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RESOLUTION OF HOLOGRAMS PRODUCED BY THE FLUID EXPERIMENT SYSTEM AND THE HOLOGRAPHY GROUND SYSTEM

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ABSTRACT

The Fluid Experiment System (FES) was developed for the purpose of studying low temperature crystal growth of triglycine sulfate from solution in a low gravity environment onboard Spacelab. The first flight of FES was in 1985 on SL 3. FES uses an optical system to take holograms of the growing crystal that can be analyzed after the mission in the Holography Ground System (HGS) located in the Test Laboratory at Marshall Space Flight Center (MSFC). Microscopic observation of the images formed by the reconstructed holograms is critical to determining crystal growth rate and particle velocity. FES and HGS were designed for a resolution of better than 20 micrometers, but initial observation of the flight holograms show a limit of 80 micrometers. This paper investigates the resolution of the FES holograms, and the role of beam intensity ratio and exposure time on the resolution of HGS produced holograms.

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INTRODUCTION

The Fluid Experiment System (FES) was developed for the purpose of studying the growth of crystals in the low gravity environment aboard Spacelab. An optical system surrounding the test cell produces holograms during the entire growth period of the crystal. After the flight, the holograms are developed and allow the investigator to reconstruct an accurate three dimensional image of the cell. It is possible to complete a detailed study of this image with a microscope.

According to the design specifications of FES, the limiting resolution of the holograms should be less than 20 micrometers. However, the initial observations of the flight holograms placed the limit at 80 micrometers. This paper continues to investigate the resolution of the flight holograms in two ways. First, the flight holograms have been reconstructed and examined under the microscope. Second, a series of holograms of the test cell were produced in the Holography Ground System (HGS) under a variety of conditions. The goal of this two fold approach is to determine the ultimate resolution of the holograms and the optimal conditions for producing holograms on future flights.

OBJECTIVES

The objectives of this work were to:

1. Microscopically analyze reconstructed images of holograms of the crystal growth test cell from the Fluid Experiment System, flown on Spacelab 3, to determine the resolution of the holograms.

2. Construct holograms of the test cell in the Holography Ground System to determine variables that impact resolution.

3. Provide recommendations on changes to improve the ultimate resolution of the holograms of the cell.

THEORY

Resolution refers to the ability to separate two small objects (Department of Defense, 1962). This is somewhat different than the ability to detect isolated objects. It is possible to see single objects that are smaller than the resolution limit of an optical system, but it would be impossible to be certain that it is a single object. For the purpose of this paper, the ability to see an object will be referred to as detectability.

When considering the ultimate resolution of an image that is reconstructed from a hologram many different factors affect resolution including illumination, contrast, film, and aperture. A fundamental limitation is the use of coherent light from the laser to construct and reconstruct the hologram, which reduces the resolution because of the reinforcing nature of the diffraction patterns (Caulfield, 1970).

For holography, the illumination problems centers on the nature of the beams that are used to construct the holograms. First it is important to start with point source of laser light that had a small bandwidth (Smith, 1975) which is easily accomplished in HGS with the Spectra Physics Model 125 laser and the spatial filter. The ratio of the reference beam intensity to the object beam intensity should be between 3 and 10 (Meyer-Arendt, 1972, Stroke, 1969, Abramson, 1981). The insertion of a diffuser plate into the object beam may improve the overall illumination of the object, but will introduce a speckle pattern into the hologram that will mar small details (Caulfield, 1970).

The contrast between the object and the background also affects resolution. It is much more difficult to see a small bright red object against a red background, as is the case in the FES holograms, than it is to see a white object on a black background. Resolution under low contrast

conditions may be only one-third of the resolution under optimum high contrast conditions (Department of Defense, 1962).

It is important to use the proper type of film to record the hologram. The film must have a uniform, fine grain emulsion which is very sensitive to the 632.8 nm light from the laser. Care must be exercised in processing the film to avoid distorting the emulsion. Despite these cautions, the resolution limit of the film used in FES and HGS is on the order of 1 micrometer (Klein, 1970 and Stroke, 1969).

Resolution is also limited for holograms by the distance that the film is placed from the object and the aperture of the opening between the object and the film, in a manner that is similar to the resolution limit of conventional lens system (Caulfield, 1970). This restriction for the FES system would limit resolution of primary holograms to 2 micrometers and the transverse holograms to 4 micrometers.

Even if the holograms are recorded under optimal conditions, it may be difficult to achieve good resolution in the reconstructed images for many different reasons. The reconstruction beam needs to be as identical as possible to the original reference beam. It should be of a similar bandwidth and wavelength, unless additional magnification is desired by reconstructing with a longer wavelength (Francon, 1974). The beam must strike the film at the same angle as the reference beam in order to avoid astigmatic images and spherical aberrations (Caulfield, 1970). Of course the conventional optics in the microscope must have better resolving power than the holographic image.

PROCEDURE

Analysis of reconstructed holograms was completed on HGS using the modified microscope and hologram holder locations with the auxiliary turning mirror. The hologram holder is mounted on HGS between BS3 and the test cell. The turning mirror is inserted between M1 and BS1, and directs the reconstruction beam toward the hologram holder. The hologram is mounted in the holder in order to project a real image of the cell toward the outer edge of the table. The microscope is mounted near the edge of the table and directly observes this real image.

Since there are no small particles of known size in the test cell, a dummy sting was machined from aluminum to provide a reference target for determining resolution in the HGS produced holograms. Six pairs of grooves were cut near the tip of the sting (see Figure 1). These grooves ranged in depth from 10 to 120 micrometers and were from 20 to 170 micrometers wide. The exact dimensions of the grooves were determined by direct microscopic observation. Holograms were produced on HGS of the sting alone and the sting in Cell 101 which was filled with water. Primary holograms were produced in the manner described by TAI in the operators manual (TAI, 1984) with the diffuser plate inserted in the object beam. Transverse holograms were produced by removing M3, rotating BS4 out of the beam reflected from M6 and using the auxiliary turning mirror to send the reference beam to the hologram holder located in the standard position (see Figure 2.) Neutral density filters were introduced into the beams to produce various intensity ratios. These ratios were determined from the power readings obtained at the film plane by the Newport 815 power meter.

Most of the holograms were developed in the standard manner (TAI, 1984), although a few sets were processed in the automatic developing tank that had been previously used for the flight holograms.

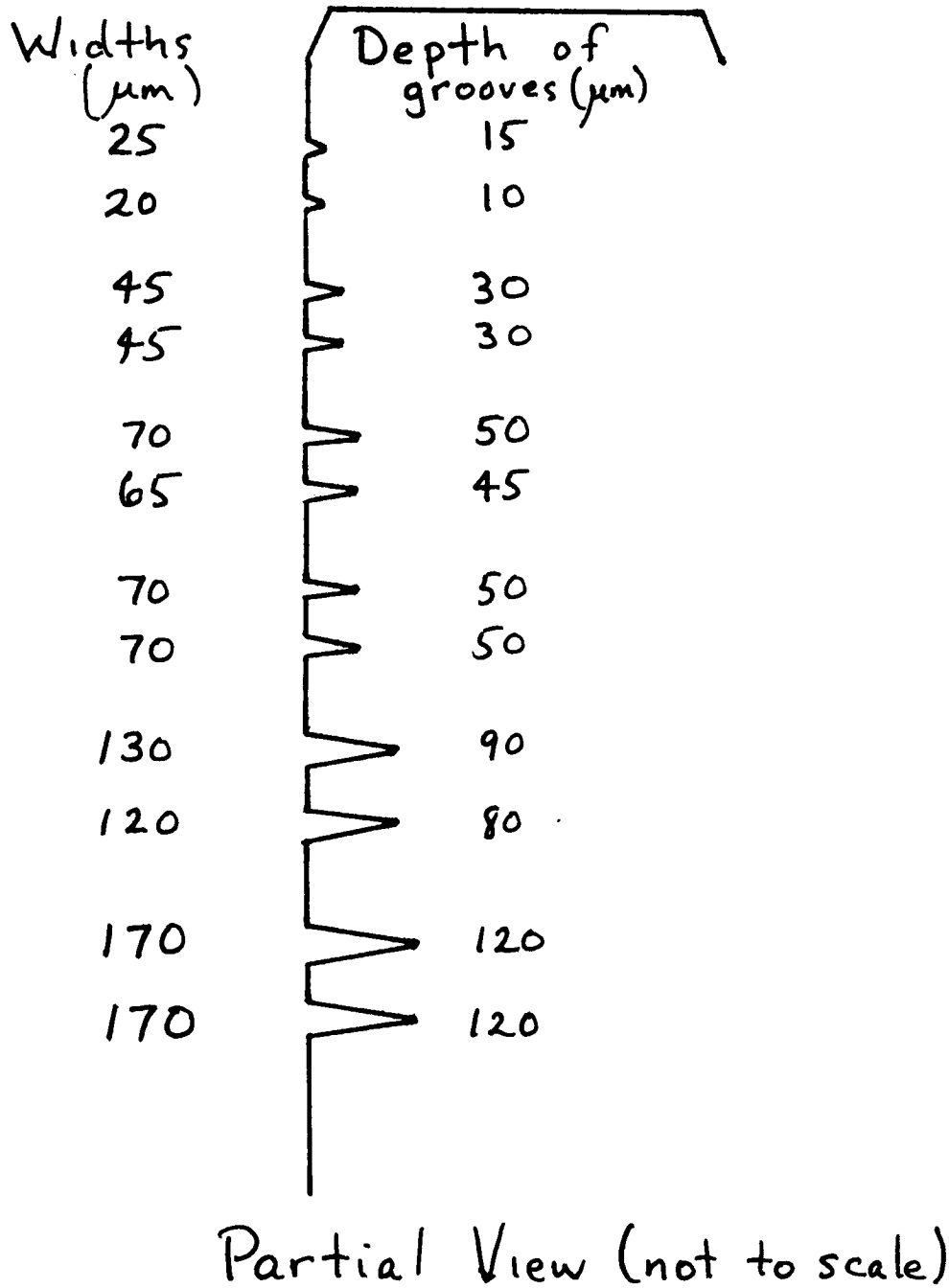

Figure 1- Optical Sting, FES TI 007

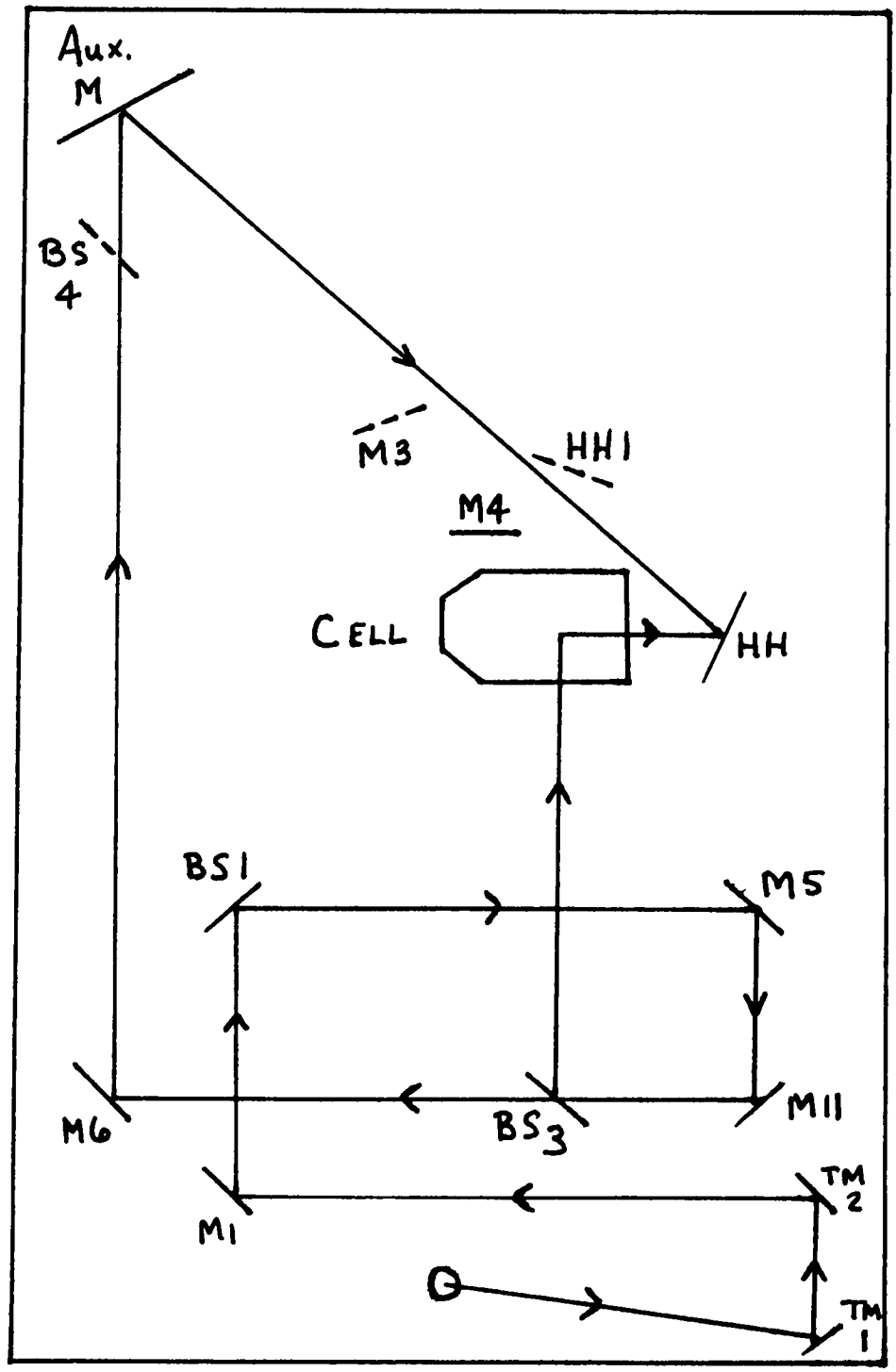

Figure 2- Modified HGS Configuration for Transverse Holograms

RESULTS

Resolution of the flight holograms was investigated for the calibration cell, Cell 203, and Cell 204. It was possible to observe the USAF 1951 resolution target in the calibration cell in both the primary and transverse holograms. Small particles, less than 100 micrometers, were only observed in the transverse holograms of Cells 203 and 204. Resolution of the optical sting, FES TI 007, was investigated in the transverse direction for the sting alone and the sting installed in Cell 101 with water, both at room temperature and at 45 degrees Celsius.

Holograms of the calibration cell were recorded during the Spacelab 3 mission both before and after the three test cells were installed on the optical bench. The resolution limits were determined as the width of a line pair of the smallest resolvable element in the USAF 1951 target. Prior to cell installation, the resolution of primary holograms (using Hologram Sequence # 1) was better than 35 micrometers and the transverse limit (using Hologram Sequence #T017) was better than 62 micrometers. After the test cell runs observations of primary sequence #348 and transverse sequence #T371, showed no change in the resolution limit.

It was very difficult to detect small particles in the holograms of the test cells. Since no small particles of known size were in the cells, the only way to determine the limit of detectability was with a systematic search of the cell volume. The microscope has a limited field of view, about 1 mm deep and 25 mm in cross section, even at low magnification. The scanning of the test cell with the microscope was a tedious process.

No particles or bubbles were found in the primary holograms of Cells 203 and 204 that were smaller than 100 micrometers. Probably the back lighting

of the object beam on the small particles coupled with the speckle pattern caused by the diffuser plate made it impossible to observe tiny objects.

The first transverse hologram of Cell 203 showed 17 spherical objects between 25 and 100 micrometers in diameter. These objects were scattered throughout the cell with 4 located in the region near the crystal. In the next hologram, taken about seven minutes later, the particles near the crystal are not seen while the far field particles are still in their same positions. The disappearance of these particles near the crystal can be explained if the small pieces were triglycine sulfate crystal which would have dissolved into the hot solution. Efforts to detect the floater crystals, which became very large during the growth period, while still very small were unsuccessful. Unfortunately there was a gap of almost eight hours in the holograms that were recorded of the flight cell. The last hologram before the gap shows no small particles in the observable portion of the solution near the crystal and the next hologram displays the floater crystals that are about a millimeter in diameter.

Small particles were also found in the transverse holograms of Cell 204. Typically 6 to 12 particles were found in each image. These particles were located in the back portion of the cell, as seen through the transverse window, and appeared to drift slowly through the solution. The smallest spherical particle was 20 micrometers in diameter, and some of the particles definitely appeared as cylinders, 20 to 30 micrometers in diameter and 100 or more micrometers long. It did not appear that these objects changed size throughout the growth period, suggesting that they were not crystalline material.

All primary configuration holograms of the optical sting produced on HGS failed to show any evidence of the grooves near the tip. As was the case with

the flight primary holograms, this failure is explained by the fact that the cylindrical sting is back illuminated by the object beam and fails to reflect light from the sting onto the film. The only possible way to detect the grooves would be to see the profile of the sting which is not possible because of the speckle pattern introduced by the diffuser plate.

Table 1 summarizes the transverse holograms of the optical sting that were produced on HGS. These holograms show a face on view of the grooves. The quality of the image depended on the beam ratio and the exposure time. For the optical sting only the best image, with a detectability of less than 20 micrometers, was recorded with a 10:1 beam ratio and a 100 ms exposure. The 2:1 beam ratio exposure at 500 ms also showed all the grooves as did the 30:1 100 ms hologram. It is significant to note that all exposures at the 10:1 beam ratio showed all the grooves on the optical sting. The less favorable beam ratios only had good resolution for one exposure times.

The transverse holograms of the optical sting installed in Cell 101 exhibit the same dependency on beam ratio and exposure time. Again the best holograms were at the 20:1 ratio. There appeared to be no effect on the detection with the heated cell. The use of the automatic development tank permitted over exposed holograms to be underdeveloped and usable. In fact, the 20:1 1 and 2 second exposures and 100:1 200 ms, all overexposed, were the best of the auto-developed sequences.

Considering the role of beam intensity ratio on the resolution of the holograms, it was decided to measure power of the beams on the FES optical bench and the influence of the test cell on the beam intensities in HGS. The locations of the power measurements are shown in Figure 3 and Figure 4 shows the power readings for light entering Cell 101 on HGS. Table 2 summarizes the power

measurements from the FES table and estimated power readings with a cell in place. The cell has four windows in the primary direction, each of which absorbs some of the light. The inner, thick windows transmit 88% of the incident light. The outer, thin windows transmit 94% of the incident light. The diffuser plate in HGS transmits 24% of the light. Calculations using the best available value for the extinction coefficient for water at the 632.8 nm wavelength (Hale and Query, 1973) indicate that 97% of the light will be transmitted through 10 cm of water. The result of having all the windows and the water in the beam will be an overall transmission of 66% under ideal conditions (ignoring the effect on the transmission coefficient of a saturated triglycine sulfate solution) for the primary beam without diffuser and 16% for the primary beam with diffuser. Independent measurements of the transmission coefficients for both the primary and transverse object beams were made by taking the appropriate power ratio of light entering the test cell to that reaching the film plane(see Figure 4). For the primary object beam without diffuser, the measured transmission coefficient to the film plane is 50% and for the diffused primary beam the coefficient is 9%. It appears that the beam ratios for the flight holograms which can be analyzed with the microscope are on the order of 40:1 or larger (see Table 3).

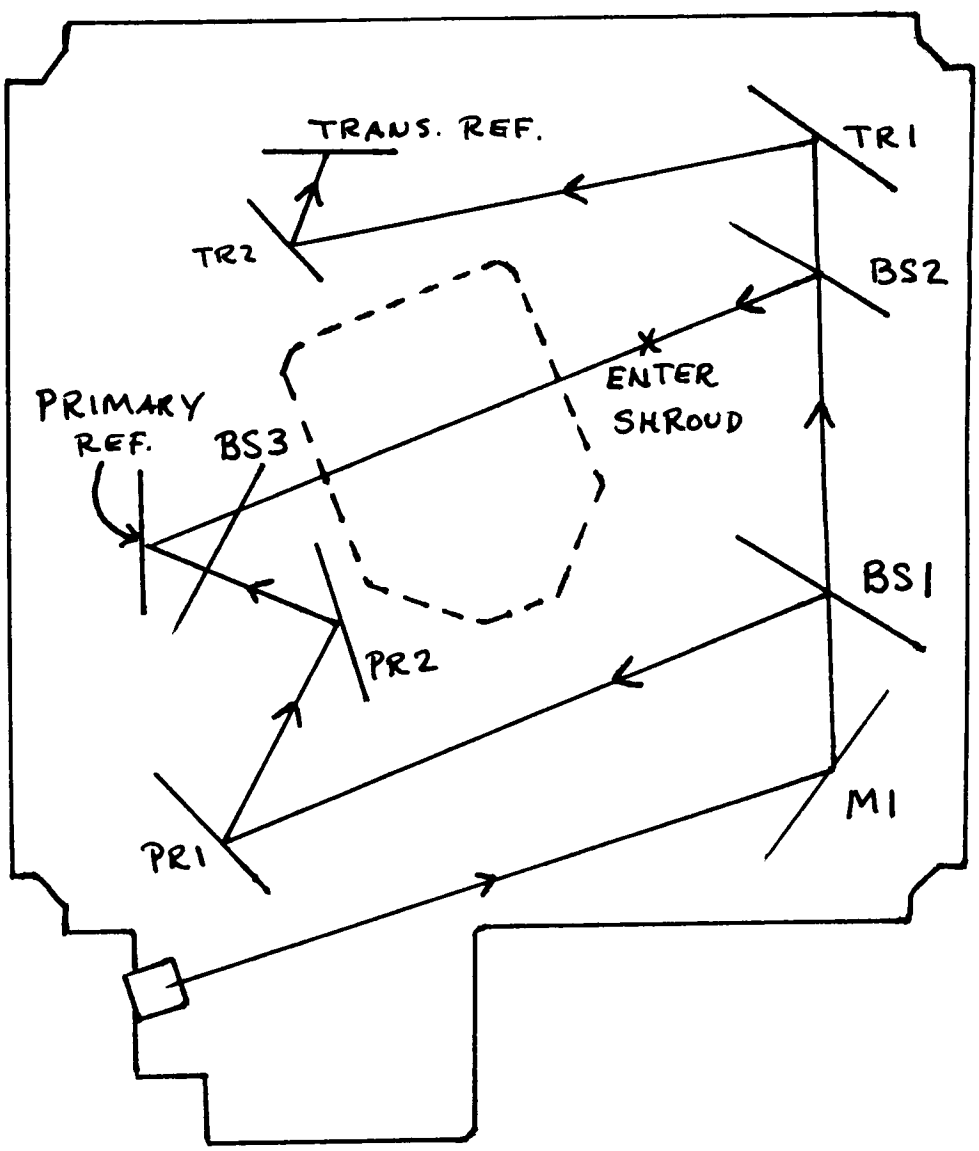

Figure 3- FES optical bench with measurement locations marked.

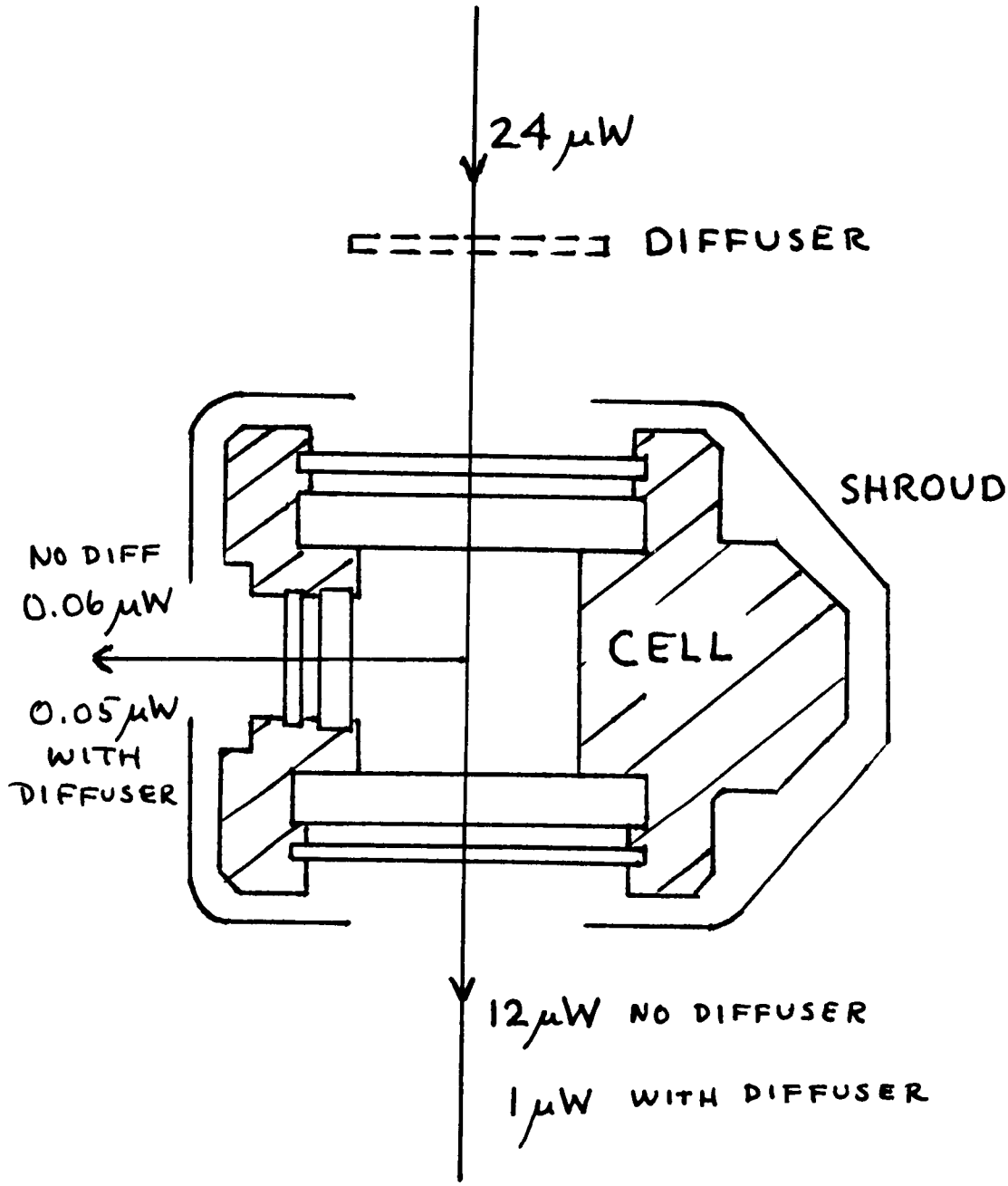

Figure 4- Cell 101 with power readings for appropriate beams indicated.

TABLE 1

Transverse Optical Sting Holograms Produced in HGS

No.	Beam Ratio	Exposure	Cell	Temp	Comments
1	30:1	20 ms	No	Cold	poor
2	30:1	50 ms	No	Cold	poor
3	30:1	100 ms	No	Cold	Best of set
4	30:1	200 ms	No	Cold	Too Dark
5	2:1	500 ms	No	Cold	Best of set
6	2:1	1 s	No	Cold	partial
7	2:1	2 s	No	Cold	incomplete
8	10:1	100 ms	No	Cold	Best of set
9	10:1	200 ms	No	Cold	OK
10	10:1	500 ms	No	Cold	OK
11	100:1	20 ms	Yes	Cold	poor
12	100:1	50 ms	Yes	Cold	Best
13	100:1	100 ms	Yes	Cold	partial
14	100:1	200 ms	Yes	Cold	Too dark
15	100:1	200 ms UD	Yes	Cold	poor
16	100:1	500 ms UD	Yes	Cold	Very dark
17	20:1	100 ms	Yes	Cold	Nothing
18	20:1	200 ms	Yes	Cold	poor
19	20:1	500 ms	Yes	Cold	Good
20	20:1	1 s	Yes	Cold	Best
21	20:1	2 s	Yes	Cold	Too Dark
22	20:1	2 s UD	Yes	Cold	Good
	AUTO DEVELOPED HOLOGRAMS FOLLOW (23-36)				
23	20:1	100 ms	Yes	Cold	poor
24	20:1	200 ms	Yes	Cold	Nothing
25	20:1	500 ms	Yes	Cold	fair
26	20:1	1 s	Yes	Cold	Best
27	20:1	2 s	Yes	Cold	OK
28	20:1	200 ms	Yes	Hot	partial
29	20:1	500 ms	Yes	Hot	partial
30	20:1	1 s	Yes	Hot	Best
31	20:1	2 s	Yes	Hot	OK
32	20:1	9.2 s	Yes	Hot	partial
33	100:1	20 ms	Yes	Hot	poor
34	100:1	50 ms	Yes	Hot	poor
35	100:1	100 ms	Yes	Hot	poor
36	100:1	200 ms	Yes	Hot	Best

NOTE : UD = underdeveloped

TABLE 2

POWER MEASUREMENTS ON FLIGHT BENCH
(IN MICROWATTS)

PRIMARY REFERENCE	65
TRANSVERSE REFERENCE	13
ENTERING CELL SHROUD	127
PRIMARY OBJECT NOT DIFFUSED (WITHOUT CELL)	14
PRIMARY OBJECT NOT DIFFUSED (EST. WITH CELL)	7-9
PRIMARY OBJECT DIFFUSED (EST. WITH CELL)	0.6-2
TRANSVERSE OBJECT NOT DIFF. (EST. WITH CELL)	0.3
TRANSVERSE OBJECT DIFF. (EST. WITH CELL)	0.26

TABLE 3
ESTIMATED FLIGHT BEAM INTENSITY RATIOS

PRIMARY	
WITHOUT DIFFUSER	7 - 9:1
WITH DIFFUSER	32 - 100:1
TRANSVERSE	
WITHOUT DIFFUSER	43:1
WITH DIFFUSER	50:1

NOTE: Range of values in primary ratios show the difference between the calculated and measured transmission coefficients for the test cell.

CONCLUSIONS AND RECOMMENDATIONS

After completing this study, it appears that it is possible to detect particles about 20 micrometers in diameter in the FES holograms that were recorded on the SL-3 mission. However, only a small number of particles were found; many more particles were removed from the cell in the post flight draining of the cells. The inability to see most of the small particles may be a result of the large reference to object beam intensity ratios that are apparently built in to the FES optical bench. The lack of detectable small particles in the primary holograms is explained by a combination of the bad beam ratio, poor lighting angle for the particles, and the speckle pattern introduced into the holograms by the diffuser plate.

The HGS produced holograms confirm that proper beam ratio and exposure time are critical to achieving good resolution in the reconstructed images. If the beam ratio is much larger than 20:1 then the image clarity suffers. Underexposure of the hologram makes it impossible to see small details, but slightly overexposed holograms exhibit good detectability.

If small particles are going to be intentionally introduced into the test cell, for the purpose of determining fluid velocity, then another series of holograms should be made of the test cell with particles. This series should determine the optimum exposure time and beam ratio to easily detect the particles.

Regardless of the addition of small particles to the cell, it is recommended that the caps in the test cells be grooved in a fashion similar to the optical sting. A hologram of the grooved cap, before it is retracted, would insure that the actual flight cell is not adversely affecting the

resolution of the holograms. The modified cap would give the investigator a known small feature at a known place in the cell.

Depending on the final results of the series of holograms of the test cell with small particles, action should be taken to reduce the beam intensity ratios on the FES optical bench. Changing the value of the first beam splitter could improve the primary ratio as would a change in the value of the beam splitter just in front of the primary film plane. Changing the beam splitter that separates the object beam and the transverse reference beam could help both ratios. The insertion of a neutral density filter in the transverse reference beam would help the transverse ratio.

Exact changes could be more easily determined if the HGS optical bench was equipped with optical components that match those of the FES flight bench. The optical elements also should be obtained that would permit HGS to record both primary and transverse holograms during the same test.

The Fluid Experiment System and Holography Ground System have the capacity to provide detailed information on the growth of crystals in the low gravity environment of Spacelab. With a few minor adjustments even more data can be retrieved from future flights.

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