launch and deployed in space from a cylindrical drum. Any length up to kilometer scale could be contemplated.

Keywords: diffraction grating, primary objective, spectroscopy, gossamer membrane

1. INTRODUCTION

On the four hundredth anniversary of the invention of the astronomical telescope little has changed in the first principles of the primary objectives first introduced as lenses and shortly thereafter as mirrors. Yet the observational goals of astronomy have long since expanded to include spectroscopy as a key component of telescope design. It could be said that spectroscopy runs against the grain of the primary objective. A motivation for Newton's mirror primary derived from his studies of refractive dispersion, because he correctly assessed lenses as defective with regard to chromaticity. At the time, chromatic dispersion had no utility in astronomical observation, and mirrors offered superior achromatic image formation. They still do. However, something changed in the nineteenth century, nearly 200 years after Newton, when the spectrometer was introduced into telescoping. The achromatic mirror robs the secondary of chromatic dispersion, and spectroscopy requires an extension of the ray path to include ancillary dispersers: prisms, gratings and grisms.

Mirror primaries are three dimensional objects which are held to tolerances that are fractions of a wavelength and must remain immune to dimensional variations to a similar level of precision. Space deployments of large mirror apertures have been problematic. Despite the self-evident utility elevating astronomical telescopes above the earth's atmosphere, space deployments of mirror primary telescopes are contemplated at apertures which are a fraction of terrestrial telescopes. Although the optical surfaces needed to form images are essentially without mass, the substrates required to support mirrors carry a substantial weight penalty. Moreover, for diameters greater than the fairing of lift vehicles, mirror segmentation before launch and subsequent space assembly complicate the deployment.

In 2002 one of the authors introduced a paradigm shift in primary objective first principles by describing the concept of a primary objective grating (POG) astronomical telescope that exploited the dispersion of the primary to acquire spectra in the secondary through a process of dual dispersion.¹ The dual dispersion POG telescope enjoys an intrinsic spectrographic capability.² Unlike an earlier POG concept dating back to Fraunhofer, the dual dispersion design disambiguates overlapping spectra.³ When configured at grazing exodus, the POG enjoys an anamorphic magnification feature as well as an extraordinarily wide field-of-view over the free spectral range of the first diffraction order.⁴ A POG shows relative immunity to defects in surface flatness when compared with mirrors.⁵ Furthermore, the POG can be a flat gossamer membrane deployed from a cylindrical roll that is easily stowed inside a rocket fairing.⁶ A ribbon-shaped POG can unfurl to fill apertures in the hundreds of meters without segmentation.⁷ Unlike interferometric sparse apertures, the POG can be part of a continuous structure and has integrity that precludes the necessity of formation flying.⁸

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2. PRINCIPLE OF OPERATION

Figure 1 is a diagram of the POG concept, illustrated with a transmission grating. The concept is the same for a reflection POG. For any object at an angle of incidence to the the POG there is a corresponding wavelength detected after the secondary spectrometer. Acquisition of a line of right ascension is achieved by rotation of the assembly. On earth the rotation is accomplished though the rotation of the planet. In space the platform rotates. A star at a particular angle is

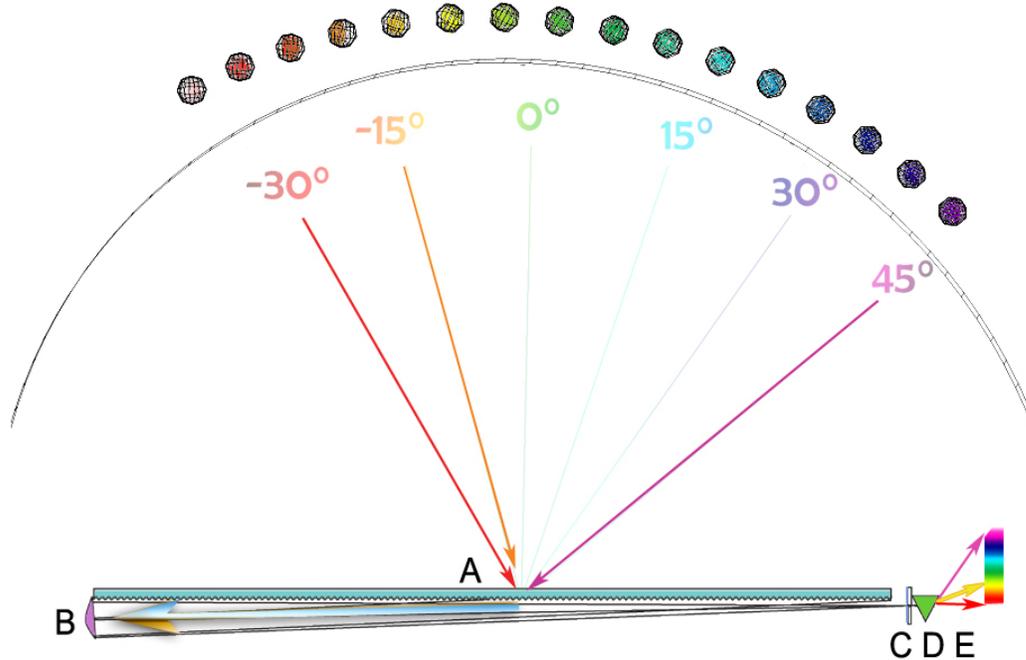


Fig. 1 Dual dispersion POG astronomical telescope

diffracted by POG **A** to secondary parabolic mirror **B**, and the light is focused on slit **C**. A secondary disperser, **D** separates out all the visible objects as spectrum **E**. Three distinct targets at angles -30° , -15° and 45° are illustrated in bold lines, but the entire line is covered. As the POG rotates and the stars precess, their entire spectra are taken over the course of an observation cycle. The image of the sky at E is the same image that would be produced by parabolic mirror B, but a very high resolution spectral spread is superimposed over the image. Data reduction correlates temporal data with angle of incidence. Any one object has its spectrum assembled from a series of snapshots, Figure 2.

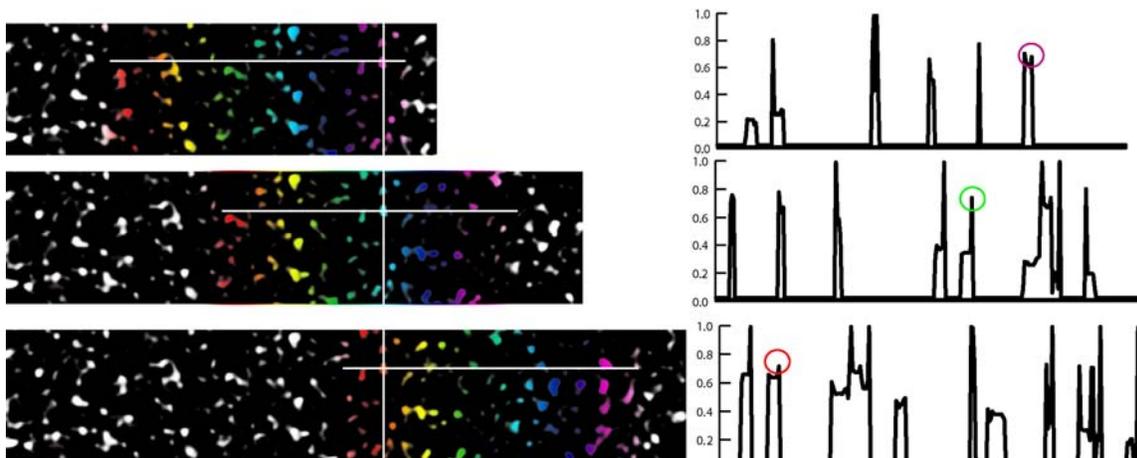


Fig. 2 Three frames from a simulated observation cycle. The cross hairs track one object. The instantaneous amplitude of all objects at unique wavelengths can be stored as a table for data reduction after the observation cycle.

3. EMBODIMENT OF OPTICS AS A WORKING MODEL

Newton could have demonstrated the dual dispersion principle upon which the POG telescope depends by extending his famous “Crucial Experiment” of 1668. Of course, dispersion would have been by prism, since the diffraction grating wasn’t reported in the literature until 1785 and was not ready for spectroscopy until well into the nineteenth century. Taking liberties with a page from Newton’s notebook, we show in Figure 3 how two sources focused onto a prism can pass through a hole in a mask to form two images in two colors at displacements proportional to the original sources.

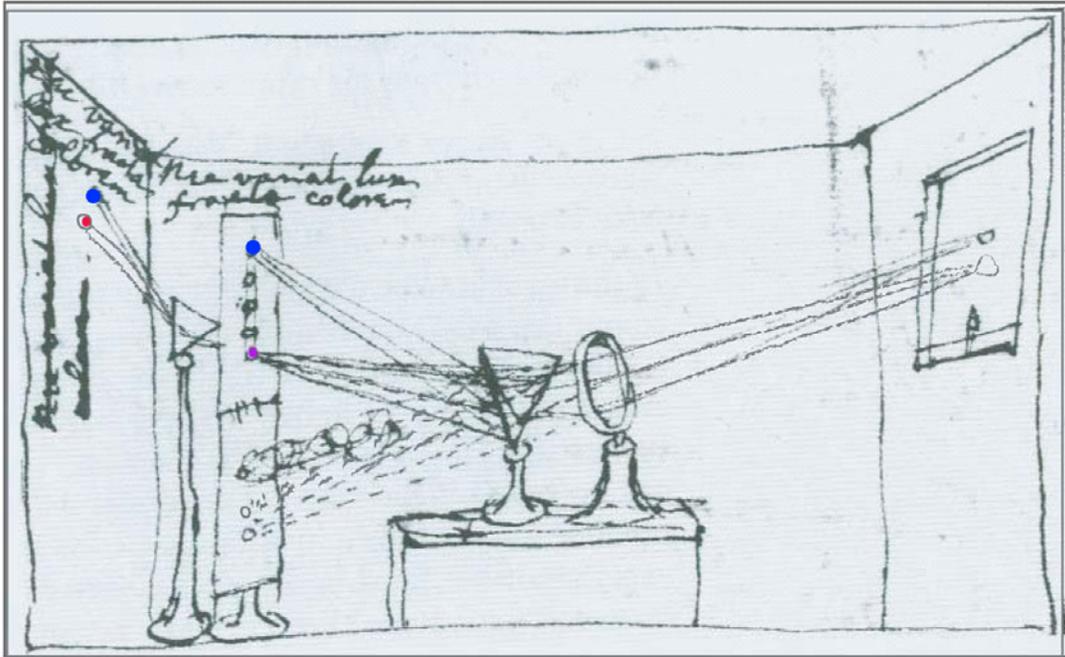


Fig. 3 *Il Experimentum Crucis Subiectum* [The Counterfeit Crucial Experiment] with apologies to Isaac Newton

3.1 First Laboratory Demonstration

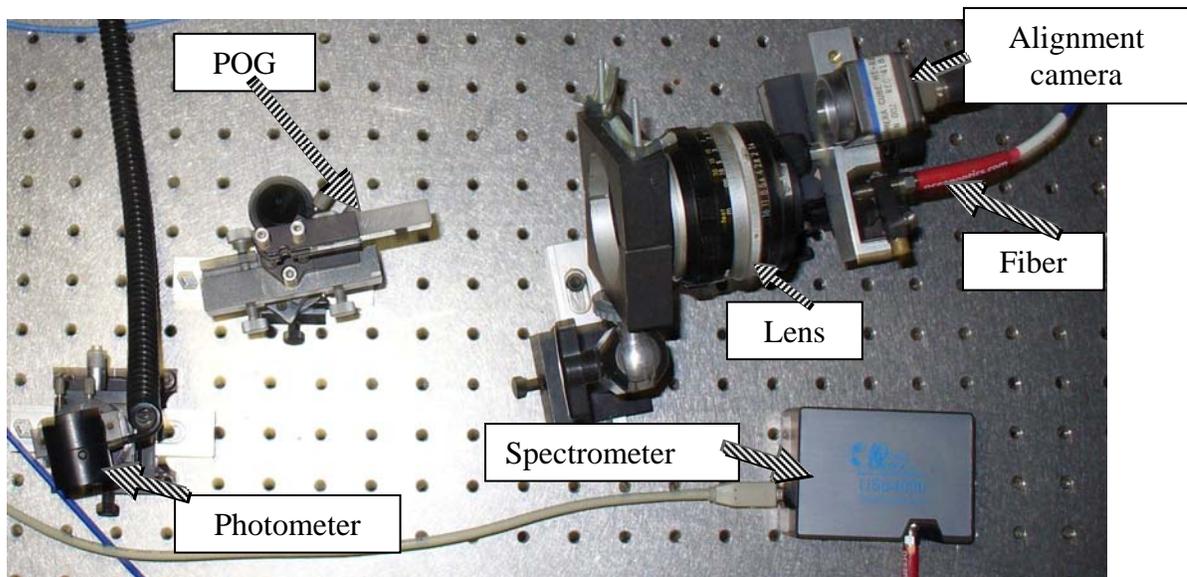


Fig 4 Our Crucial Experiment. 50 mm POG, lens, fiber fed spectrometer, alignment camera and photometer.

Figure 4 is the bench set-up used to first demonstrate that a secondary spectrometer could disambiguate overlapping spectra from a POG and report separate sources at distinct locations along a spectrogram. Not constrained to capturing sunlight through a masked window, as Newton was compelled to do, we used three incandescent sources with an embedded laser in front of one of the sources.



Fig 5 Three halogen artificial “stars” with a 650 nm pointer diode laser positioned directly in front of the third “star.”

The baseline of the sources was determined by their distance from the POG which was merely a couple of meters in the case of Figure 6 where the plane wave from the laser is a spike inside the envelope originating from its correlated incandescent source. When the sources were moved 5 meters from the bench, the baselines narrowed, and the three sources can be seen side by side in Figure 7. Notably two of the sources were at the same “latitude” and appear at equal brightness, while the third is slightly higher, and its intensity is less at the fiber optic distal end of the spectrometer. The laser, which only could be seen at a specific incident angle corresponding to 650 nm in the spectrum was not acquired after the second stage of dispersion.

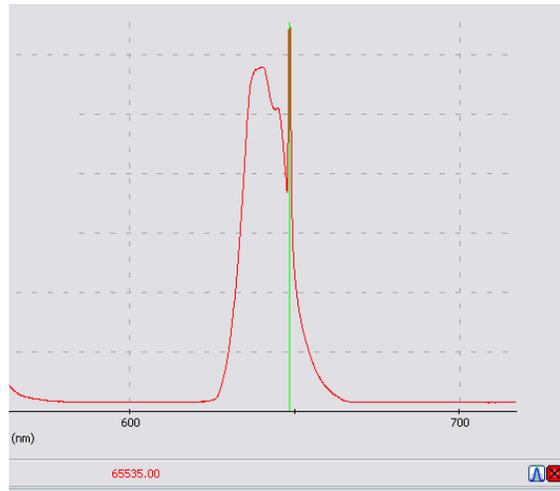


Fig. 6 A 650 nm laser embedded in broadband source

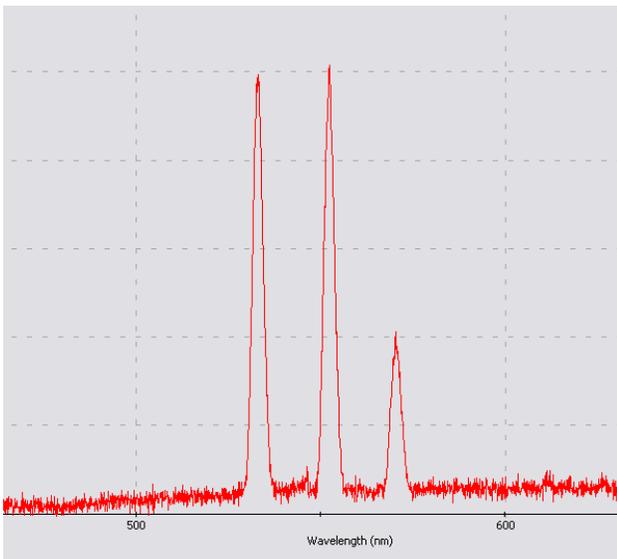


Fig. 7 Three artificial “stars” at 5 m from bench

The example of Figure 8 shows a source at 33.3 m with the baseline further reduced as the source more closely approximates a plane wave. A single source positioned at 5 meters was moved in 0.05 inch increments corresponding to 55 arcsecond steps, and the resulting change in the received wavelength was read out of an Ocean Optics USB4000 spectrometer. The result is recorded in Table 1. Centroid extraction in Ocean Optic’s SpectraSuite® software provided a refinement over raw optical resolving power, and variations in wavelength on the average of 0.135 nm were detected.

Table 1 Experimental result correlating the angular resolution with spectral resolving power

inches	deg	arc sec	nm	$\Delta\lambda$
0.00		54.28	555.51	
0.05			555.49	0.012 discarded
0.10	0.015	0.00	555.35	0.14
0.15	0.015	54.28	555.21	0.14
0.20	0.015	108.56	555.09	0.12
0.25	0.015	162.84	554.95	0.14
0.30	0.015	217.12	554.81	0.14
0.35	0.015	271.40	554.69	0.12
0.40	0.015	325.68	554.56	0.13
0.45	0.015	379.96	554.42	0.14
0.50	0.015	434.24	554.28	0.14
0.55	0.015	488.52	554.15	0.13
0.60	0.015	542.80	554.01	0.14
0.65	0.015	597.08	553.87	0.14
0.70	0.015	651.36	553.74	0.13
0.75	0.015	705.64	553.6	0.14
0.80	0.015	759.92	553.47	0.13
0.85	0.015	814.20	553.33	0.14
			Avg.	0.135

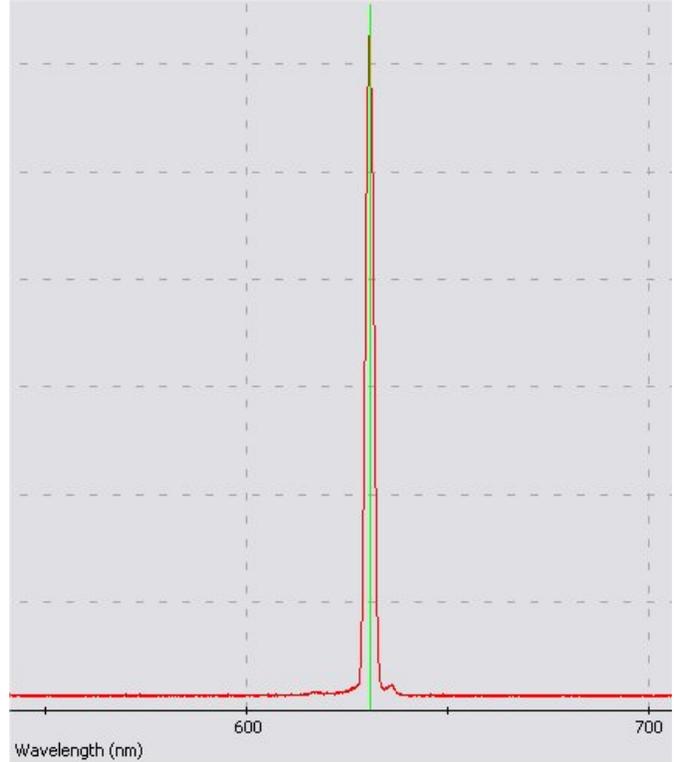


Fig. 8 Baseline of a spike narrows at source distance of 33m.

3.2 Membrane POG

We replaced the glass substrate holographic plane grating used for the initial proof-of-principle with a plastic embossed plane grating sold for decorative purposes by the Spectratek company nominally priced at wholesale for \$0.01 per square inch. Our 1 square inch scientific grating was obtained for \$200. The bench set-up is shown in Figure 9.

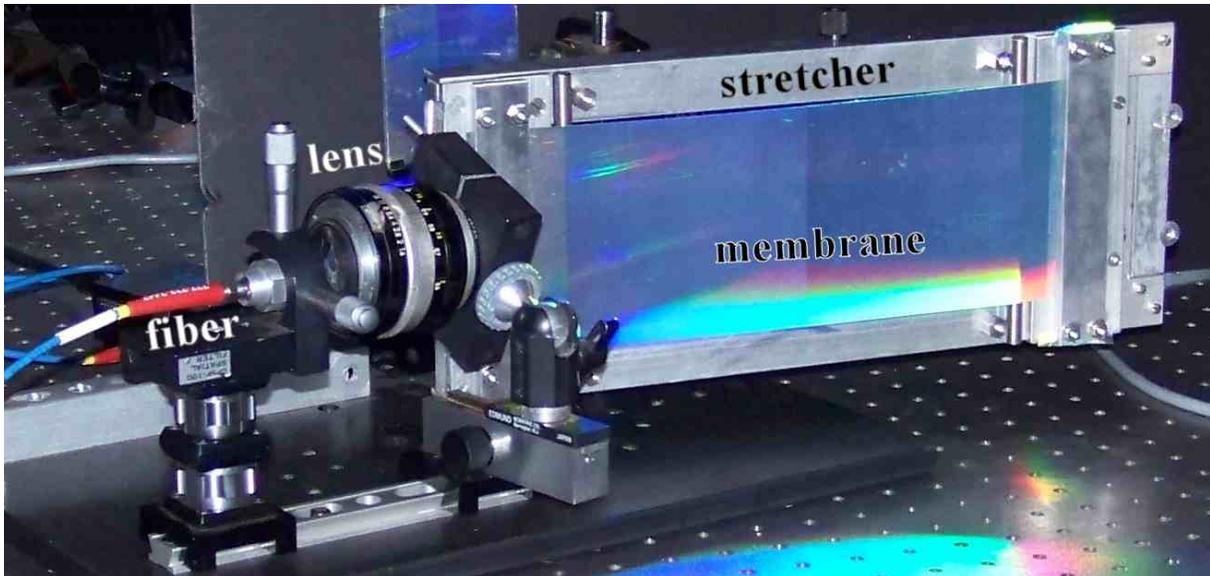


Fig. 9 POG constructed from a decorative plastic membrane plane grating held taut on a metal stretcher



Fig. 11 A pair of “white” LED sources

Using the membrane, we imaged two “white” light LED’s at a distance of 5 meters from the membrane POG. One LED was super-luminescent with a plastic collimating lens. At the POG it could be measured at an intensity of $0.10 \mu\text{W}$ with our photometer. The other LED, rated at 400 m lumens by the manufacturer had a water clear flat lens, making it a weak point source radiator. Its intensity was not measurable at the POG by our photometer. The pair, photographed in daylight, are shown in Figure 10. Their spectrogram, *also taken in daylight*, is shown in Figure 11. Ambient room illumination at the POG was roughly 100 times the intensity of the brighter source, but the system discriminated the target.

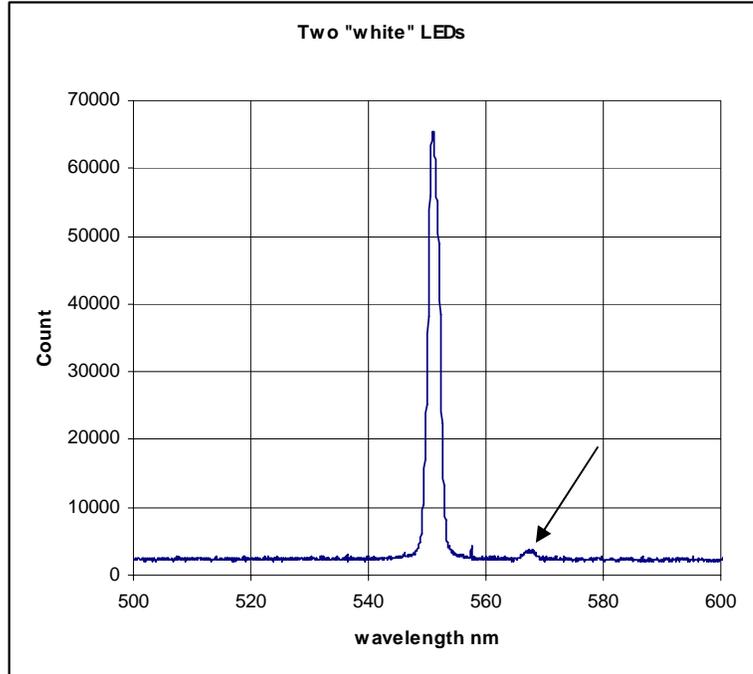


Fig. 12 Two “white” LED’s. An arrow points to dim LED

3.3 The Mark 3 version

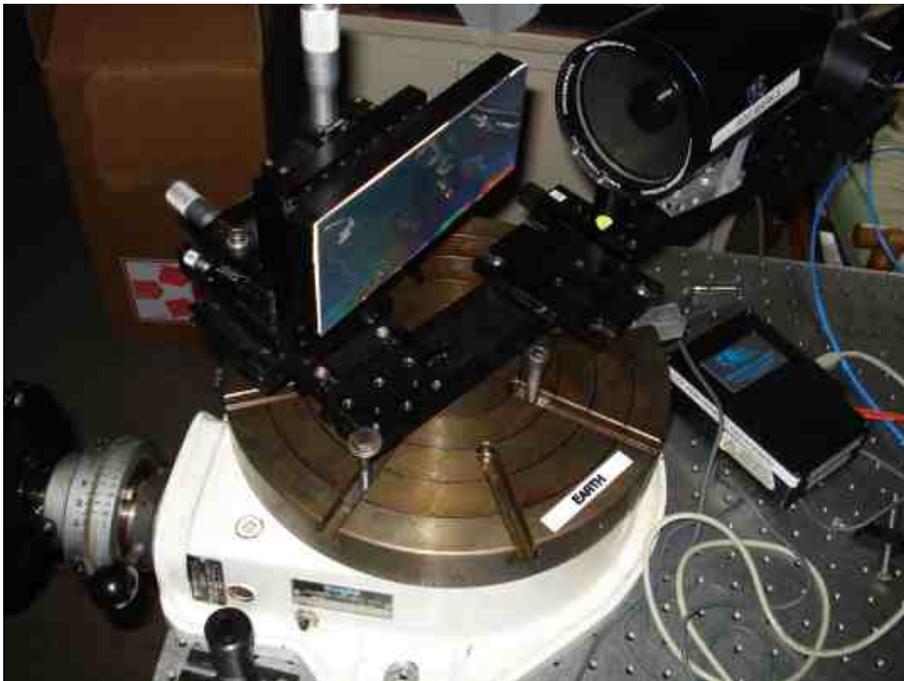


Fig. 13 Mark III bench model on “Earth,” a rotary platform

A version of the model telescope (Mark III) was installed on an optical bench where the POG was an embossed plastic grating laminated onto a metal substrate with a glue layer. The angle of grazing exodus from the POG from the secondary (a spot Maksutov-Cassegrain) was 77° off the POG plane normal. By placing the model telescope on a rotary table, labeled as “earth” in Figure 13, a sequence of amplitudes could be recorded over the free spectral range. A reference incandescent source, a halogen flashlight, was used for normalization, Figure 14. A “white” light diode was directly recorded as a spectrum, Figure 15. The spectrum derived from the telescope scanned over 34° in

increments of 1° is shown as Figure 16. An anomalous trough appears in the blue. A likely cause is the uneven surface of the POG, a detail of which is shown in Figure 17.

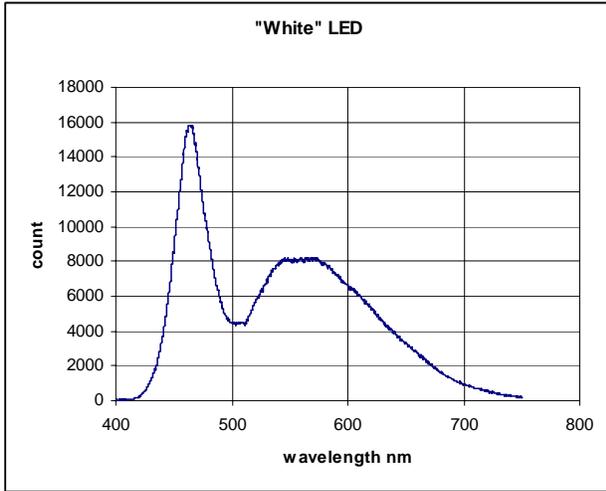
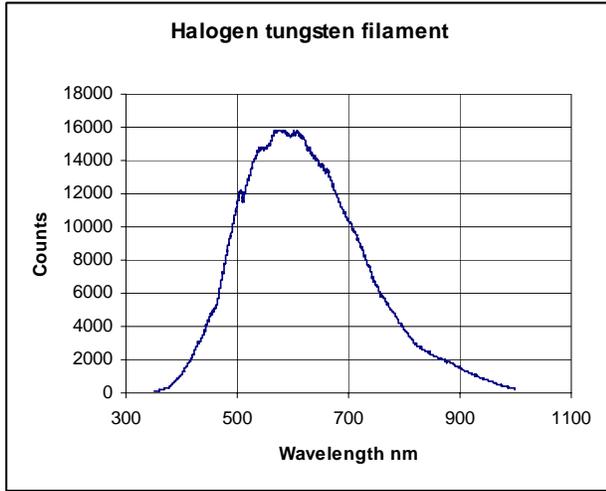


Fig. 14 Spectrogram of reference “black body” source Fig. 15 Super-luminescent blue LED and yellow phosphor

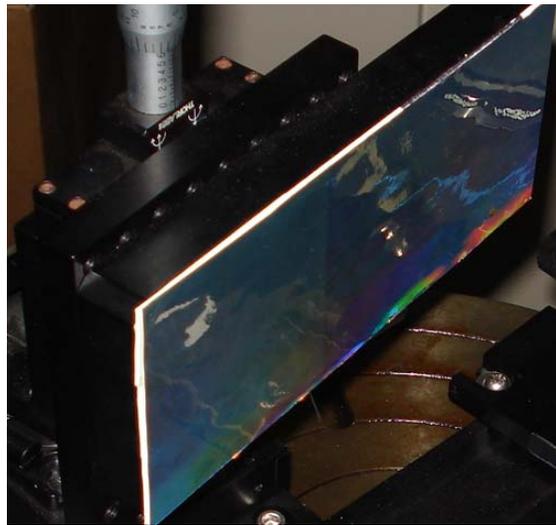
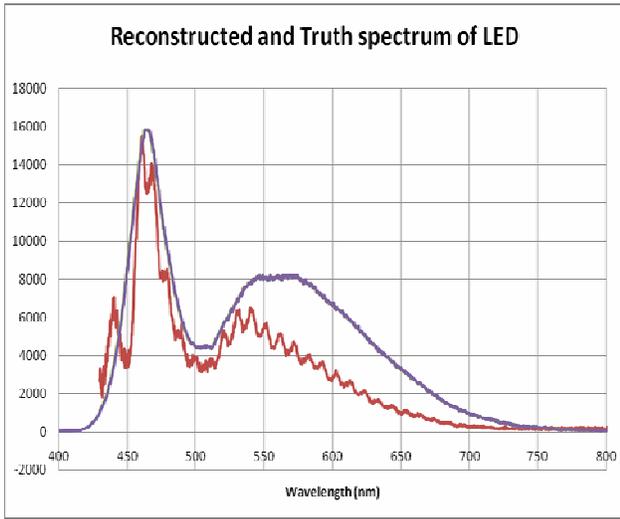


Fig 16 White LED spectrum reconstructed from Mark III (red), truth spectrum (blue)

Fig. 17 Plastic grating glued onto metal substrate

4. CONCLUSION

It is possible to build working models of a double dispersion POG telescope using readily available laboratory components. In the initial demonstration the most expensive component was a fiber fed spectrometer. The laboratory grade plane grating used in the proof-of-principle was replaced with a plastic embossed plane grating seems to have comparable performance to the glass grating when stretched taut. There are limits to how uneven the surface can be, as we learned by simply gluing it to a metal substrate. In that case, artifacts of uneven spectral amplitude began to appear.

The Holy Grail for space deployed large aperture telescopes would have features that the dual dispersion POG seems to demonstrate. The primary is low in mass and easily stowed in a delivery vehicle. It is possible to contemplate kilometer scale in the dimension where diffraction takes place. Under rotation, the multiple object spectrographic capability would

be unprecedented, because every object is taken as a spectrum. The resolving powers suggested by the length of the POG would presumably conform to design specifications needed for extra terrestrial biology and possibly exoplanet detection.

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