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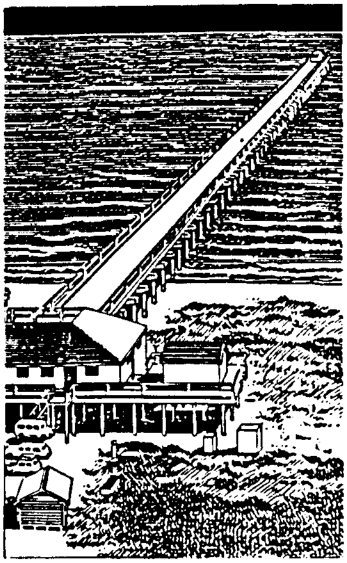

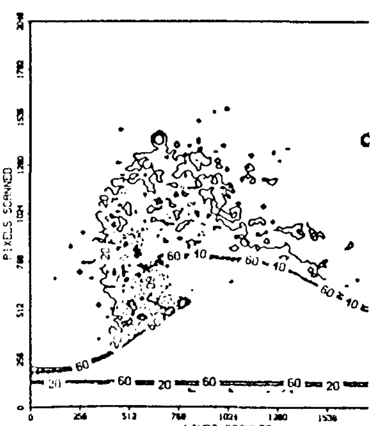

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LABORATORY MEASUREMENT OF SPATIAL AND TEMPORAL SUSPENDED SEDIMENT CONCENTRATION UNDER WAVES

by

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This study examines the feasibility of obtaining spatial and temporal suspended sediment concentrations in the laboratory through the use of high-speed filming and image analysis. A series of filming experiments was conducted in a laboratory wave flume to investigate filming parameters and to determine optimum conditions for filming high quality footage of sediment transport. A relatively simple procedure is used to map the contours of light intensity returned from digitized 16mm film images and to relate these contours to the concentration of suspended sediment. Improvement of this nonintrusive measurement technique could provide researchers with the capability to perform quantitative measurements of sediment transport at the microscale.

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PREFACE

This study demonstrates the feasibility of quantifying spatial and temporal changes in suspended sediment concentrations in the laboratory by means of a combination of high-speed photography and image processing. The research was conducted by the US Army Engineer Waterways Experiment Station (CEWES) for the Assistant Secretary of the Army (R&D) as an In-House Laboratory Independent Research (ILIR) Project under Project No.4A161101A91D, Task Area 02, Work Unit 169.

Dr. Steven A. Hughes of the Coastal Engineering Research Center (CERC) conducted the research and prepared the report under the general supervision of Mr. H. Lee Butler, Chief, Research Division; and Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Chief and Assistant Chief, CERC, respectively.

Dr. Charles Long, Mr. Greg Green, and Mr. Thomas Price made valuable contributions to the study, as did members of the Wave Dynamics Division of CERC who assisted in experiment preparation and operation of the wave flume. High-speed photographic work was performed by Messrs. Jon Warwick and Vessen Magee, Photography Branch, Information Products Division, Information Technology Laboratory, CEWES. Technical review was provided by Ms. Kathryn Gingerich, Dr. Nicholas Kraus, Mr. Mark Byrnes, and Mr. Bruce Ebersole.

Dr. Tsuguo Sunamura, University of Tsukuba, Japan, provided valuable technical guidance on filming sediment motion.

Commander and Director of CEWES upon publication of this report was COL Dwayne G. Lee, CE. Dr. Robert W. Whalin was Technical Director.

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LABORATORY MEASUREMENT OF SPATIAL AND TEMPORAL SUSPENDED SEDIMENT CONCENTRATION UNDER WAVES

PART I: INTRODUCTION

Background

1. Coastal sediment transport measurements can be grouped into three classes based on the scale of the process. Micro-scale processes have small length scales, on the order of centimeters, and time scales on the order of less than a wave period. This is the scale where turbulent water motions move individual sand grains, and it is a scale suitable for investigations into the fundamental physics of sediment transport. Meso-scale processes have a length scale ranging from several meters to the length of the active surf zone and beyond, and time scales spanning several hours to several days. Sediment research at the meso-scale attempts to develop correlations between time-averaged changes in observed transport behavior and characteristic parameters of the hydrodynamic flow regime. At the macro-scale, length scales can vary up to many kilometers, and time scales can extend to years. Studies such as regional sediment budgets and shoreline response to coastal projects fall into this category.

2. The difficulty in obtaining reliable measurements of spatial and temporal suspended sediment concentrations at the micro-scale in both the laboratory and the field has forced researchers to focus on quantifying sediment transport at meso- and macro-scales, where techniques such as profile change analysis (Larson and Kraus in review, Kriebel 1987), impoundment at

littoral barriers (Dean et al. 1982, Bodge and Dean 1987), and time-averaged trapping of sediment (Kraus 1987, Kraus and Dean 1987) have provided the necessary data for quantifying sediment transport rates. These engineering approaches, often involving empirically determined coefficients, are valuable for addressing problems within the range of conditions for which they are developed, but insight into the fundamental physical mechanisms underlying the process at the micro-scale is not forthcoming.

Purpose

3. The purpose of this study is to investigate a promising technique for measuring spatial and temporal changes in sediment concentrations at the micro-scale level under controlled laboratory conditions without disturbing the flow field. The technique involves high-speed filming of suspended sediment motion and image analysis of the digitized film to obtain the concentrations.

Scope

4. This report is organized into seven parts. Part II summarizes present techniques for measuring and quantifying suspended sediment concentrations at different scales. Part III introduces the concept of examining suspended sediment transport using image processing techniques. Part IV discusses in detail two experimental filming runs in which filming parameters were systematically varied to determine the optimum combination for producing film suitable for image analysis. Part V describes the image digitizing equipment used to process the film images. Part VI discusses

approaches and factors to be considered in an image analysis technique to determine suspended sediment concentrations. The approach adopted for this study is described, and results are presented. Part VII summarizes findings of the study and presents conclusions.

PART II: METHODS FOR MEASURING SUSPENDED SEDIMENT

5. Several techniques have been used in the field to obtain point measurements of suspended sediment concentrations within the surf zone. Kana (1979) identified three basic methods:

- a. Pump systems that gather a time-averaged sample of water and sediment at fixed points (Fairchild 1972, 1977).
- b. Trap systems that gather relatively instantaneous bulk water/sediment samples.
- c. Indirect measurements of sediment or water turbidity by light attentuation, backscatter of light (Downing, Sternberg, and Lister 1981, Downing 1984), or gamma absorption.

A recently developed technique involves the time-averaged trapping of sand at fixed locations using hydraulically efficient streamer traps (Kraus 1987, Kraus and Dean 1987). This method is used primarily under quasi-unidirectional flow conditions.

Laboratory Measurements

6. Although the listed methods have merit for making field measurements of suspended sediment concentrations at the meso-scale, only pumping and optical/electronic sensing are readily adaptable for making measurements in the laboratory at the micro-scale.

7. Two fundamental problems enter into making laboratory measurements of suspended sediment concentrations at the micro-scale. The first is the requirement to be nonintrusive (i.e., without substantially affecting the flow field and sediment concentration), and the second is to obtain both spatial and temporal coverage of the concentration.

Pump Samplers

8. Pump samplers in the laboratory are usually arranged in a vertical probe array, and suspended sediment samples are collected by applying suction to the probes for a fixed time period. Ideally the fluid velocity in the sampler nozzle should equal that in the surrounding fluid; in practice this is very difficult to achieve. The pumping technique has three distinct disadvantages:

- *a*. The presence of the probe in the flow and possible acceleration caused by pump action have potential to disrupt the flow field.
- *b*. The resultant sample provides a time-averaged concentration, hence temporal aspects cannot be investigated.
- *c*. Adequate spatial coverage would result in a multitude of probes which could significantly alter the flow conditions.

An improvement in the temporal sampling limitation has been made by Staub, Jonsson, and Svendsen (1984) who also report that differences in probe orientation can lead to significant measurement disparities.

Electronic Instrumentation

9. Three types of electronic instrumentation have been used to obtain suspended sediment concentrations in the field or laboratory. Nakato et al. (1977) measured concentration profiles under laboratory conditions using miniature electro-optical probes consisting of a light source and sensor separated by about 3 mm. This technique provides useful temporal data at isolated locations, but its capability to provide wide spatial coverage is restricted by the number of probes that would be required and by probable disruption of the flow field. Katoh, Tanaka, and Irie (1984) utilized a more

robust vertical arrangement of light source and sensor pairs for surf zone measurements in Japan.

10. High-frequency (3 MHz) acoustical sensors have been deployed for field use for nonintrusively measuring suspended sediment concentrations. Hanes and Vincent (1987) report a vertical resolution of 10 mm and a temporal resolution of about 1 sec for these sensors. Horizontal resolution is a function of sonar beam width and distance from the sensor. Because of relatively poor spatial and temporal resolution with respect to sediment motions at the micro-scale, use of this technique in the laboratory is limited.

11. Similar problems preclude or restrict use of optical backscattering sensors (OBS) for laboratory measurements at the micro-scale. The OBS, a flow-intrusive probe, measures infrared light backscattered from a volume estimated to be about 1.3 cc (Sternberg, Shi, and Downing, 1984). Adequate spatial coverage is not possible because the large number of probes required would adversely disturb the flow field.

12. The techniques discussed above for measuring suspended sediment concentrations are of limited value for obtaining laboratory measurements because they are flow-intrusive and do not provide suitable spatial and temporal resolution of the micro-scale process.

High-Speed Filming

13. Sunamura, Bando, and Horikawa (1978) overcame the aforementioned limitations by filming suspended sediment motion through the glass side wall of a laboratory wave flume using a 16-mm high-speed movie camera. This novel

approach provides nonintrusive recording of sediment motion with spatial coverage at a temporal rate (200 to 500 frames per sec) sufficient to track individual sand grain movements. The main disadvantage of the filming method lies in subsequent analysis of the developed film to quantify the sediment motions. Details of suspended sediment clouds and tracking of individual grains can only be done by tedious counting of sand grains within a unit volume, or by manually mapping individual grains on a frame-by-frame basis. In these cases, the data soon overwhelm the researcher.

14. Two minor shortcomings are that the success of a filming run cannot be determined until after the film has been developed (i.e., no real-time feedback), and the filming procedure requires somewhat sophisticated knowledge of photography. In the future, high resolution video will alleviate both problems.

15. Sunamura (1980) presented an example of the types of results that can be obtained from the filming technique. In addition to a thorough physical description of sediment transport over a rippled bed, he was able to quantify some of the gross micro-scale transport characteristics.

PART III: IMAGE PROCESSING APPROACH TO MEASURING SUSPENDED SEDIMENT CONCENTRATIONS

Background

16. In the present study, analytical determination of suspended sediment concentration by means of the high-speed film technique is approached from an image processing perspective. Image processing is the digitization of an image (if not originally collected in digital form) and subsequent computer manipulation or enhancement of the digitized image to extract information. Until recently, image processing was usually associated with satellite imagery or analysis of images obtained by scanners used in the medical profession. However, researchers are beginning to adapt this technology to investigate and quantify complex phenomena in the fluid flow regime.

17. Haenscheid, Kirschbauer, and Rouve (1985) investigated the feasibility of utilizing image processing systems for data acquisition in hydraulic laboratories, and they described the necessary system components for acceptable performance in several specific examples. Broward and Plocher (1985) used image processing to investigate the motion of single sediment grains in a spot of turbulence in unidirectional flow. Holman and Lippmann (1987) applied image processing techniques to infer nearshore coastal morphology using time-averaged video images, and Holman also has developed automated acquisition of wave runup data using video cameras and image analysis (Richardson, Kraus, and Hughes 1987).

Application to Suspended Sediment Transport

18. The present study investigates the feasibility of applying image processing methods to automatically extract suspended sediment concentrations from digitized 16-mm film images of sediment motion under wave action. The success of using image analysis techniques depends on obtaining sufficient contrast between the suspended sand grains and the surrounding fluid when filming. Good contrast is necessary so that relatively rapid and simple computer algorithms can be used to process the digitized images into sediment concentration values.

19. The capability to perform such an analysis successfully would allow researchers to employ the filming technique to obtain high-quality and nonintrusive suspended sediment measurements with a high density coverage in both space and time. These types of measurements are essential for developing understanding of the sediment transport process at the micro-scale and for testing new hypotheses which attempt to quantify the physical processes involved.

20. This feasibility study was divided into two components. The first involved filming of suspended sediment motion in the laboratory under a wide variety of filming conditions. Examination of the resulting film quality and image contrast provided guidance for optimization of the various filming parameters for future experiments. The second component examined film digitizing processes and data manipulation techniques that might be employed. The goal was to optimize image processing time while minimizing data storage requirements.

21. The main objective of the investigation was to demonstrate the feasibility of this approach. Final system development and systematic experimental data collection were beyond the scope of this work; therefore, no concurrent flow measurements were made during the course of the study. Such flow measurements would also need to be nonintrusive.

PART IV: FILMING OF SEDIMENT TRANSPORT IN THE LABORATORY

22. At the onset of this study, discussions were held with Dr. Tsuguo Sunamura of the University of Tsukuba, Japan, who had previously conducted filming of sediment transport in the laboratory (Sunamura 1978, 1980). Dr. Sunamura provided practical advice and guidance on most aspects of filming and lighting techniques, selection of wave and sediment parameters, and potential problem areas. His experience enabled this project to focus on approaches and techniques that would most likely produce optimum contrast between sediment and fluid.

Experiment Preparation

Wave Flume

23. Filming experiments were conducted in a glass-walled wave flume at the Coastal Engineering Research Center (CERC). The flume has a length of 45 m, a width of 0.46 m, and a depth of 0.9 m. Wave motion is provided by a programmable hydraulic wave board, and waves are dissipated on a gently sloping concrete beach at the far end of the flume. Figure 1 is a photograph of the wave flume. For this project there were few criteria for wave flume selection. The principal requirements were a clear glass side wall panel through which to film the sediment transport and wave motion generation capability. Additional criteria for actual data gathering experiments on micro-scale sediment transport include the capability to generate irregular and nonlinear wave motions, the capability to impose a mean current in the flume, and the capability to utilize flow measurement instrumentation commensurate with the intended level of analyses.

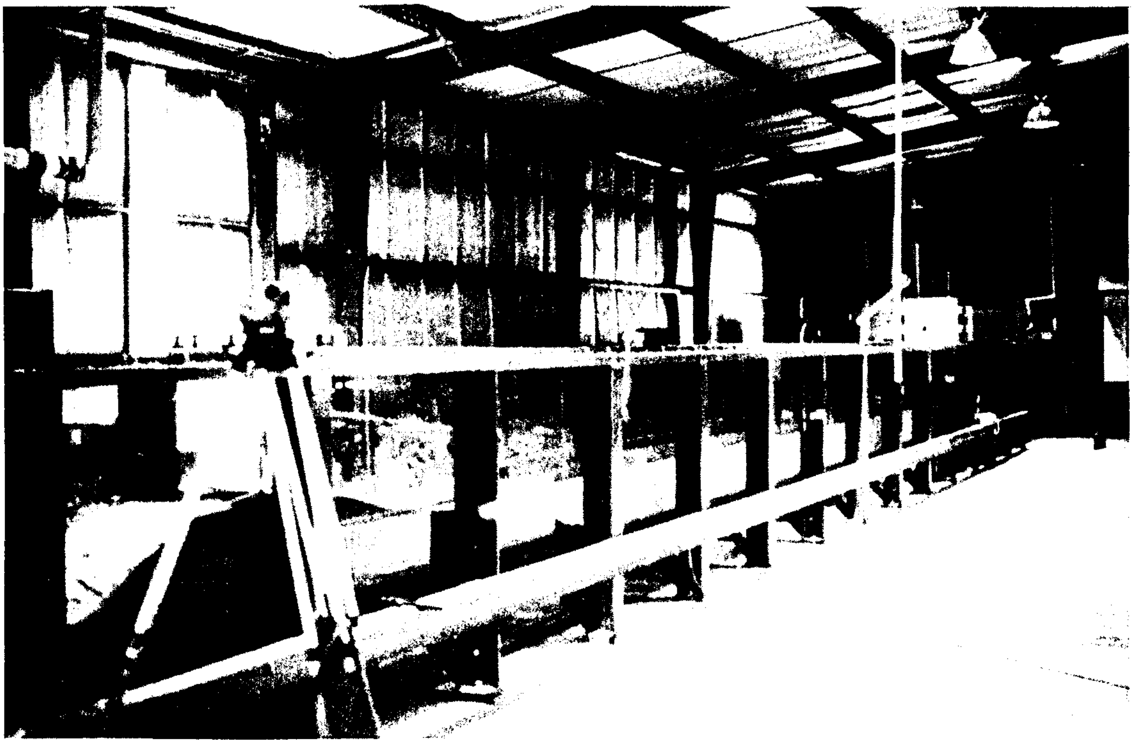


Figure 1. Photograph of wave flume.

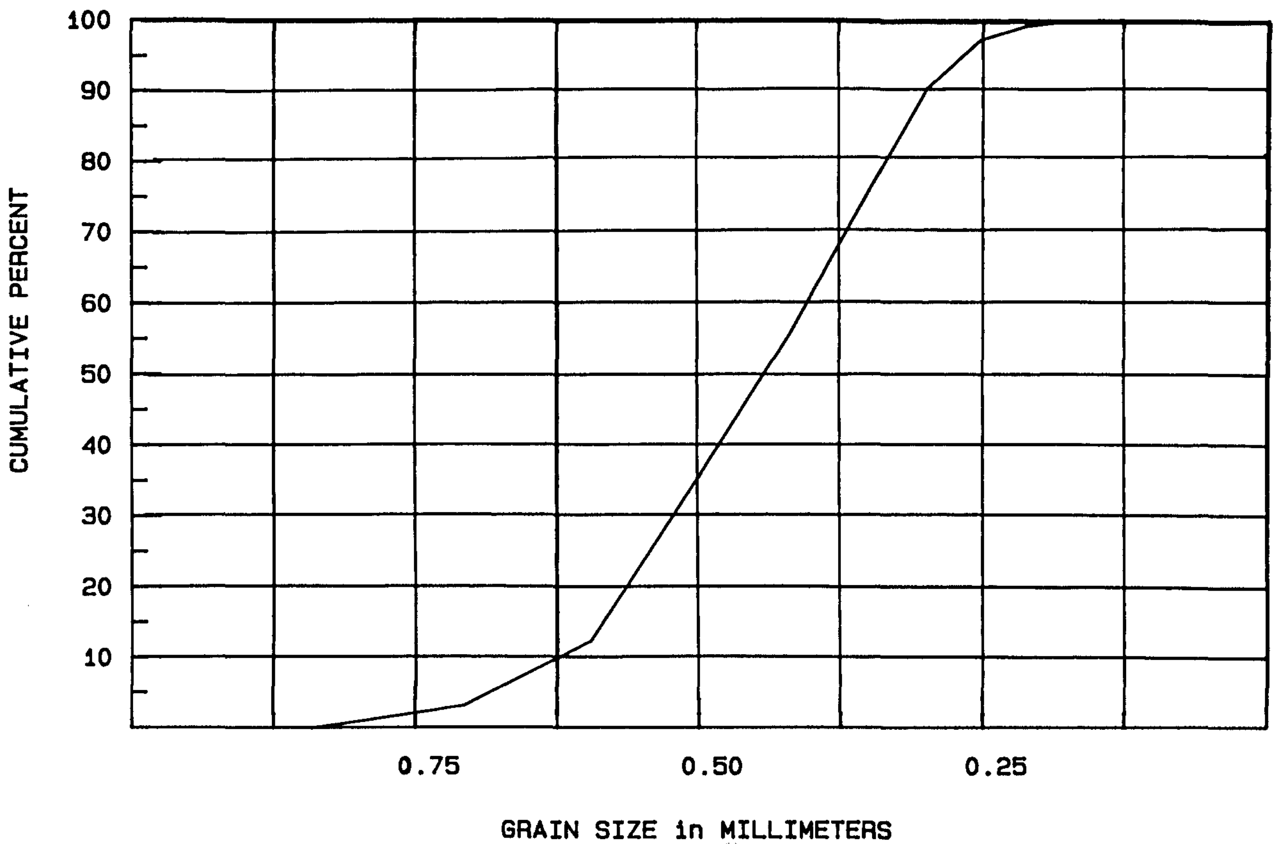


Figure 2. Cumulative grain size distribution of sand used in experiments.

Sediment

24. The sediment used in this study was prepared by sieving river sand in a large shaker using two screens with mesh sizes of 0.8 mm and 0.3 mm. Sand passing through the 0.8-mm screen and retained on the 0.3-mm screen was used for the filming experiment. The resulting sand had a mean grain size of 0.43 mm and a standard deviation of 0.24 mm. The cumulative grain size distribution is shown in Figure 2. Sieving was performed to obtain a sand sample sufficiently uniform in size to minimize variation of light intensity returned from individual grains.

25. The sand was thoroughly washed to remove dust particles and organic material. Washing is necessary to preclude clouding conditions, which make it difficult to observe suspended sand grains through the side glass of the flume. A second washing took place after the sand was placed in the flume. Waves were run in the flume, and a rake was used to agitate the sand to suspend very fine particles. The resulting murky water was then drained. A sufficient quantity of sand was prepared and placed in the flume to form a sand veneer approximately 2.5 m long, 0.45 m wide and 7 cm deep. In retrospect, this amount was more material than actually needed to perform the experiment because of the use of a flume "splitter plate" that served as a filming backdrop.

Splitter Plate

26. The splitter plate was a rectangular piece of heavy gauge sheet metal measuring approximately 1.0 m on the horizontal axis and 0.6 m on the vertical axis. It was placed in the flume parallel to the side walls close to the glass through which filming was to occur. Figure 3 shows a plan view of

the experimental arrangement and the location of the splitter plate. The plate penetrated the sand veneer, and in essence, subdivided the width of the flume into two compartments, one with a very narrow width next to the glass side through which filming takes place. The plate was painted flat black, and it had a square grid of white dots spaced at 50 mm centers. These dots provided reference position and length scale factors for use in filming and subsequent analyses.

27. The primary function of the splitter plate was to provide sharp contrast between the target sand grains and the flat black background. If filming had been done without the splitter plate, it would have been difficult to determine sediment concentrations because the depth of field would be unknown. That is, grains in suspension beyond a certain unknown lateral distance from the glass side wall would not be seen by the camera because of lens focal length. By placing the splitter plate in the flow, a known depth of field was established within the range of camera penetration into the flow field.

28. Care was taken in placing the splitter plate in the flume and fixing its position to maintain the plate parallel to the side wall. This is believed to have minimized flow disruption; however, no substantiating flow measurements were taken. Distance between plate and glass side wall was varied during the experimental filming to determine the best width of flow field. A width that is too narrow has the potential of introducing excessive side wall boundary layer effects into the flow field, whereas an excessive flume width would result in too many sand grains in the background being either out of the camera's focal range or obscured by grains in the foreground.

Photographic Equipment and Placement

29. Filming was conducted using a LOCAM 16-mm movie camera manufactured by the Redlake Corporation. It has the capability of filming at a rate of 500 frames per second (about 3.8 m of film per second). The camera was placed on a tripod situated approximately 30 cm from the glass side wall at an elevation slightly below the sand bedform in the flume. This positioning eliminated from camera view that part of the bedform extending into the flume from the side wall. This aided in distinguishing suspended sand grains from the bedform. Camera lenses of various focal lengths were employed in conjunction with extension tubes to provide viewing frame sizes to be tested during filming runs. All filming runs were conducted using Kodak Ektachrome video news film, high-speed SO-251, 400 ASA.

30. High-speed filming requires bright lights to illuminate sand grains to make them stand out against the background. Two 5-kilowatt tungsten lights with focusing capability were used to illuminate the filming region. Two basic lighting arrangements were tested, lighting from the side and lighting from overhead. Because of the intense heat generated by these lights, they were turned on only during focusing and filming to avoid overheating of the glass side wall plate. However, differential thermal heating did crack the 25-mm thick glass plate during an overhead lighting experiment.

31. Several actions were taken to reduce reflections off the glass side wall. The glass plate was kept as clean as possible; other laboratory lighting within the vicinity of the experiment was turned off; and the camera was draped with black cloth prior to filming. Figure 3 illustrates camera and

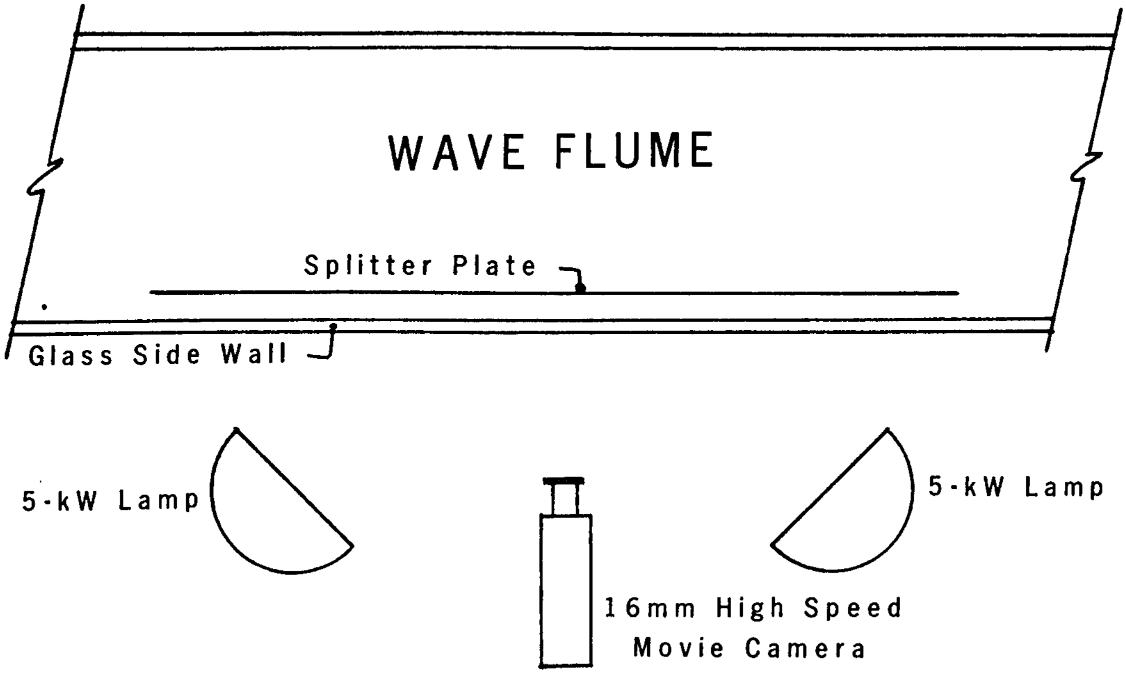


Figure 3. Plan view of experimental arrangement.

Figure 4. Photographer preparing for a filming run.

light positioning. The photograph in Figure 4 shows the photographer preparing for a filming run. Note the splitter plate in this photograph.

Filming Experiments

32. Two filming test series were performed to optimize the various experimental parameters required to achieve good contrast between suspended sand grains and the black background. The still-water level in the flume was fixed at about 20 cm above the sand surface for all filming runs. Tests performed before the filming experiments indicated that monochromatic waves with a wave period of 1.5 sec and a height of about 13 cm would sufficiently suspend grains of the sand sample. These wave conditions were used throughout filming. The waves were not meant to have a scaled relationship to prototype events; their only function was to provide an oscillatory flow regime that would suspend sand grains. Prior to filming, waves were run over the sand bed to establish rippled bedforms characteristic of oscillating flow.

First Filming Series

33. On May 6, 1986, the first series of filming experiments were performed. A total of 35 separate combinations of filming parameters were tested and compared to assess the best method for filming suspended sediment transport. Table 1 lists the experiments and associated filming parameters. Three rolls of film (18,000 frames each) were exposed. The second roll (experiments 12 - 23) was a repeat of the filming parameters used for the experiments on the first roll, but it was processed using a method called "push processing" that involves underexposure of the film during shooting and overexposure during development. The push method is claimed to produce

Table 1. First Filming Experiment.

Experiment Number	Lighting Position	Frame Size (cm)	Exposure f-Stop	Flume Width (cm)
Roll #1 - Standard Development				
1	Side	25	8-11	38
2	Side	25	5.6-8	38
3	Side	25	11-16	38
4	Overhead	25	8-11	38
5	Overhead	25	5.6-8	38
6	Overhead	25	11-16	38
7	Side	10	8-11	38
8	Side	10	5.6-8	38
9	Side	10	11-16	38
10	Overhead	10	8-11	38
11	Overhead	10	5.6-8	38
12	Overhead	10	Film Ran Out	38
Roll #2 - Push Process Development				
13	Overhead	10	8	38
14	Overhead	10	11	38
15	Overhead	10	16	38
16	Side	10	8	38
17	Side	10	11	38
18	Side	10	16	38
19	Side	25	8	38
20	Side	25	11	38
21	Side	25	16	38
22	Overhead	25	8	38
23	Overhead	25	11	38
24	Overhead	25	16	38
Roll #3 - Standard Development				
25	Side	25	8-11	25
26	Side	25	5.6-8	25
27	Side	25	11-16	25
28	Overhead	25	8-11	25
29	Overhead	25	5.6-8	25
30	Overhead	25	11-16	25
31	Side	25	8-11	75
32	Side	25	5.6-8	75
33	Side	25	11-16	75
34	Overhead	25	8-11	75
35	Overhead	25	5.6-8	75
36	Overhead	25	11-16	75

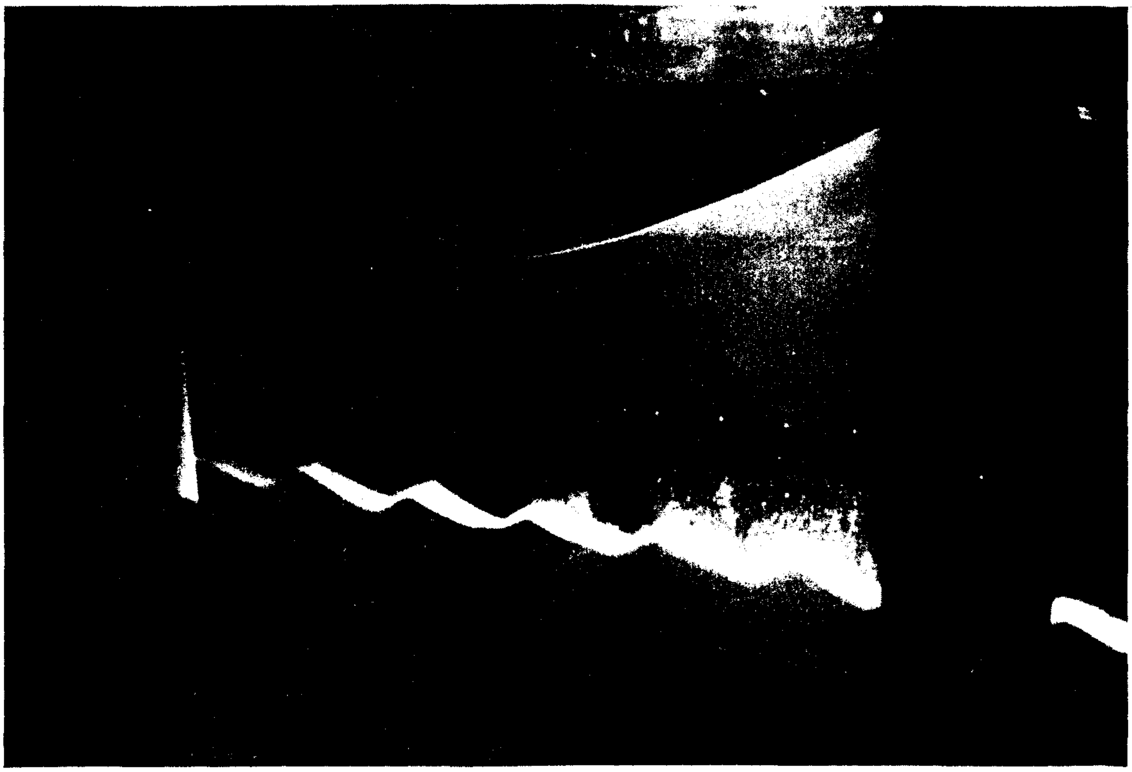
sharper contrast, but in the present case the resultant images were inferior to those produced using standard filming and development techniques.

34. Film exposure was determined by the photographer using a light meter and an exposure reference guide for high-speed filming. An experiment was filmed once at the determined aperature setting, then tests were run at one f-stop underexposure and one f-stop overexposure. These are shown as groups of three on Table 1. All experiments listed in Table 1 were filmed at a rate of 300 frames per sec, and the duration of each run was approximately 5 seconds (1,500 frames). This duration of filming covered about three wave cycles.

35. The splitter plate was moved during the shooting of the third roll of film to test two additional test section flume widths. The purpose of this variation was to determine the largest flume width that could be used before a loss of definition occurred on the film.

36. The column labeled "Frame Size" in Table 1 provides an approximate horizontal dimension of the field of view as seen through the camera lens. This was estimated using the white dots on the splitter plate. Different lenses were used to achieve different frame sizes; the purpose of this variation was to investigate the areal extent of filming that will still produce usable imagery for determination of sediment concentrations.

37. Finally, two different lighting techniques were employed for illuminating the suspended sand grains: lighting from overhead and lighting from the side (see Figure 3 for side lighting placement). Figure 5 provides still-photography examples of the two types of lighting. Both lighting methods successfully illuminated the sand grains, but the overhead lighting is flawed by light refraction during passage of a wave. The curved water surface



(a) Overhead lighting.

(b) Lighting from the side.

Figure 5. Experiment lighting.

of the wave crest causes light refraction and focusing of light that sweeps across the bedform with each passing wave. This change in light intensity over a wave cycle would make it difficult to automatically determine sediment concentrations from variations in light intensity levels.

38. After viewing the three rolls of film from the first filming experiment, the following conclusions were drawn:

a. Standard film development is better than push process development.

b. Side lighting is superior to overhead lighting because of the consistant level of light intensity.

c. A filming speed of 300 frames per sec is sufficient to capture the temporal nature of the sediment transport process.

d. A maximum flume width of 40 mm could be used without significant loss of detail.

e. All film was underexposed and too dark for automatic analysis.

Second Filming Series

39. The darkness of the film from the first test series prompted a second filming series that was conducted on August 21, 1986. Two rolls of film were exposed and 16 experiments were performed as listed in Table 2. For these experiments, wave conditions were as before, the splitter plate was situated to provide a 38-mm-wide flume, side lighting was used, and films were processed in the standard manner. The initial run of each set was shot at the determined exposure, then two additional runs were made to provide a one f-stop and a two f-stop overexposure. Other parameters that were varied included filming run time, field of view frame size, and filming speed. Suitable footage for use in developing image analysis techniques was obtained from the runs conducted with a two f-stop overexposure.

Table 2. Second Filming Experiment.

Experiment Number	Frames per Second	Frame Size (cm)	Exposure f-Stop	Run Time Seconds	Flume Width (cm)
Roll #4 - Standard Development					
37	300	20	5.6	10	38
38	300	20	4	10	38
39	300	20	2.8	10	38
40	300	38	5.6	5	38
41	300	38	4	5	38
42	300	38	2.8	5	38
43	300	10	5.6	5	38
44	300	10	4	Film Ran Out	38
45	300	10	2.8	Film Ran Out	38
Roll #5 - Standard Development					
46	300	10	5.6	5	38
47	300	10	4	5	38
48	300	10	2.8	5	38
49	200	20	8	10	38
50	200	20	5.6	10	38
51	200	20	4	10	38
52	200	38	8	5	38
53	200	38	5.6	10	38
54	200	38	4	10	38

Filming Conclusions and Recommendations

40. The two filming series, composed of a total of 51 different combinations of filming parameters, have provided the following conclusions and recommendations for high-speed filming of suspended sediment transport in a laboratory wave flume:

a. A splitter plate in the flume, installed parallel to the glass side wall and painted flat black, provides a constant low-intensity background and establishes a known depth of field for filming. A distance from the side glass of about 40 mm provided good results for this study.

b. Horizontal, high-intensity lighting provides uniform illumination of the region being filmed. Overhead lighting that must penetrate the water surface will be focused by the curved water surface causing a nonuniform lighting condition over a wave cycle.

c. Filming speeds between 200 and 300 frames per sec are adequate to characterize temporal aspects of suspended sediment transport at micro-scale.

d. The best contrast between sand grains and the background was obtained for runs filmed with a two f-stop overexposure and processed in the standard manner. However, anyone contemplating experiments of this type should conduct pretesting over a range of aperature settings using the intended lighting since the present conclusion may be a function of specific camera, lens, and lighting equipment.

e. Clean, well-sorted sand is needed for the experiment. Grain size selection is closely related to resolution capability of the imaging system and field of view of the camera during filming runs.

f. When it becomes practical, high-speed, high-resolution video equipment should replace 16-mm movie film in order to eliminate the film processing delay in the quality control feedback loop.

PART V: IMAGE DIGITIZING AND ANALYSIS HARDWARE

41. The second phase in demonstrating the feasibility of the photographic method for determining suspended sediment concentrations involved the processing and subsequent image analysis of the 16-mm movie film. Two available systems at CERC were used to accomplish this task.

16mm Film Digitizer

42. The 16-mm film digitizer is a modified Eikonixscan Model 785 Image Digitizer manufactured by Eikonix Corporation. The modification to the basic machine is the 16-mm film transport and corresponding optics necessary to meet the required sampling interval of

$$0.00392 \text{ mm} < X < 0.137 \text{ mm}$$
$$0.00392 \text{ mm} < Y < 0.137 \text{ mm}$$

on a 16-mm film image. The instrument can resolve and digitize up to 2048 by 2048 pixels, registering up to 256 gray levels (8 bits) of light intensity per pixel. Manual controls are provided for setting filtering, magnification, focus, exposure, and manual scanning of the image. A prism can be moved into place so that the image can be viewed directly through the view finder. When the prism is shifted out of the way, the current scan line is represented on a CRT screen as levels of light intensity. The machine can digitize a 2048 x 2048 image to memory in 50 secs. Additional time is required to write the image from memory to hard disk.

43. The 16-mm film digitizer interfaces to the host computer through a direct memory access (DMA) board located on the computer's backplane. The host computer is a Digital Equipment Corporation PDP-11/24 minicomputer

running Version 4.2 of the RSX-11M operating system. Most of the functions of the film digitizer can be controlled through a library of Fortran-callable subroutines. These include digitizing specified subregions of the image at specified levels of resolution, automatically advancing from one frame to the next according to a given sequence, and initiating decision branches based on a specified level of light intensity. The usual output device for the digitized image is a hard disk; however, 9-track magnetic tape is available as an option.

Interactive Image Analysis System

44. Investigation of various attributes of the digitized film images was conducted on an interactive system that allowed viewing of the digitized image and application of standard image enhancement techniques. This allowed feedback into the digitizing process so that image enhancement could be performed automatically during digitization. The interactive image processing system at CERC is the Gould DeAnza FD5000 with several enhancements. Its image memory is configured as 1024 x 1024 pixels with each pixel 28 bits deep. This allows 8 bits for red (0 - 255 gray levels), 8 bits for green, 8 bits for blue, and 4 bits for an alphanumeric overlay at each pixel. The large memory facilitates the manipulation of full color images. For the present application, the digitized images prepared for viewing were monochrome images of a size 512 x 512 pixels, the size of the viewing screen of the monitor.

45. Images were viewed on a 19-inch Conrac color monitor, model 7211. This is a high-resolution (1080 horizontal x 809 vertical) RGB color monitor designed specifically for image processing applications. The FD5000 drives

the monitor at a 60 Hz refresh rate, providing flicker-free viewing of the image. Hardcopy of any image viewed on the monitor is obtained using a Polaroid Model 4 Film Recorder. This programmable unit reproduces the image onto a self-contained monitor (of less resolution) where it is photographed by a specially mounted 35-mm SLR camera. The interactive image analysis system is interfaced through a DMA controller to a Digitial Equipment Corporation PDP-11/44 minicomputer running Version 4.2 of the RSX-11M operating system. Image analysis and enhancement are performed using application software packages which are supported on the minicomputer.

PART VI: DETERMINATION OF SEDIMENT CONCENTRATIONS

Approaches

46. Automatic determination of suspended sediment concentrations from digitized images conceivably can be accomplished by two methods. The first technique would provide absolute concentration through identification, counting, and mapping of individual sand grains. The second method entails mapping of light intensities returned by sand grains, and correlating light intensity per unit area to actual hand-counted sediment concentrations. Both methods impose requirements on the image resolution and assume good light intensity contrast has been achieved between sediment grains in suspension and the background.

Resolution

47. At a minimum, the resolution of the digitized image should be such that one sand grain diameter is equal to the length of three pixels (picture elements). This assures that a sand grain will completely overlap at least the full area of one pixel, and the returned light intensity will dominate that pixel. Computer algorithms can then be employed to search the digital image file for those pixels having light intensities representative of the sand grains. For the film digitizer used in this study, with the capability of representing a 16-mm frame as a 2048 x 2048 pixel matrix, this minimum requirement translates into a maximum field of view of 20 cm x 20 cm for smaller grains (0.3 mm in diameter) in the grain size distribution used in this experiment.

Individual Grain Tracking

48. Initially it was thought that a computer algorithm could be written to read through the file of a digitized image, identify individual sand grains, and map their spatial position. This is probably achievable, but several difficulties need to be overcome. The major problem is the effective computer recognition of an individual sand grain. Because grains have different size, shape, and color, they reflect varying amounts of light. This ambiguous situation is compounded by the fact that the grains have facets that will reflect greater or lesser amounts of light depending upon their particular orientation. Of lesser importance, but still a consideration, is that grains in the foreground will be brighter on the film than grains in the background. Nonetheless, a successful computer algorithm could be written and, in some instances, the complexity and computer overhead would be warranted. However, this study employed a simpler method for determining concentration, with the thought that more elaborate algorithms would evolve after demonstration of the method's feasibility.

Light Intensity Mapping

49. Provided a sufficient number of sand grains are in suspension, it is possible to process and spatially map light intensity levels reflected off the grains. Portions of the flow regime with heavier concentrations will return more light than regions with fewer suspended grains. A calibration procedure is needed to relate levels of light intensity to suspended sediment concentrations.

There are several advantages to using this approach:

a. It is easy to implement and test.

b. Digitization and data storage are rapid so that large quantities of data can be analyzed in a reasonable amount of time.

c. Opportunities exist that allow data decimation with minimal reduction in data quality. This results in reduced computer file storage requirements.

d. Mapped light intensities are easily contoured and plotted to provide quantitative spatial and temporal pictures of relative concentrations.

e. Light intensity differences between individual grains become less important to the extent that they represent variations around the mean intensity being returned from a small area of the image.

50. The disadvantage of light intensity contouring is that calibration is required to obtain sediment concentrations. Additionally, the contouring method does not allow Lagrangian tracking of individual grains between frames which, in principal, could be achieved by a method that maps individual sand grains.

Digitization

51. A FORTRAN program was written that controlled the automatic digitizing of the 16-mm film frames. The program was designed in a manner that allows the operator to initialize certain parameters of the digitizing process prior to the program beginning automatic control of the procedure. This permits each application to be tailored to the specific imagery being examined; for this study, it allowed systematic investigation into the effects of varying several controlling parameters.

Parameter Selection

52. After performing a required calibration of the light sensing diodes that comprise the scanning head, the operator establishes the film sequencing. Several modes of sequencing are available for automatic advancing of the 16-mm

film in the film drive. The first is digitizing of specific frame numbers (e.g., Frames 1, 10, 15, 22, 23,...). The second method digitizes a given number of frames, skips a designated number of frames, then digitizes the same number of frames as before (e.g., digitize two, skip ten, digitize two, skip ten,...). The third sequencing method is the most useful for the kind of application described here. The user specifies a beginning and ending frame number along with a spacing interval (e.g., 1,100,5 means start at frame one and digitize every fifth frame up to frame 100). For each method of film sequencing it is necessary for the operator to specify the frame number of the frame currently in view at the start of the digitization.

53. Often only a portion of the image will be of interest, so the digitizer can be programmed to scan, digitize, and store only a selected subregion of the full image. Designation of a subregion is performed during initialization.

Data Decimation

54. The potential large volume of data resulting from full digitization of each frame (2048 x 2048 = 4,194,304 pixels) led to two means of reducing the amount of stored information. The first, mentioned above, was judicious selection of a subregion of the image to digitize. The second method involved averaging of light intensity returns from all pixels contained within a given block, and then saving only the averaged value. Significant storage savings are achievable by using this technique, but selection of the block size is critical to retaining data quality. The size of the block must be chosen such that the average obtained from a block with one sand grain in it is

sufficiently different from both a block with no sand grains in it and a block with two sand grains in it.

55. The capability to subdivide the region to be digitized into square blocks containing a specified number of pixels and then to perform light-intensity averaging within the block during the digitization process was included in the computer program. The operator supplies this information during initialization.

56. Investigation into the effects of data decimation involved repeated digitization of the same film image at different levels of data decimation and subsequent manual examination and comparison of numerically averaged values. This procedure is perhaps best illustrated by way of example.

57. An image with a field of view of about 9 cm x 9 cm has resolution on the 16-mm digitizer of about 7 pixel lengths equal to one grain diameter for the smaller grains (0.3 mm) and about 18 pixel lengths equal to one grain diameter for the largest grains (0.8 mm). Of course, these values are approximate and differ from grain to grain for reasons previously discussed. The image was digitized and decimated using blocks measuring 4, 8, 16, and 32 pixels per side. Manual comparisons were made by locating within the computer file the spatial position of individual sand grains, and then comparing averaged light intensity values with those from the same spatial position in other computer files. In addition, intensity contours for the image were generated and compared for each file. Only the image that used blocks measuring 32 x 32 pixels showed a noticeable loss in data quality due to the averaging technique. For this large area, the bright intensity returned from the sand grain or grains often was lost in the average, whereas in cases of

smaller blocks, single grains heavily influenced average light intensity.

58. A tentative rule-of-thumb is that an image can be successfully decimated up to about twice the mean grain size without appreciable loss in data quality. If data storage and speed of digitization are not important considerations, it is recommended that block size be reduced as much as possible.

Automatic Operation

59. After all initializing data have been entered, the digitizer falls under automatic control. Each frame is scanned according to the parameters given, the scanned data are decimated and written to disk, and the next scheduled frame is advanced into place. Appropriate file headers and identifying information are placed into the computer file. For the example cited above, a full image measuring 2048 x 2048 pixels was digitized and decimated into an area containing 128 x 128 blocks measuring 16 x 16 pixels each. This represents a reduction factor of 256 over retaining the entire set of values. The image was scanned and processed in 7.5 minutes. The digitizer scanned 16 lines and the computer performed the averaging procedure. It appeared that the digitizing process was delayed by the relatively low performance of the host computer's central processor. Hosting the 16-mm digitizer on a present-day superminicomputer would probably make the digitizing time dependent on digitizer scanning speed and disk output. It is estimated that the processing time per image could be reduced to about two minutes using a newer host computer.

60. An alternate method, not tested during this study, would be to digitize the image and save every other pixel or every fourth pixel. These

files would be further decimated on a more powerful computer using the averaging technique described above. If storage is not a problem, the digitized images could be kept in the original form for analysis.

Contouring

61. The digitizing method discussed above produces a square matrix containing averaged values of light intensity. A visual representation of the data can be easily obtained by contouring the data using standard subroutines to produce a graphic display. Examples of light intensity contours are given in Figures 6-9. In each figure the top half is a photograph of an image displayed on the interactive image system and recorded using the camera system described in Part IV. The resolution of the camera system is less than the image itself, hence the quality of the photograph is somewhat degraded. Image files used for the interactive system were digitized by saving every fourth pixel of a 2048 x 2048 frame to obtain a 512 x 512 image of the frame that could be displayed. Image quality was only slightly reduced.

62. The lower half of each figure presents the corresponding light intensity contour map developed from the same 16-mm film image. Using the distance between white dots on the background splitter plate as a known reference distance of 5 cm, it is seen that Figures 6, 7, and 8 have a field of view of approximately 9 cm in the horizontal, whereas Figure 9 has a corresponding field of view of about 18 cm. The scale of Figure 9 is inappropriate to obtain good detail of the micro-scale process. Also, it is likely that the decimation process, which was designed for the 9-cm images, has reduced the quality of the results given in Figure 9.

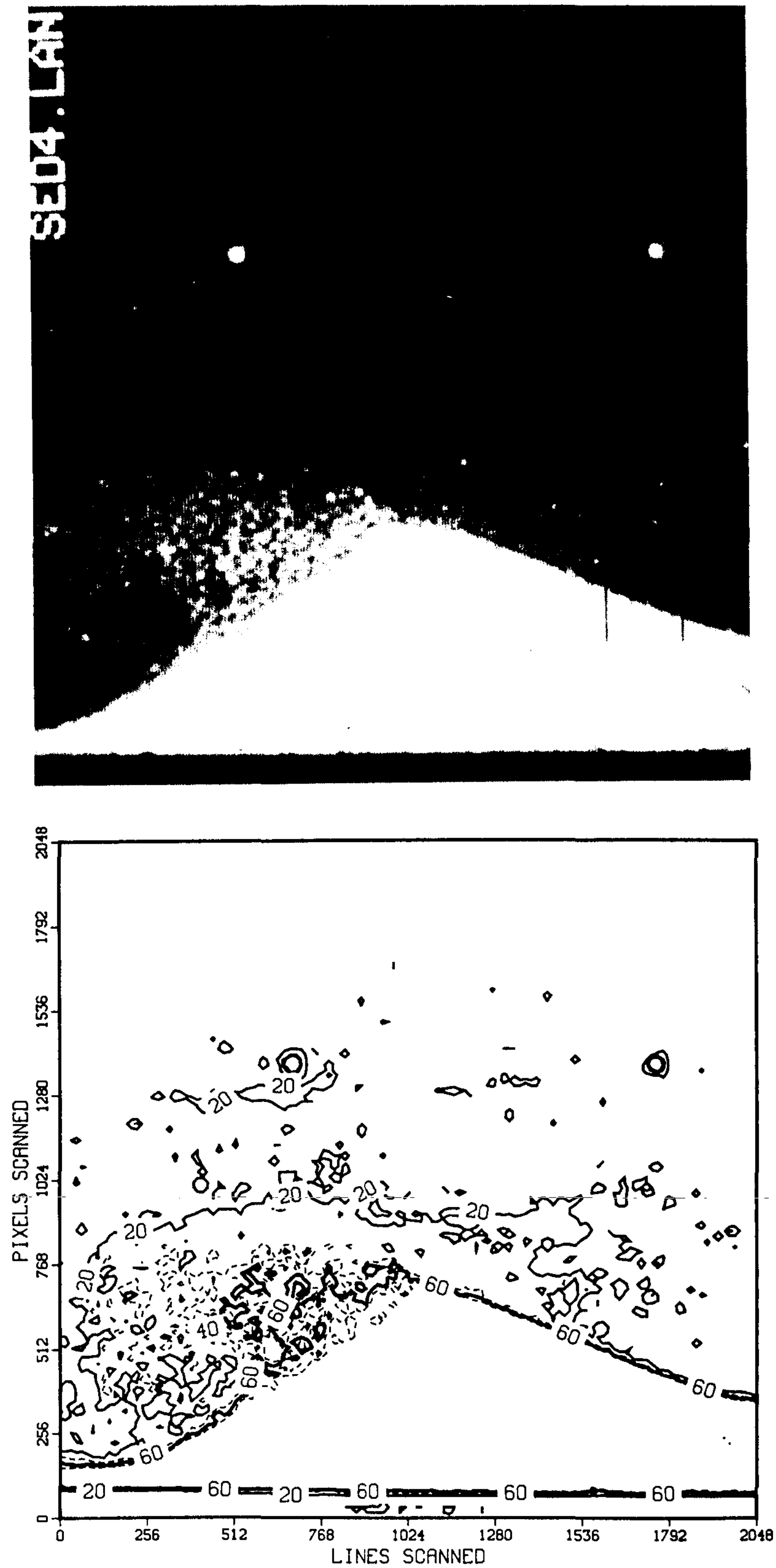


Figure 6. Light intensity contour plot from image SED4.LAN.

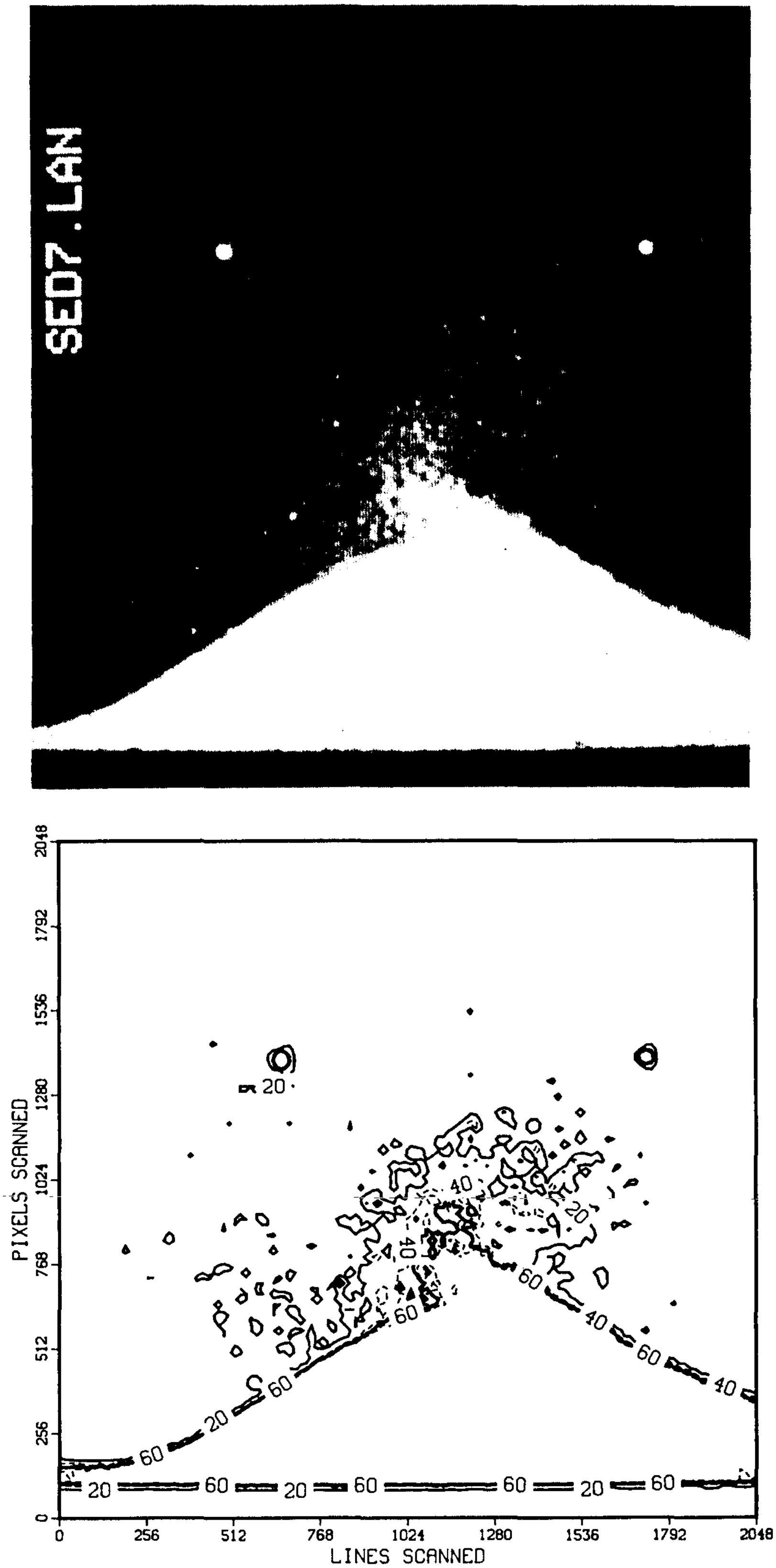


Figure 7. Light intensity contour plot from image SED7.LAN.

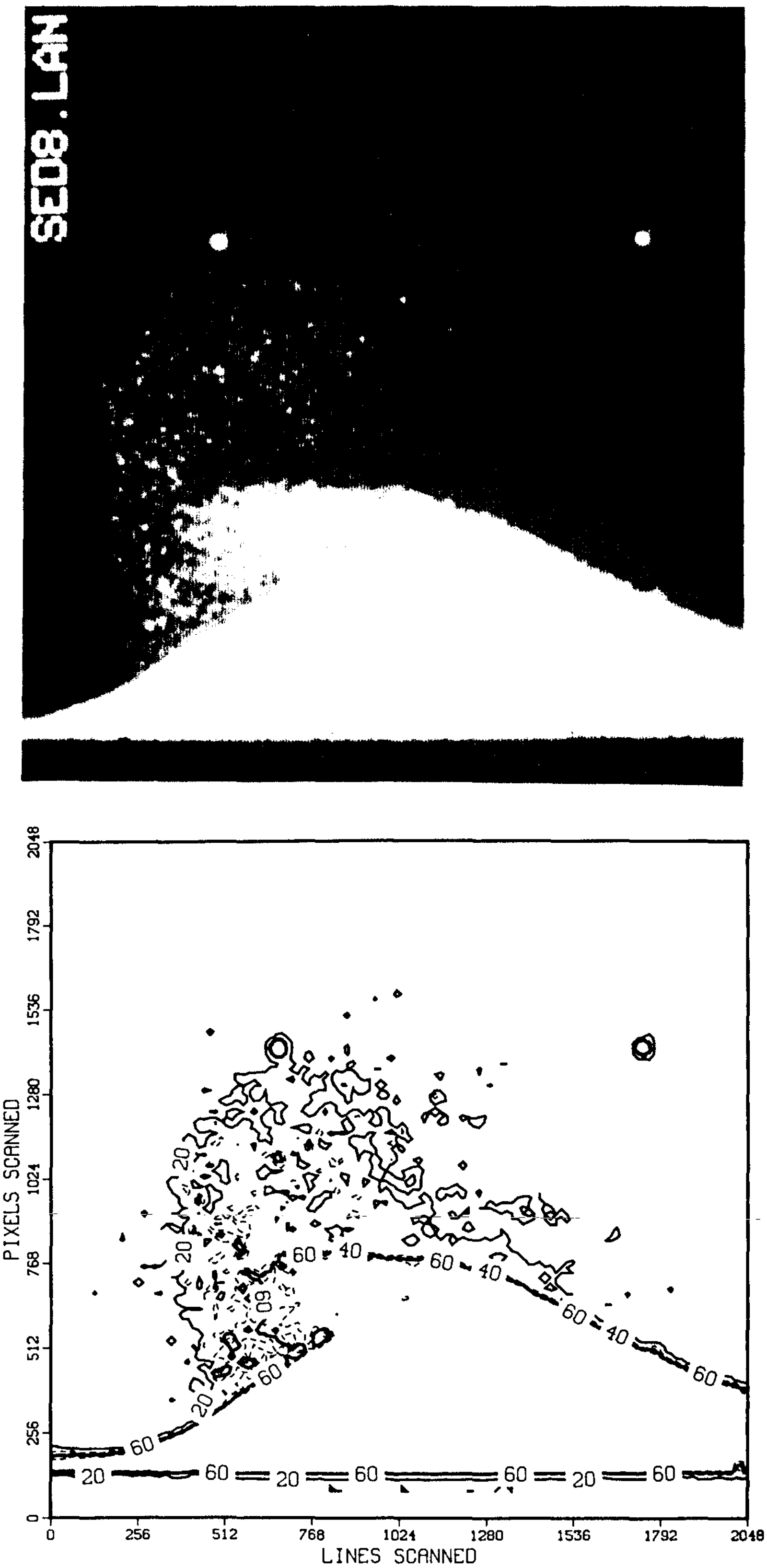


Figure 8. Light intensity contour plot from image SED8.LAN.

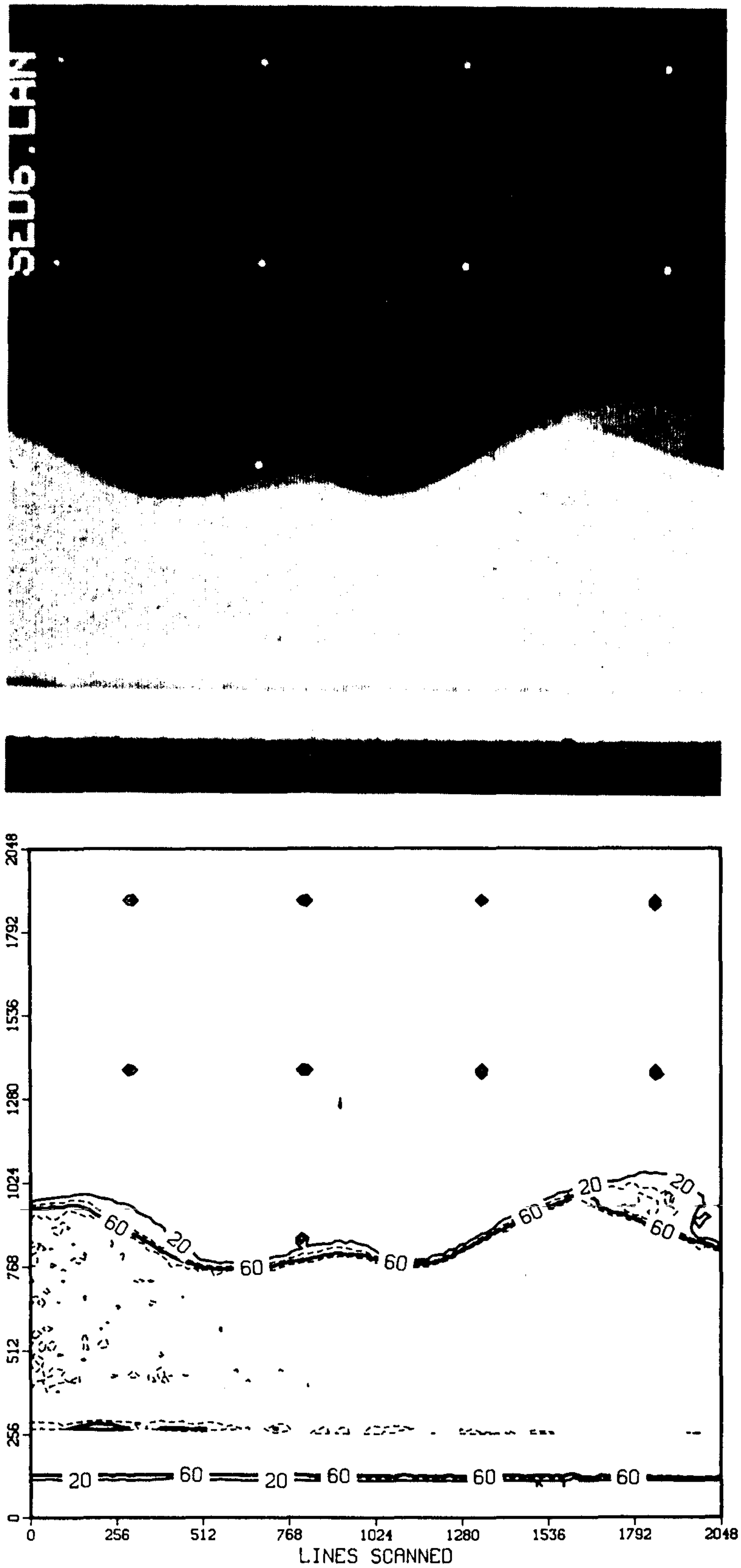


Figure 9. Light intensity contour plot from image SED6.LAN.

63. Using the reference white dots as matching points, contours can be superimposed on the photographs. This was done for the three images with a 9-cm field of view (Figures 6, 7, and 8), and the resulting composites are given as Figures 10, 11, and 12. In the three composite figures the quality of the photograph has been further reduced by the process used to obtain the overlay, but all figures show that the light intensity contours map the sediment concentrations as perceived by eye. Appendix A contains a series of contour plots illustrating the process of sediment transport over a wave cycle as mapped by light intensity contours. Thus light intensities have been shown to be useful for visualizing suspended sediment concentrations in a relative manner. What remains is to establish a calibration technique that can translate light intensity differences into sediment quantities.

Calibration

64. Most instrumentation requires calibration so that instrument response can be related to the physical process being measured. Exceptions are instruments that measure a quantity that can be theoretically linked to the physical process using fundamental physical principles. But even in the case of a theoretical calibration, validation of the instrument response is desirable. Often calibration is a straightforward procedure, such as plotting of the response of a resistance-type water level gage to known water level variations, because there exist alternate methods for measuring the physical quantity for comparison to the instrument output. Calibration becomes more difficult, if not impossible, if the instrument is attempting to measure a physical process for which no alternate means of measurement exists.

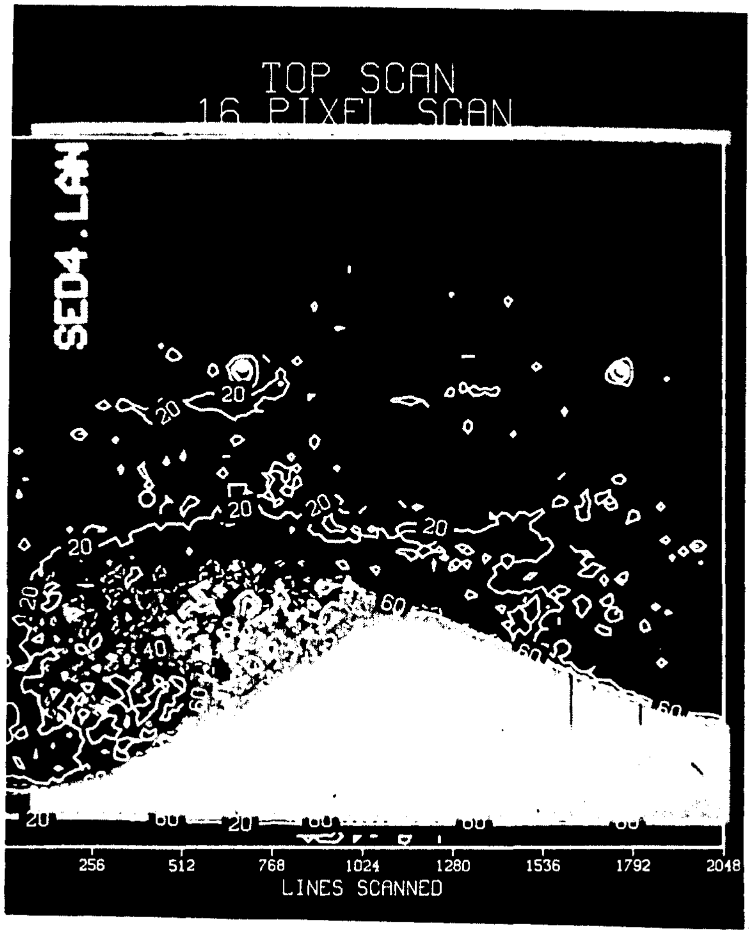


Figure 10. Image and contour overlay from Figure 6.

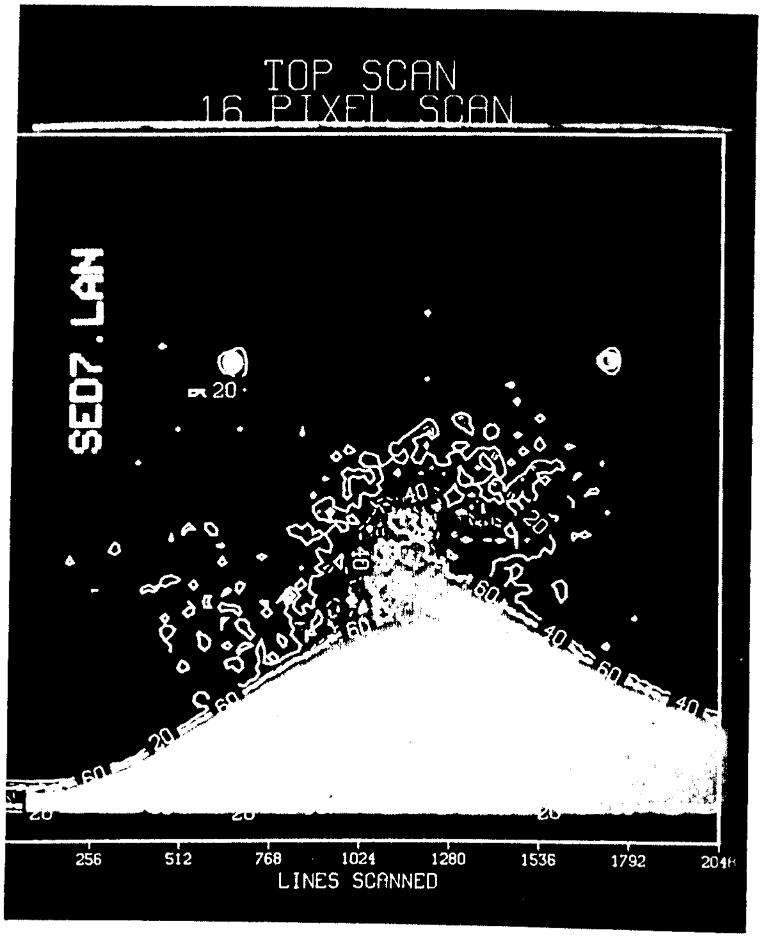


Figure 11. Image and contour overlay from Figure 7.

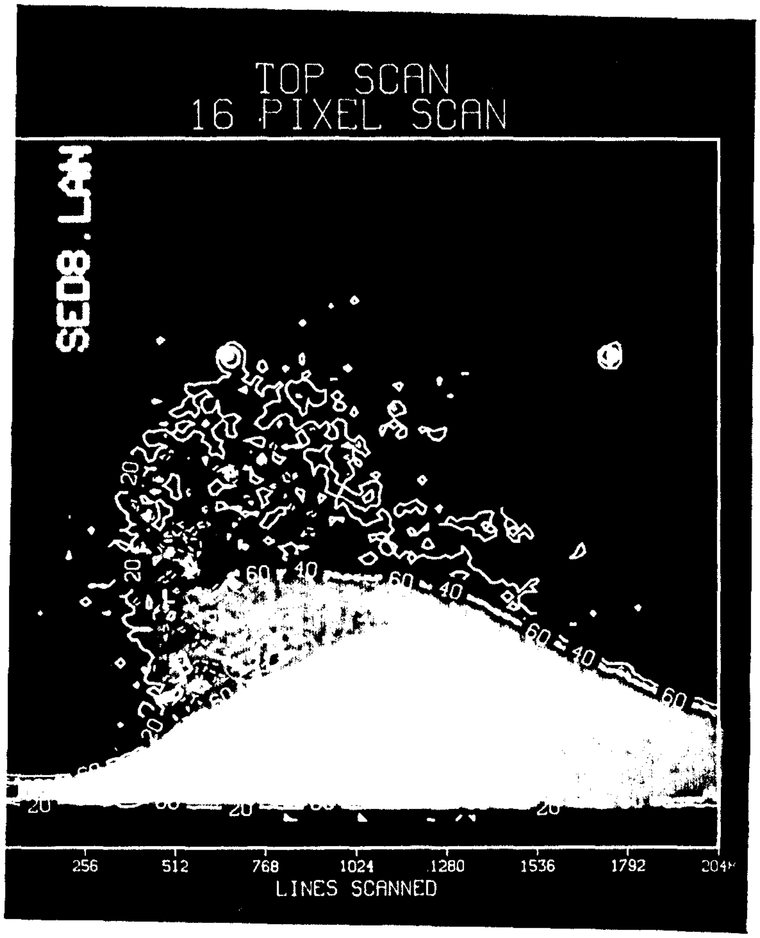


Figure 12. Image and contour overlay from Figure 8.

65. Calibration of the suspended sediment measurement technique described in this report was not performed. Such a calibration would require relating levels of light intensity density to corresponding levels of suspended sediment concentration.

66. A suggested calibration technique would be to relate the number of sand grains visible in a selected unit area of the image to the average light intensity returned from that area. The size of the selected area must be sufficiently large so that a reasonable variation in grain concentration could exist within the area, but sufficiently small so that the light intensity average is significantly altered by variations in the number of grains. The actual number of grains is obtained by hand-counting the grains within the area from an enlarged version of the 16-mm frame.

67. This method was attempted for the image shown in Figure 13. The overlayed grid subdivides the image into blocks measuring approximately 6 mm on a side. Figure 14 presents the same grid with the averaged light intensity values indicated for each cell. Qualitatively, the averaged intensity increases with concentration of suspended sediment; however, sufficient hand-counted values of sand grains within a cell could not be obtained to provide a thorough calibration. Hand-counting sparsely populated areas of the image was easy, but difficulty arose in determining the number of grains in areas of high suspended sediment concentration. This difficulty may be attributed, in part, to the relatively low quality image used in this attempt (Figure 13). Use of a high-quality reproduction of an actual 16-mm film image may have enabled successful calibration.

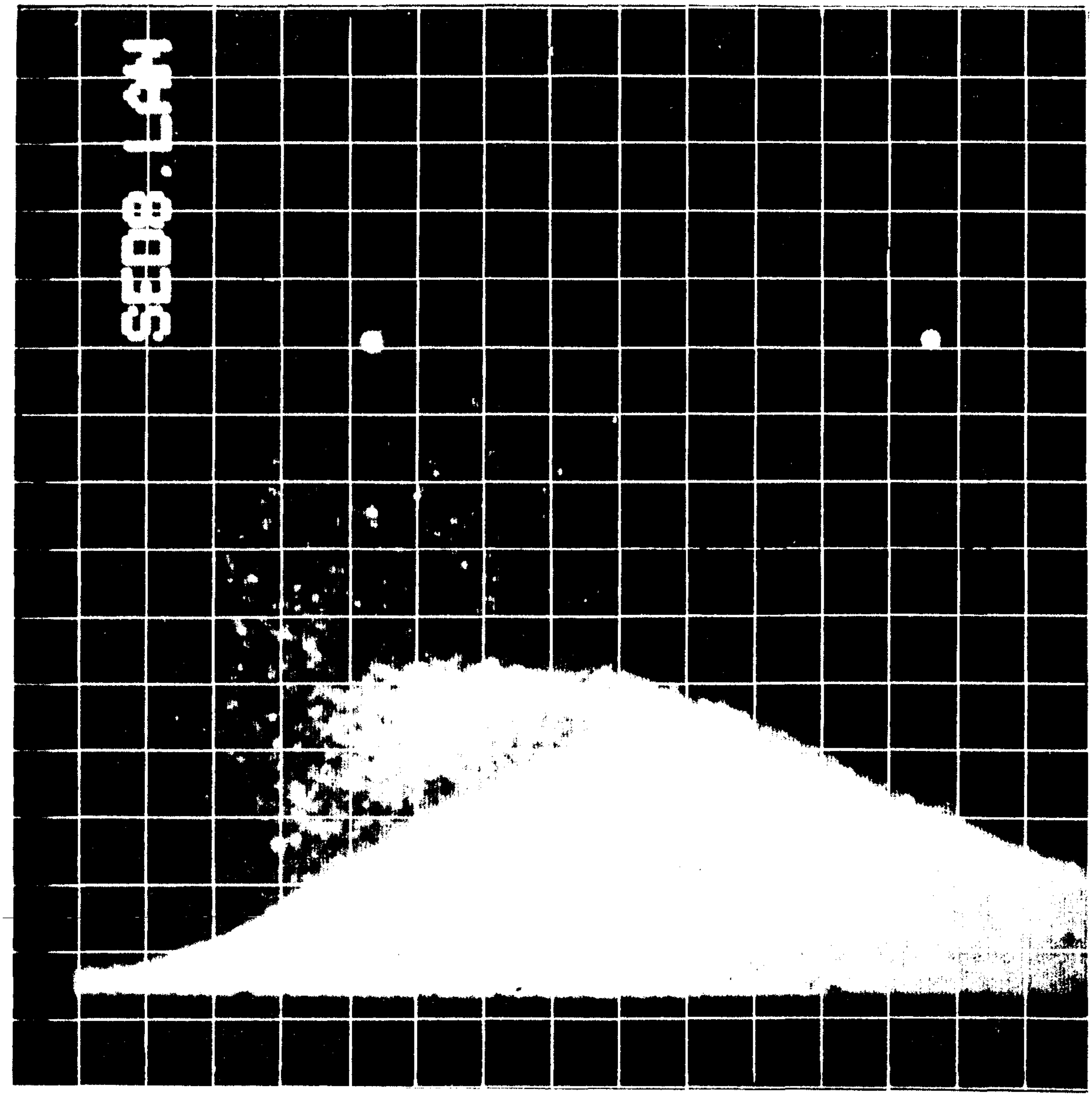


Figure 13. Image with superimposed grid for calibration.

11	12	13	15	15	15	16	16	15	15	15	15	14	14	13	13
12	13	13	15	15	15	15	16	16	15	15	15	15	14	14	14
13	14	14	15	16	16	16	16	16	16	16	15	15	15	14	14
13	14	15	16	16	16	17	17	17	16	16	16	16	15	15	14
14	15	16	17	17	Dot 29	18	17	17	17	17	16	16	Dot 28	16	15
15	16	16	17	19	27	21	19	18	18	18	17	17	18	16	15
15	15	16	19	21	23	22	21	20	18	17	17	17	17	16	16
15	16	17	25	27	30	26	23	19	18	18	17	18	18	17	16
15	15	18	27	31	25	27	24	21	19	19	19	18	17	17	16
15	16	17	31	35	34	40	38	31	22	19	18	18	18	16	16
15	16	18	28	48	91	126	127	135	173	113	33	18	18	17	16
14	15	16	26	46	78	112	186	235	240	235	190	96	28	16	15
14	15	15	25	53	134	224	228	231	225	218	212	187	158	87	36
13	14	15	62	179	211	217	225	232	217	206	190	178	156	142	115
49	61	105	152	165	171	180	171	176	174	164	153	135	123	103	87
12	13	14	15	16	17	17	17	17	17	17	17	17	16	15	15

Figure 14. Averaged light intensities for cells shown in Figure 13.

PART VII: SUMMARY AND CONCLUSIONS

68. This study examined the feasibility of obtaining spatial and temporal suspended sediment concentrations in the laboratory through the use of high speed filming and image analysis. This nonintrusive measurement technique would provide a tool to assist in quantifying sediment transport at the micro-scale.

69. Successful implementation of this technique requires that a high contrast be obtained between suspended sediment grains and the background. A series of filming experiments was conducted in a laboratory wave flume to investigate various filming parameters and to determine optimum conditions for filming high quality footage of sediment transport. It was concluded that best results can be achieved by using a black backdrop, or splitter plate, to limit the width of the experimental region to within 40 mm. High intensity light directed horizontally through the glass side wall provided uniform lighting conditions throughout the wave cycle, and greater contrast was achieved by overexposing the film two f-stops. A filming speed of 200-300 frames per sec is more than adequate for capturing the temporal nature of sediment transport.

70. The field of view for filming is determined by the resolution of the image digitizing equipment. If it is important to map individual sediment grains, the spatial resolution should be no coarser than three pixel lengths equal one grain diameter. For light intensity contouring, the resolution requirement can be relaxed to about one pixel length equal one grain diameter.

71. Although mapping of individual sand grains on a frame-by-frame basis appears possible, it would require somewhat sophisticated grain identification algorithms and would consume more computer resources. An alternate approach, examined in this study, is to map the light intensity levels returned from the suspended sediment. Computationally, this is much easier to implement, and the digitized image often can be selectively decimated to reduce disk storage space.

72. The light intensity contouring technique was implemented, and it was shown that the contours map the suspended sediment concentrations. Determination of actual suspended sediment concentrations requires correlation between number of sand grains in an area and light intensity level returned from that area. Requirements for calibration were discussed, and a preliminary calibration was attempted, but the image used in the calibration was not of suitable quality to obtain accurate grain counts.

73. This study demonstrates that high-speed photography and image analysis can be applied to make spatial and temporal measurements of suspended sediment transport in the laboratory. This method has the potential to provide researchers with quantitative measurements and insight into the micro-scale physics of sediment transport.

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APPENDIX A: LIGHT INTENSITY CONTOURS OVER A WAVE CYCLE

1. The Plates contained in this Appendix present a time series of light intensity contours representing sediment transport that occurred over one wave cycle. Each contour plot was generated from a 128 x 128 array of light intensities obtained using the method described in Part VI of this report.

2. From the original film, shot at 300 frames per sec, every 25th frame was digitized and contoured. Hence, the plots are evenly spaced at 1/12th-sec intervals, and the 20 contour plots shown on Plates 1 through 5 represent a time span of 1.58 sec in the wave tank. The plots are arranged in chronological order beginning with the upper left corner of Plate 1. The series progresses on each Plate from upper left to upper right, then from lower left to lower right.

3. The sequence on Plate 1 initially shows a decreasing movement of suspended grains from left to right as the horizontal water velocity slows and reverses direction. The final plot on Plate 1 indicates bed mobilization to the right of the ripple crest as the flow accelerates to the left.

4. The plots on Plate 2 span the time of maximum horizontal water velocity toward the left. Sand grains are sheared off the top of the ripple and carried in suspension to the left and out of the frame.

5. Plate 3 contour plots are perhaps the most interesting because they show sediment being thrown into suspension by the vortex generated in the lee of the sand ripple. The horizontal water velocity has decreased and started to change direction while the flow field is being dominated by the turbulent motion.

6. In Plate 4 the horizontal flow is accelerating to the right, moving the suspended cloud of sediment to the right and exhibiting a strong shear on the crest of the ripple.

7. The final sequence, presented on Plate 5, shows the completion of the wave cycle with decreasing horizontal flow velocity to the right, settling of grains to the bed, and the bedform taking on a quasi-stable configuration. The suspended sediment shown predominantly on the lower two plots of Plate 5 is a cloud of sediment moving into the frame from the left. This cloud was spawned on the adjacent ripple during a turbulence episode, and it had been moving to the right during the latter half of the wave cycle.

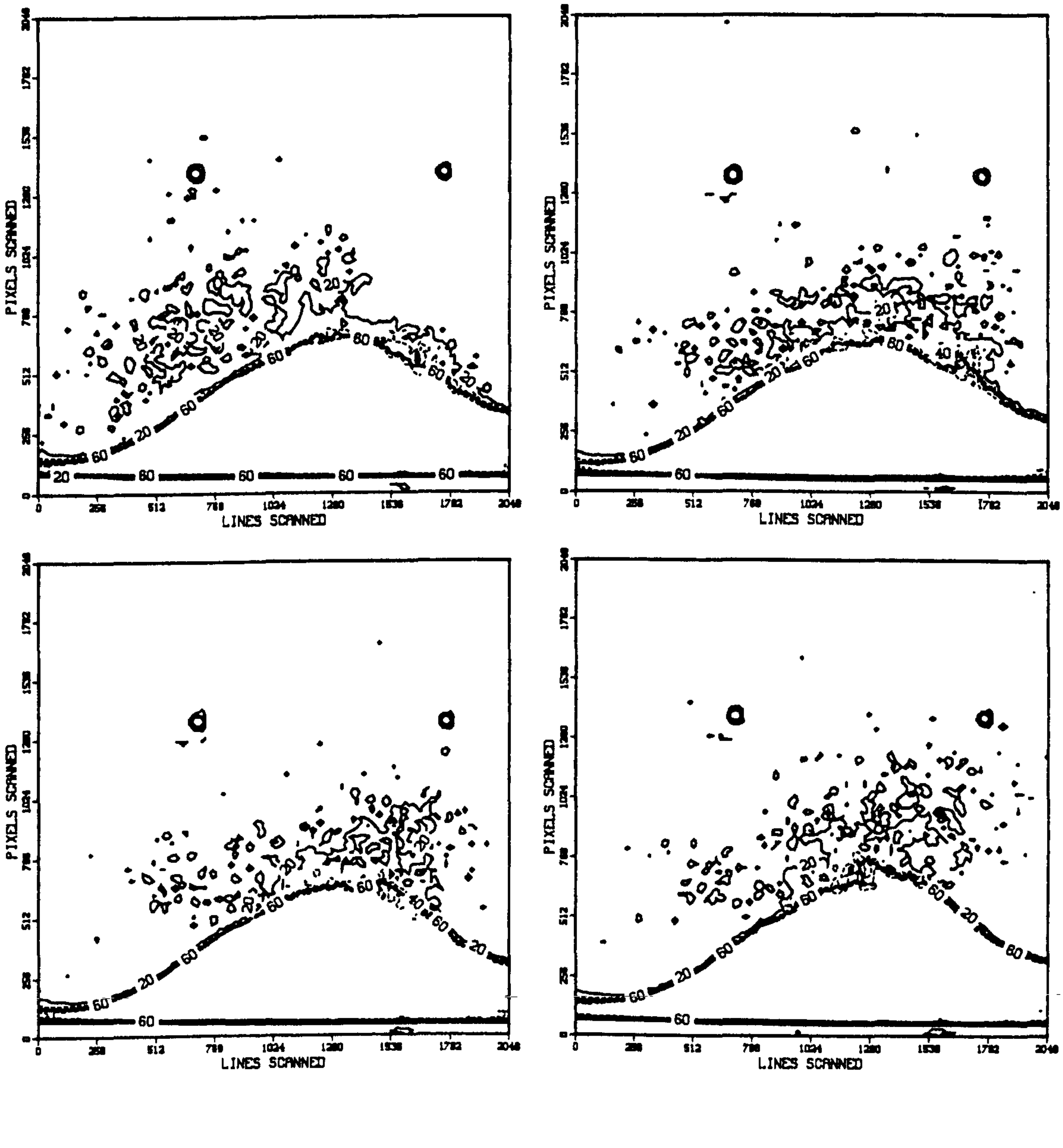
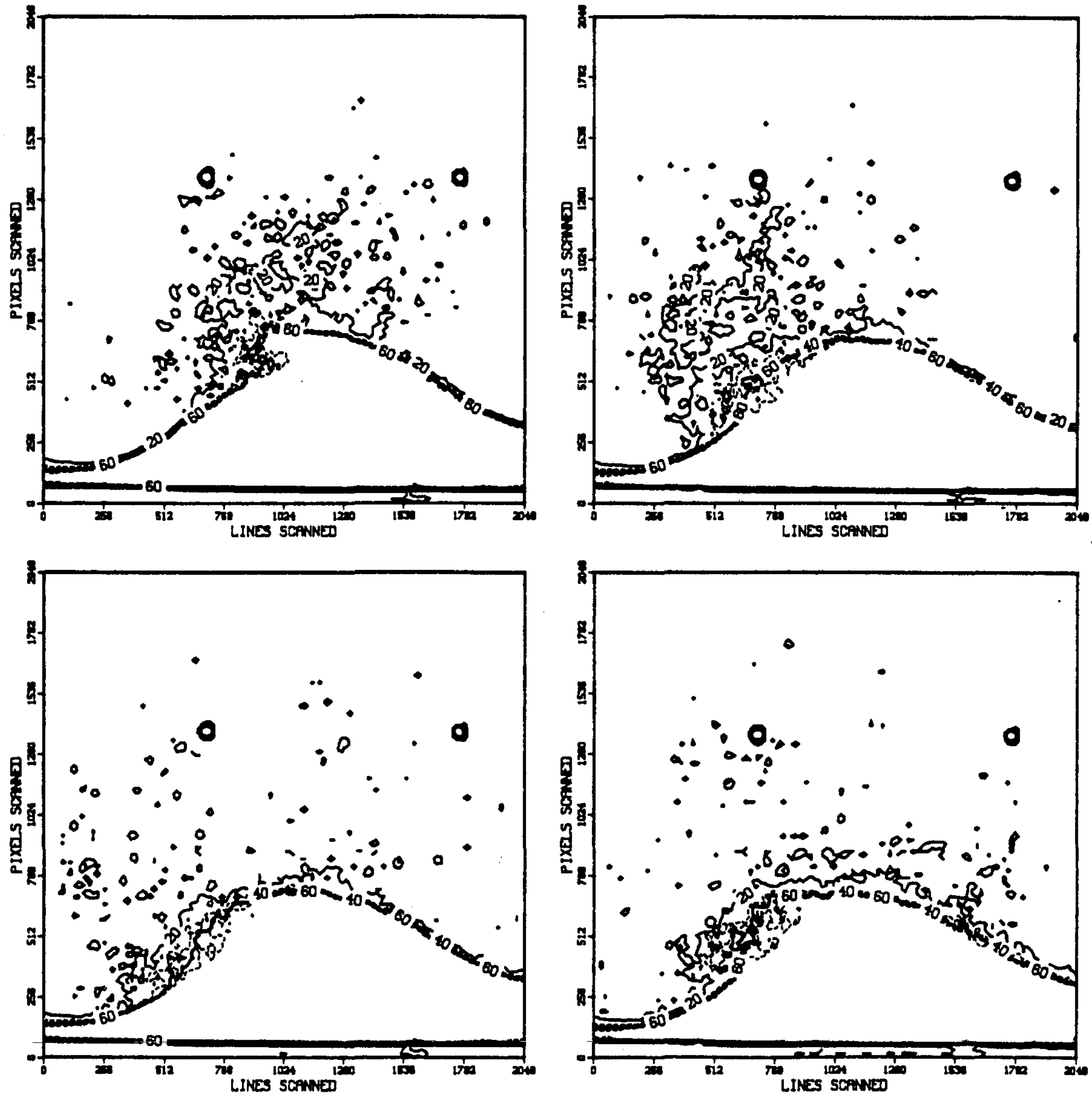

PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED

Plate 1.


PIXELS SCANNED
LINES SCANNED
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512
768
1024
1280
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2048
20
40
60

Plate 2.

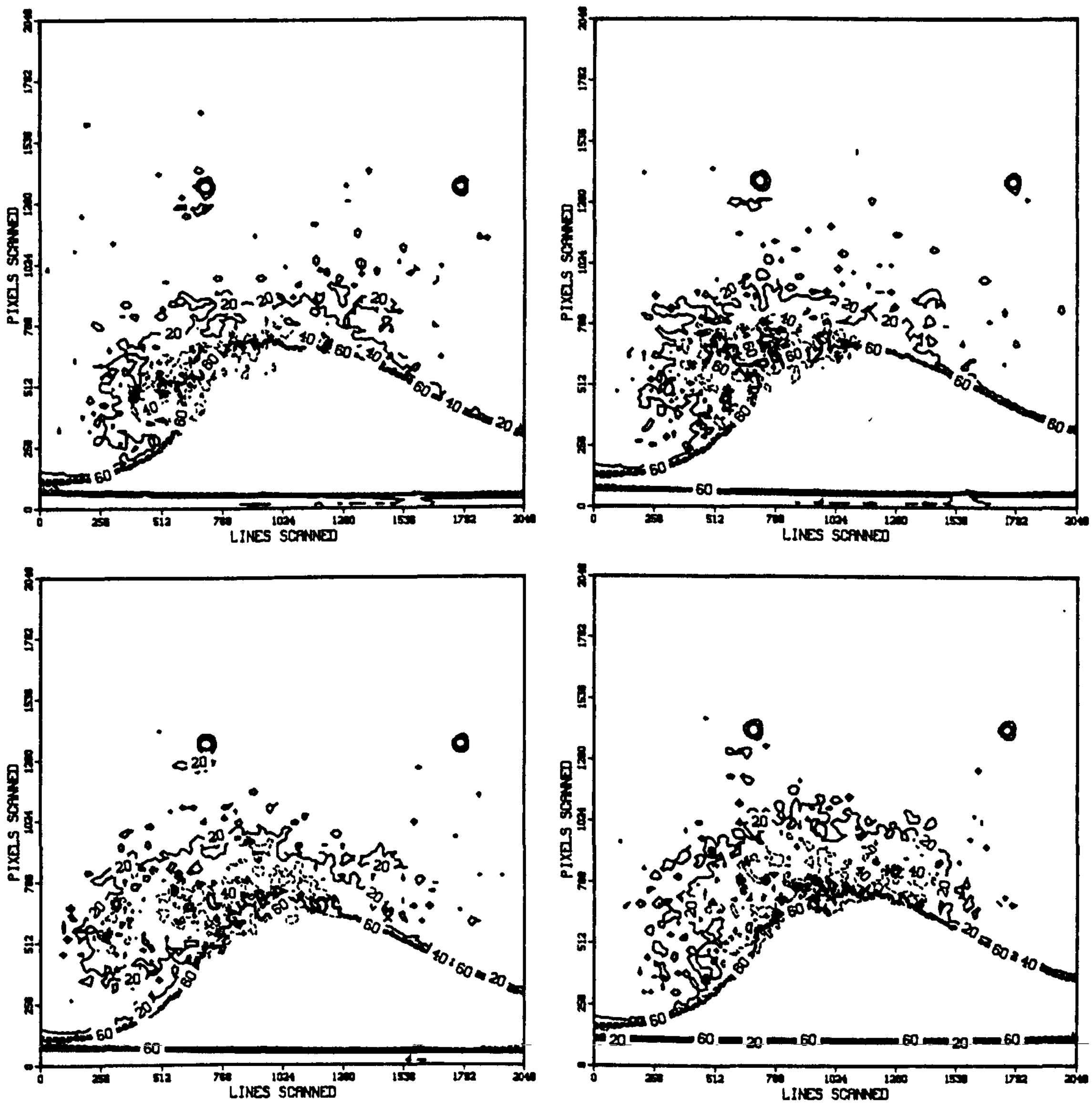
PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED
PIXELS SCANNED
LINES SCANNED

Plate 3.

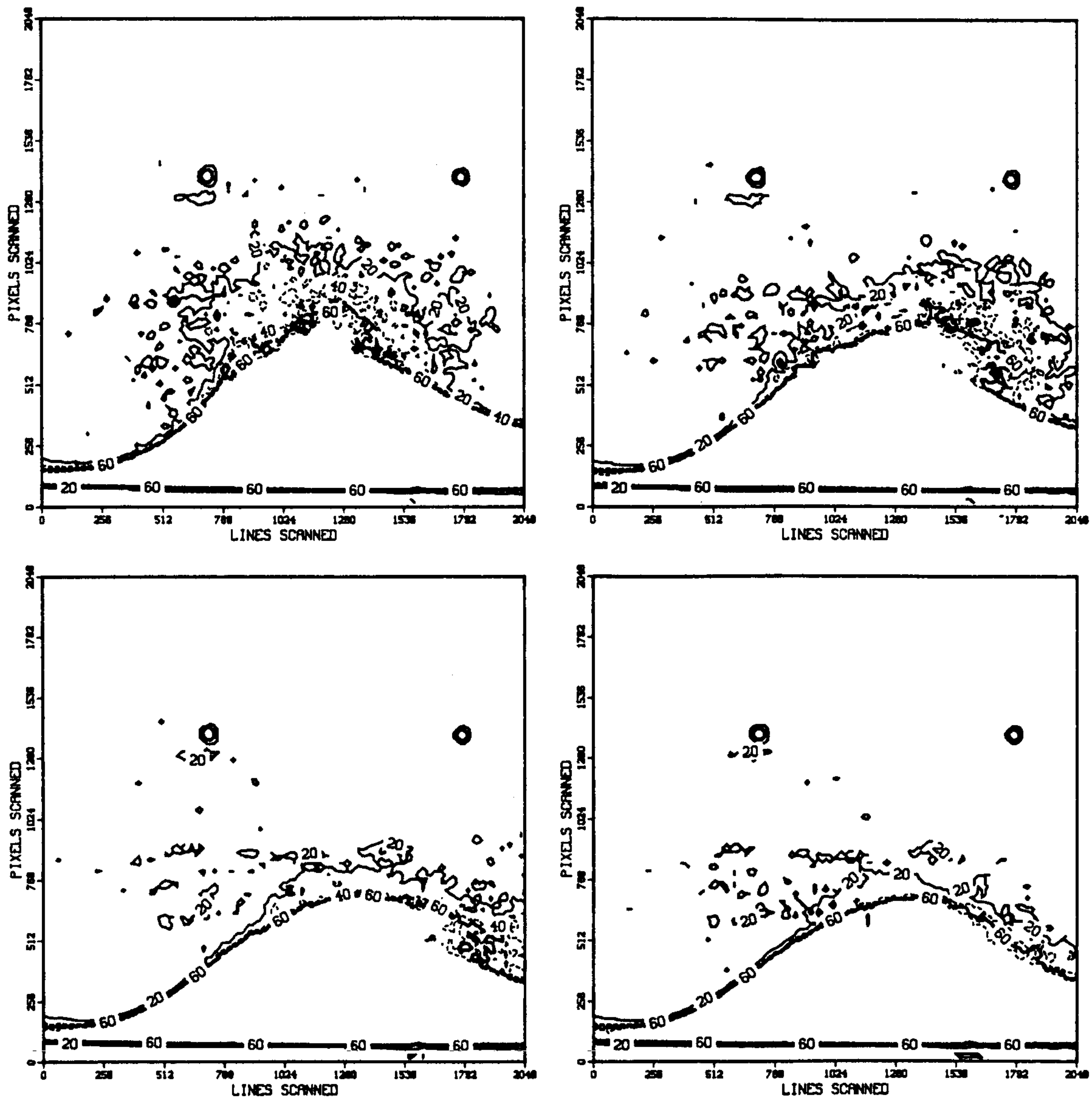

Plate 4.

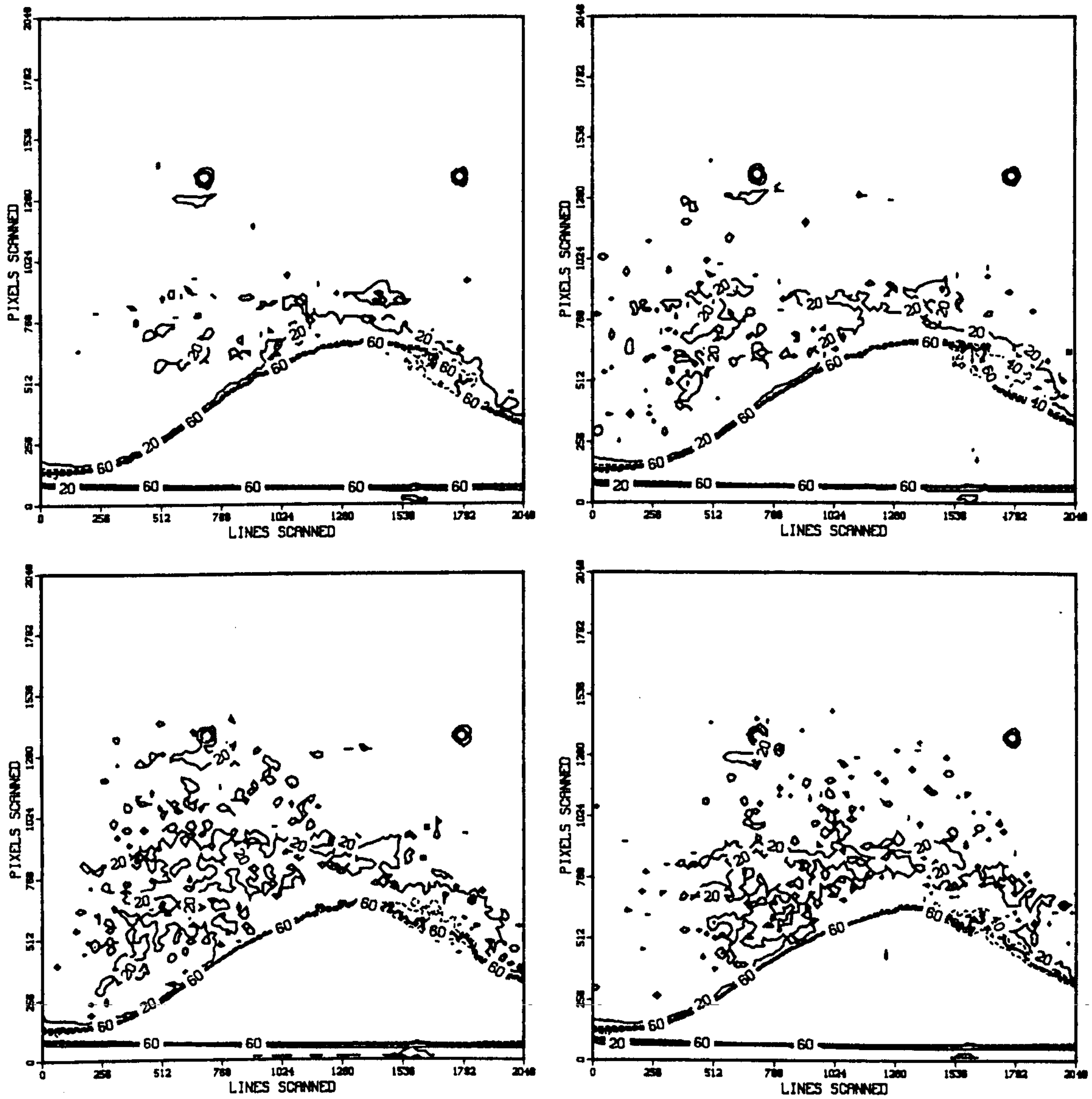

Plate 5.