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UCID - 16705

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LLL IMAGE-CONVERTED SPECTROGRAPH: INSTRUCTION MANUAL

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August 23, 1972

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INTRODUCTION

The LLL image-converted spectrograph (shown in Figure 1) is basically a 1-meter, Littrow-type, grating spectrograph equipped with an image converter and camera system. This is shown schematically in Figure 2. Light enters through the slit and is collimated by the lens, which is positioned one focal length from the slit. The collimated light is incident on the grating and is diffracted back through the lens where it is focused onto the photocathode of the image converter. The spectrum displayed by the image converter is then photographed with the oscilloscope camera. The primary application of the image-converted spectrograph is in continuous monitoring of mode-locked laser bandwidths. This and other applications of the spectrograph system and experimental dispersion and resolution data are discussed in another report.⁷

The first section of this report details the steps to be taken in assembling the spectrograph. A set of assembly drawings, a parts list, and several photographs of key sub-assemblies are included to aid in the assembly process. This is followed by a section discussing the principles of operation of the image-converted spectrograph, both theoretical and practical. Included in this section are the alignment procedure and a discussion of the use of the various modes of operation of the system. The final section discusses techniques which may be used to obtain calibrations (wavelength and focus tuning, dispersion, and resolution) needed for accurate data analysis. Useful and readily obtainable spectral sources are mentioned in this section and the wavelengths of their useful lines are tabulated. For those desiring to learn more about diffraction gratings and grating spectrographs, a comprehensive list of references is included at the end of this report.

AUTHOR'S NOTE: This manual is intended as an operating procedure for the LLL Image-Converted Spectrograph. It is written at a level for the person with little or no experience with spectroscopy or spectroscopic techniques.

Figure 1

Photograph of the LLL Image-Converted Spectrograph

Schematic diagrams of LLL image-converted spectrograph
Figure 2

ASSEMBLING THE SPECTROGRAPH

Should you be in the position of having to assemble the spectrograph, some hints as to how to proceed may prove useful. Table 1 is a list of parts used in the LLL image-converted spectrograph (ICS). The item numbers in the table refer to the numbers on the assembly drawings, Figures 3 through 7 (portions of UCLLL Drawing No. AAA 72-108586-0A). Part numbers refer to the specific detail drawings used for fabrication purposes.

The ICS is best assembled into five sub-assemblies before the final assembly: the grating holder, the lens holder, the image converter system, the spectrograph body, and the turning mirror and slit. Ease of assembly requires that these sub-assemblies be put together in a certain order. In assembling the grating holder sub-assembly, Figure 8, the grating cradle (see Table 1 and Figures 3 through 7 for identification of the specific parts mentioned) should first be attached to the grating spindle with loctite. Next, the adjusting saddle is fastened to the grating cradle. The fine-threaded hole on the saddle should be to the rear when the grating cradle is held with the saddle on the left (when viewed from the front). The grating holder (minus the grating) is then attached to the cradle with cone point screws (also secured with loctite), in such a manner that the projection of the grating holder fits into the adjusting saddle. Next, the adjusting screw and spring plunger are screwed in place and the grating clamp ring is secured to the spindle. A small nylon screw is screwed into the bottom of the inside of the grating holder and the grating is placed into the holder (see CAUTION below), ruled surface towards the front with the grooves vertical and the blaze towards the left (as viewed from the back of the holder). The grating springs are inserted between the sides of the holder and the grating and two nylon-tipped set screws are screwed into the top of the holder to secure the grating. Finally, the back cover is screwed onto the grating holder.

CAUTION: The optical components used in a spectrograph have delicate coatings which must be handled with care. The ruled surface of the grating should not be touched under any circumstances. Any cleaning of the grating surface (other than dusting with a FREON microduster) should be done only by specially-trained personnel. Similarly, the lens may be anti-reflection coated and should always be handled accordingly. That is, the surfaces of the lens should not be touched except for cleaning (only when absolutely necessary) with a soft tissue.

To assemble the lens holder, Figure 9, the lens spindle is first screwed into the back lens ring and secured with loctite, as is the lens pivot. After the two adjusting screws are screwed into the back lens ring from behind, the lens ring, positioned so the groove and the countersink fit over the lower adjusting screw and the lens pivot, respectively, is attached to the back lens ring with four springs. The springs which come with the spectrograph are too weak and should be cut in half before use. Lastly, the plano-convex lens should be placed in the lens ring, plane side first and secured with the nylon lens clips.

A close-up of the front end of the ICS, showing the turning mirror and slit assembly, is found in Figure 10. Before assembling this unit, the outer jaw guard of the slit (a thick ring of metal fastened to the front of the slit with two small screws) must be removed. This is done to provide free rotation of the turning mirror once the final assembly is complete. After removal of the jaw guard, the slit is attached to the adapter plate with four screws. Next, the turning mirror spindle is attached to the turning mirror yoke (see Figure 7) and the large slip washer is slipped over the spindle, which is then inserted through the adjusting arm. This unit is now inserted through the second slip washer and the turning mirror base, the blade of the adjusting arm being positioned between the prongs on the turning mirror base. The turning mirror spindle is secured with a socket head screw and a steel washer. The tip of the screw should be coated with a dab of epoxy cement, carefully screwed into the spindle (being careful not to cement the spindle to the base) and tightened until the mirror yoke barely slips on the slip washers when a

torque is applied. After the epoxy is dry, the mirror yoke is locked in place with the lock screw. The adjusting screw and spring plunger are inserted, and the turning mirror base is bolted to the adapter plate under the slit. Finally, the gold mirror (with the mirror surface recessed from the edge of the frame) is secured in the turning mirror frame by three nylon-tipped set screws and the turning mirror frame is fastened to the yoke by the two gimble screws

The body of the spectrograph is assembled in the following manner. First, the levelling screws are screwed into the feet on the frame and the frame is placed on the mounting plates which are bolted onto the magnetic bases. Next, the table rod is attached to the rotary table through the small universal joint and the slide rod is attached to the lens slide through the large universal joint. The lens spacer is bolted to the lens slide and the lens stand is fastened onto the spacer. After positioning the lens stand at the rear of the lens slide (by turning the translation screw mechanism), the entire unit is then placed into the housing assembly and screwed onto the frame through the holes provided. One of the two counter bearings is placed into the left hole in the camera bulkhead (as viewed from the front of the spectrograph) from the inside. The back plate of the Microdial counter #1315 is then fastened to the counter bearing with a jam nut. The main gear of the counter is fastened to the counter slide rod, which is then inserted through the counter bearings. Finally, the counter slide rod is attached to the slide rod with a universal joint and the dial fitted over the counter gear and fastened to the counter back plate. Now, the table adapter is screwed onto the rotary table and the entire unit is bolted onto the frame through the table spacer. The Microdial counter #1314 is fastened to the right side of the spectrograph and connected to the rotary table in the same manner as the #1315 counter is fastened to the lens slide.

Next, the high voltage connector and a ground terminal are screwed into the hole provided in the camera bulkhead. A length of high voltage lead (20 kV test) is then soldered to the connector (inside the spectrograph body) and the loose end of the lead is slipped out through another hole in the bulkhead. With this accomplished, the adapter plate assembly is bolted to the camera bulkhead.

Another close-up of the front end of the ICS, showing the image converter and camera system, is found in Figure 11. Figure 12 shows part of the dis-assembled unit. The image converter housing is first bolted to the camera plate with the holes for the boss pointing down. Next, one of the contact rings is inserted into the housing and the ground wire, which is inserted into the contact ring through a small hole in the housing, is secured with a set screw. The image converter tube is placed in the housing, phosphor end (end with the dull gray-green appearance) first. This is followed by the second contact ring. The high voltage lead is inserted through the boss and through the hole in the image converter housing where it is secured to the second contact ring. After fastening the boss onto the housing with screws and inserting the spacer, the image converter assembly is ready to be attached to the spectrograph body. This is accomplished by bolting the free end of the housing to the adapter plate and the camera plate to the frame. Note: a 3/8-inch steel washer should be inserted onto each bolt between the frame and the camera plate to insure proper alignment of the image tube. At this point, the ground wire from the image converter is attached to the ground terminal. Ground wires are also connected to the camera plate and the adapter plate. Finally, four 10-32 5/8" long set screws are screwed tightly into the camera plate and the Tektronix C-30 Camera Bezel is attached.

When all this has been accomplished, the assembly of the spectrograph is complete and the system is ready for alignment. Alignment and operation of the system will be discussed in the next section.

TABLE 1

Parts List For The LLL Image-Converted Spectrograph

NOTES:

4. THREADS ON THESE ITEMS ARE TO BE COATED WITH LOCTITE OR EQUAL BEFORE FINAL ASSEMBLY.
 5. ATTACH ITEM #99 WITH POP RIVETS OR EQUAL.
 6. FOR OTHER CAMERA BACKS SEE TEKTRONIX CATALOG.

QTY	PART NO.	DESCRIPTION	NO. REQD	MATERIAL	QTY	STOCK NO.
4	99	HANDLE	4	MOLMES #FAH-IP		
2	98	SCR FLAT HD. 10-32 X 1/2 LG.	2	STL.		
2	97	SCR SOC. HD. 8-32 X 1/2 LG.	2	STL.		
2	96	SCR SET CONE PT. 6-32 1/2 LG.	2	STL.		
12	95	SCR SOC. HD. 4-40 X 1/8 LG.	12	STL.		
3	94	SCR SOC. HD. 6-32 X 1/2 LG.	3	STL.		
4	93	SCR SOC. HD. 10-32 X 3/4 LG.	4	STL.		
4	92	SCR SOC. HD. 4-40 X 1/8 LG.	4	STL.		
4	91	SCR HEX HD. 3/8-16 X 1 LG.	4	STL.		
2	90	JAMNUT 3/8-32	2	STL.		
4	89	SCR HEX HD. 3/8-16 X 1 LG.	4	STL.		
3	88	SET 4-40 X 1/8 LG.	3	NYLON TIP		
2	87	FLAT HD. 4-40 X 1/4 LG.	2	STL.		
4	86	SCR SET 10-32 X 5/8 LG.	4	STL.		
1	85	WASHER #6 NOM. PLAIN	1	STL.		
1	84	SCR SOC. HD. 6-32 X 3/8 LG.	1	STL.		
1	83	CONNECTOR MALE	1	HEYNOLDS 167-5516		
1	82	CONNECTOR FEMALE	1	HEYNOLDS 167-5517		
2	81	SCR SOC. HD. 6-32 X 1/8 LG.	2	STL.		
4	80	SCR SET 4-40 X 1/8 LG.	4	STL.		
4	79	SCR SET HD. 10-32 X 1/2	4	STL.		
2	78	SCR BULK HD. 6-32 X 1/2 LG.	2	STL.		
4	77	SPRING LENS	4	LEE #LE-029C		
2	76	SCR SET HD. 1/4-20 X 1/2 LG.	2	STL.		
2	75	SCR FLAT HD. 4-40 X 1/8 LG.	2	STL.		
4	74	SCR ADJUST	4	STL.		
6	73	SCR SET 8-32 X 1/4 LG.	6	STL.		
2	72	SCR SET 8-32 X 1/4 LG.	2	NYLON TIP		
4	71	SCR HD. HD. 5-40 X 1/4 LG.	4	STL.		
2	70	SCR SET 6-32 X 1/4 LG.	2	STL.		
3	69	SCR TORQUE (HUMB 1/4-20 X 3/4 LG.)	3	STL.	REIDS GB-1	
7	68	SCR THUMB 1/4-20 X 3/4 LG.	7	STL.	REIDS SL-4	
2	67	SPRING PLUNGER 1/4-20 X 1/4 LG.	2	STL.		
1	66	SCR HD. HD. 8-32 X 3/8 LG.	1	NYLON		
4	65	SCR HEX HD. 3/8-16 X 1/2 LG.	4	STL.		
9	64	SCR SOC. HD. 10-32 X 1/2 LG.	9	STL.		
1	63	LENS PLANO-CONVEX	1	OPTICAL INDUSTRIES LPX-397		
1	62	IMAGE CONVERTER TUBE	1	KCA 6914		
1	61	GRATING SPINDLE	1	ALUM.		
1	60	SLIDE ROD	1	ALUM.		
1	59	COUNTER SLIDE ROD	1	ALUM.		
1	58	LENS SLIDE	1	UNISLIDE A-2509-A		
1	57	GRATING CRANK	1	ALUM.		
1	56	ROTARY TABLE	1	KILMATIC RT-175		
2	55	SPRING GRATING	2	STL.		
1	54	UNIVERSAL JOINT, 3/16" I.D.	1	PIC-B-2		
3	53	LENS CLIP	3	BLACK NYLON		
1	52	TABLE ROD	1	ALUM.		
1	51	COUNTER TABLE ROD	1	ALUM.		
2	50	COUNTER BEARING	2	SST.		
1	49	CAMERA BULKHEAD	1	PHENOLIC		
1	48	LOCK SCREW	1	SCREW		
1	47	SCREW ADJUSTABLE	1	WATTEL ASH #12-000-A		
3	46	UNIVERSAL JOINT 1/4" I.D.	3	SST.	1/2-1/2	
1	45	ADAPTER PLATE	1	ALUM.		
1	44	TURNING MIRROR	1	PHCX		
1	43	TURNING MIRROR BASE	1	ALUM.		
1	42	ADJUSTMENT ARM	1	SST.		
1	41	MICRODIAL COUNTER	1	AMPHENOL #1515		
1	40	MOUNTING PLATE C/SINK	1	ALUM.		
1	39	CAMERA PLATE	1	ALUM.		
1	38	MOUNTING PLATE FLAT	1	ALUM.		
1	37	MICRODIAL COUNTER	1	AMPHENOL #1314		
1	36	TURNING MIRROR Yoke	1	ALUM.		
2	35	GIMBLE SCREW	2	SST.		
1	34	TURNING MIRROR FRAME	1	ALUM.		
1	33	WASHER SLIP TAB-1	1	ALUM.		
1	32	WASHER SLIP TAB-2	1	TEFLON		
1	31	SCOPE CAMERA	1	TEKTRONIX C-30A-RE		
1	30	IMAGE CONVERTER HOUSING	1	DELTRIN		
1	29	BOSS	1	DELTRIN		
2	28	CONTACT RING	2	BRASS		
1	27	SPACER	1	DELTRIN		
1	26	SPINDLE TURNING MIRROR	1	SST.		
1	25	HOUSING ASSY.	1	ALUM.		
1	24	FRAME	1	ALUM.		
1	23	LENS SPACER	1	ALUM.		
1	22	LENS STAND	1	ALUM.		
1	21	LENS SPINDLE	1	ALUM.		
1	20	LENS PIVOT	1	SST.		
1	19	LENS RING	1	ALUM.		
1	18	LENS BACK RING	1	ALUM.		
1	17	GRATING HOLDER	1	ALUM.		
1	16	GRATING No. 35-43-5-520	1	BAUSCHE & LOMB		
1	15	MOD. TABLE ADAPTER	1	ALUM.		
1	14	TABLE SPACER GRATING	1	ALUM.		
1	13	CLAMP RING GRATING	1	ALUM.		
1	12	WASHER	1	PHENOLIC		
1	11	ADJUST SADDLE	1	ALUM.		
1	10	GRATING BACK PLATE	1	ALUM.		
1	9	BACK BULKHEAD	1	PHENOLIC		
1	8	MAGNETIC BASE	1	BROWN & SHARPE #7743		
1	7	MOUNTING PLATE GROOVED	1	ALUM.

FIGURE 3

Assembly Drawing Of The LLL Image-Converted Spectrograph. Side View.

FIGURE 4

Assembly Drawing Of The LLL Image-Converted Spectrograph. Top View.

FIGURE 5

Assembly Drawing Of The LLL Image-Converted Spectrograph. Front End View.

FIGURE 6

Assembly Drawing Of The LLL Image-Converted Spectrograph. Back End View.

Detail Of Turning Mirror Assembly

FIGURE 8

Photograph of Grating Holder Sub-Assembly

FIGURE 9

Photograph of Lens Holder Sub-Assembly

FIGURE 10

Close-up Photograph of the Front End of the Spectrograph
Showing the Turning Mirror and Slit Sub-Assembly

FIGURE 11

Close-up Photograph of the Front End of the Spectrograph
Showing the Image-Converter Sub-Assembly

FIGURE 12

Photograph of the Disassembled Image Converter Showing
the Positioning of the Interior Components

OPERATION OF THE SPECTROGRAPH

Before the ICS may be used, it must be aligned. This is easily accomplished in the following manner. First, the slit is opened to its maximum extent, while the decker is closed until all but 3 or 4 mm in the center of the slit length are obscured. With the back door of the spectrograph open and the lens and grating holders removed, the beam from a 1 mW He-Ne alignment laser (see SAFETY NOTE below) is directed onto the slit with the aid of two mirrors and the turning mirror. The beam should be readily observable out the back of the spectrograph with the aid of a piece of paper or ground glass. Using the mirrors, the laser beam is now positioned to pass directly down the center (in the horizontal direction) of the spectrograph. The lens holder is now inserted into the lens stand with the adjusting screws to the rear, rotated to be perpendicular to the laser beam, and tightly secured. The two screws holding the lens stand to the lens slide are loosened and the lens stand is positioned horizontally so the laser beam passes through the center of lens. The lens stand is now tightly secured to the lens slide. At this point, the laser beam is positioned vertically (again using the mirrors and turning mirror) so that it passes through the lens approximately 3/4" above the center line (the beam should still be centered horizontally). The lens gives rise to two weak reflected beams (even if the lens is AR coated at 1.06μ), a diverging beam from the convex surface and a collimated beam from the plane surface, which may be observed on the back surface of the adapter plate. The adjusting screws on the lens holder are adjusted so as to position the divergent reflected beam directly above the photocathode of the image converter and the collimated reflected beam directly below the photocathode. It is essential that neither of these beams strike the photocathode or spurious images and background noise will result.

When this has been done, the image converter system should be turned on. The image converter requires a 15 kVDC power supply (current requirements are minimal, $\sim 10 \mu\text{amp}$), which is connected to the image converter tube through

the Reynolds high-voltage connector. The Microdial #1314 counter is now rotated until the dial reads 000.0 and locked in place, and the grating holder is inserted into the rotary table. The clamp ring is loosened and the grating holder rotated until the grating is perpendicular to the laser beam.

SAFETY NOTE: Despite the low power of most alignment lasers, the possibility of eye damage is still present. Care should be taken to avoid looking directly into the beam or its reflections.

A number of beams will be observed reflecting from the grating, one mirror reflection and several diffracted beams. The mirror reflection (called the central image) is now positioned vertically (with the adjusting screw) and horizontally until it strikes the center of the photocathode. When centered, the clamp ring is tightened and the grating holder is securely clamped into the rotary table. Note: the image produced on the image converter by the central image should be centered after the grating holder is clamped in place. If it is not, the clamp ring and grating holder should be loosened and the mirror adjustments made until the image is centered after the grating holder is secured. The purpose of centering the central image with dial setting 000.0 is to provide a simple unambiguous zero point for wavelength tuning. As can be seen from the grating equation (below), the central image corresponds to the zero-wavelength point.

The source to be analyzed is aligned in a manner similar to that used for the alignment laser, i.e., by using mirrors if the source is a laser or a large, immovable source, or by proper source positioning if it is a small, portable source such as a spectral tube. When a maximum intensity central image is centered on the image converter output, the source is aligned. When working with pulsed sources or very weak sources, it is frequently desirable to have a strong, CW, secondary source with a spectral line close to or in the wavelength region of interest of the primary source. The secondary source line may be used to focus the spectrograph or the camera and to aid in finding the proper vertical and horizontal positioning of the primary source spectrum. Since the spectrograph turning mirror is

rotatable through 360° , the secondary source beam may be brought into the spectrograph from the side opposite to that of the primary source beam. Once both sources are aligned, the beam to be analyzed may be selected simply by rotating the mirror. Very often, the secondary source also serves as a calibration source having several lines in the spectral region being diagnosed. Several useful calibration sources are discussed in the last section.

The major alignment of the spectrograph is now completed. Before use, however, the spectrograph must be calibrated. Tuning, focusing, dispersion, and resolution data are necessary before useful data can be obtained and interpreted. Calibration of the spectrograph is the subject of the last section and will not be discussed further at this time. Once calibrations have been obtained, the system is ready for use.

All grating spectrographs obey the grating equation,

$$m\lambda = d (\sin \alpha + \sin \beta) \qquad m = 0, \pm 1, \pm 2, \dots$$

where m is the order number of the diffracted beam, d is the spacing between the grooves of the grating (called the grating constant, λ is the wavelength of interest, and α and β are the angles between the normal to the grating surface and the incident and diffracted beams, respectively. For a Littrow spectrograph, $\alpha \approx \beta$, so the grating equation may be rewritten

$$m\lambda = 2d \sin \beta$$

The resolving power, R , of a grating is given by

$$R = \frac{\lambda}{\Delta\lambda} = m N$$

where N is the number of grooves of the grating illuminated by the light source. The linear dispersion, D , is given by

$$D = \frac{dx}{d\lambda} = Mf \frac{d\beta}{d\lambda} = Mf \frac{m}{d \cos \beta}$$

where M is the magnification of the recording system (image converter plus camera) and f is the focal length of the system. Thus both the dispersion and the resolving power increase as the order increases. The usable wavelength range, defined as the range of wavelengths visible on the image converter at any one time, on the contrary, decreases as the dispersion increases.

For any wavelength within the response range of the S-1 photocathode ($.3 \mu < \lambda < 1.1 \mu$), at least three orders may be observed for the standard 600 line per mm. grating. Thus, a number of useful wavelength ranges and corresponding dispersions and resolutions are available for any wavelength to be diagnosed. The nature of the source spectrum and the information desired dictate the order to be used. For example, at 1.06μ , first order ($250 \text{ \AA}$ useful wavelength range) would be necessary to obtain the bandwidth ($\sim 150 \text{ \AA}$) of a self-phase-modulated, mode-locked Nd^{3+} :glass laser pulse while third order ($1.2 \text{ \AA/mm}$ dispersion) would be necessary to obtain the bandwidth ($\sim .2 \text{ \AA}$) of a 100 psec. mode-locked Nd^{3+} :YAG laser with an intracavity etalon.

The large number of observable orders can cause problems. As seen from the grating equation, many combinations of m and λ can satisfy the equation at any given angle. This overlapping of orders makes accurate identification of lines more difficult in many spectrograph systems unless some form of order separation is employed. The wavelength-dependent focusing characteristics of the lens used in the LLL ICS accomplish some order isolation by allowing only one $m\lambda$ combination to be in focus at a time. However, the defocused images from lines in other orders, if present, can cloud the picture and mask details in the desired spectrum. Order separation in the ICS is best achieved by filtering out (using Schott or Corning glass color filters) all wavelengths from the source which could possibly interfere with the desired spectral region. Single-wavelength output makes such filtering unnecessary if laser sources are considered.

Once the wavelength and order to be examined have been chosen, the grating position dial setting to be used is determined by finding the dial setting corresponding to $m\lambda$ on the wavelength tuning curve. Similarly, the lens position dial setting is determined from the focus tuning curve.

The dial settings so obtained are only approximate, due to the necessary coarseness of the tuning curves, however, they are sufficiently close to allow final adjustments, if any, to be made quickly and easily. In fact, the depth of focus of the f/7 spectrograph system is sufficiently large, that further focusing is, in all probability, not necessary. After the focusing and wavelength adjustments have been made, vertical positioning of the spectrum may be necessary. This is accomplished with the adjusting screw at the back of the grating holder. It is useful to remember that the image converter tube inverts the image. Thus, raising the image when viewed (by reflection) on the photocathode corresponds to lowering the image on the phosphor.

Data acquisition from the ICS may be accomplished in two ways, either visually or photographically. The ICS is equipped with a standard C-30A oscilloscope camera with an electronic shutter. This gives the user the option of using either Polaroid (roll or pack) or 2 1/4" by 3 1/4" cut film. Thus, either rapid-feedback spectral monitoring or permanent-record spectrum measurements (suitable for microdensitometry) may be performed with this system. For mode-locked laser bandwidth monitoring, film with ASA 3000 speed is required. Both Polaroid Type 47 and Kodak Royal-X Pan cut film (developed for 10 minutes in DK-50 developer) satisfy this requirement. The operation of the camera is straightforward and needs no further discussion.

Interpretation of the data is a different story. The ICS was aligned so that increasing the wavelength dial setting corresponds to increasing the wavelength at the center of the image converter. However, because of the image-inverting properties of the image converter tube, the wavelength, as viewed on the phosphor output, increases from right to left, instead of the usual left to right. With photographic data, this can be easily corrected by rotating the picture through 180° (i.e., holding Polaroid pictures with the letters at the bottom, instead of top). After rotation, the wavelength increases left to right. In the higher orders, a noticeable slant to the lines will be observed (explanation in Reference 13). When taking microdensitometry measurements of tilted lines, it is essential that the microdensitometer slit be scanned horizontally and not perpendicular

to the lines. Wavelength dispersion occurs in the horizontal direction. Thus, accurate dispersion measurements may be made only with a horizontal scan.

The ICS was designed to allow for easy interchangeability of gratings. This is accomplished by using a separate grating holder for each grating to be used. Once a grating and grating holder have been aligned and the clamp ring tightened, the grating holder may be removed and replaced as often as desired with no effect on the position or quality of the image. The vertical position may be locked by tightening the spring plunger, against the projection on the grating holder and the adjusting screw, until it stops. The dial settings are resettable to within less than ± 0.001 (which corresponds to approximately one milliradian) because care was taken to eliminate backlash and slippage in the design. Thus, after several gratings and their holders have been aligned and any appropriate dial settings recorded, and after the gratings have been interchanged and the dial settings varied any number of times, any particular grating may be reinserted and the dials reset to their original values with no significant differences in the original image position or quality. This feature is quite convenient if frequent monitoring of several different laser systems (each requiring a different grating for optimum monitoring performance) is required.

As was mentioned earlier, calibration is essential for effective operation of the system. A simple procedure for obtaining the necessary calibrations, as well as useful spectral sources, is discussed in the next section.

CALIBRATION OF THE SPECTROGRAPH

As mentioned several times earlier, a number of accurate calibrations are necessary before the ICS may be put to effective use. The following specific calibrations are required: wavelength tuning, focus tuning, dispersion, and resolution.

Light sources for calibration purposes must have special properties. First, they must have discrete line spectra whose wavelengths are well-tabulated and easily identifiable, and second, they must be sufficiently intense that the spectra may be easily recorded. Several sources which are available at LLL have been analyzed with the ICS to determine their useful wavelengths. Table 2 lists the sources examined and tabulates the wavelengths of the lines observed experimentally with the ICS. Many of the lines are very weak, requiring photographic exposures of over a minute in order to be observed, while others are so strong that even at the shortest exposure (1/60 sec.) additional attenuation is required. Yet, all are potentially useful for calibration purposes. Other sources, if available, such as ion lasers, other noble gas or halogen spectral tubes, and iron or carbon arcs, may also be used. Complete wavelength tabulations for a number of atomic and molecular spectral sources are contained in References 14 and 17.

The first step in calibrating the image-converted spectrograph is to obtain the wavelength tuning curve. One point of the curve has already been determined. That is, the $m\lambda = 0$ point (central image) has been preset to dial setting 000.0. A crude approximation to the remainder of the curve is obtained using the He-Ne alignment laser. Five points of the curve may be obtained by centering on the image converter, in succession, each of the five orders of the 6328 Å line and recording the grating position dial settings. Note: the system should be crudely focused by adjusting the lens position dial before attempting these measurements, as a sharp image is more

easily centered. One more point may also be obtained using the He-Ne laser, the $\beta = 90^\circ$ limit. From the grating equation it is seen that when the light enters at grazing incidence and is diffracted straight backwards (i.e. $\alpha = \beta = 90^\circ$), $m\lambda$ is a maximum and is equal to $2d$. This point is obtained by rotating the grating until the laser light just ceases to strike the front of the grating holder (as observed visually through the back door of the spectrograph). At this point the grating surface is parallel to the laser light and the dial setting corresponds to the $\beta = 90^\circ$ limit. These seven points crudely define one quarter-cycle of a sine wave (as the dial setting is proportional to β , the curve is essentially a plot of the grating equation). A more detailed experimental curve may now be obtained by taking several other wavelengths from another source (using the crude tuning curve and the wavelength tables for proper identification of the lines, if necessary) and finding the dial settings at which their various orders are centered on the image converter. Figure 13 shows a wavelength tuning curve obtained using the 6328 Å He-Ne laser line and the 10830 Å triplet from a He spectral tube. A detailed tuning curve may be used to identify the wavelength of any line at the center of the image converter to within ± 20 Å (the larger $m\lambda$ is, the smaller the error becomes) and is essential for accurate identification of spectral lines. More accurate identification can only be made by comparison with tabulated values or by direct interpolation between two lines of known wavelength when all three lines are simultaneously compared.

Because the ICS uses a lens for collimation and focusing, the focal length of the system will be a function of wavelength (chromatic aberration). Thus to obtain sharp lines and minimum linewidths, the system must be re-focused for each different wavelength examined. The focus tuning curve allows this to be done unambiguously and in a minimum of time. A line whose wavelength is known is centered on the image converter, the lens position is adjusted until it appears focused to the naked eye, and the lens position dial setting is noted. Next, the line is photographed at this dial setting and at settings, on each side of this setting, of 25.0 units difference up to a difference of 100.0 units. The dial setting at

which the line appears most in focus is chosen (unless it is the end setting, in which case, photographs should be taken at 25.0 unit intervals for another 100.0 units) and this number recorded. If two of the settings look equally focused, then the midpoint is recorded. This procedure is repeated for a number of lines throughout the entire usable range (ultra-violet to near infrared) and the values plotted (dial setting versus wavelength). The result is the focus tuning curve, a typical result being shown in Figure 14. The large uncertainty in the focal position (about ± 20.0) is due to the finite spatial resolution of the image converter and camera system as well as the large depth of focus of the lens.

Armed with the two tuning curves, one can proceed to calibrate the dispersion and resolution at any wavelength and order desired. The basic procedure is as follows. Once the wavelength and order, at which the calibration is to be made, are chosen, a source (or perhaps two sources) is chosen which has several usable lines in that wavelength region. All of the lines to be used must lie within a usable wavelength range (as defined earlier) of each other. Since a knowledge of the usable wavelength range is obtained only by a measurement of the dispersion, the first choice of source(s) may not be adequate. The usefulness of a source or set of sources may be quickly checked by taking a Polaroid picture of the spectrum. If three or four lines are visible, the source or sources may be used. A picture of these lines is then taken on cut film. If two sources are necessary, the film should be exposed once to the spectrum of each source with no adjustments other than rotating the turning mirror. This film is then developed, microdensitometered, and each of the peaks identified as to wavelength. The slope of the straight line portion of a plot of wavelength versus position on the film gives the dispersion. Note: the dispersion is usually tabulated as its reciprocal, $1/D$, in $\text{\AA}/\text{mm}$.

Dispersion data may be taken, in the manner described above, at a number of wavelengths in each order and curves of dispersion versus wavelength plotted for each order. However, this is an extremely time-consuming project and may not be necessary. If the spectrograph is to be used solely for laser

bandwidth monitoring, dispersion data is needed only at the laser wavelength for each order. The result is a considerable reduction in effort. Additional dispersion information may always be obtained later if it is needed.

Resolution determinations require the use of a CW laser or other narrow linewidth source ($\Delta\lambda < .01 \text{ \AA}$). The spectral tubes mentioned earlier, are sources, and pulsed lasers all have linewidths which are too large to accurately determine the instrumental linewidth of the spectrograph. The instrumental linewidth is defined as the linewidth that would be observed if a pure monochromatic light source ($\Delta\lambda = 0$) were analyzed. The observed linewidth is the convolution of the true linewidth with the instrumental linewidth. Functionally, this may be written

$$I_{\text{obs}}(\lambda) = \int I_{\text{true}}(\lambda') g(\lambda' - \lambda) d\lambda'$$

where I_{obs} and I_{true} are the observed and true envelopes of the spectral line and g is the instrumental response function. For gaussian functions, this reduces to

$$\Delta\lambda_{\text{obs}}^2 = \Delta\lambda_{\text{true}}^2 + \Delta\lambda_{\text{inst}}^2$$

Thus, as long as $\Delta\lambda_{\text{true}} \ll \Delta\lambda_{\text{inst}}$, then $\Delta\lambda_{\text{obs}} \approx \Delta\lambda_{\text{inst}}$. If the linewidth, $\Delta\lambda$ is uniformly defined as the full-width-at-half-maximum-intensity (FWHM), then $\Delta\lambda_{\text{inst}}$ is equal to the resolution and $\lambda/\Delta\lambda_{\text{inst}}$ is the resolving power. That is, two very narrow lines, which are separated in wavelength space by $\Delta\lambda_{\text{inst}}$, will be barely resolved.

Values for the instrumental linewidth, and thus the resolution, may be obtained in the following manner. The line from a CW laser is photographed on a piece of cut film. Before developing this film, a photographic stepwedge with a P-20 (or P-11, if P-20 is unavailable) phosphor simulation filter is exposed on another piece of cut film of the same age and handling history. This will be done by Tech Photo upon request. The stepwedge and

the spectrum are then developed simultaneously. From a microdensitometer trace of the stepwedge, a D-log E curve (film density versus $\log_{10}$ of the exposure) is obtained. This may be used to determine the half-maximum intensity points on the microdensitometer trace of the laser line. The product of the distance between the two half-maximum intensity points (mm) and the reciprocal dispersion ($\text{\AA}/\text{mm}$) is the linewidth, $\Delta\lambda_{\text{inst}}$. As in the case of dispersion data, complete resolution versus wavelength curves are difficult to obtain. This is due not only to the time involved but also to the large number of different lasers required.

At the present time, the lasers (in the visible and near infrared) most under study at the laboratory are ruby and Nd^{3+} . A neon spectral tube provides a good dispersion calibration at the ruby wavelength while either an argon spectral tube or a 1.08μ He-Ne laser plus a He spectral tube accomplishes the same function near the Nd^{3+} wavelength. Resolution near the ruby line can be obtained by using the $6764 \text{\AA}$ line of a krypton ion laser while resolution near the Nd^{3+} line can be obtained by using either an etalon-narrowed CW Nd^{3+} :YAG laser or the 1.08μ He-Ne laser. Both the dispersion and the resolution, in any one order, are slowly varying functions of wavelength. Thus, calibrations made at wavelengths within one or two hundred Angstroms of the desired wavelength will be accurate to within a few percent.

For specialized spectroscopic studies, other calibrations such as absolute wavelength sensitivity, diffraction efficiency as a function of grating angle, and even film reciprocity data may be needed. However, the need for these calibrations is so rare and the techniques used to obtain these calibrations are so difficult, that they are beyond the scope of this report and will not be mentioned further.

TABLE 2

USEFUL SPECTRAL SOURCES AND OBSERVED WAVELENGTHS

Source	Wavelength ($\text{\AA}$)
He-Ne Laser	6328.19
He-Ne Laser	10798.12 10844.54
He spectral tube	3888.65 4471.48 4685.38 4685.71 4685.92 5015.68 5875.62 5875.97 6559.77 6560.10 6560.21 6678.15 7065.19 7281.35 10829.09 10830.25 10830.34
Hg spectral tube	3650.15 4046.56 4358.33 5460.73 5789.66 10139.79
H spectral tube	4101.74 4340.47 4861.33 6562.73 6562.85

Source	Wavelength ($\text{\AA}$)
Ne spectral tube	5330.78 5341.09 5343.28 5400.56 5764.42 5820.15 5852.49 5881.89 5944.83 5965.47 5974.63 5975.53 6030.00 6074.34 6096.16 6143.06 6163.59 6217.28 6266.49 6304.79 6334.43 6382.99 6401.08 6402.25 6506.53 6532.88 6598.95 6678.28 6717.04 6929.47 7024.05 7032.41 7059.11

TABLE 2
(Continued)

Source	Wavelength (Å)
Ne spectral tube (Continued)	7173.94
	7245.17
	7438.90
	7472.43
	7488.87
	7535.77
	7544.05
	7839.08
	7937.01
	7943.18
	8082.46
	8118.55
	8136.41
	8259.38
	8266.08
	8300.33
	8301.54
	8365.75
	8376.41
	8377.61
	8417.18
	8418.43
	8463.37
	8495.36
	8571.36
	8591.26
	8634.65
	8647.05
	8654.38
	8679.49
	8681.92
	8704.15
	8771.70
	8780.62
	8783.75
	8853.87

Source	Wavelength (Å)
Ne spectral tube (Continued)	8865.33
	8865.76
	8919.50
	8988.58
	9148.68
	9201.76
	9200.05
	9221.59
	9226.67
	9300.85
	9310.58
	9313.98
	9326.52
	9373.28
	9425.38
	9459.21
	9486.68
	9534.17
	9547.40
	9665.42
	10562.43
	10798.12
	10844.54
	11143.09
	11177.59
	11390.53
	11409.24
	11522.82
	11525.11
	11536.41
	11614.18
	11766.87
	11789.11
	11789.93

Wavelength Tuning Curve for the LLL Image-Converted Spectrograph

Figure 13

Focus Tuning Curve for the LLL Image-Converted Spectrograph

Figure 14

REFERENCES

For those desiring further information on gratings and grating spectrographs and their applications, the following references may be useful.

1. M. Born and E. Wolf, Principles of Optics (Pergamon Press, London, 1964), pp. 401-404.
2. G. A. Boutry and R. Auerbach, Instrumental Optics (Interscience, New York, 1962), pp. 512-535.
3. C. Candler, Modern Interferometers (Hilger-Watts Ltd., Glasgow, 1951), pp. 256-288, 345-456.
4. G. L. Clark, The Encyclopedia of Spectroscopy (Reinhold Publishing Co., New York, 1960), pp. 173-188.
5. S. P. Davis, Diffraction Grating Spectrographs (Holt-Rinehart-Winston, New York, 1970). This reference contains a bibliography of several hundred journal articles on various aspects of diffraction grating spectroscopy.
6. Diffraction Grating Handbook, Bausch and Lomb Analytical Systems Division, Rochester, New York (1970).
7. R. C. Harney, "An Inexpensive Image-Converted Spectrograph for Monitoring Mode-Locked Laser Bandwidths", (UCRL in preparation).
8. G. R. Harrison, R. C. Lord, and J. R. Loofbourow, Practical Spectroscopy (Prentice-Hall, Englewood Cliffs, 1948), pp. 27-50, 71-95.
9. F. Jenkins and H. White, Fundamentals of Optics (McGraw-Hill Book Company, New York, 1957), pp. 328-352, 422-445.
10. D. O. Landon and A. J. Mitteldorf, "The Diffraction Grating", The SPEX Speaker, 10 #3 (1965).
11. D. O. Landon and A. J. Mitteldorf, "The Diffraction Grating II", The SPEX Speaker, 17, #1 (1972).
12. C. F. Meyer, The Diffraction of Light, X-rays, and Material Particles (J. W. Edwards, Ann Arbor, 1949), pp. 112-278, 430-448.
13. R. Minkowski, "Curvature of the Lines in Plane-Grating Spectra", The Astrophysical Journal, 96, #2, pp. 306-308 (1942).
14. K. Rao, C. Humphreys, and D. Rank, Wavelength Standards in the Infrared (Academic Press, New York, 1966).

15. R. A. Sawyer, Experimental Spectroscopy (Prentice-Hall, Englewood Cliffs, 1944), pp. 18-49, 127-192.
16. G. W. Stroke, "Diffraction Gratings", Handbuch der Physik, Vol. XXIX (Springer-Verlag, New York, 1967), pp. 426-754.
17. A. N. Zaidel', V. K. Prokof'ev, S. M. Raiskii, V. A. Slavnyi, and E. Ya. Shreider, Tables of Spectral Lines (IFI/Plenum, New York, 1970).

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