Exo-Planet Finder Telescope
with
Diffraction Grating Primary

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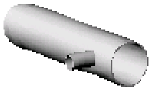
ABSTRACT

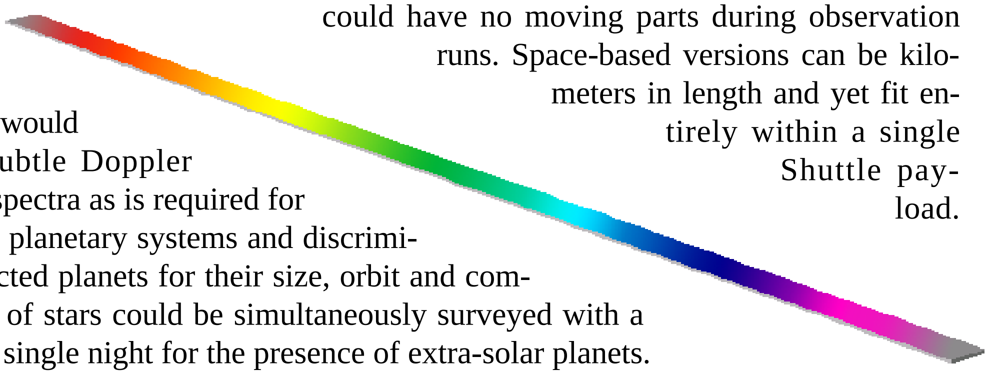
Diffraction grating primaries are attractive in that they are well suited for spectrographic astronomy, particularly the Doppler shift studies that have recently been useful in extra-solar planet detection. We propose a unique static mount for terrestrial installations where the only moving part is the earth itself. For space-based installations, a new type of membrane telescope is proposed that can be orbited as a roll of plastic and unfurled as a ribbon over many square kilometers. The geometry of grazing incidence and evanescence allows for very long gratings. Fabrication can exploit recent technologies such as ultra violet holography and roll embossing of multiple-kilometer length membrane substrates. In the course of a night's observation, a plurality of stars within a narrow band of 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. Planetary orbits can be discerned quickly, and individual planets differentiated by means of the very precise Doppler moment readings.

Concept Description

Never has the problem of making large primary elements for astronomical telescopes been more vexing than it is today. The size of the collector dictates both resolution and sensitivity. The Next Generation Space Telescope and its ground-based cousins are conceptualized in terms of breakthrough collector size. While strides have been made in scaling up the classical parabolic reflector, manufacturing techniques for large mirrors remain similar to traditional methods, only the scale and subtlety of the operation has changed. Even if a large primary can be fabricated, this does not solve the equally vexing problem of how to point it. For space-based instruments, pointing is not the unsolved problem, but launching the large mirror is.

We propose an new type of telescope. Its primary collector is not a parabolic reflector but a diffraction grating viewed in grazing incidence. This design reverses the conventional configuration for spectrographic telescopes, and the consequences are startling to contemplate. Collectors can be envisioned that cover thousands of square meters. Terrestrial versions of the device could have no moving parts during observation runs. Space-based versions can be kilometers in length and yet fit entirely within a single Shuttle payload.



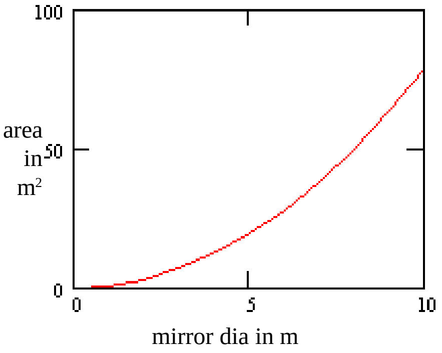


The spectral resolving power of the primary would detect extremely subtle Doppler shifts in compound spectra as is required for detecting extra-solar planetary systems and discriminating between detected planets for their size, orbit and composition. Thousands of stars could be simultaneously surveyed with a single telescope in a single night for the presence of extra-solar planets.

We use the term “grazing incidence” as a term of art referring to a shallow angle that is subtended between the telescope’s diffractive primary objective and a secondary receiver. Perhaps “grazing exodus” would better describe the light path, but regardless of the coinage, the proposed configuration is both novel and unique to diffraction gratings. While it is common in x-ray telescopes to use grazing incidence reflectors, x-ray collectors are not flat, and the grazing angle varies along the collector’s considerable length thereby limiting the finite length of the collector. On the other hand, if the collector is flat, as gratings can be, collector length is not restricted by a curved surface geometry at the primary.

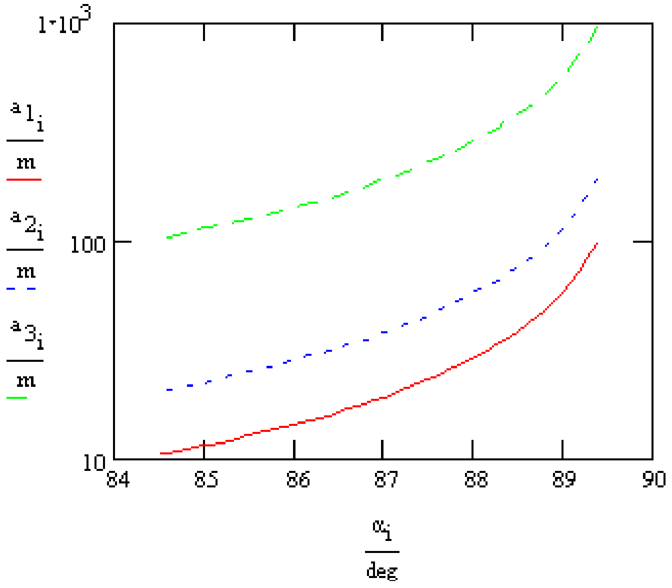
In the proposed telescope using a flat grating, the length of the primary objective is limited by the angle of grazing incidence. Moreover, in a special case of zero degree grazing incidence relative to the grating plane, the energy collected at the grating is tunneled through the grating substrate itself. This special condition of evanescence is unique to diffraction gratings. In an evanescent grating telescope, the length of the collector theoretically has no limit.

In astronomical observatories today, mirror primary sizes reach diameters of 10 meters; the collector area is about 80 square meters. With a garden variety 1 meter parabolic reflector as the secondary, a 1 x 160 meter diffraction grating collector at a grazing incidence of 89º would enjoy double the collecting area of the Keck. With the Keck as a secondary, the grating collector could be 10,000 square meters.

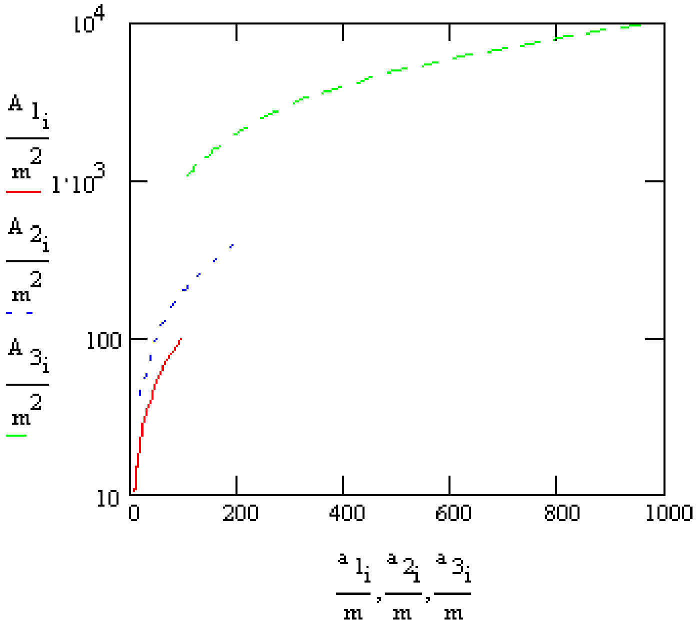


Today’s mirror sizes peak at 80 meters sq.

A few simple calculations demonstrate the leverage provided by a grazing incidence configuration. Consider what happens when mirrors of 1 meter (amateur class), 2 meters (HST class) and 10 meters (Keck class) are used as secondary receivers in grazing incidence configurations with diffraction gratings. Where α is the angle of grazing incidence, a is length of grating and A is the area of the grating we can graph:



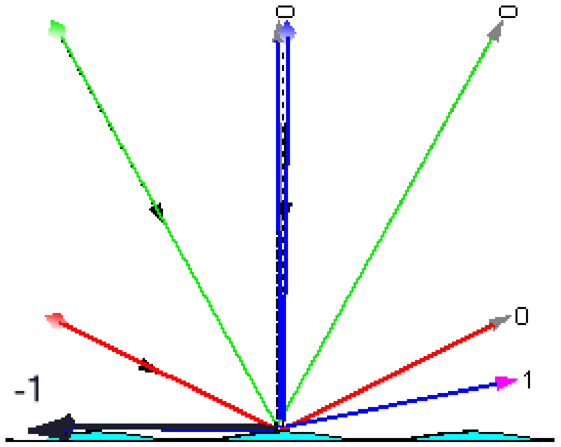
Grating length as a function of the angle of grazing incidence



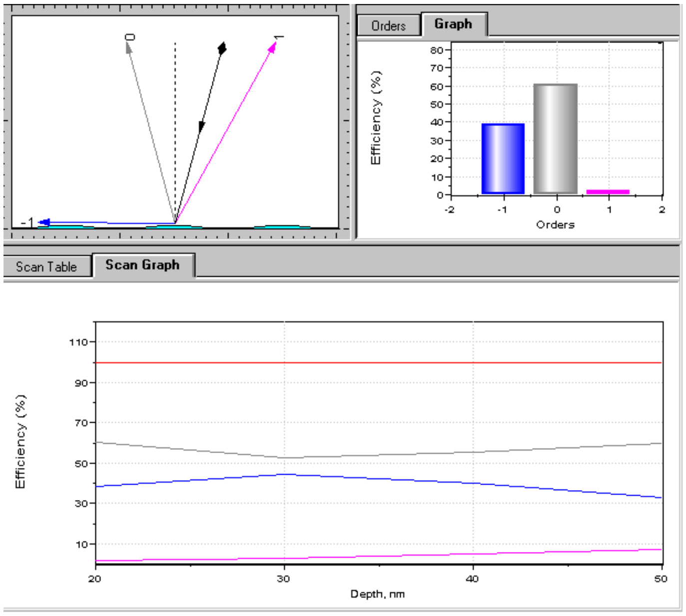
Grating area (log scale) as a function of length

The size of the diffraction grating collector would be irrelevant if it did not diffract a significant amount of light toward the receiver. A.A. Michelson understood that at grazing incidence diffraction gratings possess high resolution, but he abandoned hope of using them, because of their inefficiency. That was 100 years ago. Things have changed dramatically with improvements in grating fabrication technology. Today we can make sinusoidal grooves, the preferred blaze for first-order radiation, using conventional image holography. Holographic grating structures also are used in spectroscopy where first-order images are the utilized. A miniaturized version of a grazing incidence holographic grating appears in the Littman Metcalf cavity, a frequency shifting device for diode lasers. When fabricated to the frequency band being controlled, energy losses are negligible in this widely practiced application.

Computer programs have been written that can approximate the efficiency of gratings as a function of their blaze, depth and pitch. These programs used iterative numerical methods as applied to electromagnetic radiation predicted in Maxwell's equations. Predictions show that grazing incidence configurations can be tuned within reason for service as astronomical primary collectors. We have used PC Grate® to make a preliminary study of a grazing incidence configuration at 89.5° off the grating plane normal. A grating of pitch of 1650 lines/mm with a 30 nm sinusoidal groove profile was studied for light of 1150, 900 and 600 nm.



Ignoring metalalization conductivity, efficiencies hover around 45% with the remainder of the light being reflected into the zero-order except for the shorter wave lengths which exhibit an opposed first-order.



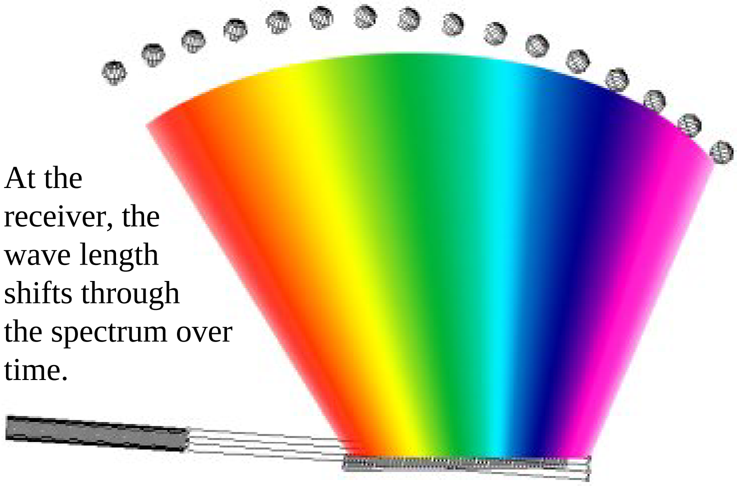
Variations in groove depth do affect efficiency. As an example, the behavior of light at 450 nm was studied and the ruling depth sampled from 20 to 50 nm. The bar graph shows the predicted efficiency of the first sample at a depth of 20 nm, and it is slightly less than 40%. The profile chart shows that some of the energy has been redirected into an opposed first-order, but the loss to that order is in single digits. The zero-order takes up half of the energy. The sum of energy in all orders is used as an accuracy confirmation of the numerical approximation. The sum is very nearly 100%.

Admittedly, this is a model and is not tested here empirically. Broadband spectra taken at grazing incidence are known to be idiosyncratic. Manufacturers test their products and provide calibration charts unique to each grating, especially when the gratings have a pitch shorter than the wavelengths dispersed by the grating. At grazing incidence with a high frequency grating, polarization angles can reverse themselves unpredictably, although their sum follows a more stable continuum.

Bearing in mind that the geometric collection area for a given parabolic mirror secondary can be expanded by two orders of magnitude using a diffraction grating at grazing incidence, a criterion for a killer loss in efficiency would have to be one order of magnitude or greater. Here we have shown that a loss of 1:2 can be expected. If this is true, then an amateur’s 1 m Newtonian combined with a 1 x 160 m grating suffering a 50% efficiency loss in the first-order could collect as much of any one wave length as the Keck, and if the Keck were used as the secondary, it theoretically could enjoy a collector that amounted to having a 5,000 square meter mirror.

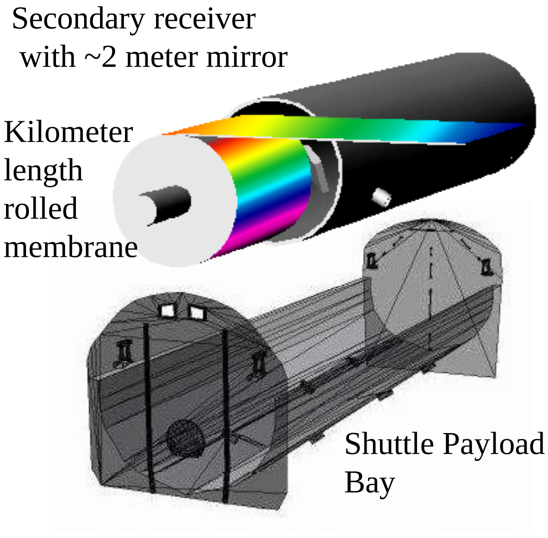
This begs the question of whether or not such large primary collectors could track a star. It’s hard enough to point the Keck much less a kilometer long grating.

As the earth rotates, the angle of incidence changes.



At the receiver, the wave length shifts through the spectrum over time.

The solution we propose is to let the earth do the pointing as it rotates. If the grating is fixed in East/West orientation along its considerable length, the right ascension of a star will sequentially expose the secondary objective to the sequence of the star’s spectra in the course of a night’s observation. All other stars in the right ascension can be blocked out with a variable band pass filter. No movement of primary or secondary is required.



Space-based large telescopes present launch-weight and orbit-assembly problems. Segmented rigid mirror assemblies have members that are placed into orbit as separate components and must be assembled in space, preferably by robotic means. In contrast, rolled plastics tuck nicely into the Shuttle payload along with their receiving optics, such as one or two meter dish mirrors inside a tubular rigid structure. Deployment for a ribbon shaped diffraction grating on a roll is easily specified. It simply must be unfurled. The distal end of the roll would require an applied force in zero-gravity sufficient to overcome the friction of the mandrel holding the roll. Such forces are available from its inertial guidance, e.g. solar powered motorized gyroscopes. Once unfurled, the taut ribbon would have a tendency to stay flat – the requisite optical surface for a diffraction grating. Twisting, stretching, and distorting caused by temperature, plasma and solar wind pressures or other forces could be detected by laser beam interferometers that monitored grating posture from the grating plane or by outboard free flying monochromatic sources that calibrated the device. Deformations in the diffraction grating ribbon could be corrected by gyroscope forces, centrifugal force, outboard shades and active compensation at the extremities including adaptive optics inside the secondary receiver. While these are non-trivial issues, the challenges of maintaining a flat membrane are refreshingly simple to contemplate when compared to those of parabolic membrane mirrors. Out gassing of inflation pressure would not be an issue. Exoskeletal structures are less critical for flat optics than for curved optics. Optical surface quality, while a critical issue in a grating, is a problem posed in one less dimension than a parabolic shell. The anticipated challenges of formation flying may be ameliorated by a long ribbon, since it offers a mechanical linkage as compared with free floating mirror segments that require exquisite zero-g guidance and control.

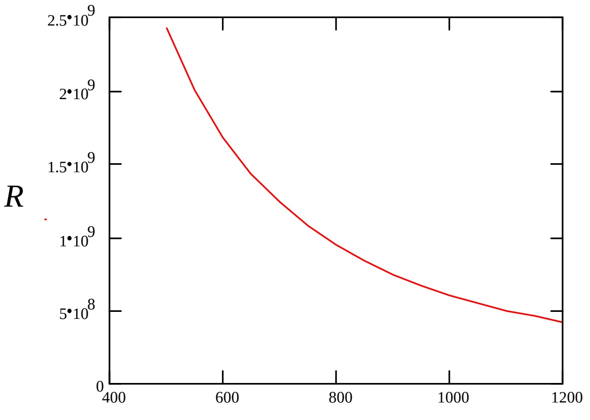
Both earth- and space-based versions of the proposed grating telescope enjoy unprecedented spectral resolving power. The geometry of grazing incidence forces the grating into a long and narrow shape with the rulings perpendicular to the considerable length. The extraordinary length is well suited to provide "leverage" to take spectra, because the considerable length of the grating is applied toward the one dimensional measurement of wave length.

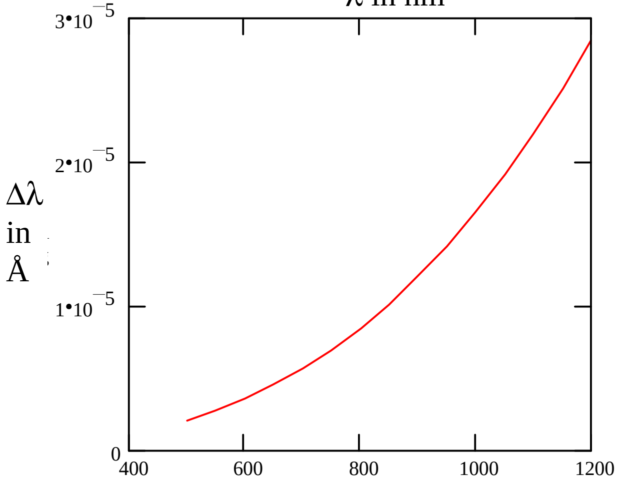
The dimensionless parameter for spectral resolving power R of a grating is the ratio of the wavelength to a perceptible change in the wave length.

$$R = \lambda / \Delta\lambda \qquad (1)$$

R is understood to be dependent upon the number of grating grooves in the grating N. The behavior of diffraction is such that the number of grating grooves N over considerable length L is directly proportional to the angles of diffraction i (incidence) and r (reconstruction), and at a grazing incidence for r, the groove number is maximized. Resolving power in terms of the spectral sensitivity of a spectrometer can be expressed as

$$R = Np(\sin i + \sin r)/\lambda \qquad R = L(\sin i + \sin r)/\lambda \qquad (2a \ \& \ 2b)$$





Hence the spectral resolving power of a one kilometer length diffraction grating acquiring the wave length of 0.6 microns is theoretically well over a billion to 1. The theoretical resolving power is graphed to the right. This is well beyond any prior astronomical spectrometer. Considering both grating length and the grazing incidence angle at which it works, the graph is not surprising. The resolving power is without precedent, because historically all astronomical spectrometers have had a telescope mirror as their primary receivers. Since telescopes were not used exclusively for spectroscopy, spectral resolving power suffered.

Basing a calculation solely on the parameters of diffraction angle and grating length, our proposed primary objective theoretically resolves visible colors at better than 0.00005 Å spacing. Certainly issues of grating quality, surface flatness, and secondary receiver acuity are not in this basic calculation, and such issues are limiting factors given the extraordinary grating resolving power predicted here. These other issues deserve study.

Spectral resolving power is relevant, because recent advances in the search for extra-solar planets have been based on Doppler shift spectroscopy. Current practice is aimed at charting star radial velocities that oscillate under the gravitational pull of nearby orbiting massive planets. There are no competing spectra from the planetary systems under study, because the planets are invisible under the glare of their suns.

However, if exo-planets did produce detectable spectra, their Doppler shifts would be taken to differentiate them from the star and from each other. Differentiation of a plurality of planets within extra-solar systems would require minute separations between competing spectra. In this scenario the extremely high resolving power of the diffraction grating telescope would seem to have a meaningful application. The spectra would lead to characterizations of each planet's orbit and material composition. Among these spectra would be the signatures of any earth-like planets.

The glare of a sun-like star over its planets ranges from 10 million times in the mid-infrared to 10 billion times in the visible. For example, at visible wavelengths, the flux from the planet - the entire flux in the visible part of the spectrum is typically 1/20 photon per square meter of mirror area per second. Some researchers are now looking to create coronagraphs for distant stars. The angular resolution of their telescopes cannot yet begin to accommodate the extinction angles needed.

On the other hand, the proposed diffraction grating primary solves the problem by providing extraordinary amounts of collecting real estate. With one photon per second over 20 square meters, the planetary signal could be minimally from 100 to 5000 photons per second in the visible and one thousand times greater in the mid-infrared. If grating telescope's secondary could then covert the captured radiation into signals above a noise floor of 1 part in 10 million, the planetary infrared spectra would be seen. Can 24 bits of sensitivity be achieved with an infrared photo collector? It can be done today with time integration and binning. 32 bits of visible light sensitivity are also possible.

It can be argued that conventional spectrometers have detected star wobbles as small as 3 meters/sec, so micro-Angstrom resolution is not called for when the Doppler shifts of orbiting planets are generated at thousands of meters/sec. The red shift is the inverse of grating resolving power:

$$z = \frac{v}{c} = \frac{\Delta l}{l} \tag{3}$$

Where z is the Doppler shift
v is the speed of the source
c is the speed of light

The Doppler resolving power would not be as great an issue if we could observe reflected spectra of planets directly. But to find them in the glare of a star, subtle distinctions become important, because the spectrum is a one-dimensional signal.

To find the “needle” planets inside the “haystack” of starlight, the astronomer can go to the absorption line holes. Spurious emissions of energy inside a star’s absorption bands can be studied as candidate Doppler shifted spectra coming from adjacent emission lines pushed or pulled into the absorption band hole by the angular velocity of a planet. Similarly, energy missing from a star’s emission lines may be in a pattern that matches a planet’s absorption lines as they are Doppler shifted under reflected starlight. Individual planets can be differentiated from each other by anomalies in the amplitude of the star’s spectral emissions.

Much as a listener hears the individual instruments of the orchestra within their one-dimensional temporal sonic wave form, the astronomer can see the spectral emissions of many planets inside a common broad spectrum radiated by their host sun. Earth-like planets will absorb according to concentrations of water and oxygen. Planetary Doppler shifts will indicate orbits inside the star’s warmth but outside the boiling point of water. Candidate earthlike planets can be studied for minutia. To carry the musical metaphor a step further, the “timbre” of each planet will be made distinct through reflection spectra shaped by planet composition. Arguably the astronomer may be able to report specific flora signatures on an earthlike planet. Imagine finding deciduous forests on one planet and conifers on another. To turn the musical metaphor into a pun, the “timbre” would describe the timber.

Once planets are detected, very high resolving power gives immediate feedback to studies of planet velocity. Orbital vectors can be discerned immediately and entire orbits inferred after a few observations.

There are surveys in progress that look at many stars for occlusion phenomena that suggest occultation of the star by a planet. Statistically this is an unrewarding way to survey, because the occurrence of an equatorial orbit matching our vantage point is a 1:1000 shot, and even at those odds one must stare for at least one planet year awaiting the ephemeral moment of eclipse.

With the proposed large diffraction grating primary, it is possible to survey all stars in transit at the declination line under study. Each star will report its unique part of the spectrum at any instant in time. Secondary receivers fitted with their own spectrometers can *simultaneously* survey the entire line of stars visible at the secondary collector. Depending on star magnitudes and collector size, a typical survey could be for thousands of stars per observation cycle. Unlike occultation methods, this approach gives meaningful data on all the candidates at once. After one discounts planets eclipsed behind their host sun and further discounts those planets with no Doppler moment as seen from out vantage, the statistical probability of being sensitive to a planetary system is 1000:1, rather than 1:1000, as with occultation surveys.

In survey mode, the grating primary telescope uses all higher-order energy dispersed to the collector. Whether enough energy can be made available to detect planetary spectra is an open question. The extreme cases of micro-Angstrom resolving power presume enough energy at the spectral line being read, and there may not be enough. One solution to a shortage of flux is to increase the size of the collector. This means increasing the angle of grazing incidence. However, as grazing incidence approaches 90º the high-order energy is directed into the grating substrate itself. With a reflection grating this means total extinction of the light, but in a transmission grating the light is tunneled.

It is possible to contemplate a species of evanescent grating telescopes that have no mirror secondary at all, because the energy is delivered to sensors at the grating edge. This evanescent grating concept suggests that terrestrial observatories could be made up of grating farms with thousands of large glass plates laid out in a grid and populating square kilometers. Stacks of these transmission grating plates would result in sequential decreases in zero-order losses, so that higher-order efficiencies might go from 50% with one plate to 88% with a stack of three. It is true that transmission media influence the spectral response, but in targeted studies for earthlike planets the choice of glass can be optimized for the spectra in question. The evanescent grating scope has no theoretical limit in length. Alternatively, modules can be segmented. For space applications, very thin glass fabrication is an option, but unlike mirrors now planned, the substrate would be flat interchangeable modules that could be fabricated like plate glass.

In the literature of revolutionary developments in space science, our concept fits a classic definition. We wish to investigate the consequence of turning things upside down. Where in the past the collector was a mirror, we propose a diffraction grating. Where the secondary held the grating, we contemplate a mirror. Semantics of the word “revolution” aside, we argue that there is an avenue open for study where no study has been done. Our goal is to describe in a how that study would take place.