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# THE DIFFRACTION GRATING II

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IT'S almost seven years since our last article on diffraction gratings in THE SPEX SPEAKER, Vol. X No. 3, and, in accordance with the obsolescence-half-life theory of modern technology, a sequel is long overdue. During these years, evolution, spurred by competitive selection, has resulted in overall improvement of gratings with respect to efficiency, scattered light, ghost intensity, resolution and polarization peculiarities. Larger engines have been painfully assembled and are now ruling gratings so huge they cannot be wrapped in newspaper. The Horsfield engine utilizing hydraulics instead of the customary leadscrew has produced several respectable gratings. The holographic grating, once thought to harbor the same great potential as the laser which begets it, appears to be fizzling down into just a new optical element, its bad features offsetting many of the good. Most important from the standpoint of the researcher and analytical chemist, libraries of excellent gratings covering a wide gamut of blazed wavelengths and ruling constants are now available from several sources. Mighty few of us remain who can even recall the bad old days when scientists had to convince Prof. R.W. Wood that their need for a grating was pressing enough for him to rule one on the sacrosanct Johns-Hopkins engine.

Astronomers are always fighting for improved optical speed. This was the compelling reason for the construction of the Mt. Palomar telescope over smaller ones: its ability to record faint objects in the sky during an exposure period so short that noise introduced by atmospheric dust and shimmer would not obscure the signals. But, although mirrors up to the Palomar 200-inch diameter had been successfully figured, the largest gratings available in 1965 were 125 x 250 mm.* They were ruled on MIT's famous interferometrically controlled engine, built from mechanical parts inherited in 1947 from a basement at the University of Chicago by Prof. G.R. Harrison of MIT and David Richardson of Bausch & Lomb. Begun by A.A. Michelson, the engine, after more than 40 years of only occasional attention, was in sad shape. Its leadscrew a hollow tube about 3″ $\phi$ (so it could be kept at a constant temperature with a flow of thermostated oil) had sagged longitudinally and had partially collapsed in cross-section. Even though the departure from trueness was only a few ten-thousandths of an inch these errors were some 600-times what could be tolerated for the preparation of modern gratings. Dr. Harrison found to his further astonishment that the metal itself crept incessantly. Measurements made with a commensurator over a period of many months at MIT showed the screw's skewness to be constantly shifting. Reworking it seemed pointless and the proverbial necessity mothered invention.

Instead of attempting to correct the screw, the MIT group, which by 1950 included Dr. G.W. Stroke, opted to rely on it only for rough positioning of the grating. Exact placement was controlled by an interferometer, fringes from a Hg-198 lamp guiding the diamond carriage during every stroke. Actually, two different interferometric corrections were found necessary, one to displace the diamond by the exact ruling constant, the other to overcome "fanning." When a large grating is ruled, shifting of the ways is enough to keep it from moving exactly perpendicular to the grooves. To correct the resulting fanning of grooves, yaw control was introduced, the blank being rotated on a vertical axis to keep the rulings parallel. Not until 1955, after 8 years of perspiration, was the fanning problem finally diagnosed and corrected. Almost immediately, good gratings were produced and the A engine was still further cajoled, this time to rule larger gratings with reduced scattered light, satellite structure and false lines. At this writing it has produced hundreds of superb gratings and echelles up to 10″ long and 300 g/mm. In this interim as well the more modern B engine was put to work.

Construction of the B engine required a sizable financial outlay. Fortunately, various Government agencies plus Bausch & Lomb committed money for the decade of work it took to whip and cajole it into shape. The starting point was a #3 measuring engine of the Moore Special Tool Company. One by one its components were tested, reworked and modified. By the time these things had been done, commercial lasers appeared on the market and a He-Ne laser was substituted for the Hg-198 lamp source of monochromatic light for the interferometers. In addition to nearly doubling the maximum possible ruled length (from 10″ in the A engine to 17″) the B engine produces gratings with consistently lower scattered light and satellite structure.

In 1970, Dean Harrison [1] and S.W. Thompson outlined the initial achievements of MIT's B engine. By that time, dozens of gratings up to 210 x 410 mm had been ruled with spacings as fine as 316 g/mm.*

*To be sure, grating-mosaics had long before been pieced together for telescopes. But, since the grooves could never conceivably be phase-locked, the gain in speed was not matched with a concurrent gain in resolution. Zeeman splitting and isotopic structure are examples of measurements beyond the resolution capabilities of these mosaics.

*This odd ruling constant is set by the spacing between 10 fringes produced by a He-Ne laser (6328A) controlling the interferometric servo. There is no fundamental reason why the optics cannot be turned or gears changed to rule at 1200 grooves/mm, submultiples thereof, or any other desired spacings.

Many of the gratings produced on the B engine are blazed for very high angles (up to 84°) and, for visible and ultraviolet applications, are operated typically in the tenth to fourteenth orders. Meant to be half-way devices between ordinary gratings and coarse echelons, they were named echelles by Harrison. Incidentally, echelons are little more than a curiosity today because so few have actually been constructed. Instead of being ruled, they are made by laboriously fastening the edges of polished glass plates together in step-wise fashion. It is a procedure that has proved too taxing except for theorists.

Performance of even the largest MIT echelles produced on the B engine has been truly remarkable by comparison with those produced on the A engine. Half-width resolution approaches theoretical in the green Hg line; typical peak efficiencies hover above 70%; the level of Rowland ghosts is less than $2 \times 10^{-5}$ and scattered light has been stifled to about that arising from smaller gratings. Any focal power —due to residual blank curvature—is so small that echelles may be rotated fully and remain in focus.

The B engine has recently been installed at B&L's David Richardson Grating Laboratory in Rochester. B&L's gain is turning out to be MIT's gain, too: the Dean can now concentrate on the still larger C engine. Maximum ruling area of this engine is 450 x 628 mm.

The C engine is based on a #4 Moore measuring machine. Supported by a concrete block which is itself floating on a cushion of compressed air, its temperature is controlled to 0.001C; that of the room is maintained to 0.01C and of the outer control room to 0.1C. Barometric fluctuations which effectively alter the wavelength of the laser radiation are automatically and continuously compensated as well.

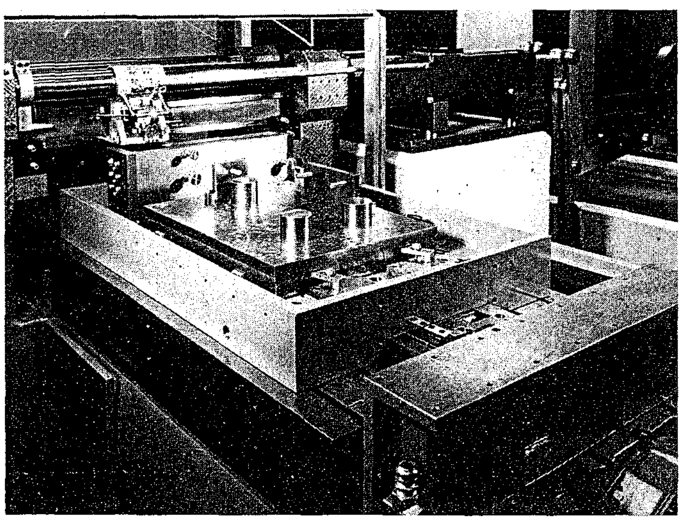

**Fig. 1 Since this photo of the newest and largest MIT C engine was taken, the ground steel diamond carriage guide has been replaced with a fused sillica bar. The interferometers were removed for this photo.**

Despite all of these precautions and corrections, most of which had been taken earlier for the B engine, other changes had to be instituted in order for the performance of the larger gratings produced by the C engine to match that of the B engine gratings. Sources of error were even harder to recognize. For example, it was found after much study that air turbulence from the reciprocating carriage disturbed the two laser beams sufficiently to effect ruling errors. The four beams—two for yaw and two for lateral control—were stacked above the ruling carriage but separated vertically by several inches. Turbulence therefore disturbed and changed the wavelength of the closer beam to a much greater extent than the other. Simply by cutting the distance between the beams to less than one inch, this source of error was removed.

Heat generated by the power supply and plasma was controlled with insulation and thermostating of the small laser to prevent warping of the engine. Next, a heavy, hardened steel bar against which the diamond carriage rode was found to deflect enough during ruling to introduce an error; it was changed to a block of 4"-thick, ground-and-polished fused silica. Finally, Dr. Harrison credits solid state electronic components for help from a reliability standpoint. Until all of the control circuitry was switched to modern solid state devices, the unruliness of the vacuum tube necessitated a grating sitter throughout the entire 2-week ruling periods. Now operating without a night nurse, the engine has not had a malfunction while ruling the last 12 large gratings.

Ultimately, even larger gratings will doubtless be produced. Funded by NASA, an engine is now under construction [2] designed to rule gratings up to 32" wide by 20" tall. The guardian of this engine is Dr. G.W. Stroke who began the work while he was at the University of Michigan in 1964. At present, dividing his time and efforts between the Harvard Medical School and the State University of New York at Stony Brook, he is supervising construction of the engine which has many novel features. The blank remains stationary while the diamond is moved along by two coupled leadscrews. Yaw as well as lateral positioning are controlled interferometrically. Dr. Stroke feels that there are advantages to both continuous as well as stop-go ruling so he has designed the engine to operate in either mode. Wear of the diamond which, after trudging 20 miles, understandably begins to show signs of diminishing stamina, remains the limitation for ruling finer, larger gratings.

## ABOUT GHOSTS

Before Laser Raman spectroscopy, most effort by grating manufacturers was directed toward making larger and larger gratings. But with the advent of Laser Raman spectroscopy, tremendous pressure was placed on manufacturers to minimize light scattered from gratings, and to eliminate entirely false lines, whatever their position or intensity. Manufacturers have responded nobly to the demands, and today many essentially ghost-free gratings are available. In fact, the present crop of gratings made for the UV and visible are much closer to being "perfect" in this respect than is generally realized. Presented in Fig. 2 are averages of several measurements of scattered light, all taken in the same imaging optical system, a Spex 1704, 1-meter Spectrometer. The best ruled and holographically produced gratings give virtually identical scattering performance, which performance is only slightly inferior to that of a top quality mirror.

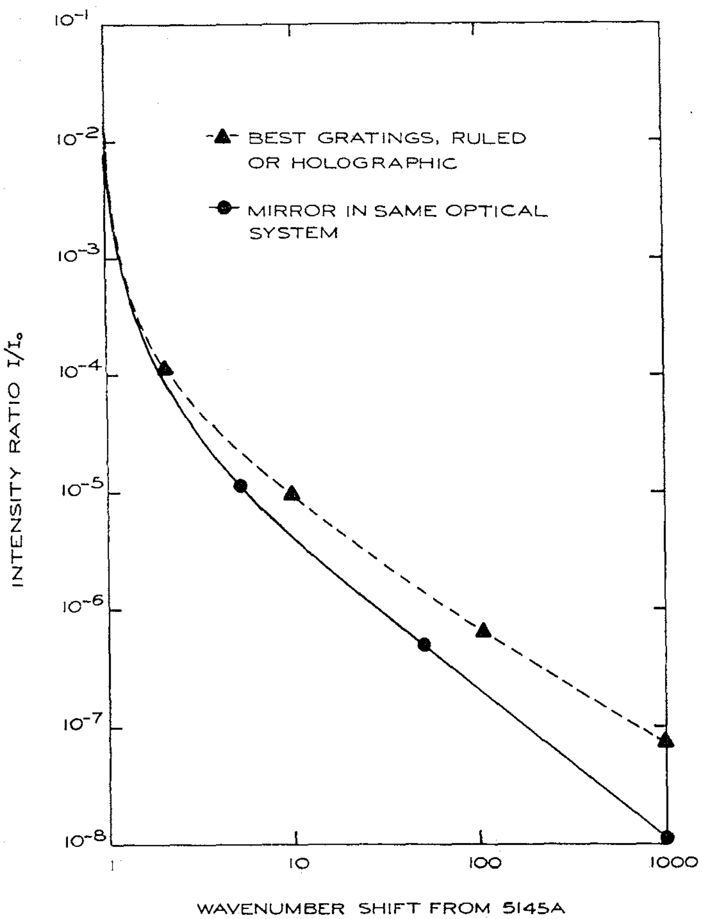


**Fig. 2 Comparisons of light scattered by high-quality gratings and a good aluminized mirror reveal that little room for improvement remains in this parameter.**

There is obviously very little room for improvement in this area. Ghosts or false lines, are a type of scatter still bothersome. Though the classic Rowland and Lyman ghosts have been effectively eliminated from modern interferometrically produced diffraction gratings, other false lines appear. Satellites are one type (Fig. 3). Another referred to as walking ghosts by Robert S. Wiley of B&L, is the result of random errors and appears as weak ($I/I_0 = 10^{-5} - 10^{-6}$) peaks or spikes. Unlike the classic ghosts, the positions of which are solely wavelength dependent, these "walking ghosts" appear at positions which are a function both of wavelength of parent-line and its angle of incidence on the grating. They may be unrelated to the interferometer control but due instead to diamond bounce. Whatever their source, these little imperfections will ultimately succumb in man's endless battle with the grating ruling engine.

## POLARIZATION ANOMALIES

The birth of the laser, with the revival of interest in Raman spectroscopy was also responsible for a greater concern by spectroscopists with the polarizing properties of their grating spectrometers. Since knowledge of polarization ratios is extremely important in characterizing the vibrations emanating in Raman spectroscopy, it is necessary for the measurements to be accurately corrected for instrumental polarization (or, better, for polarization effects to be altogether eliminated in the instrument). Since the diffracting efficiency of a grating varies with polarization of light, intensity measurements are also obviously subject to instrumental effects which must be known (or compensated for).

The theory of the blazed diffraction grating as given by Madden and Strong [3] predicts two different but smooth curves of reflectivity vs. wavelength for the p and s polarizations and has been idealized. Unfortunately, when one looks at the reflectivity curves in polarized light for a real grating, some startling departures from smooth curves are obvious. Known as polarization anomalies, these have been the subject of numerous studies. A common type has long been referred to as "Wood's anomalies" after R.W. Wood, their discoverer.

Seven years ago the theoretical understanding of polarization effects by gratings was fragmentary. While still an area of incomplete knowledge, it is showing distinct progress. The Staff of the grating department at Bausch & Lomb have, under the guidance of its director, Dr. Erwin Loewen, made significant contributions to our understanding of polarization effects, and the next part of this discussion is taken from their publication, [4] an excellent, concise general text.

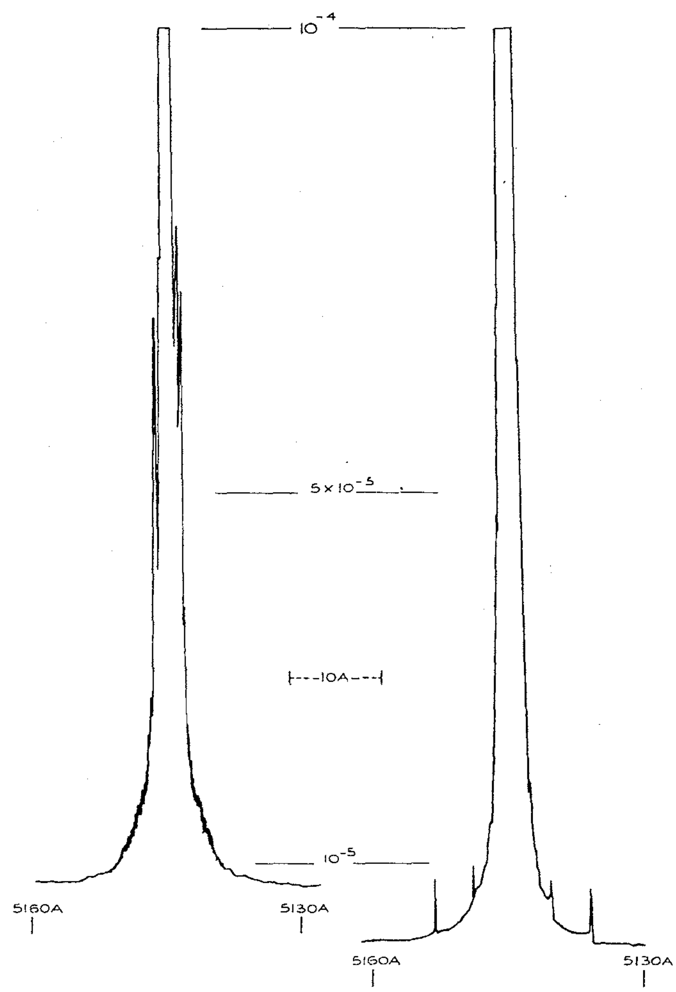


**Fig. 3 Near scatter is broken down into satellite structure when measurements are made under high resolution conditions. Although both these gratings are far better with respect to near scatter than older ones, they, nonetheless, show distinct differences.**

The general equation for diffraction by a grating is:

$m\lambda = d\,(\sin\alpha \pm \sin\beta)$ where: [1]

$m$ is the order of diffraction
$\lambda$ is the wavelength of the diffracted light
$d$ is the spacing between successive grooves of the grating
$\alpha$ is the angle of incidence of light on the grating

and

$\beta$ is the angle of diffraction of light by the grating.

It is simplest to treat diffraction gratings in a Littrow mount, where $\alpha = \beta$. Here the equation becomes:

$$m\lambda = 2d\,(\sin\alpha) \qquad [2]$$

With the common 1200 groove/mm gratings, $d = 0.8333\mu$, and $m\lambda$ cannot exceed $1.666\mu$. It is clear that for any $\lambda$ which is equal to or less than half $\lambda$ maximum, light will be diffracted into two or more orders on each side of the grating normal. Thus, for light of wavelength $0.67\mu$, we will have four diffracted orders, which are labelled +1, +2 and -1 and -2, the sign indicating on which side of the grating normal the diffraction occurs.

The simple facts just presented lead to an explanation of the anomalous energy distribution. In 1902 R.W. Wood discovered that, on many gratings, narrow spectral regions exist where the amount of energy diffracted shows a sharp increase or decrease compared to that diffracted at other wavelengths. Depending on the application and the severity of the phenomenon this effect may be disturbing. Fortunately this is not often the case.

The exact theoretical explanation of all the effects observed has not yet been formulated. Grating groove shape plays some role and anomalies are always associated with polarization phenomena. In fact it was thought for some time that anomalies were present only in the S-plane, the incident light plane-polarized perpendicular to the grating grooves. More recently, less prominent anomalies have also been observed in the P-plane, light polarized parallel to the grating grooves.

In a general way the S-plane anomalies can be regarded as a surface wave phenomenon, and it was Lord Rayleigh who discovered that the S-plane anomalies always occur at angles of incidence where other orders of diffraction, both higher or lower than the one under observation, diffract at an angle of 90°. Hence his designation of pass-off orders.

The S-plane anomalous wavelengths $\lambda_{Am}$ can be derived from the grating equation (1) by setting $\beta = 90^\circ$,

$$\lambda_{Am} = (d/m)\,(\sin\alpha \pm 1) \qquad [3]$$

For the Littrow configuration an explicit solution for $\lambda_A$ can be derived simply by noting that in this case $\sin\alpha = \lambda/2d$, so that Eq. (3) reduces to

$$\lambda_{Am} = \pm\,(2d)/(2m-1) \quad \text{(Littrow)} \qquad [4]$$

from which it is evident that in this special case $\lambda_{Am}$ is a function only of grating spacing and orders. It may also be noted that $\lambda_{Am}$ is the same for a negative order and the next numerically higher positive order. However, the latter is no longer true if there is any appreciable departure from Littrow conditions.

A practical example will illustrate this for a 1200 groove/mm grating.

From equation (3) the anomalous wavelengths (Littrow condition) are:

| m | $\lambda_{Am}$ |
|---|---|
| +1 | $1.66\mu$ |
| -1 and +2 | $0.55\mu$ |
| -2 and +3 | $0.33\mu$ |
| -3 and +4 | $0.24\mu$ |

Now in a spectrometer that deviates from the Littrow conditions, such as an Ebert or Czerny-Turner mount, the actual pass-off wavelengths must be calculated taking into account the included angle between the incident and diffracted beams. Following equation [3], the Littrow values can be modified with adequate accuracy by multiplying them by $(\sin\alpha \pm 1)\,(\sin\alpha_L \pm 1)$ where $\alpha_L$ is the Littrow angle of diffraction, and $\alpha$ is the actual angle of incidence $\alpha = \alpha_L - \theta/2$. In a typical spectrometer with $\theta = \cong 14^\circ$, $\alpha$ will be $\alpha_L - 7^\circ$, and the pass-off wavelengths are:

| m | $\lambda_{Am}$ |
|---|---|
| -1 | 0.63 $\mu$m |
| +2 | 0.52 |
| -2 | 0.37 |
| +3 | 0.31 |
| - 3 | 0.26 |
| +4 | 0.22 |

Figure 4 shows the efficiency curves of a 1200 groove/mm grating, blazed at 3000A. The curves referenced were taken in a Spex 1702 (3/4-meter) spectrometer, and the polarization anomalies are obvious, with the peak in the curves falling at the calculated wavelengths. The shorter wavelength anomalies though weak are observable at the predicted wavelengths. For comparison, the S polarization data obtained in a Littrow mount is presented; here we see that the peaks for the -1 and +2 order coincide at the predicted wavelength, $0.55\mu$.

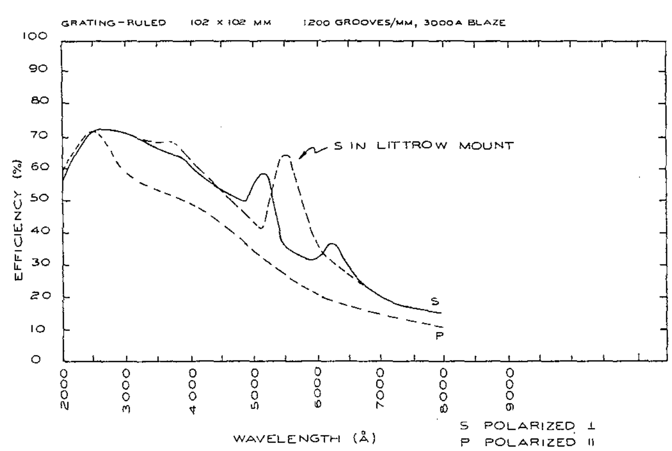


**Fig. 4 Wood's polarization anomalies for a 1200 g/mm ruled grating blazed at 3000A.**

All 1200g/mm gratings display polarization anomalies at identical wavelengths, in the same instrument. However, the theoretical derivation reveals nothing concerning the intensities of these anomalies, and the intensities do vary greatly with the blaze angle of a grating. Figure 5 shows the efficiency curves for a 1200 groove/mm, 5000A blaze grating. At first glance, this grating appears free from the S anomalies, and it takes a more careful inspection to establish that the anomalies are indeed present, but almost imperceptable. The other side of this coin can be seen in the data for the 1200g/mm 7500A blaze grating shown in Figure 6. The S anomalies are very pronounced here. In fact this type of grating shows the most extreme polarization anomalies of any that we have ever seen.

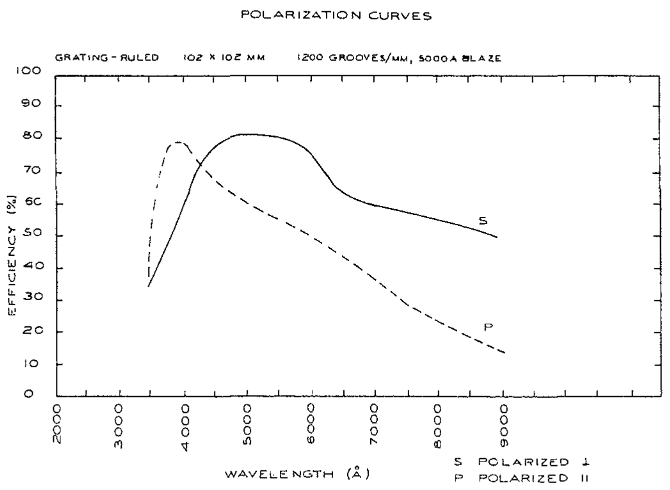


**Fig. 5 Wood's polarization anomalies for a 1200 g/mm ruled grating blazed at 5000A.**

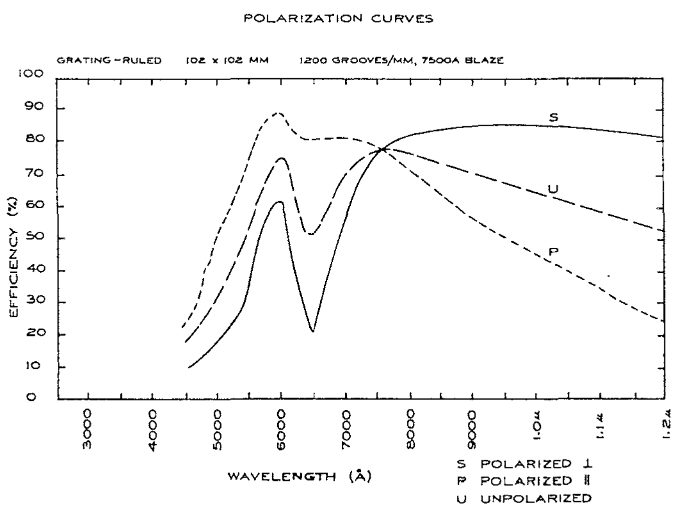


**Fig. 6 Wood's polarization anomalies for a 1200g/mm ruled grating blazed at 7500A are far more pronounced than those depicted in Fig. 4 and 5. Theory predicts positions of the dips not their intensities.**

Summing this all up: While our theoretical knowledge of polarization effects and anomalies exhibited by diffraction gratings has improved, it is by no means adequate to predict all observable phenomena. Therefore, at the present time there is no substitute for complete, experimentally derived information concerning these effects, for each grating-instrument system.

## HOLOGRAPHIC GRATINGS

Preparation of so-called holographic gratings actually predates the technique now considered holography. In the '40s, James Burch, now at the National Physical Laboratory in Teddington, made the first holographic gratings with light fringes produced by two interfering beams from a high-intensity Hg lamp. When the laser was invented, A. Labeyrie, then at the University of Michigan, realizing that much sharper fringes could be obtained, made several gratings with laser illumination. By this time, the mid '60s, Shankoff of the Bell Labs worked along similar lines, receiving a patent on the production of relief gratings to obtain blaze qualities [5]. Focusing properties can be imparted to a flat holographic grating and a patent on this technique is held by R.E. Brooks and L.O. Heflinger of TRW Inc. [6].

Reading the enthusiastic articles that have appeared on holographic gratings over the past three years [7,8] a newcomer to the field might well be tempted to specify such a grating as the dispersive element of a spectrometer. That few holographic gratings have actually found homes in spectrometers is a clue to their fallibility at this point in time.

But before going into what's wrong with them, let's start with what is right and their method of production. If light interference fringes are exposed on a photographic medium the graininess of which is finer than the distance between lines, the developed image without further processing, will be a transmission grating. Reflection gratings are, of course, much more of interest to the spectroscopist. These can be made by coating a suitable blank with a photosensitive resist and, after exposure and development, evaporating a layer of aluminum or another metal on the image. Photo-resist has the additional advantage of texture; after development, the unexposed areas are washed away leaving the raised surface of the exposed fringes. One way of attempting to blaze such a grating is by evaporating aluminum on it at appropriate angle to the substrate.

Several ways of exposing holograms have been devised (Fig. 7). For holographic gratings under 100 mm wide, lenses serve both to expand and collimate the beam. For larger gratings, cost often dictates the substitution of mirrors for lenses. The angle between the two beams establishes the spacing or ruling constant:

$$d = \lambda/2 \sin\alpha$$

One of the problems associated with making holographic gratings is exposure time. Because of the requirement for an essentially grainless photo-resist, it is necessarily slow to react to light and exposures in excess of half-hour are common. During this time almost imperceptable air currents or fluctuations in atmospheric pressure invariably result in refractive index waves in the air which are large enough to change to wavelength slightly and finally deteriorate the resolution of the holographic grating. To offset this, Labeyrie proposed [9] directing the two interfering beams through a prism contacting the treated surface on which the hologram is to be exposed. But obtaining a sufficiently homogeneous piece of glass is not easy. Practically speaking, the limit size as well as number of grooves/mm of any grating produced in this manner will be the attainable uniformity of the prism. In fact, the quality of all optical components in the system—including

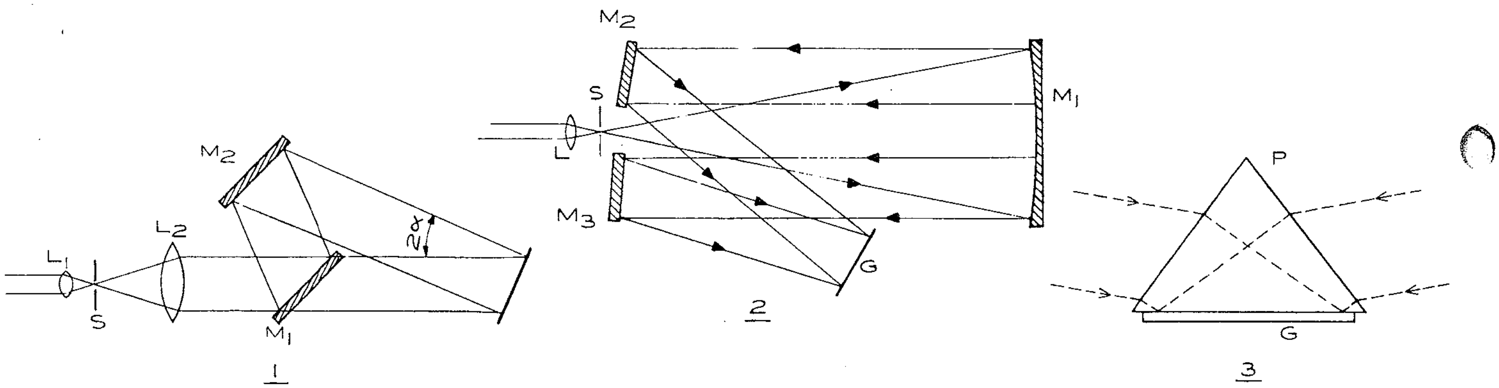


**Fig. 7 Three techniques for preparing holographic gratings. Fig. 7.3 depicts a method of substituting a fixed refractive index medium (glass) instead of air in which small currents upset the resolution of the image as it is exposed.**

the often neglected air path itself—imposes the size limitation, ultimately requiring a vacuum chamber for exposing the resist.

These difficulties notwithstanding, gratings up to 6000 g/mm have been prepared holographically. Even better in this respect than ruled gratings, some exhibit resolution bordering on theoretical. Thanks to the virtually grainless medium, the grooves are smooth and scattered light, therefore, extremely weak. And, unlike any conventionally ruled grating, holographic gratings are entirely free of satellites, "grass," ghosts or spurious lines of any sort. This characteristic can be exceedingly valuable when the spectroscopist is faced with trying to decide whether a vanishingly weak line in his spectrum is real.

Against these advantages must be balanced two serious shortcomings of holographic gratings: efficiency and polarization anomalies. Three holographic gratings produced by Jobin & Yvon in France and by Drs. G. Rudolph and G. Schmahl of the University of Gottingen have been examined in our laboratory. All have exhibited similar properties. Efficiency is comparable to conventionally ruled gratings, but—and here's the rub—in only one plane of polarization. When illuminated by perpendicularly polarized light, efficiency plunges almost to the vanishing point. Even in parallel polarized light, the gratings do not show a blaze at a particular wavelength. Instead, they show a progressive improvement in efficiency toward the red. See Fig. 8.

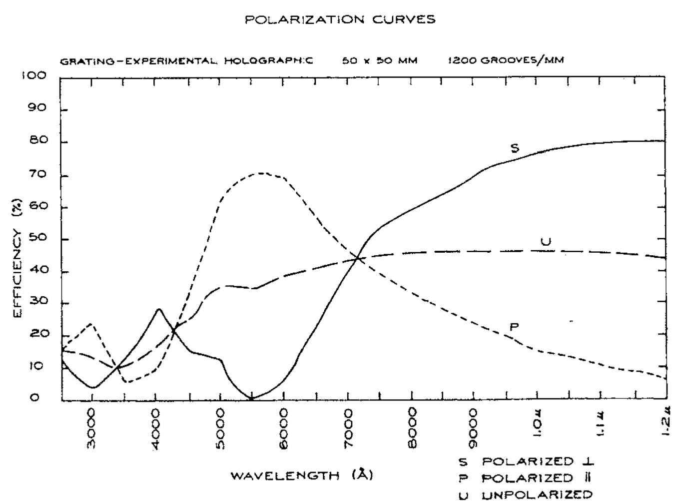


**Fig. 8 Severe polarization effects and poor efficiency remain as unsolved problems with holographic gratings.**

Even more disturbing than the poor efficiency in the S-plane of polarization are the strange polarization peculiarities which give efficiency curves of holographic gratings a roller coaster appearance. Since these dips occur at the predicted pass-off wavelengths—the diffraction limits of the grating for various positive and negative orders—their origin is well known. Their intensity, however, many times that in ordinary ruled gratings, seriously disrupts measurements of intensity. Undoubtedly, these severe polarization (Wood's) anomolies result from the shape of the grooves. Although a number of investigators have tried to produce sharply angled grooves by a variety of tricks, the grooves invariably turn out to be sinusoidal. Holographic gratings may eventually prove their worth in special applications. Spex recently sold a spectrometric system for automatically testing production photomultipliers; it is now being interfaced to a dedicated computer, which according to plan will type out wavelength vs. quantum efficiency charts for each photomultiplier on line. Because the sensitive range of photomultipliers extends from 1650A to 1.2 microns, the unblazed characteristics of a holographic grating became an advantage instead of a shortcoming. It was in this application, however, that the measuring inaccuracies introduced by the polarization dips reared up. Now a crystal quartz scrambler plate, placed between the exit slit of the Spex 1702 spectrometer and the detector, directs quasi-unpolarized light to the photomultiplier.

Other applications of holographic gratings may emerge as a result of the unique corrections for aberration which can be made in the hologram. Labeyrie [9], for example, has shown how to correct partially for astigmatism by spacing the grooves non-uniformly. Spacings between grooves in a conventionally ruled concave grating are made uniform with respect to the chord of the circumference of the dished blank. Some astigmatism is inevitable no matter how such a grating is mounted because focus in the horizontal and vertical directions never occurs in the same planes. Aside from the inelegant but easily clipped "tailed" lines characteristic of astigmatism, vertical spreading of the image results in lost light. The amount lost is particularly great in the XUV where astigmatism can amount to several hundred percent; approaching a 90° incidence angle a light source 1 mm high results in an image ten times that height. If, instead of exposing two collimated laser beams on the concave blank, the two beams originate from a point source, one of which originates at the radius of the blank, the resulting grating will be free of astigmatism at three wavelengths, according to

Labeyrie. Spacing between the fringes will vary in such a manner as to compensate exactly for astigmatism at these wavelengths. The horizontal and vertical foci will fall in identical planes.

Labeyrie suggested another possibility which may prove fruitful in special instances: producing crossed gratings holographically. Crossed gratings, resulting in order sorting and compacting a long spectrum into a circle, have unique applications. For example, a spectrum so compressed becomes compatible with electro-optical detectors such as an image dissector.

At present holographic gratings are more expensive than gratings replicated from ruled masters. Should their price come down, their blaze and polarization difficulties be licked, and should they be reproduced with finer spacings and in larger sizes than conventional gratings, they will find their rightful place in spectrometric instrumentation. Dr. Emmett Leith of the University of Michigan, with Dr. Dennis Gabor one of the co-fathers of holography, believes that the efficiency and polarization problems, are undoubtedly linked and will ultimately be solved. Present holographic gratings depend on surface relief for their reflection properties. Volume holograms have not seriously been explored for making gratings. By choosing materials with the proper dielectric and therefore refractive index properties and the proper thickness, it has been shown theoretically that blaze can be built into a reflecting grating. This would occur with a perfectly flat surface.

Until these rather severe limitations of holographic gratings are corrected, their applications will necessarily be confined to the unusual.

## HYDRAULICALLY RULED GRATINGS

Like the lofty summit of Mt. Everest to determined mountaineers, a ruling engine that could prepare perfect gratings has lured many a non-physicist into years of frustrating, often unrewarding effort. Around 1870, a New York professional lawyer and amateur astronomer, L.M. Rutherfurd, constructed an engine which, within a few years produced small gratings in speculum metal with a resolution that surpassed that of prisms of equivalent size. A more recent successful businessman to succumb to the ruling spell is W.R. Horsfield, a pragmatic English inventor. He has devised, among other things, a pea sorter to automatically discard off-color and wormy peas and machines for sawing coral into blocks and tiles with which most Bermuda buildings are constructed. In the late '40s, he learned of the imperfect grating ruling engines and soon concluded that its screw—its brain—was at the root of all error. Approaching Dr. Harrison, he suggested that an "incher" would represent a better basic mechanism around which to build a ruling engine. An incher is a device which advances like an inch-worm or caterpillar. A piezo-electric crystal expands when electrically energized, pushing its host along in miniscule increments. Horsfield believed that any positional errors introduced by the incher would be completely random and such residual errors would cancel one another, thus tending toward zero over a large number of rulings. Harrison, on the other hand, argued from the statistical standpoint: random errors tend toward a finite number different from zero. For a grating ruling engine differences in spacing between the first and last groove are just as significant as those between adjacent grooves.

Horsfield spent many persistent but futile months trying to make the incher work. When he gave up this approach he next sought to avoid the impediments of the screw with a hydraulic approach, advancing the grating blank by forcing a fixed volume of oil against it. Like the incher, this machine is entirely free of periodic errors and not subject to the roughness inherent in any mechanical system. For no matter how well they are lapped, bearings, gears, screws and nuts cannot be finished perfectly smoothly at every contacting surface. Horsfield's hydraulic ruling engine, even more than the flowers and beaches, drew dozens of inquisitive scientists and business opportunists to Bermuda.

One by one, many rules of the ruling game were broken by Horsfield. The first was site selection. According to the experts, an engine must be located deep underground to avoid any vibration source. Earthquake zones and areas that are prone to hurricanes, and thus subject to sharp barometric fluctuations, must also be avoided. But Horsfield, now well into his seventies, spared little patience for such frills. Adjoining his hilltop house in Warwick, he built a simple outbuilding from the ubiquitous coral block. The building was partitioned into two main rooms, one to house a few simple machine tools and his drafting table, the other to protect the ruling engine from nature's and man's intrusions. This inner sanctum was about 10-feet square, insulated with a thick layer of ordinary Styrofoam and ducted to an air conditioner. With elegant simplicity, despite the frugality of his approach, he was able to control the temperature of the room to 0.02C, the humidity to 2%.

The hydraulic engine [10] was designed to rule gratings up to 100 mm square. In a conventional engine, the screw serves a dual function: it drives the grating carriage while controlling the position of the carriage. In Horsfield's engine the two are deliberately separated. A hydraulic cylinder is driven by a micro pump which consists essentially of a hypodermic syringe. The volume delivered by the syringe for a 600 groove/mm grating is about 4 $mm^3$ and this causes a 0.1 mm stroke of the plunger. The actual position of the grating is servo-controlled through fringes produced by a Michelson interferometer with a He-Ne laser light source. The diamond ruling tool is raised and lowered pneumatically, the vacuum provided by an aquarium air-pump. Barometric changes are compensated through a mercury barometer acting on the position of the carriage.

At this writing the Horsfield engine has ruled several noteworthy gratings. Replicas from one — 102 x 102 mm, 1200 grooves/mm, blazed at 3000A — exhibit the best resolution we at Spex have ever measured in the first order ultraviolet, well over 90% of theoretical. Its overall efficiency equals that of the best gratings produced commercially although there is some shading from one side to the other, probably due to slight wear of the diamond. Intensity of satellites is less than $10^{-4}$ in our 1-meter spectrometer, quite similar to that from conventionally ruled commercial gratings. Scattered light at a distance of 100 $cm^{-1}$ from the 5145A $Ar^+$ laser line, though acceptable, is about twice as high as that from the best small interferometrically ruled gratings, currently those produced by B&L. Polarization curves appear normal.

Although this Horsfield grating exhibits no true ghosts, a number of very weak spurious lines do appear far from the parent line. As already mentioned, similar "walking ghosts" have been noted in the best gratings available today. They are probably due to the bounce of the diamond as it plows through the evaporated aluminum. Lending weight to this theory, the impatient Horsfield was especially proud of the high speed with which he ruled gratings. Even at twice the speed considered normal, however, ruling this 100-mm wide grating took over two weeks. A charming grin creasing his face, Horsfield described his luck with that grating. "For two weeks, we had no severe storms which might upset my barometric compensator. No heavy trucks thundered up to my house. And, most luckily, no power interruptions occurred. A rare two weeks in Bermuda, indeed!"

## THE GRATING MARKETPLACE

Emission spectrochemists have long been concerned with the limits of detection of elements in various matrices. For years it was thought that variations in detectivity resulted from measurement errors or varying degrees of author optimism. By now we have learned to be more suspicious of the grating quality, especially its scattered light and efficiency parameters. Having a wide assortment of modern gratings now readily available, today's spectrochemist might well consider replacing only the grating of his trusty old spectrograph before relegating it to antiquity. Over recent years the major change in the manufacture of spectrographs has been in grating quality. Lower scattered light can improve line-to-background ratios as much as tenfold, giving rise to an equal improvement in threshold of detection for trace elements. A ten-fold advantage achieved in grating efficiency, or speed, also extends micro-sample size limitations to 1/10 of the previous unimaginably small speck. So, where a laboratory can afford some "down" time and the spectrochemist is ambitious enough to undertake a thorough recalibration, there is unquestionable value and economy in giving the spectrograph a new grating.

One of the newest applications for gratings is the $CO_2$ laser in which an original grating ruled in metal replaces the totally reflecting mirror for isolating and pumping the lasing wavelength to generate the lasing action. In dye lasers gratings are tuning the wavelength over an ever-expanding band these days. And gratings are needed in increasing numbers for spectrophotometers and spectrofluorometers in ever-growing analytical procedures.

## ACKNOWLEDGMENTS

We wish to thank E. Loewen and J. Quartz of Bausch & Lomb for the long hours of technical discussion and permission to copy sections of the "Diffration Grating Handbook." We are grateful to G.W. Stroke of SUNY and F. Denton of PTR who were so helpful in providing anecdoted historical background. To G.R. Harrison, now Dean Emeritus of MIT, we owe a special gratitude for reviewing this manuscript, having submitted to a long interview as well. Harrison has certainly become today's candidate for membership in the exclusive hall of grating fame that numbers one man from the 18th century (Rittenhouse), another from the 19th century (Fraunhofer), and perhaps two others from this century (Rowland and Wood).

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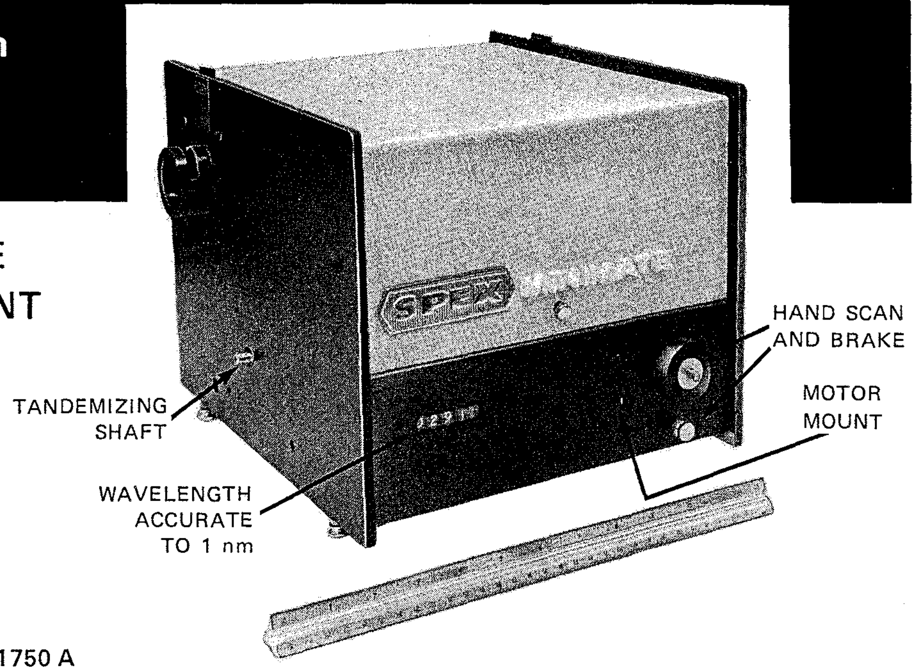


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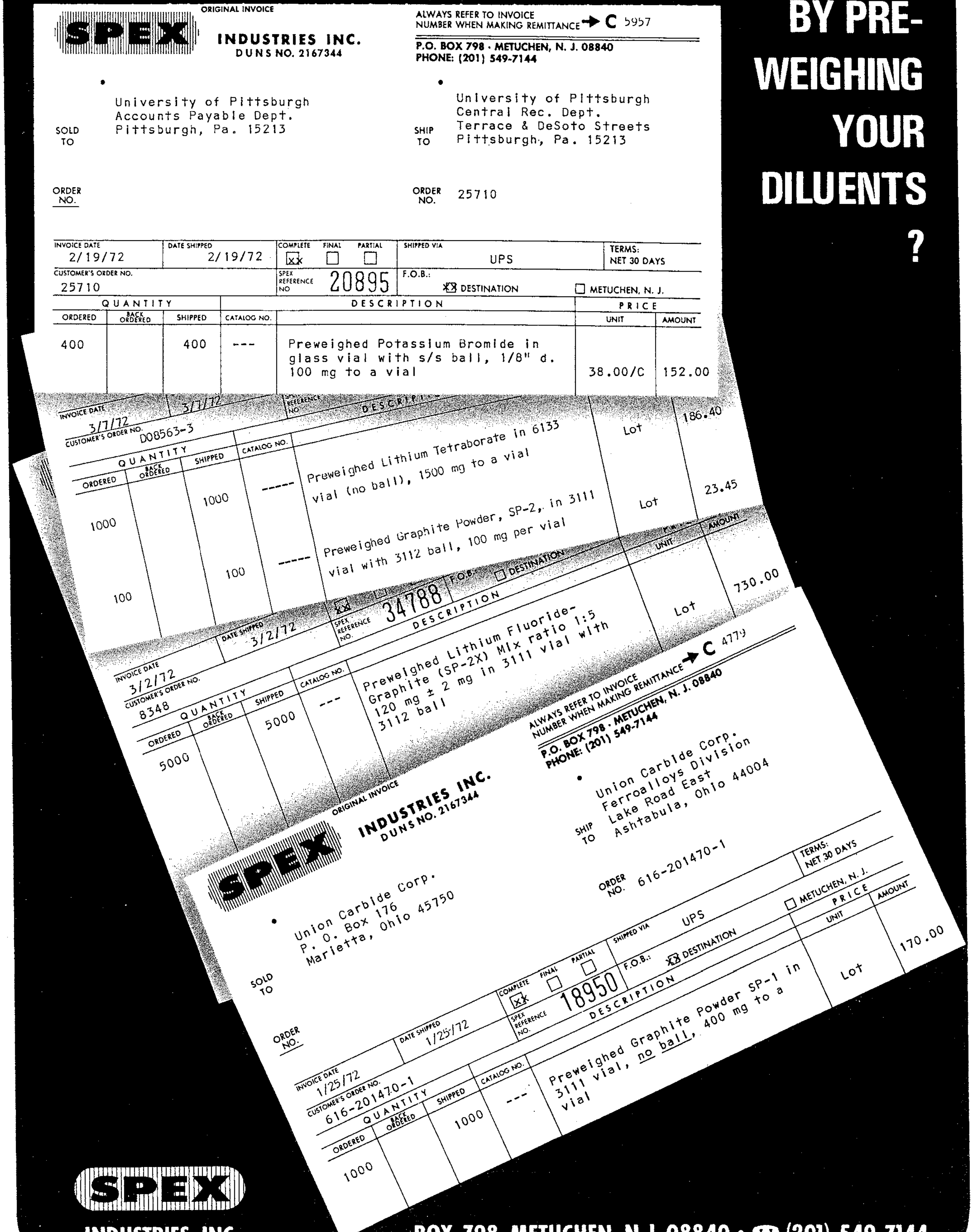


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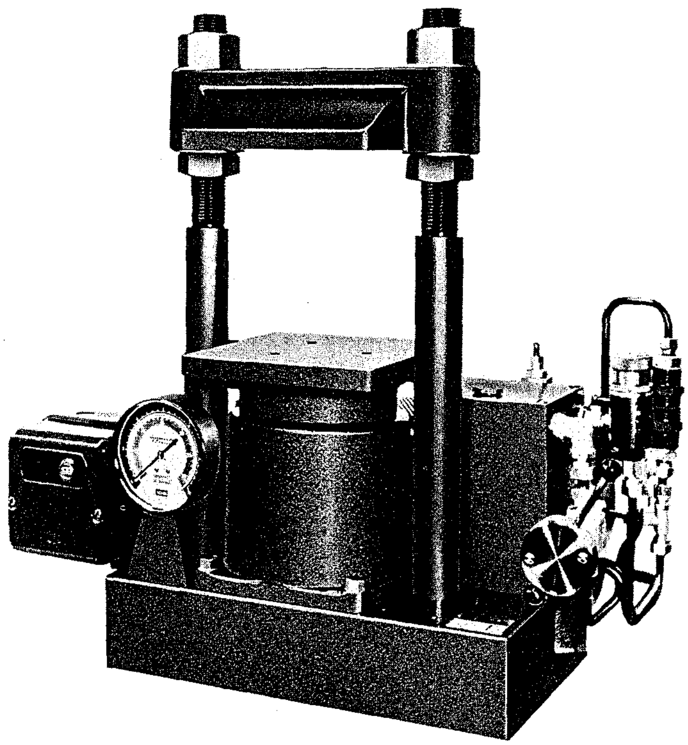
| Ram Stroke | 3.0 inches |
| Piston Diameter | 4.0 inches |
| Top Pad Adjustment | 5.0 inches |
| Adjustable Difference Between Ram Faces: | |
| Maximum Daylight | 8.0 inches |
| Minimum Daylight | 0 inches |
| Maximum with Platens | 8.0 inches |
| Minimum with Platens | 2.5 inches |
| Platen or Base Surface Working Area | 7.75 x 7.75 ins |
| High-Pressure Gauge | Calibrated every ton (1,000 Kg) |
| Hydraulic Pump Chamber Capacity | 2 pints |
| Dimensions: | |
| Base, Motorized | 18 x 16 ins |
| Distance Between Pillars | 8 inches |
| Overall Height | 24.5 inches |
| Net Weight | 228 lbs |
| Power | 220 V, 1 HP, 50-60 Hz |



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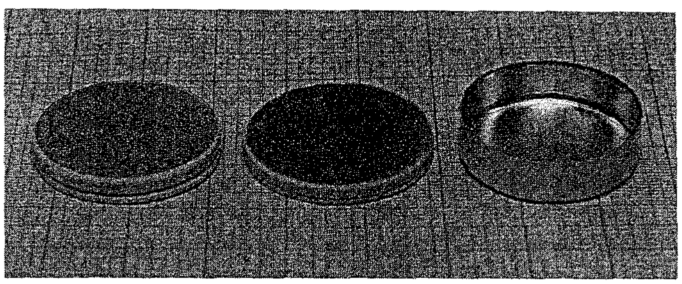

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**3623** **Evacuable Die,** may be used either with or without vacuum; optically flat, polished and parallel hardened tool steel faces; produces pellets $\phi$ 1.235" x up to 5/16" thick. Recommended for use with vacuum x-ray spectrometers, 10 lb . . . . . . . . . . . . . . . . . . . . . . . . . .
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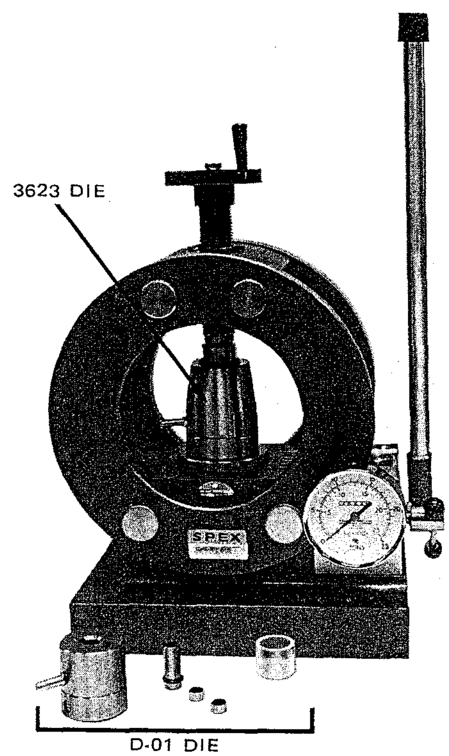


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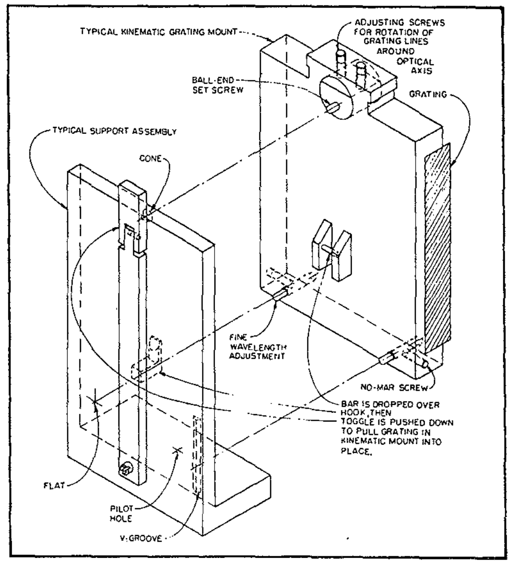
Being in the business of manufacturing spectrometers, it does not behoove us to advertise the advantages of constructing one's own. But having spent years specifying, purchasing, mounting, evaluating, comparing and selling gratings, it seems foolish for us to ignore those hardy individualists who have been, are or will be building instruments themselves. Who can deny the temptation of turning a dollar while helping a friend?

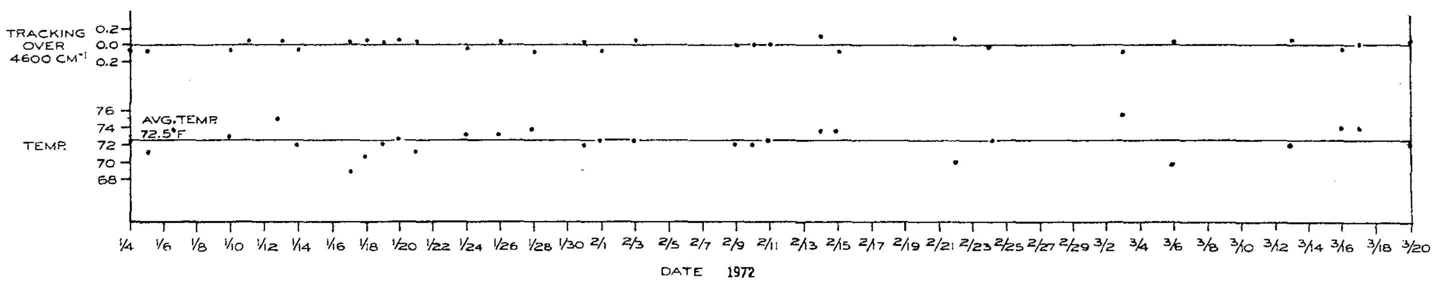
We have reams of data on many B&L grating masters and a first-rate device that makes light work of aligning, removing, interchanging or replacing gratings. To date these advantages have gone unshared. But no longer. The most popular grating sizes are herewith price-listed, each including a Spex Kinematic Mount. The Support Assembly which kinematically accommodates the mounted grating and in Czerny-Turner optical systems attaches to a rotating shaft, is sold separately, only one being needed for each spectrometer. Since wobble-free fidelity of grating motion depends upon the fit of the shaft in the Support Assembly hole, we drill only a pilot hole in line with the grating face, leaving the reaming to you. Question-answering and advice are free. Ask Lou Casper, our Sales Manager.

## STANDARD PLANE REFLECTANCE GRATINGS

| B & L Grating Size Designation | -09 | -10 | -15 | -17 | -20 | -27 |
|---|---|---|---|---|---|---|
| Blank size, mm | 69 x 69 x 9 | 76 x 85 x 16 | 110 x 110 x 16 | 110 x 135 x 25 | 135 x 165 x 30 | 135 x 220 x 35 |
| Ruled area, mm | 64 x 64 | 65 x 76 | 102 x 102 | 102 x 128 | 128 x 154 | 128 x 106 |
| 1200 g/mm | **$720** | **$950** | **$1480** | **$1875** | **$2680** | **$4045** |
| 600 g/mm or coarser | **475** | **680** | **950** | **1215** | **1720** | **2460** |
| Support Assembly | **95** | **120** | **120** | **180** | **260** | **260** |




## CURRENT TRACKING DATA FOR THE 1401 DOUBLE SPECTROMETER




Taken over a three-month period during the winter when our laboratory temperatures fluctuated about 7°, these data points establish the tracking performance of the first and second spectrometer halves to be within 0.1 $cm^{-1}$—or 2-1/2 times better than the resolution capabilities of a .85-meter spectrometer.

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