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Reduce Fluid Experiment System Flight Data from IML-1

by

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16. Abstract

Processing and data reduction of holographic images from IML-1 presents some interesting challenges in determining the effects of microgravity on crystal growth processes. Use of several processing techniques, including the Computerized Holographic Image Processing System and the Software Development Package (SDP-151) will provide fundamental information for holographic and schlieren analysis of the space flight data.

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BACKGROUND

The Fluid Experiment System (FES) is a Marshall Space Flight Center flight experiment facility, dedicated to the analysis of crystal growth experiments aboard the space shuttle. FES materials are grown from seed crystals placed in cell chambers filled with liquid growth solution. The cells are installed in a Spacelab double rack and controlled with standard facilities such as power, avionics, air and water, and the results from the forming crystal are recorded with holograms taken at chosen time intervals.

The Holographic Ground System (HGS) at Marshall Space Flight Center is the FES ground support facility for studying solidification processes and fluid dynamics of the crystals by applying optical techniques to the flight holograms. It consists of a 5ft X 16ft air-suspended isolation table, with a vibration damping of >50 Hz, located in a lightproof room. The table is outfitted with mirrors, beamsplitters, various lenses, and a 50 mW HeNe laser that provide holographic reconstruction of the flight data. The HGS also includes a camera system used for imaging and computer equipment used for image processing and recording. The camera is mounted on a high resolution x-y-z translation mount which has an accuracy of 1μ per inch of travel, 5 arcseconds of orthogonality, and maximum deviation of 2μ per 10 cm of travel. The image processing system includes Imaging Technology, Inc. Series 151 software and hardware as well as the Computerized Holographic Image Processing program that allows for recording of the flight data.

TGS EXPERIMENT

Objectives of the triglycine sulfate [$(NH_2\ CH_2\ COOH)_3\ H_2SO_4$] (TGS) experiment were as follows: characterization of the growth environment; identification of fluid convection components from crystal growth, residual microgravity, and g-jitter; and correlation of these components with other events in order to further characterize the space shuttle environment and its effects on crystal growth. The primary objective, according to principle investigator Dr. Jim Trolinger, was to "provide a measure of the concentration and concentration gradients in the vicinity of the crystal to support modeling and to help explain the properties of the resulting crystal."

Advantages of the TGS crystal are its ability to operate at room temperature and its ability to detect light wavelengths in the visible and in the infrared range. It does, however, have a slow growth rate which makes it highly susceptible to gravitational influences. It is hoped that in the future researchers will be able to minimize this imperfection by placing the seed in the near convection-free space environment.

In order to characterize the microgravity environment, small spheres were added to the fluid surrounding the crystal seed. They were then tracked and recorded in order to study the particle motion that occurred during a particular time in the experiment. This is known as particle image displacement velocimetry. Researchers hoped that the particles accurately tracked the flow of the fluid in the cell. The diameters chosen were: 199μ, 383μ, and 646μ. These sizes enabled researchers to distinguish each particle from another. The total number of spheres added to the fluid was 26983. Even though the large quantity of particles provided researchers with measurable data, they caused tracking difficulties during shuttle maneuvers.

Dr. Trolinger also decided to incorporate holographic optical elements (HOE's) on the left and right sides of the test cell in order to allow viewing of the crystal at three different angles. One view was straight through the center of the cell, while the other two were at +/- 23.5°.

EXPERIMENTAL APPROACH

Non-diffuse and diffuse holograms were produced from direct laser light passing through the cell and from diffuse laser light passing through the cell. From the experiment, Run 1A contributed 114 holograms; Run 1B contributed 133 holograms; and Run 1C contributed 136 holograms. The nature of this contract consisted of reducing the Run 1C diffuse and non-diffuse holograms. The following five tasks were completed during this contract: 1) angular registration was observed and noted at the top and bottom of the left HOE edge between seven diffuse holograms; 2) particles were tracked behind the HOE's from bottom to top of cell for the non-diffuse holograms; 3) seven sets of particle triplets were tracked for the diffuse holograms; 4) particles were tracked from the side view of the HOE's (showing the center image of the crystal) for the non-diffuse holograms; and 5) images were recorded from the diffuse holograms, following the same procedure as in the previous contracts.

The first task consisted of registering six or seven holograms in the normal manner and noting angular registration changes. These changes showed the amount of error involved in recording the holograms. The holograms used were randomly chosen from the diffuse holograms of Run 1C. The left HOE was lined up to the left side of the monitor and recorded as "H1B," the "bottom of the first hologram." Approximately 5000 steps were moved in the y-direction. From here, the top portion of the left HOE was lined up using real-time subtraction, while the change in position was noted. Appendix A shows the entire procedure for this task. To researchers, the changes in position were shown to be minimal.

The second task involved recording the left side HOE images from the non-diffuse holograms. Particles were tracked in the y-direction in each of the holograms. This resulted in seven images being recorded for each hologram, starting from the bottom and moving to the top of the hologram. Appendix A shows the procedure for this task.

The third task involved recording seven sets of particle triplets, tracked throughout the entire run. In the first set of triplets, one large particle and two small particles approximately orthogonal to each other was tracked, with the particles kept in the same position on the monitor. Dr. Trolinger and Dave Weber decided that it would be best to track one small and two large particles constantly moving in the hologram to accurately depict the fluid movement. This method was used for the remaining particle triplets. The sets of triplets can be found in Figure 1 of Appendix B. A log sheet of the skipped holograms with the crystal sting references can also be found in Appendix B.

The fourth task involved tracking the left side view of the HOE from the non-diffuse holograms. Six images were recorded of the diffracted light from the left HOE. One thousand steps in the y-direction were moved in order to obtain the six images requested. The procedure used can also be found in Appendix A.

Finally, the last task consisted of recording the diffuse images of the holograms of Run 1C. The procedure used was identical to the procedure used in the past. Appendix A contains the procedure for recording those images.

In addition to the above performed tasks, an equipment inventory was prepared and can be found in Appendix C. This is a list of the equipment acquired by FES to aid in the Holographic Ground System research. It will serve as a document for future reference. Specifications of some of the equipment utilized can be found in Appendix D.

The main procedure used for initialization of the CHIP system is discussed in following pages.

SET-UP PROCEDURE (INITIALIZATION)

Due to storage problems with the optical disk, all of the recorded images were saved on Bernoulli disks and then sent directly to Dr. Trolinger and Dave Weber of MetroLaser for their viewing. All of the above tasks were completed by using the Computerized Holographic Image Processing (CHIP) program to record the images on computer files for velocity/acceleration data. The following modified steps were required to initialize the CHIP program:

1. MAKE A DIRECTORY OF EACH HOLOGRAM. Keeping a directory is important so that the image files are not overwritten. The directory name contains the number of the hologram, for example HOE126. Each image is stored into one file in this directory, the filename referring to its location in the image matrix. The filename is in the form *vertical position.angle*, where the *vertical position* is the matrix y-value, and the *angle* denotes the matrix x-value and focus position.

2. FIND THE REFERENCE POINT. This step requires focusing on the middle plane, then finding the appropriate starting point on the plane.
   - Use the joystick manually to position the sting at approximately the monitor's center in order to offer a "good" sting view;
   - To focus, flip the x-axis dial to FOCUS and move the joystick in the positive or negative x-direction. The camera is now set at the "B" or middle plane;
   - Flip the x-axis dial back to HORIZONTAL and position the camera on the left HOE.

3. INITIALIZE THE CHIP PROGRAM FOR USE. This step connects the CHIP program to the UNIDEX and prepares the files for storing the images.

- On the UNIDEX, press RESET so that the display reads SYS RDY;
- While in the hologram's directory, type CHIP to enter the CHIP program;
- Once in the CHIP program, press UDX ONLINE to connect the program to the UNIDEX;
- Press HOLO CODE and enter the six digits of the hologram name, for example 1CP126;
- Press ANGLE and enter the appropriate angle (1A, HO1, LH1, etc.)
- Move the camera to the desired plane. In this case it is already centered in the "B" plane (middle).

There are separate procedures for the previously mentioned tasks. They can be located in Appendix A. At the conclusion of each procedure, the film must be replaced with the next succeeding hologram.

CONCLUSIONS

Hopefully, from the study of the images, researchers can gain better knowledge of particle motion and crystal growth in low-gravity environments. They hoped to do so by incorporating holographic optical elements into the cell to provide three different angles in which to observe particle movement. From previous images, researchers concluded that g-jitter was possibly a function of time and spatial coordinates. With the images from the holographic optical element area, researchers can use the new angles provided to correlate them with the previous sets of holographic images in order to gain a 3-D view of the cell and its environment. Figures 1, 2, and 3 of Appendix E show the 3-D view of the cell that researchers are studying, while Appendix F shows the HGS optical bench and system layout used to reconstruct and record the cell images.

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APPENDIX A

IMAGE ACQUISITION PROCEDURES

<u>ANGULAR REGISTRATION PROCEDURE FOR HOLOGRAMS 2T1CP197-2T1CP216</u>

Place hologram 2T1CP197 onto the film holder.
Line up left HOE with the left side of the monitor.
Record the image.
Save bottom image as "H1B."
Move Y approximately 5000 steps (1 step = 5 μm).
Save top image as "H1T."
Return to bottom.
Align hologram 2T1CP200 to "H1B."
Note X,Y registration difference.
Save as "H2B."
Move Y approximately 5000 steps.
Align hologram 2T1CP200 to "H1T."
Note X,Y registration difference.
Save as "H2T."
Return to bottom.
Repeat the above steps until hologram 2T1CP216 is reached.

IMAGE ACQUISITION PROCEDURE FOR THE LEFT HOE IMAGES FROM THE RUN 1C NON-DIFFUSE HOLOGRAMS

Using the UNIDEX, move the camera to the reference point on the image. While in the appropriate directory, enter the CHIP program. If the camera is not in the correct plane of focus, move to it now.

CM TRANSLATION
HOLOCODE
ANGLE HO1
AUTOGRAB
INC X -4700
INC Y 1905
GO
INC X 0
INC Y -1162
GO
ANGLE HO2
INC Y -1162
GO
ANGLE HO3
INC Y -1162
GO
ANGLE HO4
INC Y -1162
GO
ANGLE HO5
INC Y -1162
GO
ANGLE HO6
INC Y -1162
GO
ANGLE HO7
INC Y -1162
GO
AUTOGRAB OFF
RESET X,Y
AUTO UNIDEX OFF
UNIDEX ONLINE OFF
EXIT
EXIT

IMAGE ACQUISITION PROCEDURE FOR THE "DIFFRACTED LIGHT" LEFT HOE IMAGES FROM THE RUN 1C NON-DIFFUSE HOLOGRAMS

Using the UNIDEX, move the camera to the reference point on the image. While in the appropriate directory, enter the CHIP program. If the camera is not in the correct plane of focus, move to it now.

```
CM TRANSLATION
HOLOCODE
ANGLE LH1
INC X 900
INC Y 0
GO
INC X 0
INC Y -1000
GO
ANGLE LH2
INC Y -1000
GO
ANGLE LH3
INC Y -1000
GO
ANGLE LH4
INC Y -1000
GO
ANGLE LH5
INC Y -1000
GO
ANGLE LH6
INC Y -1000
GO
AUTOGRAB OFF
RESET X,Y
AUTO UNIDEX OFF
UNIDEX ONLINE OFF
EXIT
EXIT
```

IMAGE ACQUISITION PROCEDURE FOR THE RUN 1C DIFFUSE HOLOGRAMS

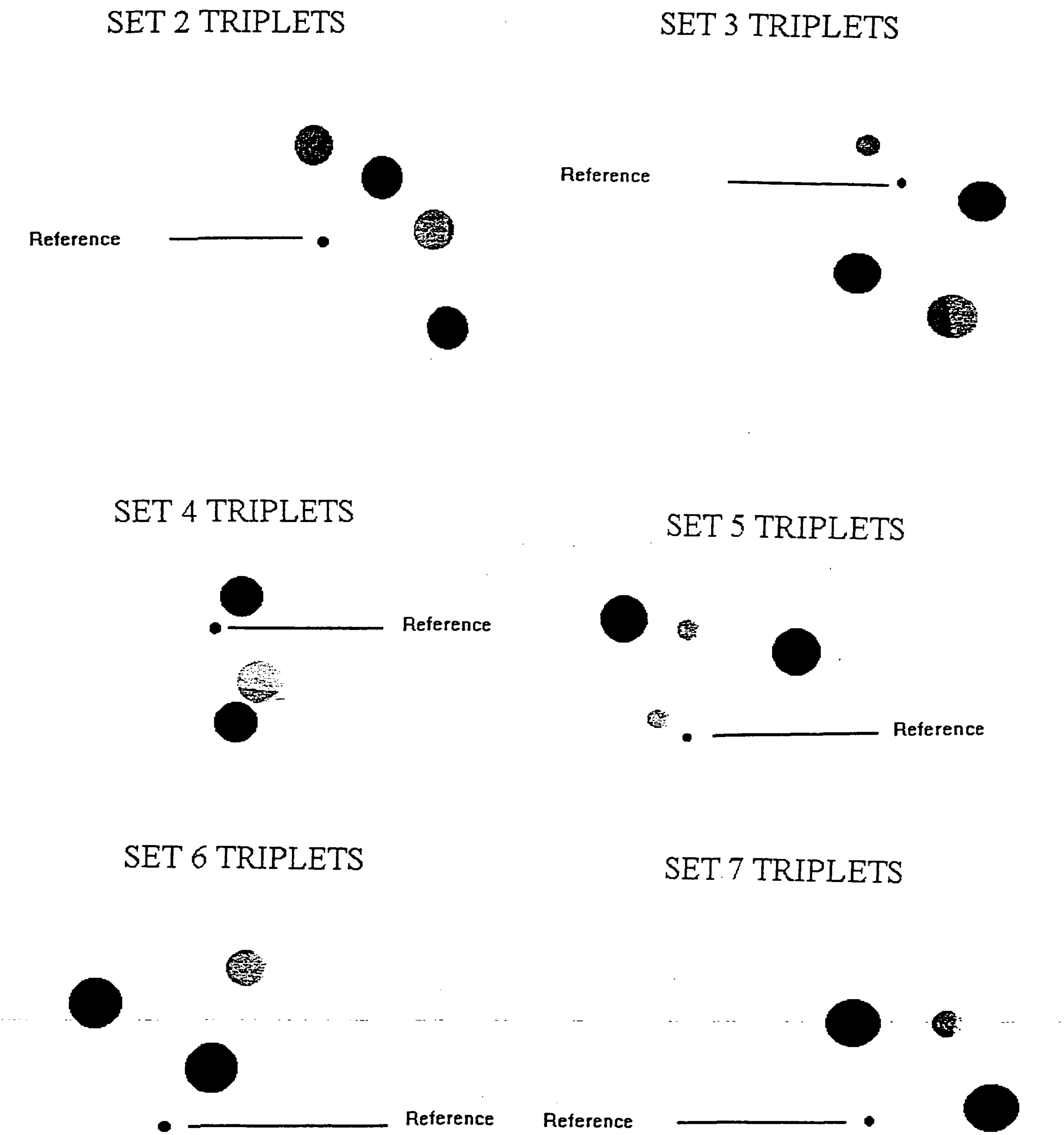
Using the Unidex, move the camera to the reference point on the image.
While in the appropriate directory, enter the CHIP program.
If the camera is not in the correct plane of focus, move to it now.

CM TRANSLATION
HOLOCODE
ANGLE 1B
AUTOGRAB
INC X 500
GO
INC X 0
INC Y -1405
GO (4 TIMES)
ANGLE 2B
INC X 1827
INC Y 0
GO
INC X 0
INC Y 1405
GO (4 TIMES)
ANGLE 3B
INC X 1827
INC Y 0
GO
INC X 0
INC Y -1405
GO (4 TIMES)
AUTOGRAB OFF
RESET X,Y
AUTO UNIDEX OFF
UNIDEX ONLINE OFF
EXIT
EXIT

APPENDIX B

PARTICLE TRIPLETS DRAWINGS AND DATA

Figure 1


SET 2 TRIPLETS
Reference
SET 3 TRIPLETS
Reference
SET 4 TRIPLETS
Reference
SET 5 TRIPLETS
Reference
SET 6 TRIPLETS
Reference
SET 7 TRIPLETS
Reference

TRIPLETS LOG SHEET

SET 1

Skipped Holograms:

2T1CP090 -cut in half

SET 2

Skipped Holograms:

2T1CP090 -cut in half
2T1CP174 -could not locate small sphere
2T1CP180 -too dark
2T1CP197 -could not locate small sphere

Sting Reference:

2T1CP126 -> X = 0, Y = 1119
2T1CP171 -> X = 0, Y = 1119
2T1CP185 -> X = 0, Y = 1119

SET 3

Skipped Holograms:

2T1CP090 -cut in half

Sting Reference:

2T1CP126 -> X = 0, Y = 843
2T1CP171 -> X = 0, Y = 843
2T1CP210 -> X = 0, Y = 843
2T1CP231 -> X = 0, Y = 843

SET 4

Skipped Holograms:

2T1CP078 -too dark
2T1CP132- 2T1CP246 -impossible to locate small sphere

Sting Reference:

2T1CP126 -> X = 2113, Y = 5619

SET 5

Skipped Holograms:

NONE

Sting Reference:

2T1CP099 -> X = -1443, Y = 1413
2T1CP126 -> X = -1276, Y = 1228
2T1CP185 -> X = -823, Y = 1153

SET 6

Skipped Holograms:

NONE

Sting Reference:

2T1CP138 -> X = -338, Y = 4508
2T1CP222 -> X = -1922, Y = 4578
2T1CP240 -> X = -2036, Y = 4568

SET 7

Skipped Holograms:

2T1CP188 -too dark

Sting Reference:

2T1CP105 -> X = -5653, Y = 4437
2T1CP132 -> X = -5473, Y = 4513
2T1CP182 -> X = -5346, Y = 4484
2T1CP225 -> X = -5457, Y = 4513

APPENDIX C

EQUIPMENT LIST

Pages Missing From Available Version:

A11 through A14

Table Optics Specifications

COMPONENT	SIZE	FLATNESS	INCIDENT ANGLE	WEDGE ANGLE	FRONT COATING	BACK COATING	TRANSMISSION	REFLECTANCE
Mirror 1	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 5	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 10	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 11	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 12	8"D x 1.25"th	λ/20	22.5°	<10 min	Dielectric	-	-	>98%
Mirror 6	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Spare Mirror 3	8"D x 1.25"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 4	6.25" x 4.5" x 1.0"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 3	6.25" x 4.5" x 1.0"th	λ/10	26°	<10 min	Dielectric	-	-	>98%
Spare Mirror 2	6.25" x 4.5" x 1.0"th	λ/20	45°	<10 min	Dielectric	-	-	>98%
Mirror 2	6.325"D x 1"th	λ/20	11°	<10 min	Dielectric	-	-	>98%
Spare Mirror 1	6.325"D x 1"th	λ/20	11°	<10 min	Dielectric	-	-	>98%
Beamsplitter 1	9"D x 1.25"th	λ/20	45°	<10 min	Dielectric	AR "V"	50%	50%
Beamsplitter 3	9"D x 1.25"th	λ/20	45°	<2 sec	Dielectric	AR "V"	50%	50%
Beamsplitter 2	6.325"D x 1"th	λ/20	8°	<10 min	Dielectric	AR "V"	50%	50%
Beamsplitter 4	9"D x 1.25"th	λ/20	45°	<2 sec	Dielectric	AR "V"	25%	75%

AR "V" : a multilayer antireflective coating that reduces the reflectance to near-zero for one specific wavelength

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NEWPORT EQUIPMENT SPECIFICATIONS

Model 675T Beam Steering Instrument

Fine Elevation Angle Range:	-20° to +7°
Elevation Angle Resolution:	15 arc sec
Fine Azimuth Angle Range:	15°
Azimuth Angle Resolution:	8 arc sec

Model AMB-2 Adjustable Mounting Base

Translation Ranges:	Top Plate:	0.5 in (13 mm)
	Slotted Base Plate:	1.75 in (45 mm)

Model 400 Dual-Axis Translation Stage

Orthogonality:		1 mrad
Runout:		< 5 μm
Load Capacity:	Horizontal:	100 lb (45 kg)
	Vertical:	8 lb (3.6 kg)

Model 420-1S Translation Stage

Stage Travel:	1 in (25 mm)
Runout:	< 5 μm
Load Capacity:	66 lb (30 kg)

Model 36-S Tilt Platform

Tilting Range:	-4.3° to +7°
Rotation Range:	+/- 2.5°
Resolution:	2 arc sec

Model 496 Precision Power Rotary Table

Resolution:	0.001°
Accuracy:	0.01°
Backlash:	< 30 arc sec
Load Capacity:	350 lbs (160 kg)
Stall Torque:	3500 in-lb (3977 kg-cm)

Model 280 Laboratory Jack

Range:	3-6 in (75-152 mm)

Model 845 Digital Shutter System

Shutter Aperture:		5.6 mm
Shutter Response Time:		< 3 ms
Exposure Duration:		10 ms - 990 s
Timing Accuracy:		0.05% +/- 10 us
Max. Repetition Rate:		10 Hz
Operating Modes:		
	TIME:	Timed shutter opening
	MANUAL:	Open & close shutter independent of time setting
	START:	Initiates timed or manual exposure
	RESET:	Closes shutter
	DELAY:	Optional 10 s delay before shutter opening
Pushbutton Cable:		96 in (2.44 m)
Power:		115 V @ 0.1 A or 230 V @ 0.05 A
Controller Dimensions:		3.25 X 6 X 6.25 in

Model 20Z20 Round Zerodur Mirror

Diameter:	2.000 in (50.80 mm)
Thickness:	0.500 in (12.70 mm)
E_{MAX}:	$\lambda/20$
Scratch & Dig:	15-5

Model 40Z20 Round Zerodur Mirror

Diameter:	4.000 in (101.60 mm)
Thickness:	0.6907 in (17.70 mm)
E_{MAX}:	$\lambda/20$
Scratch & Dig:	20-10

Model 520 Film Plate Holder

Capability:	Holds plates up to 5 in. (127 mm) wide

Newport Model 815 Power Meter

READOUT

Meter:	3-1/2 digit LCD with LO BAT
Ranges:	0.002, 0.02, 0.2, and 2 mW
Accuracy:	+/- 5% NBS traceable absolute radiometric accuracy
Repeatability:	+/- one digit
Linearity:	+/- one digit
Analog Output:	rear panel connector provides 1.999 V full scale; Output Impedance- 10K ohm
Analog Output Bandwidth:	180 KHz
Power:	9 V supplied by six AA alkaline cells with nominal 300 hour life
Case:	3.25" H x 6.06" W x 6.25" D

DETECTOR

Spectral Response:	400 nm - 1060 nm
Active Area:	1 cm^2 effective aperture
Maximum Continuous Input:	100 mW/cm^2
Responsivity:	35 mA/W typical @ 850 nm
Risetime:	170 nanoseconds
Acceptance Angle:	(at 5% fall off) +/- 45° (no filter) +/- 12.5° (with filter)
Cable:	96" BNC

ORIEL EQUIPMENT SPECIFICATIONS

Model #1625 Precision Translator

Range:	25 mm w/graduations every 0.01 mm
Resolution:	0.25 μm

Model #1636 Precision Vertical Translator

Range:	25 mm w/graduations every 0.01 mm
Resolution:	0.25 μm

Model #1643 Precision Rotator

Coarse Adjust:	360°
Micrometer Sine Drive Range:	24° w/graduations every 0.55 arc min
Resolution:	1 arc sec

ROLYN OPTICS EQUIPMENT SPECIFICATIONS

Model 20.0109 Achromat

Diameter:	21.0 mm
Focal Length:	40.0 mm
Center Thickness:	7.8 mm
Edge Thickness:	3.0 mm
Scratch & Dig:	80-50
Centration:	3 arc min

Model 20.0255 Achromat

Diameter:	37.0 mm
Focal Length:	120.0 mm
Center Thickness:	10.2 mm
Edge Thickness:	7.0 mm
Scratch & Dig:	80-50
Centration:	3 arc min

Model 20.0310 Achromat

Diamter:	31.7 mm
Focal Length:	220.0 mm
Center Thickness:	8.0 mm
Edge Thickness:	6.1 mm
Scratch & Dig:	80-50
Centration:	3 arc min

AEROTECH EQUIPMENT SPECIFICATIONS

Model ATS100-200 Positioning Stage Specifications

Total Travel:		200 mm (8 in)	
Mechanical Drive System:		Precision ground ballscrew	
Linear Resolution (2 mm lead):		1 μm (40 μin) @2000 steps/rev motor resolution (0.1 μm to 10 μm available)	
Max. Travel Speed:	Stepping Motor	50 mm/sec (2 in/sec)	
	DC Servo Motor	100 mm/sec (4 in/sec)	
	HAL Option	25 mm/sec (1 in/sec)	
Max. Load Carrying Capability:			
	Horizontal	22.7 kg (50 lbs)	
	Vertical	10.0 kg (22 lbs)	
	Side	11.4 kg (25 lbs)	
Accuracy:	Standard	+/- 6 μm (+/- 240 μin)	
	HAL Option	+/- 1 μm (+/- 40 μin)	
Repeatability:	Standard	+/- 0.7 μm (30 μin) bi-directional	
	HAL Option	+/- 0.3 μm (12 μin) bi-directional	
Straightness and Flatness of Travel:			
		Standard	HAL
	Differential	2 μm/25 mm	1 μm/25 mm
	Maximum Deviation	+/- 3 μm	1.75 μm
Nom. Stage Weight:	W/out Motor	1.2 kg (2.6 lbs)	
	W/ Motor	2.8 kg (6.1 lbs)	

Model AOM 110-2 Gimbal Optical Mount

Resolution:	0.15 arc sec
Clear Aperture:	1.82 in
Range:	+/- 5°
Diameter:	2.00 in
Thickness:	0.50 in

Model AOM 110-4 Gimbal Optical Mount

Resolution:	0.08 arc sec
Clear Aperture:	3.75 in
Range:	+/- 5°
Diameter:	4.00 in
Thickness:	0.75 in

Model 110-6 Gimbal Optical Mount

Resolution:	0.06 arc sec
Clear Aperture:	5.68 in
Range:	+/- 4°
Diameter:	6.00 in
Thickness:	1.18 in

Model 110-8 Gimbal Optical Mount

Resolution:	0.044 arc sec
Clear Aperture:	7.63 in
Range:	+/- 4°
Diameter:	8.00 in
Thickness:	1.59 in

Model 130-9 Gimbal Optical Mount

Resolution:	0.031 arc sec
Clear Aperture:	8.62 in
Range (rotational freedom):	360° azimuth & elevation
Diameter:	9.00 in
Thickness:	1.63 in

Model 130-9M Motor-driven Gimbal Optical Mount

Resolution:	0.188 arc sec
Clear Aperture:	8.62 in
Range:	360° azimuth & elevation
Repeatability:	0.75 arc sec
Diameter:	9.00 in
Thickness:	1.63 in

Model ATT 185-5 Precision Tilt Table

Range:		+/- 10°
Resolution:		0.1 arc sec
Load Carrying Capability		
	Horizontal:	10 lbs (4.54 kg)
	Vertical:	10 lbs (4.54 kg)
Weight:		3.1 lbs (1.41 kg)

Model ARS 301 Rotary Positioning Table

Resolution:		0.1 arc sec
Load-Carrying Capability		
	Horizontal:	25 lbs (11.36 kg)
	Vertical:	15 lbs (6.82 kg)
Clear Aperture:		2.68 in

Model ATS 303M ACCUDEX Series Positioning Stage

Range:		76.2 mm
Resolution:		0.025 µm
Window:		82.5 mm X 50.8 mm
Load Carrying Capability		
	Horizontal:	22.73 kg
	Vertical:	9.09 kg
Linear Scales & Vernier:		0.02 mm

Model ATS 302MM ACCUDEX Series Linear Positioning Stage

Range:		50 mm
Resolution:	200 steps/rev:	2 µm
	400 steps/rev:	1 µm
Load carrying Capability		
	Horizontal:	45.5 kg
	Vertical:	9 kg
Repeatability:		0.6 µm
Accuracy:		2.5 µm /25 mm
Straightness & Flatness of Travel:		2.5 µm /25 mm
Maximum Allowable Motor Speed:		10 rev/sec

Spectra Physics Model 125A 50 mW HeNe Laser Specifications

OUTPUT

Wavelength:	632.8 nm
Power (TEM_{00}):	50 mW

BEAM CHARACTERISTICS

Beam Diameter ($1/e^2$):	1.8 mm
Beam Divergence:	0.6 mrad

OPTICS

Output Mirror:	G3814-001
High Reflector:	G0005-003

RESONATOR CHARACTERISTICS

Transverse Mode:	TEM_{00}
Degree of Polarization:	1×10^3
Angle of Polarization:	Vertical +/- 5°
Resonator Configuration:	Long radius
Cavity Length:	177 cm
Axial Mode Spacing:	85 MHz
Plasma Excitation:	DC:25-35 mA @ 6kV RF Option: 15 W @ 40.68 MHz

AMPLITUDE STABILITY

Beam Amplitude Noise (1-100 kHz):	2% rms (0.3% w/RF option)
Beam Amplitude Ripple (1-120 kHz):	0.5% rms (0.5% w/ RF option)
Long Term Power Drift:	< 5% over 8 hours
Warm-up Time:	1 hour

ENVIRONMENTAL CAPABILITY

Operating Temperature:	10°C-40°C (50°F-105°F)
Altitude:	Sea level to 3000 m (10,000 ft)
Humidity:	Below dew point

POWER REQUIREMENTS

Voltage:	115/230 V +/- 10%, 50-60 Hz
Power:	450 W

PHYSICAL CHARACTERISTICS

Weight:	Laser Head:	45.5 Kg (100 lb)
	Power Supply:	13.6 Kg (30 lb)
Shipping Weight:		79.5 Kg (175 lb)
Dimensions:		6 x 13 x 18 in. 152.4 x 330.2 x 457.2 mm
Cable Length (Power Supply to Laser):		1.8 m (6 ft)

APPENDIX E

HOE DRAWINGS

Full View of Cell

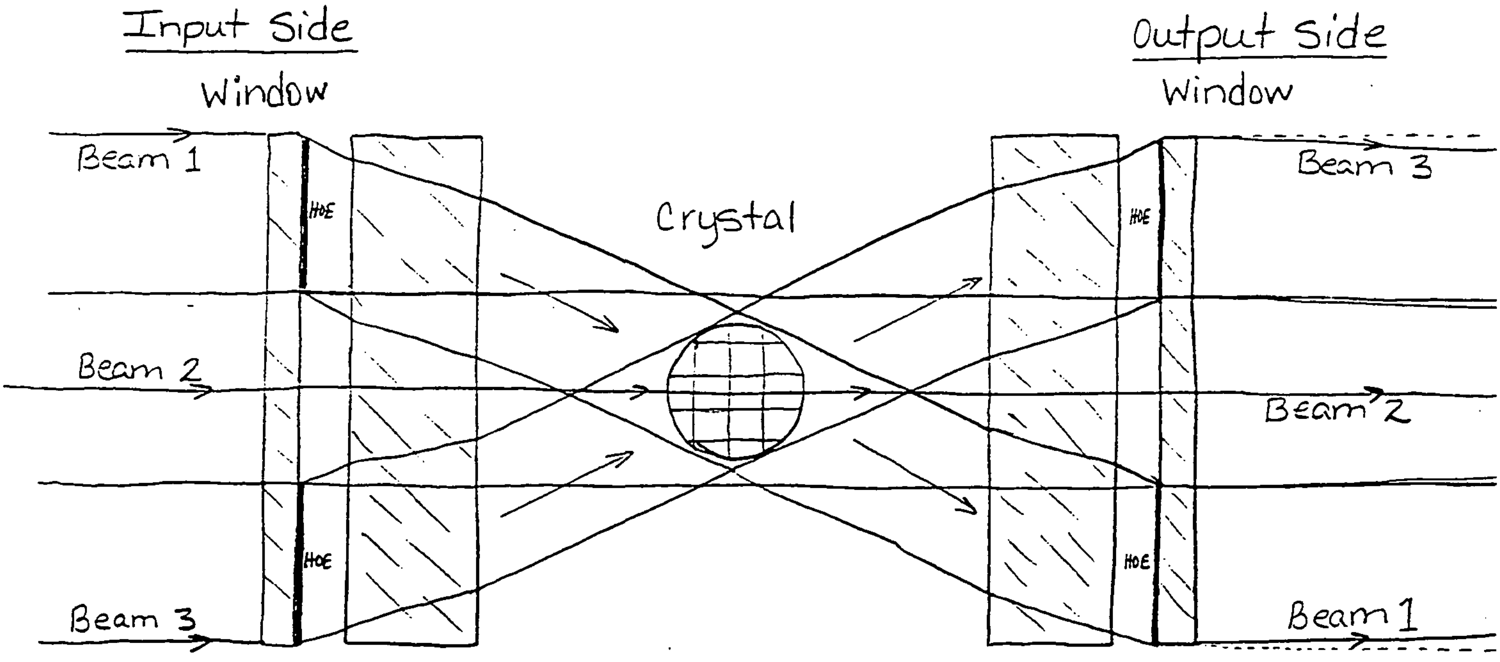
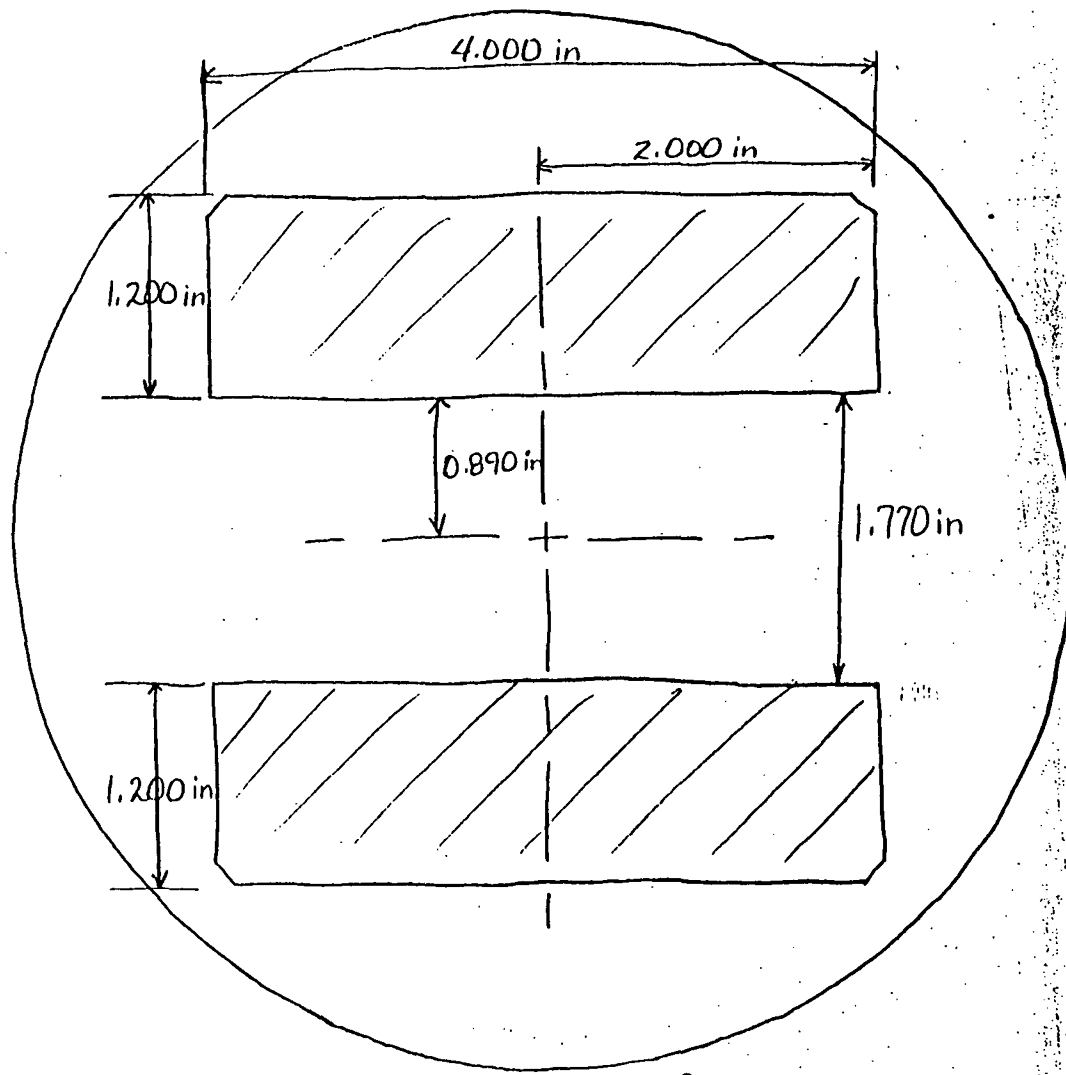


Figure 1

Cell Dimensions



Front View of Cell

Figure 2

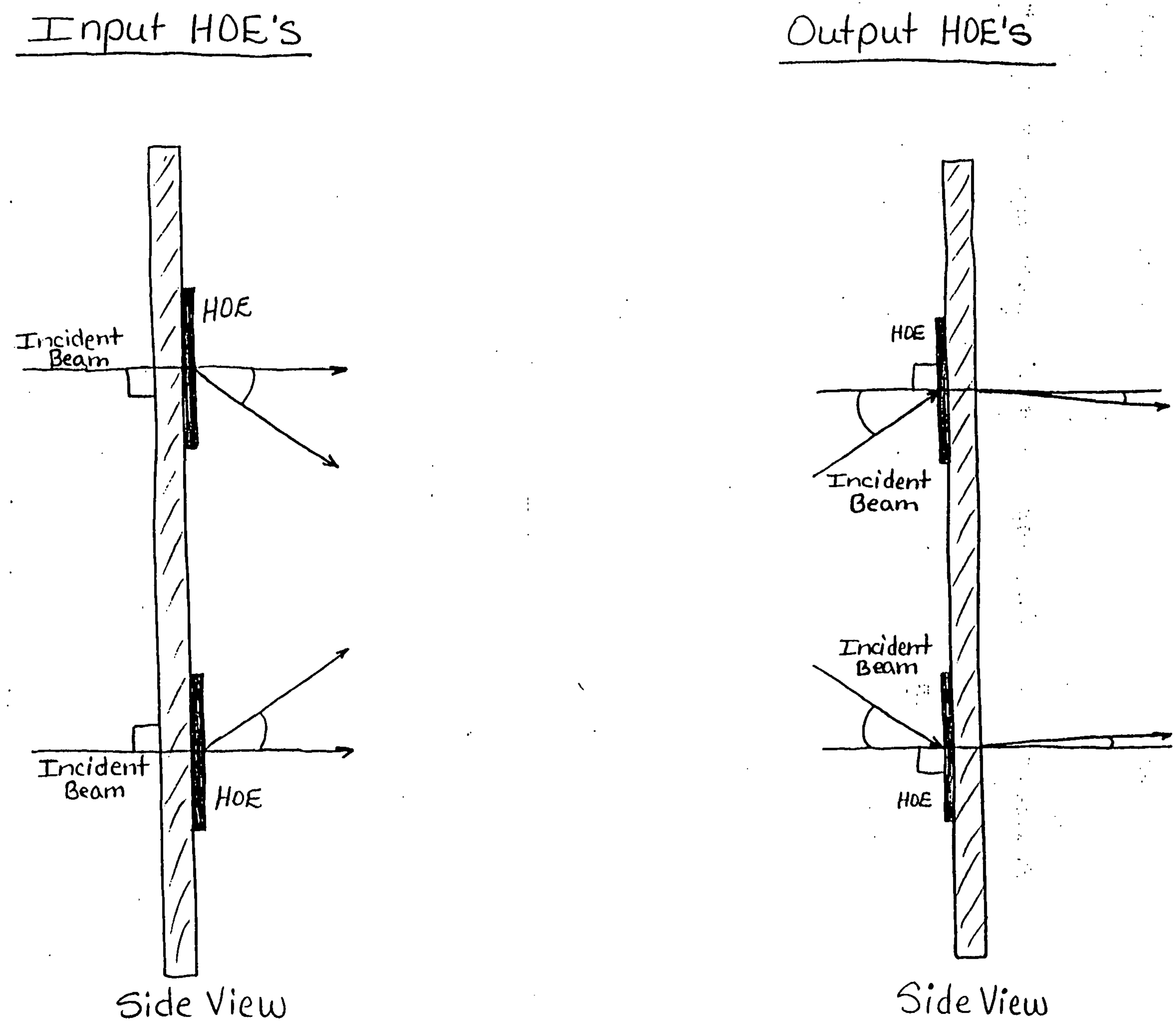
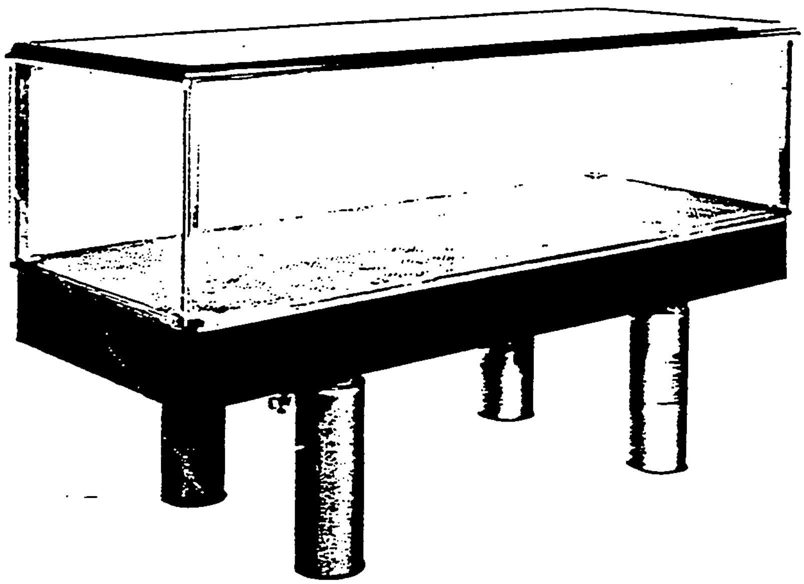

Input HOE's
HOE
Incident Beam
Incident Beam
HOE
Side View
Output HOE's
HOE
Incident Beam
Incident Beam
HOE
Side View

Figure 3

APPENDIX F
MISCELLANEOUS ILLUSTRATIONS

HGS Optical Bench



HGS HOLOGRAM RECONSTRUCTION