Kilometer scale primary objective telescope with no moving parts

Tom Ditto[*] DeWitt Brothers Tool Company, Inc.

ABSTRACT

The author proposes the use of a diffraction grating as a primary collector in a very large ground-based telescope. The grating is to be placed at grazing exodus relative to a secondary receiver and will have considerable length relative to width. Collector areas of square kilometers are being considered. Large collectors pose problems for ordinary telescopes, but with the proposed telescope, the rotation of the earth is the only requisite motion. Other than the earth itself, there are no moving parts. In the course of a night's observation, a plurality of stars within a narrow band of right ascension would yield detailed spectra. We anticipate that while acquiring the spectra of a star, the instrument would also acquire the spectra of any planetary system around it, because the high inherent resolving power of the instrument can measure subtle Doppler shifts, and the collecting area is sufficiently large to detect spectra from planets in the full glare of the star that illuminates them. Where signature spectra are available, planets can by typed, including earth-like planets which can be distinguished by their unique spectra and their implied surface temperature as inferred from orbit diameter. Our study investigates several grating arrangements, types and efficiencies including some using reflection gratings and one with a transmission grating in an evanescent mode. We explore options for grating fabrication and mounting.

Keywords: spectroscopy, hologram, diffraction, grating, extra-solar, planet, telescope, grazing, incidence

INTRODUCTION

As conventional telescope collectors scale up in size to capture enough flux to detect exo-planets, the mechanisms needed to point their very large primaries reach proportions reminiscent of Egyptian pyramids. The resulting mechanical problems combined with the many issues of large scale mirror fabrication have now opened to question the efficacy of following conventional primary objective designs above a certain scale. Many astronomers have proposed placing large mirrors in space as a means to combat gravity on the ground, but even if this is a solution, the mirror configurations going into orbit will not be conventional large glass dishes. As a result, the mirrors meant for space application cannot always be reasonably tested on the ground. HST began its mission with an embarrassment of this stripe.

Historians must wind back to clock nearly 400 years to find the last change in primary collectors. In 1636, Mersenne suggested a parabolic dish. Save for the occasional reinvention of the secondary, his innovation continues to rule. Yet many of the most significant breakthroughs in astronomical observation are based on diffraction grating spectroscopy. The discovery of exo-planets, the acceleration of the red shift, and the red shift itself are all seminal observations that never required the two dimensional representation of their targets afforded by the mirror primaries they used. Despite the fact that light received by a conventional telescope is converted by the spectrometer into a new wave front through a slit spatial filter, stars still must be tracked by moving the huge mirror, and the secondary must be supported far above this hefty primary collector.

An obvious question is "Why not use a diffraction grating primary if the output of the telescope is a spectrogram?" I have posed this question to acquaintances who seem to be unaware if this obvious question has ever been asked. This paper asks the question and presents some consequences. It turns out that a terrestrial installation of a very large diffraction grating holds a solution to the problem of moving a very large primary collector, because the rotation of the earth would provide a varying angle of incidence upon the grating from which very detailed spectrograms can be made. This benefit coincides with historic breakthroughs in grating fabrication that allow precision gratings to be made by holography and enormous gratings to be printed from these masters by embossing.

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[*] contact: 3D@taconic.net
DeWitt Brothers Tool Co., Research Dept., Box 10, Ancramdale, NY 12503-0010

1. TEMPORAL SPECTROSCOPY

Spectroscopy is often taught with a device that allows an observer to study small portions of the spectrum at a time. Typically the device rotates a microscope around a grating or prism, and the precise angles are noted as each spectral line is encountered. Similarly, monochromators rotate a grating relative to the output optics, and the spectrum is thereby scanned. There is nothing new in the idea of either taking or projecting spectra in a temporal sequence.

1.1 AS THE WORLD TURNS

Sidereal time can be converted into angles of incidence at a terrestrial receiver. In an ordinary telescope, the mechanism for pointing the mirror uses this sequence of angles to face the mirror at the star. Initially the tube is set at a north/south angle of declination, then the tube is rotated across the east/west right ascension angles as the star transits. No expense should be spared to make the mechanism as accurate as the angular resolution of the telescope. Typically, with very large telescopes, the tolerance for that angle is very small. The earth's rotation provides a mechanism with precise pointing. Of course, the rotation of the earth is the very movement that the telescope mechanism counteracts.

If a diffraction grating is placed in an east/west orientation and declined so that its surface normal intersects a band of stars on a line of right ascension, the angles of incidence *i* from that band of stars will vary as function of sidereal time.

$$i = 2\pi \frac{t}{T} \cos(\beta) \tag{1}$$

where t is time of day
T is length of day
β is the angle of declination.

The Diffraction Equation allows us to correlate wave length diffracted by a grating with the angle of incidence as per (1).

$$\lambda = \frac{\left(\sin(i) + \sin(r)\right)}{n} p \tag{2}$$

where λ is the wave length diffracted
r is the receiving angle
n is the diffraction order
p is the pitch of the grating grooves

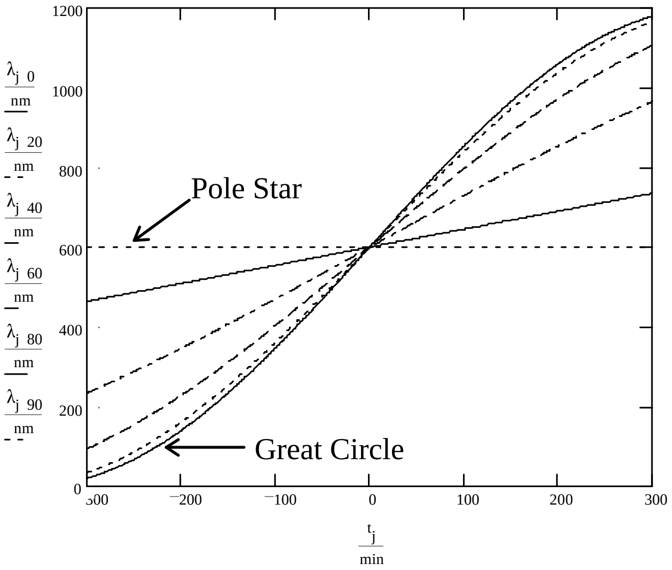

Figure 1 Wavelengths over a 10 hour night

The graph in Figure 1 shows how wave lengths at a receiver will vary over a night for various angles of declination when a receiver at *r* is nearly 90°, an angle of *grazing exodus*. The example presumes a 600 nm grating pitch and is restricted to first-order diffraction. The Pole Star will be reconstructed at a single wave length. Along the Great Circle, the wave lengths change most rapidly at the zenith.

In Figure 2, we consider the first two higher orders for a 600 nm pitch grating as a function of the angle of incidence with the receiver at grazing exodus. There is a free spectral range above 600 nm. Of course, cross-dispersion can be used to resolve ambiguity in the visible wave lengths below.

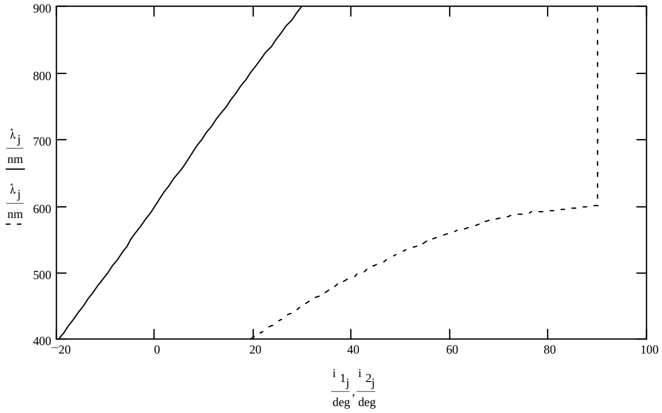

Figure 2 1st- and 2nd -order incidence angles for 400 - 900 nm

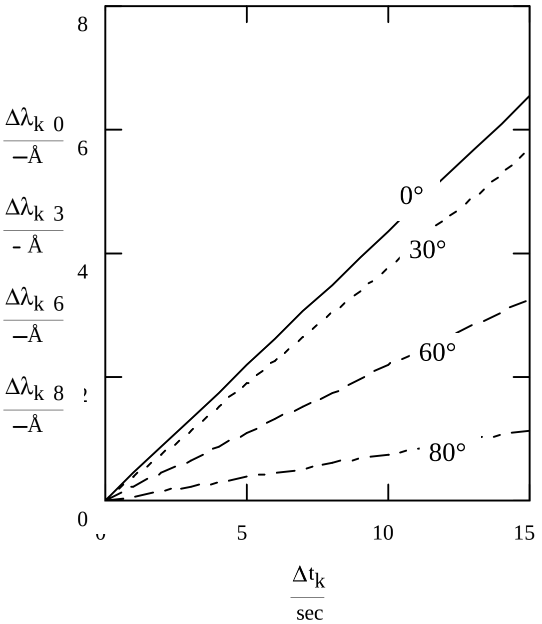

Figure 3 Integration times (sec) vs. resolution (Å) at designated angles of declination

Sensor integration times determine the resolution of a temporal spectrometer. For a spectrometer using a grating primary, the rotation of the earth determines length of exposure. Along the Great Circle, the transit of the stars is most rapid, and the integration times are the shortest. In Figure 3 we compare the change in wave length Δλ in Å as a function of the dwell time Δ*t* in seconds. The worst case in the illustrated example is a change in wave length of 0.42846 Å/sec at the zenith using a 600 nm pitch grating. In other words, the worst case is 2.33 sec per Å. Such a short period probably is not sufficient integration time for starlight with collection surfaces that correspond to areas that are no greater than conventional mirrors. However, we will see that collection areas can be orders-of-magnitude greater than convention when the grating collector is exploited. Note that integration times increase toward the pole, but there is a trade-off with the range of available wave lengths as per the graph shown in Figure 1.

Figure 4 “Temporal Spectroscopy” As a star transits, its diffracted wave length at a receiver varies over time.

In order to make the calculations of Figures 1-3, we have held the angle of reconstruction *r* to a constant near to 90º and varied the angle of incidence *i*. The model assumes that the collector is stationary and that the change of the angle of incidence upon the grating is determined solely by the rotation of the earth. The optical element being modeled is a long and thin grating primary collector with a conventional telescope as the secondary, as suggested in Figures 4 & 5. As it happens, the transit of a star results in a change of the angle incidence upon the grating and thereby produces a change in the wave length that reconstructs at the telescope. This spectrometer has no slit and collimator, because the wave front striking the grating is a nominal plane wave, that is, unmediated star light. The telescope that serves as the secondary could be placed at a smaller angle of reconstruction than grazing exodus, but as the angle of reconstruction moves toward grazing exodus, wave length discrimination is improved. Equally important, the physical layout becomes compatible with a ground-based giant telescope. The telescope is in a nearly horizontal posture at a shallow elevation, minimizing demands made on its installation. Also, the angle of view results in very long diffraction gratings with correspondingly large collection areas.

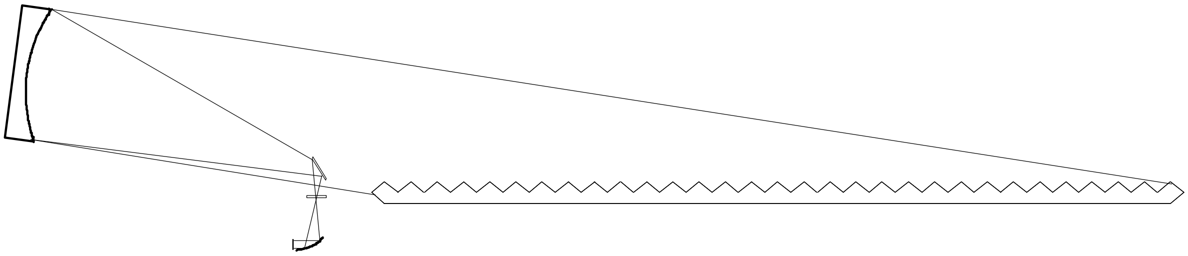

Figure 5 Cross section of the Dittoscope, a telescope that uses a diffraction grating as its primary collector

1.2 GRATING FLATNESS

To answer an *a priori* concern voiced by more than one optical engineer, I have studied whether very large gratings can produce normalized spectra. The flatness tolerances for gratings are quite strict. *The Grating Handbook* speaks of maintaining 1/10 wave surface flatness.[1] My analysis indicates that a primary collector made from a diffraction grating is quite robust. It appears that if localized flatness is as good as plate glass, 2-4 waves/cm, Ångstrom resolution can be maintained. In Figure 6 we see a calculation for a 600 nm grating with the surface flatness of common float glass. The spectral error is greatest at the zenith, which is to be expected, because the error is caused by a phase delay normal to the grating plane. In the receiving direction, an uneven surface merely causes a loss of efficiency. This prediction is based on a model that is self-published.[2]

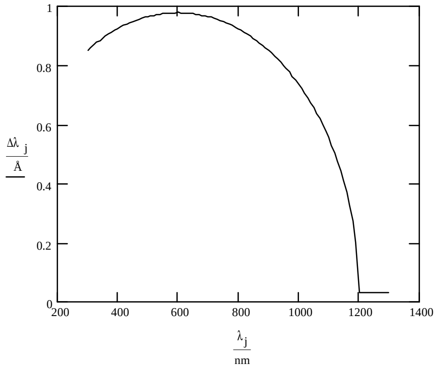

Figure 6 Induced error of an uneven surface

Localized phase errors will accumulate at the receiver, and the figure for grating flatness is extendible to the entire length of the collector, but only if all the light arrives at a single pixel on a single sensor. However, that is not the case. In fact, the ray paths to the collector can be separated from each other in single wave length divisions if the sensor has considerable width. Phase errors outside these segmented steps will not affect the amplitude of the energy recorded by the sensor. If the sensor is a strip of considerable length y any wave length segment λ can be mapped back to the grating of length L to determine the incremental steps x over which phase error must be within tolerance. The relationship is

$$x = L\frac{\lambda}{y} \qquad (3)$$

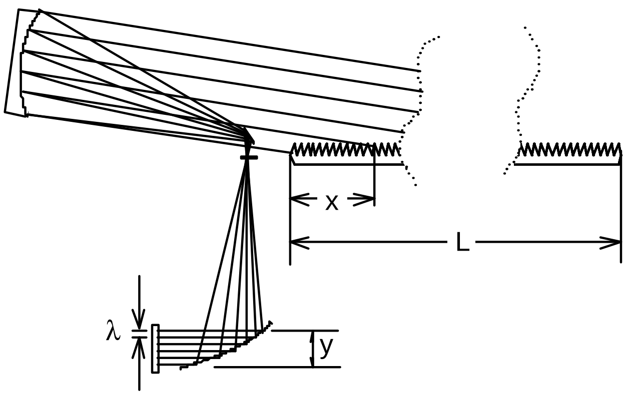

Figure 7 Coherence length phase error

This relationship is shown in a cross section of Dittoscope receiver in Figure 7. The coherence length requirement for gratings of kilometer length would be 3 mm with a sensor of length 0.333 m. Anyone who has made a hologram knows that gratings made by this method can achieve such a figure. Do 0.333 m sensors exist? Linear CMOS arrays from garden variety flatbed scanners are available that nearly achieve this extension. Their typical s/n per cell covers 12 to 14 bits, and there are more than 10^4 individual sensor cells packed onto these “hard bar” linear arrays. The implication is that when the secondary receiver sensor falls within consumer quality, the telescope might achieve amplitude readings one part in 100 million - were there enough diffracted light available to take a reading to that depth.

1.3 GATHERING FLUX

The diffracted flux available at the receiver depends on grating efficiency and grating size. When the secondary receiver is placed in the position for grazing exodus of radiation diffracted from a grating that works primarily in the first-order, the former may be a weakness; the latter a strength. Alternatively, if the grating is designed for high-order efficiency, as are most spectrographic gratings used as telescope secondary receivers today, the trade-off is reversed. It would be very difficult to produce quality echelle gratings by embossing. However, sinusoidal groove holographic gratings are routinely minted by the mile today in commercial plants that sell into the decorative arts marketplace. Given the availability of their products, initial investigation may involve their type of grating.

The evidence is that sinusoidal gratings which have a grating pitch centered on the wave length they are meant to diffract can achieve efficiencies approaching 50% near the angle of grazing exodus. A preliminary test of Spectrasheen [3] a grating with 600 nm pitch shows 25% efficiency for λ = 650 nm at an angle of reconstruction of r = 85º. A new sample recently provided by its manufacturer, which I have not yet been able to mount, appears to be even more efficient.

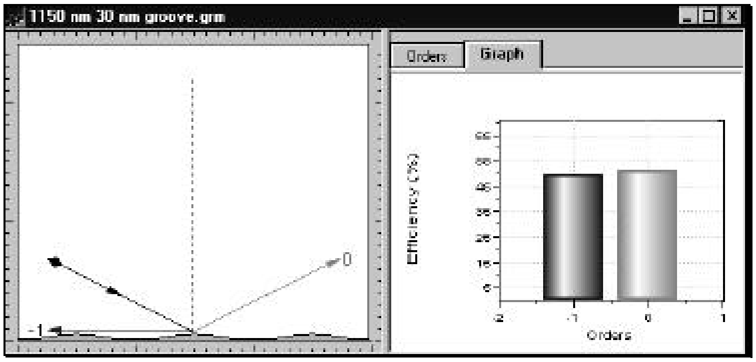

Figure 8   PCGrate prediction of efficiency

The software tool used by the author to predict grating efficiency, PCGrate [4] has a disclaimer about grazing incidence. This is not surprising, because changes in s-polarization tend to be idiosyncratic when radiation is transmitted near the grating plane. Manufacturers of grating masters will provide empirical efficiency charts for gratings rather than rely on any predictions made by theory. However, even when taken with a grain of salt, PCGrate does predict 40% efficiencies for gratings at an angle of grazing exodus. For example, in Figure 8 there is a typical efficiency chart for a 600 nm pitch grating illuminated by radiation of 1150 nm wave length. The zero-order is reflected and is over 50% efficient. The rest of the flux appears in the first-order and is over 45% efficient. This simulation did not factor in the conductivity of the coating which will incur further losses. The simulation was for a surface relief grating with a very shallow groove depth of 40 nm.

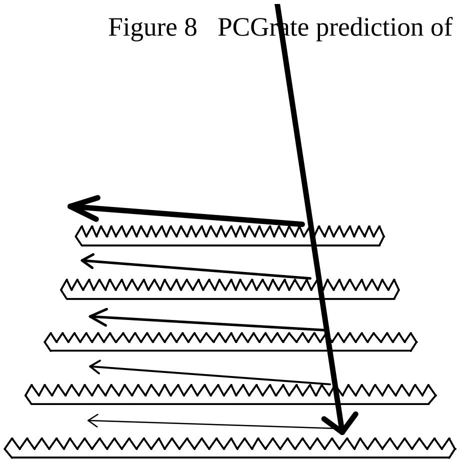

Figure 9 Cumulative efficiency gain through stacked transmission gratings.

If the grating used is a transmission type, the overall efficiency can be improved to nearly 100% by stacking multiple gratings, as per the diagram in Figure 9. The zero-order that is not diffracted is transmitted to sequential gratings until almost all of the energy is diffracted into the first-order. The narrow spacing between gratings is expedited by the use of the grazing exodus angle.

Even with an inefficient conversion of radiation to the first-order, the potential scale of diffraction grating primaries make up the difference when they are built on a large scale. The largest mirror collectors today achieve an area of about 80 m^2. There is a mandate to build mirrors with 500 m^2 to capture enough light for direct detection of exo-planets. These new mirrors would more than double the diameter of the largest existing mirror today and present many unresolved questions in fabrication and mounting.

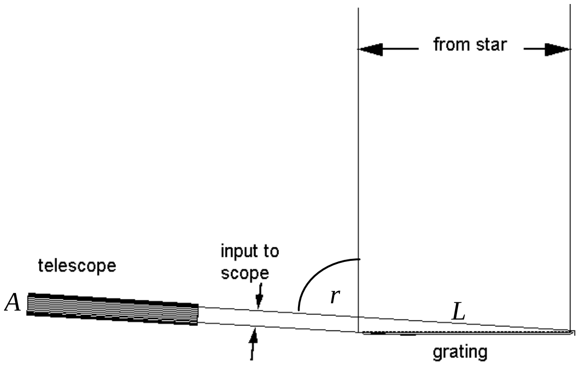

Figure 10 At grazing exodus, L increases exponentially with r

Consider the considerable area of a plane grating primary collector relative to a secondary receiver at grazing exodus. A diagram in Figure 10 shows the configuration. As the grazing angle r approaches 90º the considerable length of the grating L increases exponentially since

$$L = A\frac{\tan(r)}{\sin(r)} \tag{6}$$

where A is the aperture of the receiving telescope.

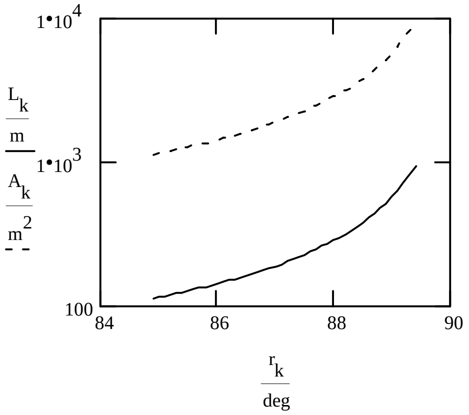

Figure 11 A Keck secondary collects from a diffraction primary to these lengths and areas.

It is interesting to contemplate the potential collection real estate if a Keck scale mirror is used as the secondary for a grating primary collector in a grazing exodus configuration. The mirror itself enjoys about 80 m^2 of collection area, but as shown in the graph in Figure 11, if this mirror serves as the secondary receiver for a grating that has a width equal to a Keck ten meter diameter then the primary can be as long as 1 km, and collection areas go from 1000 m^2 to 10,000 m^2 as the angle of grazing exodus goes from 85º to 89.5º. These dimensions exceed the target for planet finder primary collector real estate by an order of magnitude. If larger mirrors are available for the receiver, the primary grating size grows proportionately. If it were possible to make parabolic mirrors with a diameter of 25 m,, then the grating size would minimally be 10,000 m^2 and would approach 100,000 m^2 at 89.5º. At these dimensions, the limited efficiency of diffraction primary collectors is overcome by brute force.

There is a caveat. Since the flux is received a single wave length at a time, integration time for the aggregate spectrum is vastly reduced. In the example of Figure 3 I have shown a worst case of 2.3 seconds/ Å for a temporal spectrogram from a star that transits the Great Circle. This fleeting dwell time is longer toward the pole, but even at 20 sec/ Å, building a spectrogram of a faint object might require larger gratings we have modeled here. A thumb nail estimate would be that a temporal spectrogram of the visible spectrum from 420 to 620 nm in steps of 1 Å would divide the available light into 2000 parts. By this analysis, a 500 m^2 mirror using a secondary spectrometer with 90% efficiency would match a 2 km^2 diffraction grating primary collector that operated with 50% efficiency. The rotation of the earth is quite relentless. A terrestrial version of a diffraction telescope can only reconstruct wave lengths according to the clock.

2 TERRESTRIAL MOUNTS

There are several redeeming graces that make the diffraction primary worthy of serious investigation, even if efficiency is problematic. Once the angle of declination is set, there are no moving parts. The grating is a flat optical element. Grating primaries can be segmented into many identical modules. The idea of kilometer scale optics seems daunting, but its unique features may challenge our preconceptions.

2.1 FLAT OPTICS IN BITE SIZED MODULES

If a telescope is going to be assembled on the scale of square kilometers, it would be easier to build if it were flat. Gratings are almost flat. Surface relief gratings have microstructures that are in the third dimension, but these exist at the wave lengths being diffracted. The considerable mass of the device is its support structure plus the optical substrate, and these can be constrained to a plane. If a diffraction grating primary collector is flat, then all wave fronts exiting the grating are in phase and in the same direction, that is to say, they exit in phase from a plane.

If we can make a diffraction grating with pieces of float glass or float glass that has been modestly polished, the mass production of substrate material will be considerably less expensive than equivalently sized segmented parabolic mirrors. Float glass lengths do not need to reach kilometer length, either. If we place many gratings out in a row, they can sum up to a desired total length. These modules can be identical and interchangeable. As a grating farm grows from first light to final size, it can collect light.

Among the options in cultivating the grating farm are modules that have no secondary mirrors. There are holograms that were developed for edge lighting which also have been modified as back lights for LCD displays and fingerprint stations.[5] If used in the reverse, so that light is captured rather than radiated, the edge-lit hologram can serve as module in an array that catches star light.

The grating rules in a standard edge-lit hologram have a slightly parabolic shape, and a plane wave striking the surface is directed to a point where it can be measured. The substrate is a light pipe. A conceptual diagram appears in Figure 12.

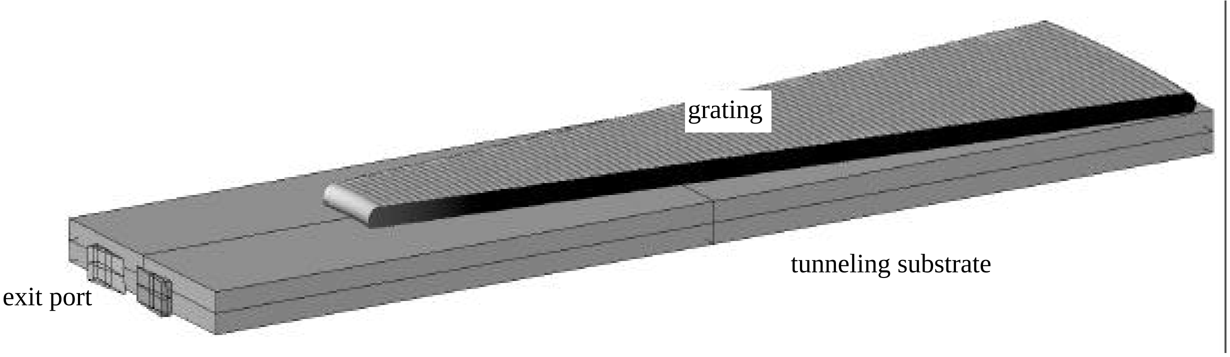

Figure 12 The edge lit hologram converted into a diffraction grating telescope module

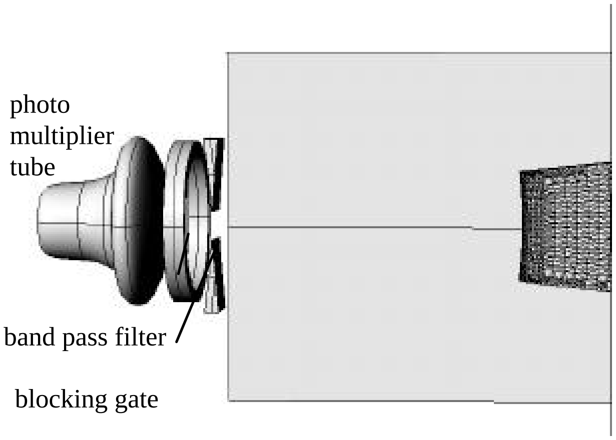

Figure 13 Photon counter and band pass filter

In Figure 13, a stop has been indicated at the exit port. This gate blocks stars that are adjacent to the target in the non-diffracting axis. If the light is collected at the exit with a photo multiplier tube, photons can be counted. A variable band pass filter can be used to extinguish the radiation from adjacent stars along the axis that is diffracted. Such variable filters [6] are made using bifringent liquid crystals and polarizers. Their ability to narrow the effective field-of-view is shown in Figure 14.

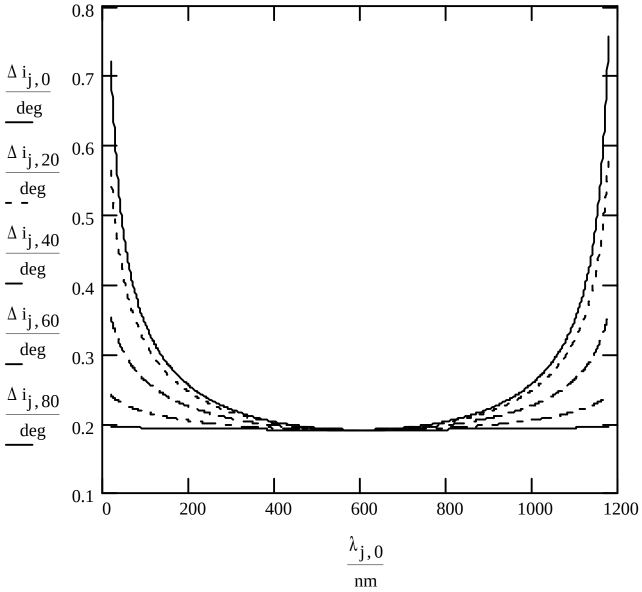

Figure 14
Extinction window maintained by a 2 nm band pass filter with a 600 nm pitch grating for varied angles of declination. The filter blocks out adjacent stars in a 0.2º to 0.7º window depending on both the angles of right ascension and declination.

The collector illustrated in Figures 12 & 13 would not tolerate any measurable phase error across its considerable length, since, unlike the example of Figure 7 the secondary receiver is flat. Therefore, it is likely that these gratings would be holographic masters made with precision lasers. They are in a class of grating primary collectors which I call *evanescent*, because it is possible to contemplate thin flat plates of this type that take advantage of surface wave radiation injected into the substrate at the evanescent angle of their target radiation. Gratings of this type are good candidates for stacking as per the concept of Figure 9, although as illustrated in Figures 12 & 13, they can only track a single star at a time.

A variation in the evanescent design places a spectrometer at the exit port (Figure 15). The spectrometer would be used to discriminate stars based on their known positions in sidereal time as they transit. Energy in each spectral band would be associated with the unique star that could produce that specific wave length at the scheduled moment in time. Devices of this type where the secondary holds a full bandwidth spectrometer can survey many stars simultaneously.

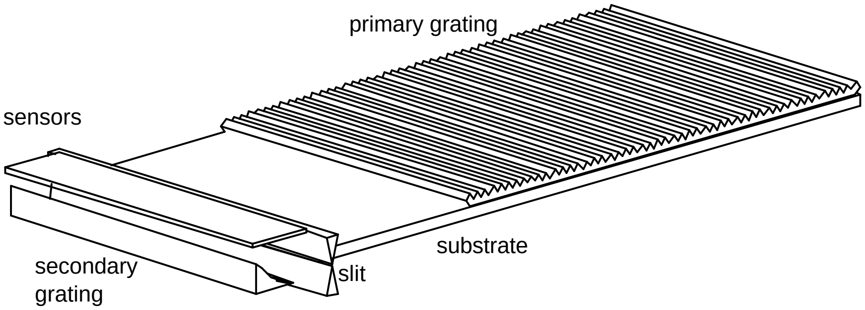

Figure 15 Spectrometer in the secondary surveys stars on the line of declination

While a survey does not increase the sensitivity of the instrument above its capacity to sense any one star (indeed, sensitivity may be lowered for the want of a photo multiplier) the multiplicity of stars being tracked would result in better use of the available energy, and mitigate somewhat against the inefficiency of temporal spectroscopy. The concept of a secondary spectrometer is extensible to any configuration of the Dittoscope, and is hardly limited to the evanescent design. Surveys of many stars to detect exo-planet signatures are now contemplated with wide field telescopes, but their targets are restricted to the unlikely 1:1000 occurrence of planets orbiting in a plane along the line-of-sight where occultation takes place. A survey for exo-planet Doppler shift moments would permit detection in all cases except when the orbit of the planet is perpendicular to plane along the line-of-sight, reversing the probability of screening for candidates to 1000:1, essentially covering every star system surveyed. If the survey covered 100 stars simultaneously, the efficiency losses of temporal spectroscopy, which are three orders of magnitude, would effectively be reduced to a factor of ten.

2.2 STATIC PRIMARY OBJECTIVE

One advantage to using a grating as the primary in a terrestrial mount is that once the declination is set, the grating does not need to be moved. It is incontrovertible that the devil lurks in moving mirrors after they reach a scale of 10 meters in diameter. A large diffraction grating, given its flat substrate, can be effective at low mass. It could be more easily moved than a large mirror, and a conventional motion mount is one possible option in designing a "Dittoscope." If the grating was dynamically pointed, *cum* a conventional German mount, selected wave lengths could be taken in regions of the spectrum favored for biometrics. However, for kilometer-scale collectors, there are no dynamic mounting solutions. Neither a mirror nor a grating of 1 km^2 could be moved.

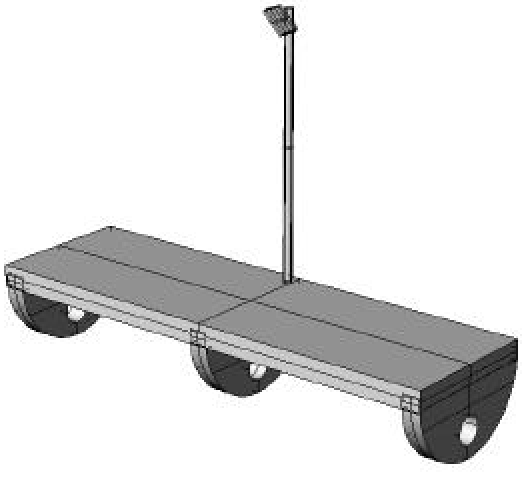

Figure 16 Single axis rotation table for terrestrial declination

The diffraction grating primary collector must be set to the proper angle of declination before observations can begin. To do this, single axis rotary tables that rotate on the narrow axis must be devised. The concept of a table segment is shown in Figure 16. The substructure provides for the single axis of rotation. The table provides support for flat substrates and micropositionsers (not shown) for adjusting the posture of the grating. The superstructure includes relay mirrors used in an alignment procedure. A single laser beam originating at the receiver must be diffracted to the same location on the receiver sensor for segmented gratings on their tables to work together in tandem as one long grating. After the alignment is made at the selected angle of declination, all tables are locked down and observations can begin without any further movement. This does not preclude some adaptive optics to accommodate atmospheric effects, but such techniques are beyond the scope of this paper.

When a line of tables is in place, secondary receivers can be utilized at both ends. With dual receivers, temporal spectrograms at each receiver will be made in opposite sequences, and the effective collecting efficiency is be doubled. The concept is illustrated in Figure 17.

Figure 17 A segmented row of gratings declined for observation with secondary receivers at both *extrema*.

The evanescent configuration would require the tables but the function of any outboard receivers would be reduced to alignment procedures. Evanescent plates could be arrayed in fields covering sufficient areas to provide complete surveys of stars producing a requisite brightness. After each survey, the field could be expanded in size to accommodate the next magnitude

3 EXO-PLANET SEARCHS

Our ears detect sources of radiation that are contained within complex aural spectra, and a diffraction grating telescope can “hear the colors of the universe.” Some of the most momentous discoveries in astronomy can be attributed to the astute study of electromagnetic spectra, and I am tempted to think of this science in a category of its own, “spectronomy.”

The radial velocities of stars have been studied spectrographically to detect subtle Doppler moments caused by the orbits of proximate large planets. During the course of an orbit, a sinusoidal shift between shorter and longer wave lengths can be charted. These observations minimally require several orbits of the planet being observed. It seems almost axiomatic that exo-planets cannot be detected in the full glare of their host stars, and there are two major projects to attenuate stellar radiation so as to reveal small planets whose gravitational effect on the host star cannot be observed due to the star’s own surface turbulence. One approach is to null out star light by interferometric comparisons between twin telescopes, and the other is to produce a coronograph that will occlude stars at light year distances. Neither approach has been proven in practice, and there is a prospect that both might fail.

One key to detecting the tiny amount of light reflected from a planet in the full glare of the star that illuminates it would be to have a sensor with a signal to noise ratio on the order of 10^{10} in the visible spectrum and 10^{7} in the near infra red. We have suggested in Section 1.2 that the Dittoscope secondary can be constructed to make such signal measurements, if there is enough available light. Garden variety visible light sensors today have electron wells sufficient to achieve 96 dB per cell in linear arrays of 256. These sensors are integrated circuits that can be ganged into lengths compatible with the type of secondary receiver modeled in Figure 7 where a nominal 0.3 m length is used as an example. If a $5 chip can sum up its 256 cells to meet this specification in the visible, surely an infrared array can be constructed to the same end. Alternatively, the grating farm of segmented evanescent grating sections will provide by its very architecture many photon counters. The radiation coming from an earthlike exo-planet might be about 1/20 photon/m^{2}/sec with the largest balance of the detectable radiation being in the infrared. We have shown that the worst case for dwell in a temporal spectrometer is about 2 sec/ Å. Presumably, over an excursion of the angle of incidence amounting to 1 Å such a grating farm would harvest 2 photons from an exo-planet with each sub array of 20 m^{2}. Mirror collectors are contemplated with 500 m^{2} areas for this purpose. The diffraction method seems preferable if real estate is the criterion, except for the caveat that the wave length selectivity of the diffraction collector excludes detection of photons that do not fit within a fleeting temporal window. A collector farm of gratings might require a square kilometer of real estate to beat out a 500 m^{2} mirror. However, even if this is true, the diffraction method deserves a rigorous evaluation. A million 1 m^{2} grating detectors might actually price out at less than the mirror alternative.

Moreover, if the grating farm was backed by secondary receivers that were themselves spectrometers, the narrow window that excludes most wave lengths per star would include slots for all stars being diffracted. The search for exo-planets is a survey problem. If 100 stars were surveyed simultaneously, a 1/2000 inferiority in efficiency of the diffraction collector method to the conventional telescope would be pared to 1/20. As we have shown, with the increased real estate and possible low price tag a 1:20 handicap might be shrugged off. When other choices for surveys are time consuming and improbable, this specialty could be sufficient cause to develop the diffraction instrument.

CONCLUSION

We have asked why diffraction gratings cannot be used as primary collectors. In fact, they can. When their unique properties are taken into account, they can provide solutions to very large collection areas needed for the detection of exo-planets in survey observations. The gratings can be mass produced. They do not need the elaborate pointing mechanisms of conventional telescopes. They can be flat surfaces within realizable tolerances. Giant arrays can be built incrementally, starting with modest demonstrations. It may be true that the temporal spectrograms they provide demand much more real estate than competitive methods using conventional collectors, but, nonetheless, it may turn out that this is the cheapest real estate in all of telescopy.

ACKNOWLEDGEMENTS

This research has been supported by DeWitt Brothers Tool Company, Inc. The discussion of the Imedge edge-lit hologram followed exchanges with Michael Metz and H. John Caulfield. My presentation at SPIE’s Astronomical Telescopes and Instrumentation Conference was underwritten by my sister, Alice Pero, a poet who follows her stars.

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