Intercomparison of in-situ particle size and settling velocity measurements

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Contract

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Prepared by .... (name) Scientist (Job title)

Approved by M P Dearnaley Project Manager

Date 28 November '95

Summary

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This report provides details of the programme and results of the Intercomparison Exercise of In-situ Measurements of Suspended Particle Size and Settling Velocity that took place in the Elbe Estuary in June 1993. HR Wallingford participated in this exercise using the video image analysis technique developed under a previous DoE funded research contract (PECD 7/6/166). The exercise provided a unique opportunity for researchers in this field to compare different techniques for measuring field settling velocities and particles size of flocculated material.

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1 Introduction

1.1 Background

The field determination of settling velocity of flocculated suspended sediment has been an objective for several decades. The need for in situ measurements became more critical when the first measurements with the Owen tube, which took a sample of water and when rotated into a vertical position acted as a settling column, showed that sampling for laboratory analysis broke up the larger higher settling velocity flocs which contributed most to sediment deposition (Owen 1976). The Owen tube was consequently widely used for determining settling velocities as essential to the prediction of sedimentation.

However, with the passage of time, the settling velocities derived from Owen tubes have themselves come into question. The physical process of breaking up the larger flocs during the capture of the water sample, the tendency for finer flocs to stick to the base biasing the results, and the sampling process have led to refinements of the Owen tube. However, these modifications have not overcome these problems sufficiently and further problems identified by video techniques, have indicated problems due to residual circulation and re-flocculation in the Owen tube (Dearnaley, 1991).

More recently high magnification video cameras have been used in-situ to enable direct visualisation of the sizes and settling velocities of individual flocs. There are many practical problems to overcome in employing such techniques which have led to a variety of approaches. The interest in these matters and the variety of devices now currently used for measuring have generated considerable data of differing qualities. Questions have arisen as to how data from different techniques can be compared and as to how interchangeable the data is.

Settling velocity and floc size are extremely important in determining the extent of future sedimentation and it is therefore imperative to test the relative performance of these instruments. To this end the international intercomparison exercise described in this study was arranged by Professors Doeke Eisma and Keith Dyer and part funded by the European Commission as part of the MAST II Project.

1.2 Outline of report

This report details the background to the current trends in in-situ measurement in Chapter 2. In Chapter 3, the measurements carried out during the exercise are described. A brief description of the different devices used in the intercomparison is given in Chapter 4. The results of the exercise are summarised in Chapter 5 and these results are discussed in Chapter 6.

2 Description of the intercomparison exercise

The intercomparison exercise took place in the Elbe Estuary near Brunsbüttel in June 1993. The location is shown in Figure 1. A pontoon (Plate 1) was made available by Hamburg University and a research vessel, the R.V. LUDWIG PRANDTL (Plate 2) was made available by the GKSS research centre in Gessthacht. The exercise aimed to determine the relative performance of a number of methods used to determine the size and settling velocity of cohesive sediment flocs. The institutes taking part were as follows:

HR Wallingford
Plymouth University
Plymouth Marine Laboratory
Netherlands Institute for Sea Research
Rijkwaterstaat
Cergrene
Hamburg University
North Carolina University
Bangor University
Delft Hydraulics
Cambridge University
Copenhagen University
GKSS Research Centre, Gesstacht

The particle size and settling velocity measurements were carried out from the pontoon at a fixed position and from the research ship while floating, during 9-11 June 1993. Measurements in each case were taken over a full tidal cycle. Measurements at all times were made as simultaneously as possible at a standard depth of 9 metres below the water surface so they were not affected either by the boat or the pontoon. This could not always be realised and some devices could not measure at this depth or continually through the tide. This was partly because some devices needed to be located on the seabed or because the velocities near mid-tide made it difficult to maintain some devices at this level. Measurements were made at intervals of as little as 10 minutes in some cases, though other instruments measured at hourly intervals.

As well as the particle size and settling velocity measurements, continuous velocity and suspended solids measurements were obtained by GKSS at the standard 9m depth with readings every 5 minutes, and vertical profiles of salinity, temperature, velocity and total suspended matter (TSM) were carried out every hour with measurements every 1m. These measurements were carried out using the apparatus shown in Plate 3.

The location of the site, some 4km upstream of Brünsbuttel, was within the turbidity maximum of the estuary where maximum concentrations are of the order of 1000 ppm and maximum current velocities of the order 1 to 1.5 m/s. The depth of water at the measurement site was about 18m. The tidal state was close to Spring tides, with a range of approximately 3m. The river discharge was close to the annual average at 316 m^3/s. The days were relatively calm with winds of up to 6 m/s from the South East. There was very little stratification of the water column and salinities varied from 11 ppt at HW to river water levels at LW.

The studies undertaken by HR during the exercise consisted of two different investigations. These were carried out using the video techniques and the traditional Owen tube analysis described in Sections 3.9 and 3.1 respectively. The first was to determine the particle size and settling velocity distributions of material immediately after a sample of suspended sediment was taken using an Owen tube. This was carried out on the 9 June with samples being taken every hour. In the second investigation, on the 10 June, filming was carried out while the traditional Owen tube analysis was carried out. It was possible using this technique to determine the settling velocity and size distributions of the sediment at a number of stages through the analysis and to observe the effect of the acceleration and deceleration that occurred as sub-samples were taken from the Owen tube. The results of this analysis are given below in Chapter 4. Further detail is given in Dearnaley (1994).

3 Methods and devices used

The devices used in the intercomparison exercise are described briefly in the following sections:

3.1 Owen tubes

The settling tubes used in the intercomparison study were Owen tubes commercially produced as the Braystoke SK110 (Plates 4 and 5). They consist of a 1m long perspex tube of 50mm diameter and a sample volume of 2 litres. A tail fin is mounted on the back of the tube causing it to line up in the flow direction when lowered into the water. The tube is sealed at both ends by a release messenger from the surface when the tube is at the desired depth. After closure the tube, remaining in a horizontal position, is taken out of the water as quickly as possible and placed in a vertical position on a tripod stand (Plate 6). At that instant the stopwatch is started, and sub-samples are withdrawn from the bottom of the tube. Generally 8-10 subsamples are withdrawn, over a period of about one hour, each with a volume of 200-250ml, so that the last sample empties the tube and this contains any residual sediment in the tube. The total concentration of suspended particulate matter is determined from the filtered weights and settling velocities are calculated from the change in concentration of the samples over time. These tubes were used by three groups - the University of Copenhagen, the University of Hamburg, and HR.

3.2 QUISSET

Quasi In-Situ Settling velocity measurements were determined using a 1m long QUISSET tube (Plate 7). These tubes are similar in principal to the Owen tube except that the water sample is captured by moving a cylinder horizontally, past a piston, to seal at a funnel shaped end. Sub samples are then taken as for the Owen tube, but in this case slightly larger samples (approximately 550 ml), and the sampling is over a larger period. For higher sediment concentrations, smaller samples were used. This method was used by the University of Bangor. The instrument was originally developed for investigating the settling properties of marine snow.

3.3 Field pipette withdrawal tube (FIPIWITU)

This is a stainless steel tube with a length of 0.3m and an intemal diameter of 0.12m. The tube has valves on each end. The tube is lowered into the water with both valves open. A messenger triggers the valves to close, with a system of springs rotating the tube into a vertical position. The clock is started and samples are taken after 1,3,6,10, 20 and 60 min like the Owen tube. The main difference to the Owen tube, besides early rotation, is that samples from the FIPIWITU tube are withdrawn through the side wall of the tube and not the bottom. This procedure reduces the problem of small flocs sticking to the bottom of the Owen tube, distorting the results for the final sample. The tube also has a double wall to insulate the sample from temperature changes. This instrument was operated by Delft Hydraulics.

3.4 Field settling tube (FST)

This was very similar to the field pipette withdrawal tube but 0.21m long and 0.14m in diameter. The system was operated by Rijkwaterstaat.

3.5 BIGDAN settling tube

This settling tube was similar in principle to the QUISSET tube except that the capture of the water sample is made vertically, the cylinder moving upwards in response to a messenger to trap a water volume of some 28 litres (Plate 8). Samples are withdrawn automatically by peristaltic pump for subsequent gravimetric analysis. This particular method suffered from problems involving the sub-sampling procedure and so the results produced were deemed unsatisfactory. The BIGDAN sampling was carried out by GKSS.

3.6 The Cambridge University settling box

This was a vertical cylinder of length 0.3m and diameter 0.25m which traps a 15 litre volume of fluid between two end plates (Plate 9). The sediment particles fall out of suspension and the declining concentration is measure by four miniature optical backscatter sensors, positioned at intervals from the top of the cylinder. These sensors are calibrated for concentration. The system was designed to be mounted in a frame on the seabed, but in these tests was suspended. Closure of the device took 10 seconds and measurements took place in-situ. For further details see Murray et al (1994).

3.7 VIS (video in-situ)

This device optically monitored the settling of flocs in a vertical tube. Suspended flocs are captured in a stilling chamber which leads into the settling tube. The settling tube contained two windows, one for a beam of light to illuminate the flocs, the other for the video camera which monitored both floc size and settling velocity (Figure 2). The resolution of the floc size was down to 50 µm. This device was operated by Rijkwaterstaat and Delft Hydraulics. For further details see Van Leussen and Cornelisse (1993).

3.8 INSSEV

This was a two chamber device, with the flocs being trapped in a horizontal deceleration chamber. A controlled number of flocs are allowed to pass into a vertical settling column containing clear water. The floc sizes and settling velocities are measure by video camera positioned 100mm below the sliding door between the two chambers (Figure 3). Resolution of size is about 20 µm. The instrument is mounted on a bed frame at a height of 0.5m to maintain stability (Plate 10). The system was operated by the University of Plymouth. For further details see Fennessy et al (1994).

3.9 HR Wallingford video system

This method consisted of a high magnification video camera to film the settling processes within a settling column after retrieval using an Owen tube (See Dearnaley (1991) for more details). The resolution of floc size achieved was about 50 μm. The technique was used to establish the settling velocity and size distribution of the flocs. In addition the technique was used to examine the performance of the Owen tube during the normal gravimetric analysis procedure.

3.10 MALVERN particle-size analyzer

This commercially developed instrument consisted of a laser reflected into the suspended sediment sample and a detection device which registers the resulting diffraction pattern and interprets the signal into particle size information (Figure 4). The output of the system is in terms of percentage of particles in a given size band, the particle spectrum being divided into fifteen such bands. The device was operated by Plymouth Marine Laboratory. For further details see Bale (1995).

3.11 NIOZ in-situ camera system

This system consisted of three cameras opposite flashlights mounted in stainless steel housings on a robust frame some 2m high and 2m in diameter (Plate 11). Two cameras were set for pictures of flocs - one of these was set for magnification and flocs less than 100 micrometers in diameter. The third camera was for an overview of what was present in the water - particularly objects much larger than flocs. The photography was processed via an image analysis system to give particle size distribution. The device was operated by the Netherlands Institute for Sea Research. For further details see Eisma and Kalf (1995).

3.12 ENDOSCOPE in-situ system

This device was composed of an endoscope attached to a video camera and a small light emitting tube attached to a halogen lamp (Figure 5). The video images were processed via an image analysis system to give particle size distribution. This device was operated by CERGRENE, Noisy-le-Grand.

3.13 ISAAC

ISAAC is a 35mm camera housed on a frame so that light from two strobes is gathered via plexiglass collimators at the focus point of the camera. A vane and weights attached to the frame allow the device to be located at the required depth and in the correct orientation (Figure 6 and Plate 12). The photography is again processed via image analysis techniques to give particle size distribution. The device was used by the University of North Carolina. For further details see Knowles and Wells (1994).

3.14 ASUWPC

This was an in-situ recorder of suspended particle size developed at the University of Hamburg. It used a high resolution CCD video camera at close range and a strong flashlight. The records gave particle size.

4 Summary of results

4.1 Particle size

The results of the particle size measurements are summarised in Table 1. The results are partly a function of the peculiarities of design of each of the various measuring devices. The particle size distribution was such that there were more smaller flocs but a small number of much larger flocs. The relatively low sizes recorded by the ENDOSCOPE system maybe because it could only be used for short periods and may have missed the few large flocs. The low values of the MALVERN system may be related to the small gap (1cm) through which particles had to pass to be sampled. Such a small aperture may have contributed to floc break-up. The same device was not able to record when concentrations were high and this factor might also have biased the results downwards. It is possible that the devices recording larger median sizes were affected by their inability to sample small particles, thus biasing their median size results upwards. Other factors like the volume of water sampled seem also to have affected the number of large flocs measured, and thus the measured particle size (Eisma et al, 1995). This feature is illustrated in Figure 7 which shows size distributions that were obtained with the ISAAC, UNC, HR Owen tube and the NIOZ Camera systems, all from the Pontoon, all at the same time. The HR measurements are based on the largest volume sample (2 litres) and the largest minimum size of particle measurable and show larger particle measurements. It is also possible that reflocculation is occurring in this case. Figure 7 illustrates the approximately linear distribution that results when the log value of particle size is plotted against 'percentage smaller'. 90% of the size distribution follows a Gaussian probability distribution.

The measurements were made at approximately the same time, but there were up to several minutes between the first and last 'simultaneous' measurements. For one particular device a variation of up to 200 µm in particle size was produced by a variation of 5 minutes in sampling time. For different instruments a 5 minute difference caused a variation of up to 300 µm. Also a difference was seen between measurements recorded on the pontoon to those recorded on the boat. This is in spite of the extra shear that would be expected from a fixed rather than floating position. The only instrument that was implemented on both pontoon and boat was the NIOZ-Camera system. This found smaller sizes for flocs measured on the boat to those from the pontoon. The reason for this difference would seem to be that the position of the pontoon was not in the centre of the channel but to the side, while the boat was in the centre of the navigation channel and so experienced greater velocities.

Bearing in mind the problems and variation associated with the different measuring devices the data agreement is good. However, the variation is still such that a measurement programme is best carried out using a single instrument.

4.2 Settling velocity

The results for the different measurements of settling velocity are summarised in Table 2. The results indicate a marked difference between the direct video devices (1,2 and 4) and the other measurements. This difference is almost an order of magnitude. It is possible that the direct measurements may have missed out the finest fractions, but it is also likely that the video measurements are able to take account of the larger flocs, with larger settling velocities, that the Owen tubes miss due to floc break up.

Comparisons of the different methods for the tidal cycles of the 9 and 10 of June are shown in Figures 8 and 9. On the 9 June there was scatter of up to an order of magnitude. The peaks in median settling velocity coincide with slack water and the turbidity maximum. This probably results from the effects of differential settling causing floc growth near to slack water, and concentration enhancing flocculation in the turbidity maximum. Both effects would increase the numbers of large macroflocs which have a larger settling velocity (Dyer et al 1995). However on the 10 June (Figure 9), the peaks are not so well defined.

There are no clear conclusions to be drawn from Figures 8 and 9. Some devices consistently record very similar measurements (for instance the FIS and FIPIWITU devices) and others record dramatically different results (such as the Copenhagen Owen tube results and the VIS results).

Possibly a more interesting comparison is made when median settling velocity is plotted against concentration. These plots are shown in Figures 10 and 11. The concentrations are those recorded by the individual results rather than the GKSS values. The main points to note are (Dyer et al 1995):

i) There is no significant difference between the results for the platform and the results for the floating research vessel.

ii) The Copenhagen and QUISSET results have very small variation about a line which suggests that the handling protocol was very carefully carried out.

iii) The Cambridge University Settling Box was consistently lower than the other systems in terms of settling velocity. This device always sampled at a shallow depth and near slack water but two problems for the system were highlighted by Murray et al (1994). The first is that each of the optical backscatter gauges used in the system should be calibrated at various concentrations and at various floc sizes to allow for the decreasing floc size with time within the box. The results presented were derived using a single calibration based solely on changing concentration. Secondly the first three minutes of every sample were ignored as it was considered that turbulence had not died away, and settling was not occurring. This would have the effect of biasing the result towards the smaller settling velocities.

iv) The HR Video and INSSEV gave results an order of magnitude higher than the average Owen tube results at the same concentration.

The best fit logarithmic curves to match the results give:

Copenhagen	W_{50} =	0.0121	$C^{0.75}$	$R^2 = 0.72$
UWB (QUISSET)	W_{50} =	$5x10^{-7}$	$C^{2.37}$	$R^2 = 0.93$
Hamburg	W_{50} =	0.0055	$C^{0.73}$	$R^2 = 0.49$
FST	W_{50} =	0.0219	$C^{0.44}$	$R^2 = 0.58$
FIPIWITU	W_{50} =	0.041	$C^{0.69}$	$R^2 = 0.74$

The exponents in these ranges all lie within the general range that has been found for estuaries (for instance, Dyer 1989), which suggests that the inter-estuarine differences may be partly the result of different handling techniques. However the Copenhagen and Hamburg Owen tubes and FIPIWITU show very similar results.

The results from VIS were used to plot settling velocity against floc size (Figure 12). The VIS results only include the larger flocs but these flocs dominate in the vertical mass flux. A clear relationship between the two is displayed - the best fit line being approximately $w_s=0.00093D^{1.31}$. The results from INSSEV were very similar suggesting that the macroflocs may be fairly stable.

On 10 June the HR Owen tube sampling procedure was subjected to video analysis throughout the sampling procedure. The smallest flocs could not be resolved by the system used, but as the mass flux is dominated by the larger flocs, the mean settling velocities measured would have been similar to the correct mean settling velocity. The change in settling velocity over the sampling procedure is shown in Figure 13. There is a gradual decrease in mass flux over time and it is an order of magnitude greater than that derived from gravimetric analysis. The observations also showed that the action of stopping withdrawal caused the flocs to 'bounce', with some of them breaking up. Additionally it is apparent that the settling velocity of the largest flocs is greater than that required to settle to the observation height after the tube was placed vertically. This suggests that circulation and reflocculation within the tube may be important processes.

5 Conclusions and discussion

5.1 Particle size measurement

1. The minimum size measured of the flocs was related to the characteristics of the instrument being used for measurement. The maximum size measured was related to the volume of water that was measured, the degree of floc break-up during measurement, and to some extent measurement device characteristics.

2. The HR Video Analysis, INNSEV, NIOZ-Camera, ENDOSCOPE, and ISAAC gave approximately the same in-situ mean sizes but with considerable variation and difference in the size range that is measured. (Because the size distributions follow a log-probability curve, the difference in size range measured does not strongly influence the median values).

3. The MALVERN values were affected by the device upper limit of detection of 564 μm and the floc break-up as the flow passes through the measuring head.

4. A measurement programme is best carried out using only one device to ensure consistency.

5.2 Settling velocity measurement

1. Some of the differences between techniques may be the result of small-scale spatial and temporal patchiness in the turbidity field within the estuary.

2. Samples need to be taken less than one hour apart to achieve an adequate definition of the changing concentrations and associated settling velocities in the turbidity maximum.

3. It is likely that Owen tubes disrupt flocs upon sampling because they generally give settling velocities an order of magnitude less than direct measurement. However a well controlled sampling protocol with the settling tubes can give consistent results.

4. There did not seem to be consistent differences between the measurements taken from the research vessel and from the moored pontoon.

5. It is concluded that the in-situ comparison of techniques is not straightforward and many questions are left unanswered regarding the properties of cohesive sediments and the practicalities of quantifying them.

5.3 Discussion of future application of Owen tubes

The results of the intercomparison exercise show a clear numerical difference between Owen tube and in-situ video results which raises an immediate question over the applicability of the results for the two techniques for engineering studies. The Owen tube approach provides information concerning the net settling of material within a column of water, taking into account the associated processes of reflocculation, hindered settling, circulations set up in the column and the effects of the withdrawal of material from the column. The in-situ video coupled with imaging analysis techniques provides more information on how individual flocs behave. It remains to determine which is more representative for engineering applications.

In an estuarine body of water there are many scales of motion but at most times there is a dominant ebb or flood motion. This dominant motion is at a velocity two or three orders of magnitude greater than the settling velocity of individual flocs. At those times when material can settle to, and adhere to, the bed the horizontal velocities are usually at a minimum. The horizontal water velocities are, however, still likely to be one or two orders of magnitude greater than the floc settling velocities. In the settling column vertical motions are greater than horizontal motions due to the restricted dimensions. Because of this it would appear that the processes occurring in the settling column over the period of sampling, from which a settling rate is often derived are likely to be unrepresentative of the natural processes occurring in an estuary when settlement to the bed occurs. There are consequently two ways forward in examining natural settlement processes. The first is to continue to examine the settling process at micro scales where individual flocs can be observed. The second is to continue development of techniques which can be considered non-intrusive in terms of the processes occurring during natural settling.

Traditional Owen tube sampling may still provide information on the gross nature and settling properties of material in suspension for environments where there are no significant differences in sediment types or concentrations and where a well-organised sampling procedure is implemented. The Owen tube may thus provide a means for demonstrating the effect of variations in concentration and possibly the influence of organic content on floc formation. Visualisation techniques can also be applied for such purposes. However, visualisation techniques, whilst enabling a better analysis to be undertaken are still in their infancy and there is as yet no robust device to replace the Owen tube as a general method for the general measurement of settling velocity.

6 Acknowledgements

This study was carried out in the Ports and Estuaries Group at HR Wallingford which is managed by Dr J V Smallman. The field measurements and analysis were undertaken by Dr M P Dearnaley, Dr J Spearman and Mr N G Feates.

The work of all those who took part in the intercomparison exercise, and especially Professors Doeke Eisma and Keith Dyer, who were instrumental in its organisation, is gratefully acknowledged.

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Tables

Table 1 Maximum, minimum and median/mean size measured during the intercomparison exercise by the different instruments

	Instrument	Min µm	Max µm	Median µm
1	**Video** HR Wallingford	100	1500	200-940
2	**INSSEV** Plymouth Univ.	50	790	411
3	**MALVERN** Plym. Marine Lab.	5.8	564	40-360
4	**NIOZ-Camera** N.Inst.Sea Res.	5	900	92-660
5	**VIS** Rijkwaterstaat	10	1000	200-500
6	**ENDOSCOPE** Cergrene	6	440	10-20
7	**ASUWPC** Hamburg Univ.	150	1500 [4000*]	260-980
8	**ISAAC** N.Carolina Univ.	16	1400	275-750

* stringer type: seen a few times.

Table 2 Maximum and median/mean settling velocities measured during the intercomparison exercise by the different instruments

	Instrument	Max mm s^{-1}	Median/Mean mm s^{-1}	Resolution mm s^{-1}
1	**Video** HR Wallingford	5	1	0.001
2	**INSSEV** Plymouth Univ.	5.2	1.017	0.1
3	**QUISSET** Bangor Univ.	0.3	0.2	0.0003
4	**VIS** Rijkwaterstaat	5.5	0.5-3	0.1
5	**FST** Rijkwaterstaat	3.5	0.2-1.1	0.15
6	**FIPIWITU** Delft	2.5	0.2	0.5
7	**Settling Box** Cambridge Univ.	30-100	0.01-0.085	0.003
8	**Owen Tube** HR Wallingford	-	0.2-0.3	0.03
9	**Owen Tube** Copenhagen Univ.	4.9	0.5	0.03
10	**Owen Tube** Hamburg Univ.	1.04	0.42	0.03

Figures

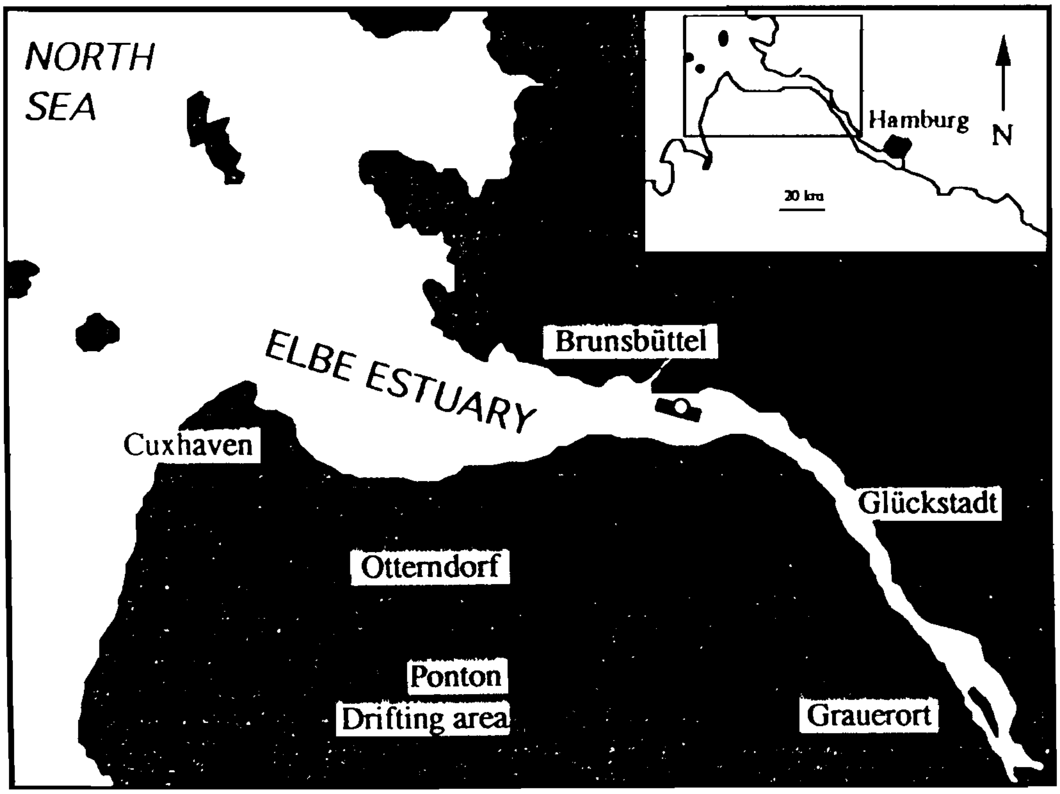

Figure 1 **A map of the Elbe Estuary, Germany. The pontoon is an anchored platform located 4km from the town Brünsbuttel.**

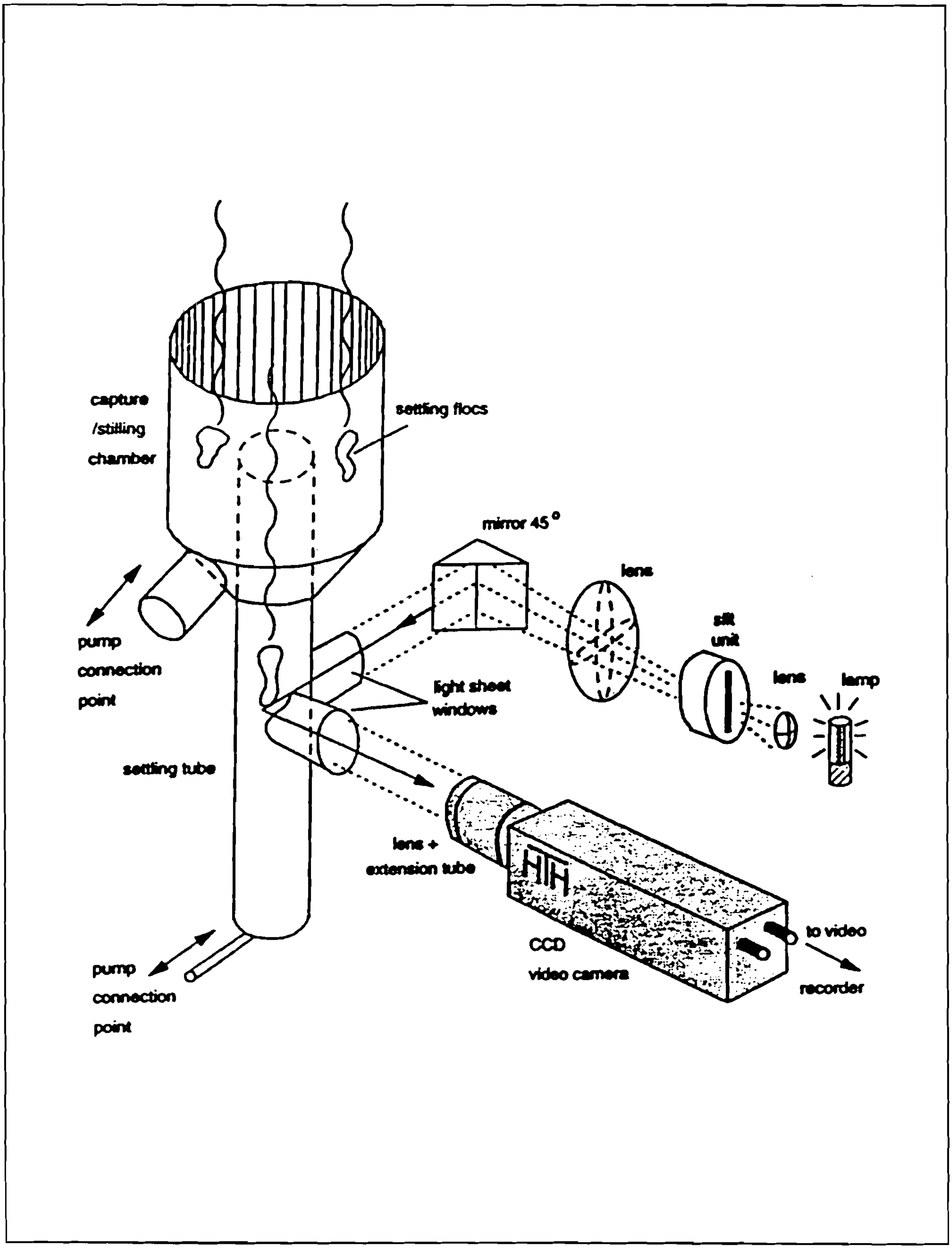

Figure 2 Schematic diagram of the components of VIS.

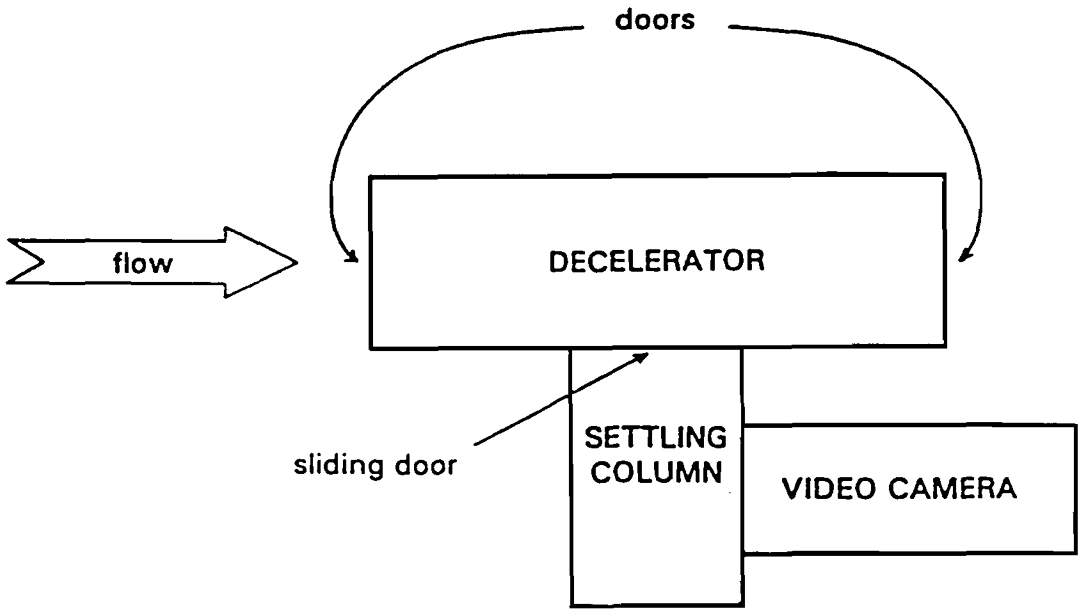

Figure 3 Schematic diagram of the components of INSSEV.

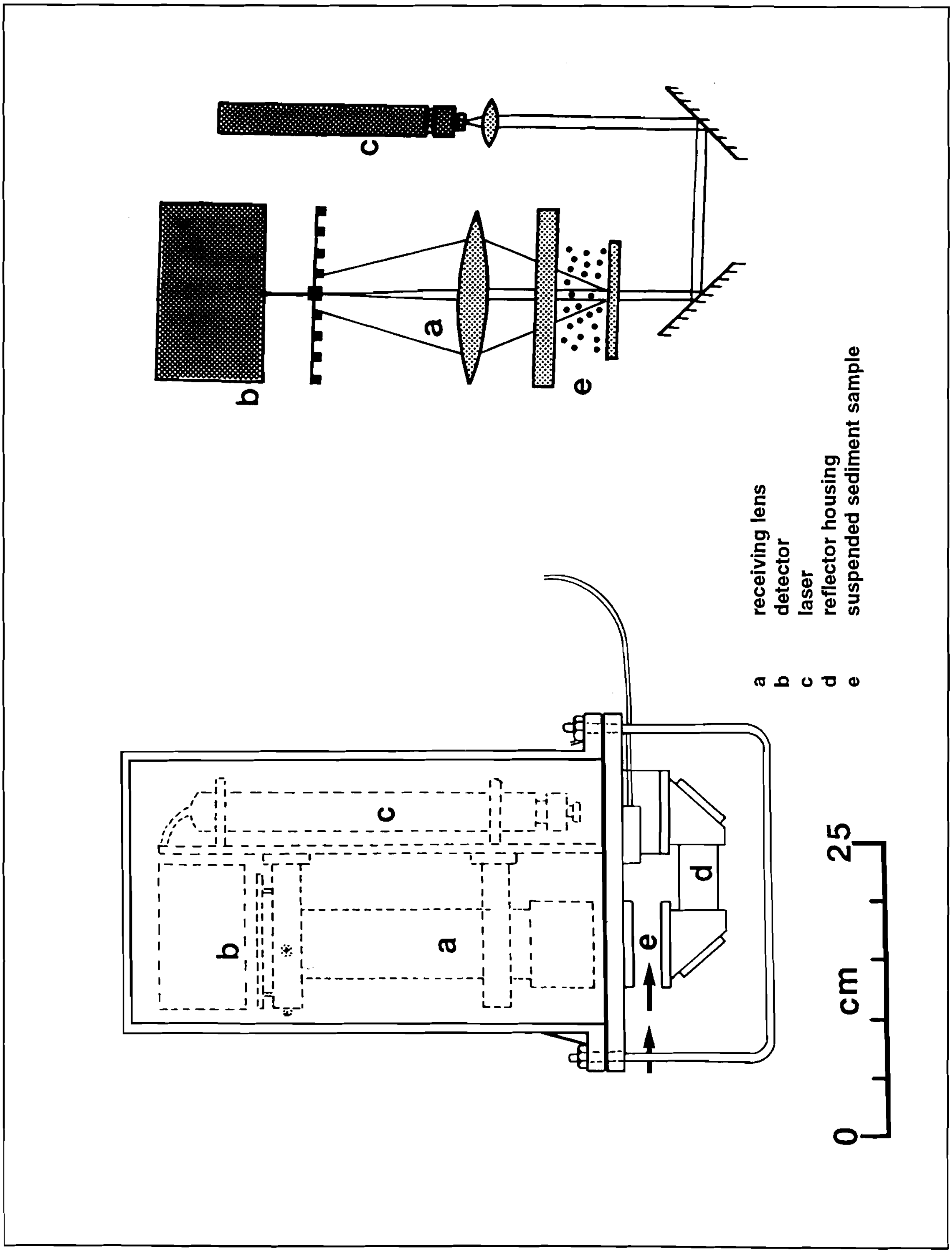

Figure 4 Schematic diagram of the components of MALVERN.

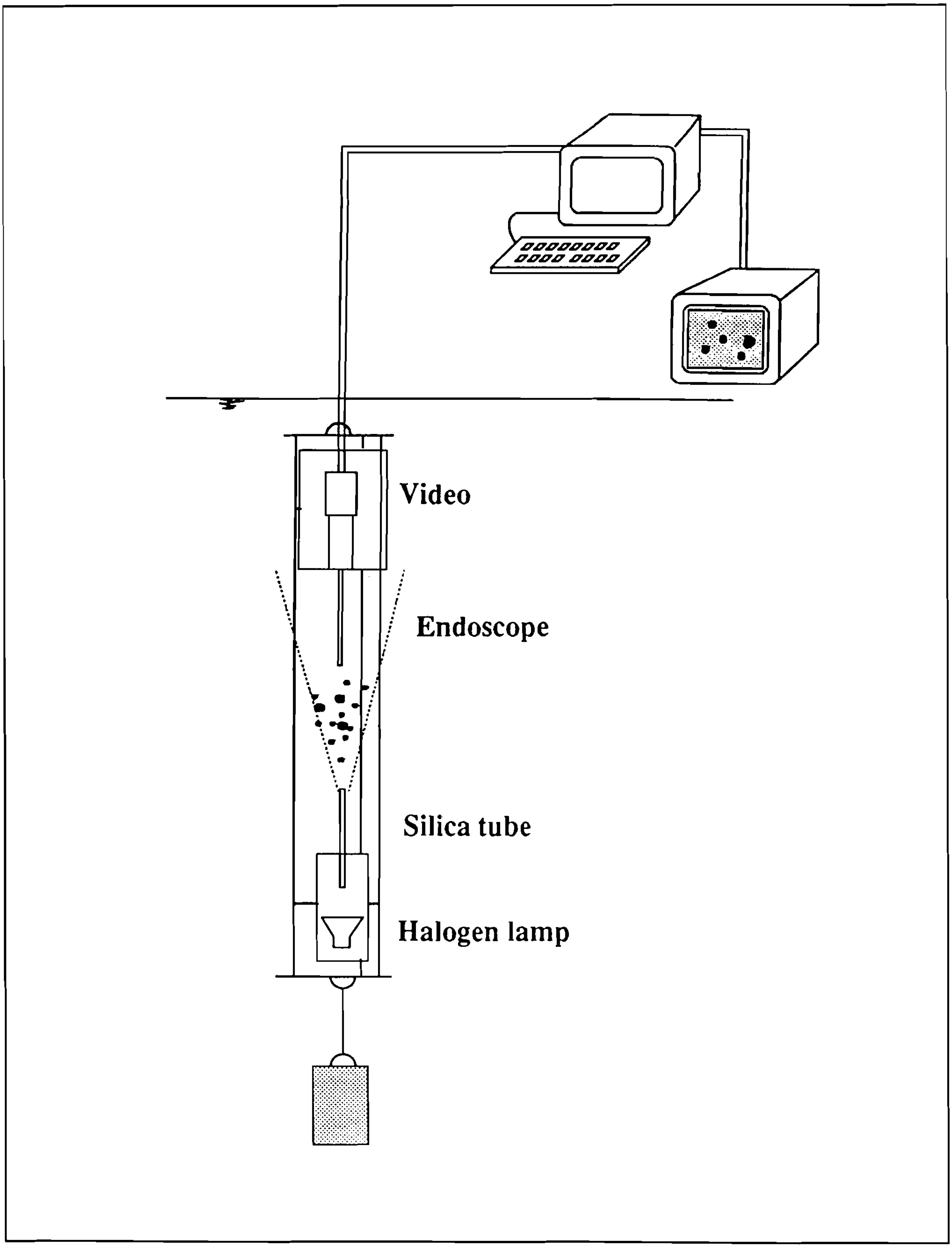

Figure 5 Schematic diagram of the components of ENDOSCOPE.

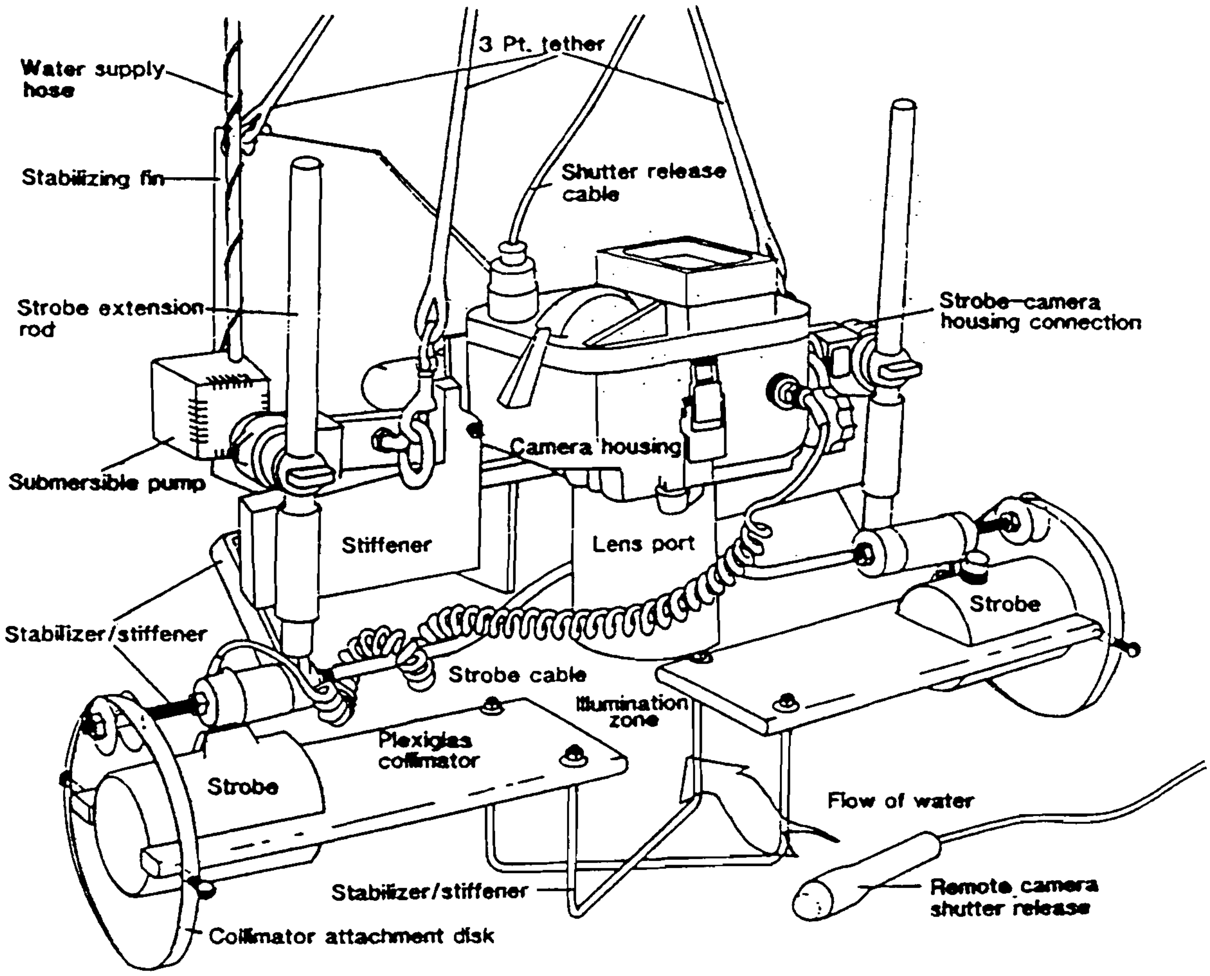

Figure 6 Schematic diagram of the components of ISAAC.

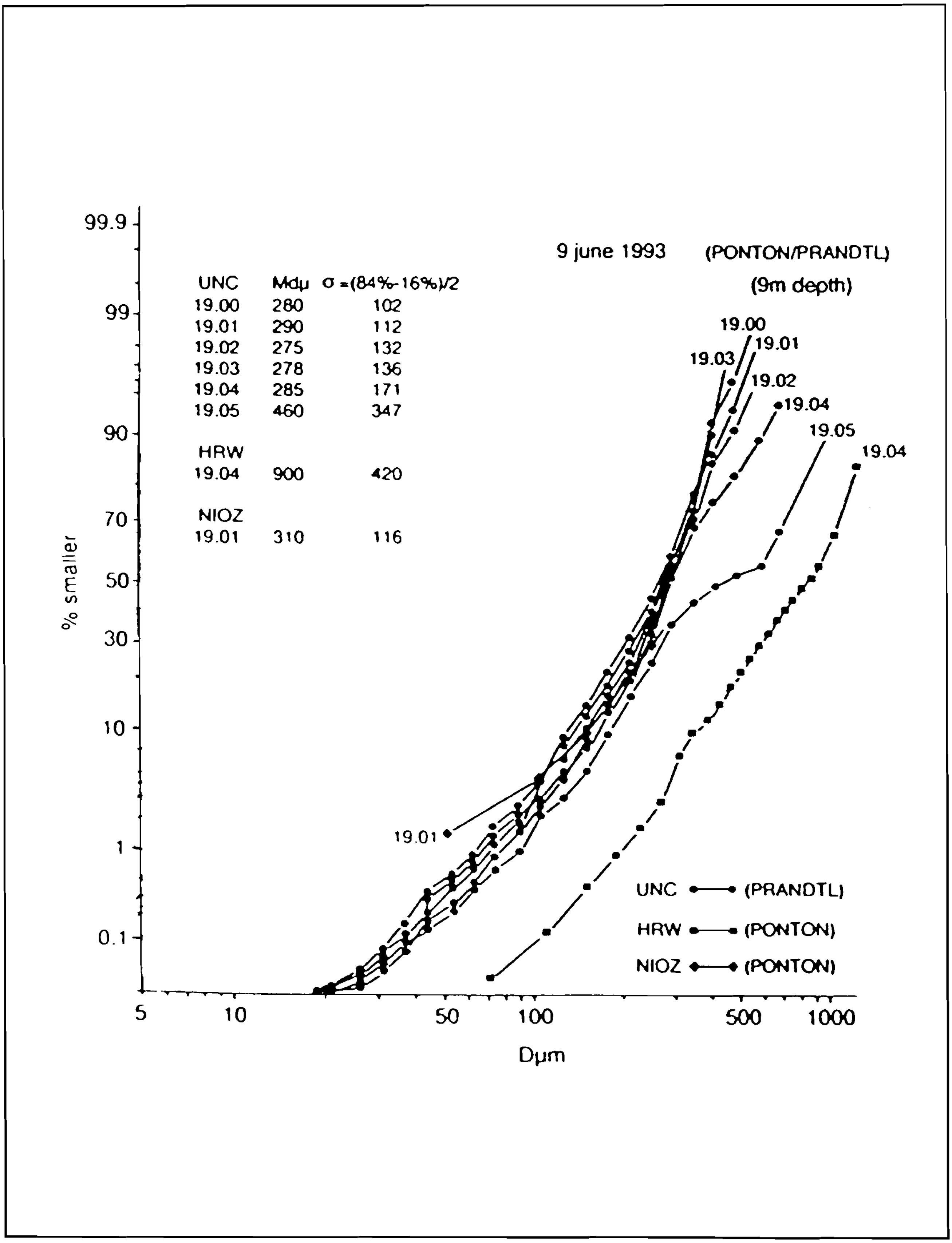

Figure 7 Simultaneously measured particle size distributions

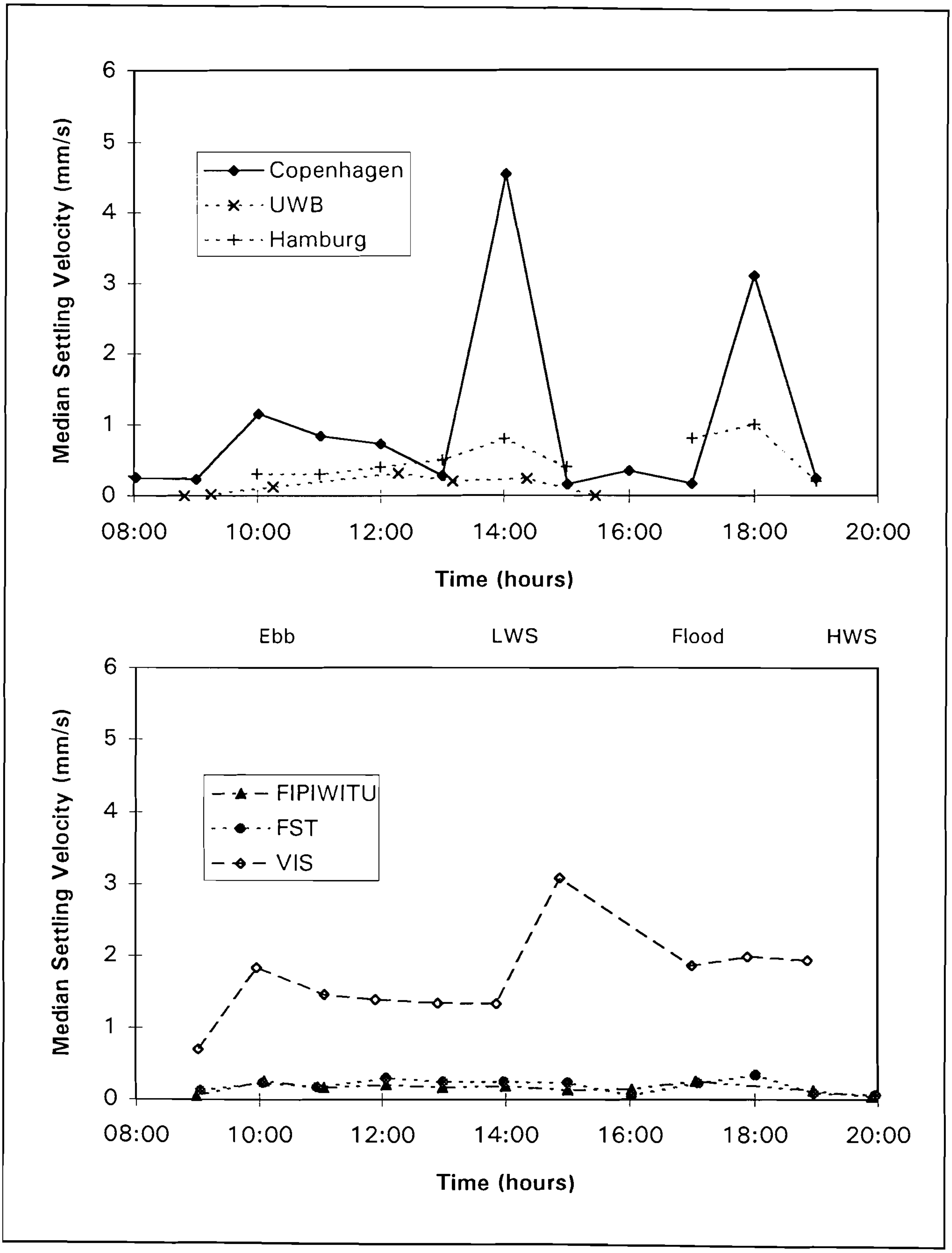

Figure 8 Measured settling velocities 9 June

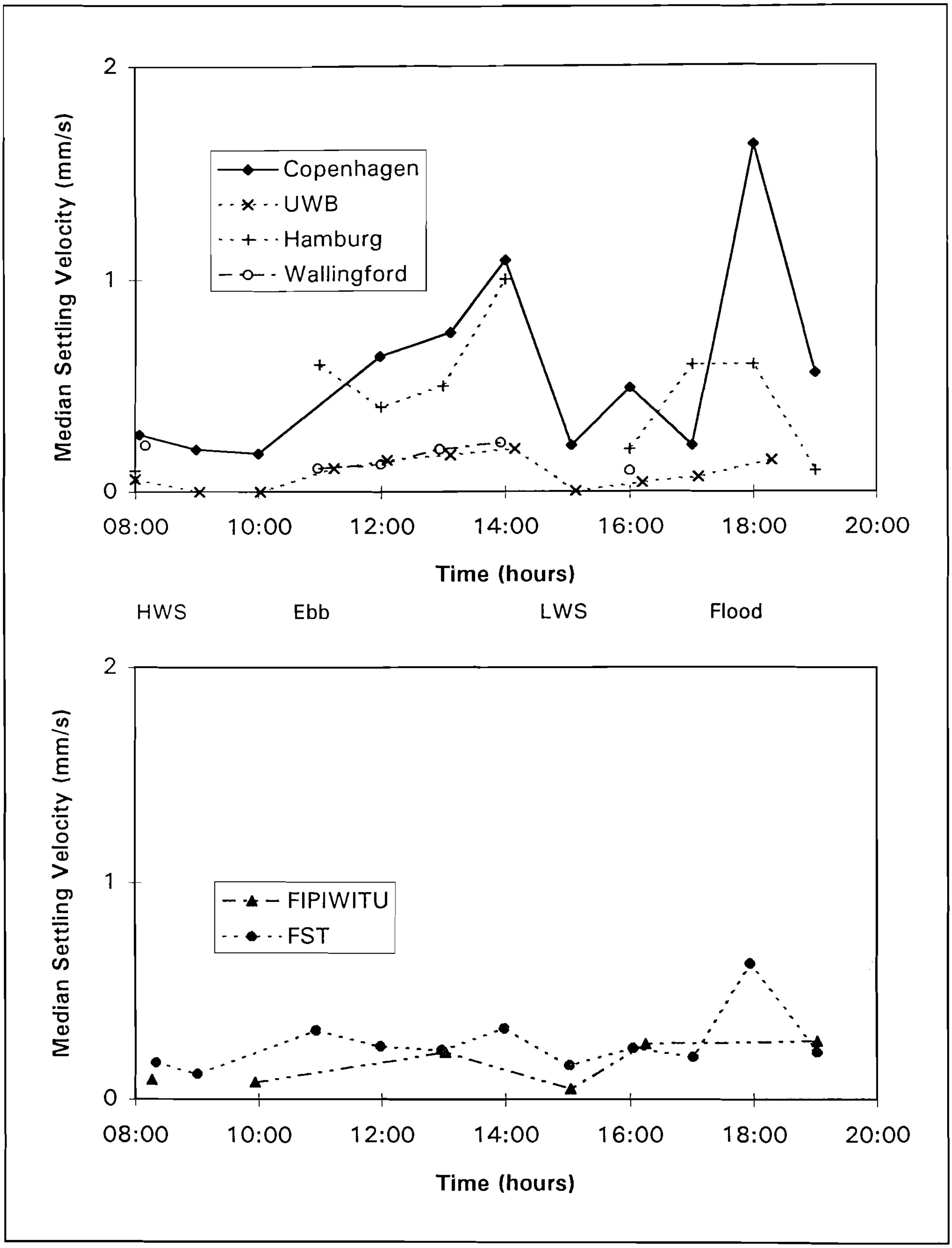

Figure 9 Measured settling velocities 10 June

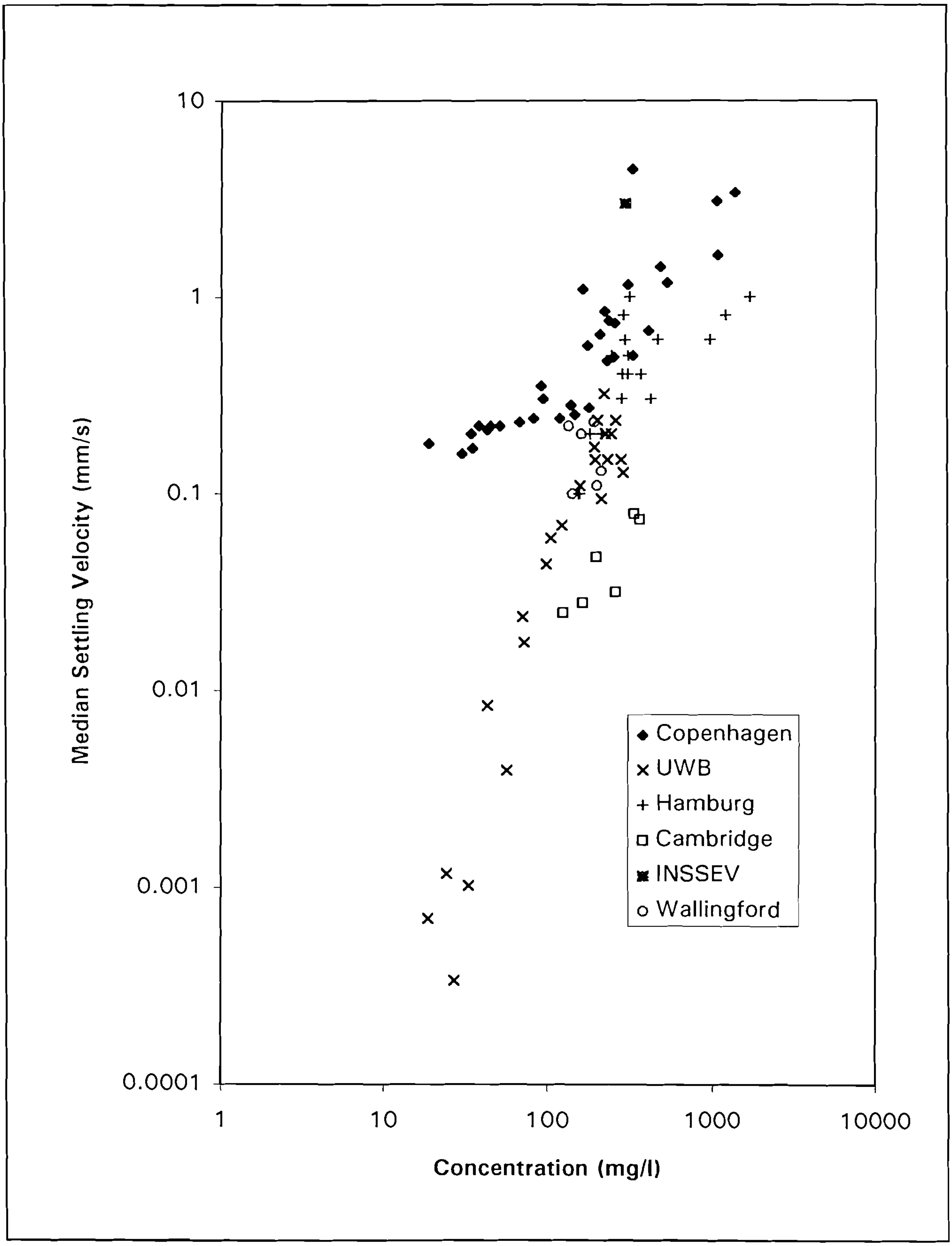

Figure 10 **Median settling velocity vs concentration measured from the pontoon**

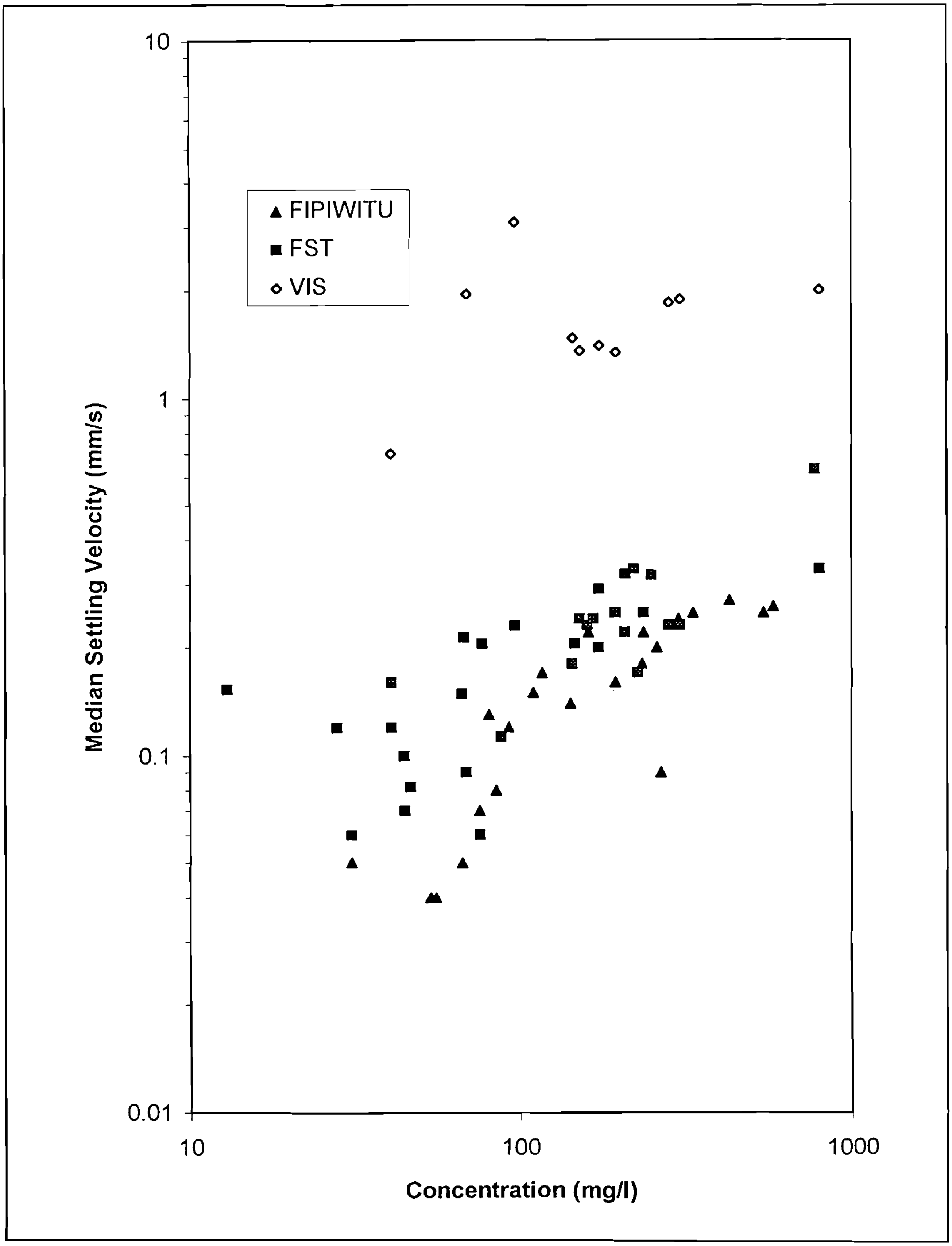

Figure 11 **Median settling velocity vs concentration measured from the R.V.LUDWIG PRANDTL**

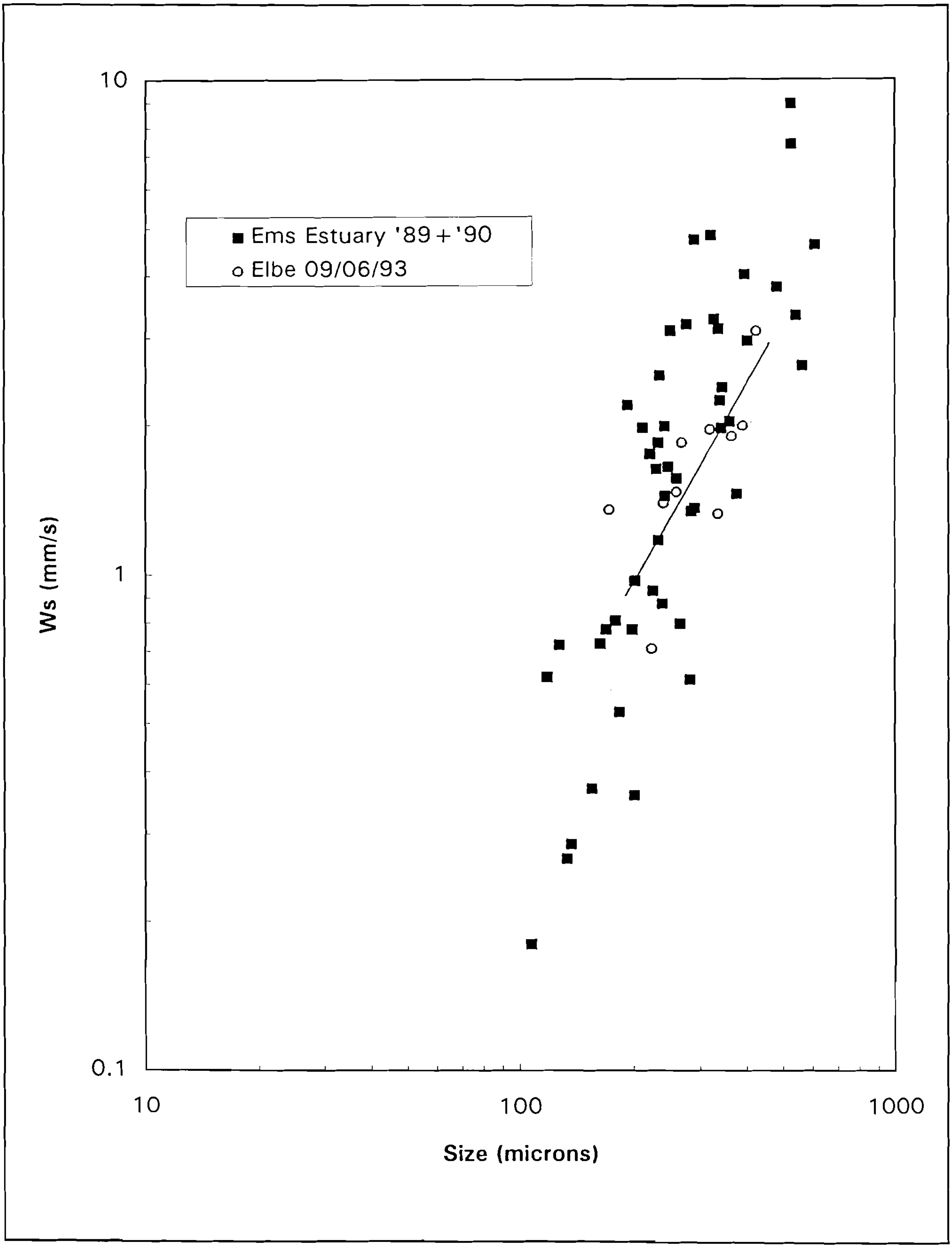

Figure 12 VIS measurements

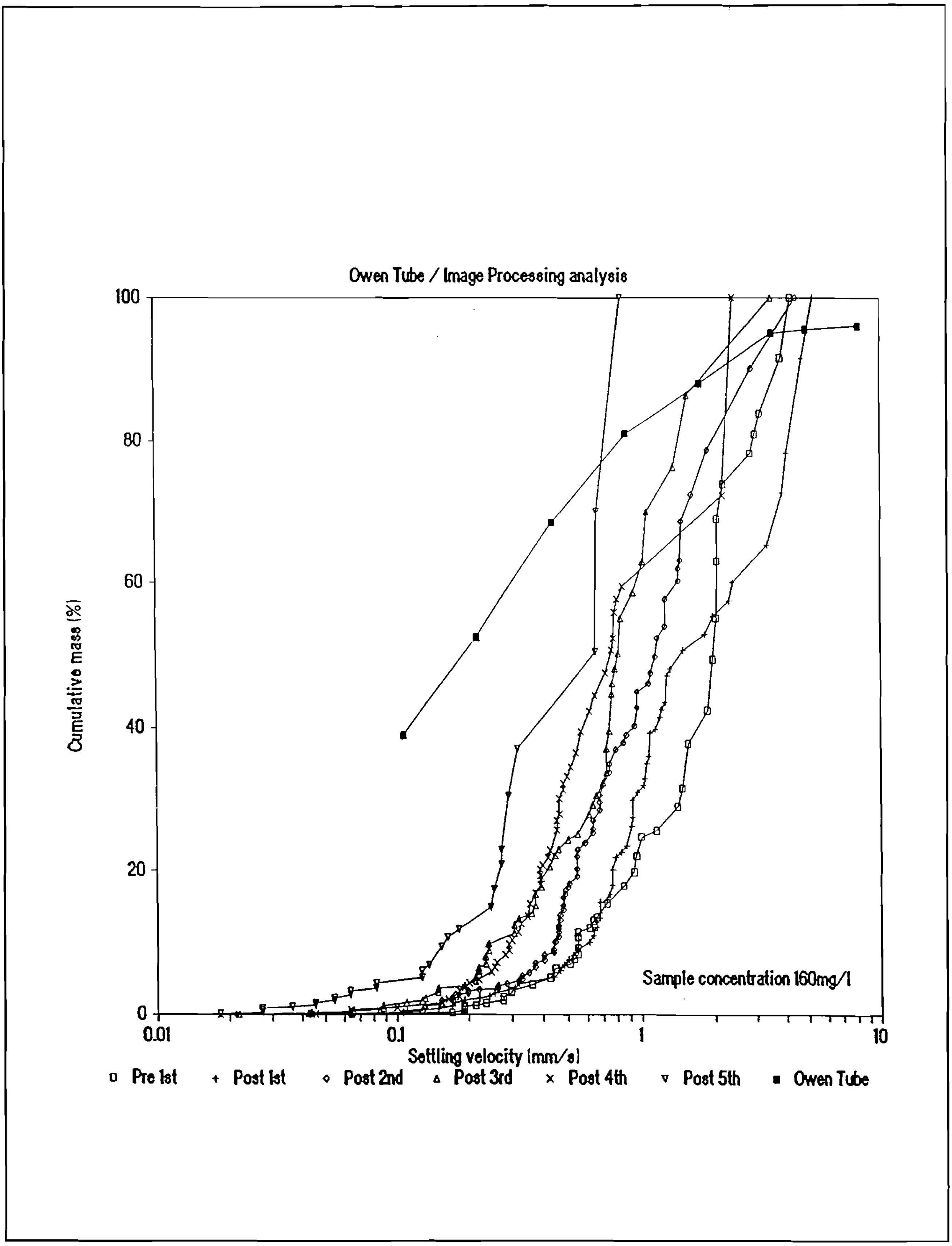

Figure 13 Cumulative mass vs settling velocity: comparison of analysis techniques

Plates

Plate 1 Pontoon used for intercomparison exercise

Plate 2 R.V.LUDWIG PRANDTL used for intercomparison exercise

Plate 3 GKSS device for measuring velocity, total suspended matter, salinity and temperature.

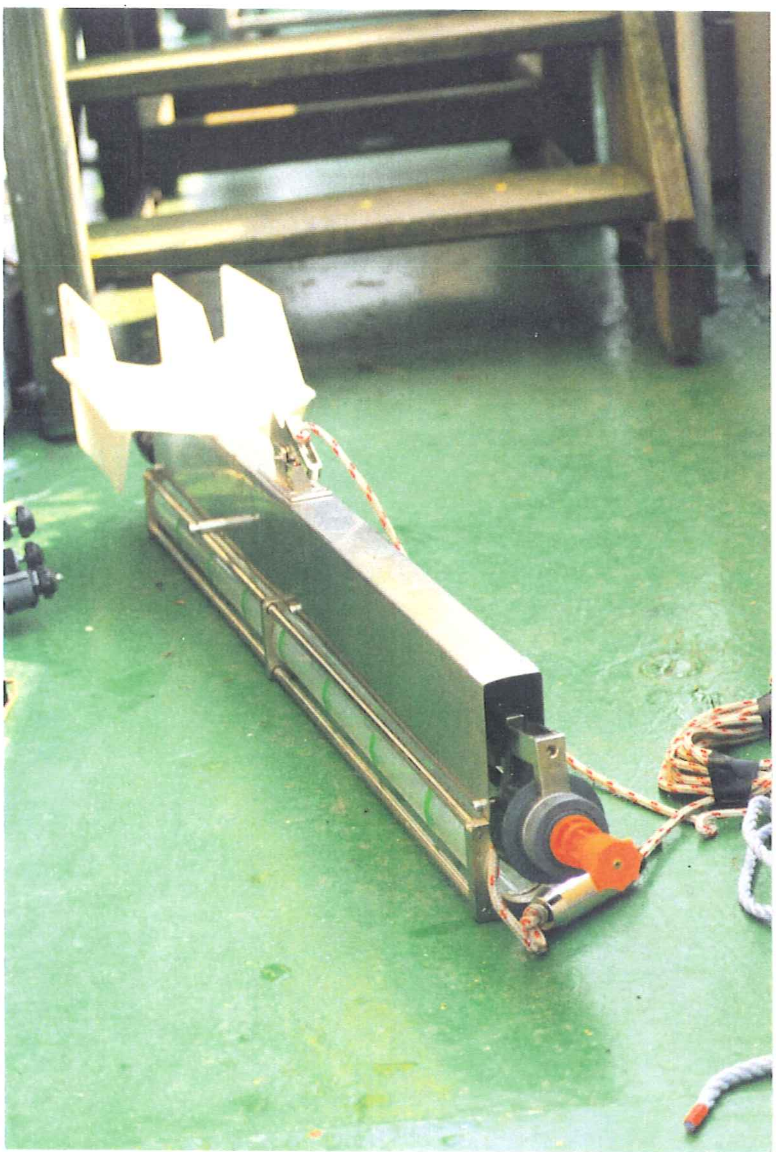

Plate 4 Braystoke SK110 (Valeport) Owen Tube

Plate 5 Equipment used for raising and lowering Owen Tube

Plate 6 Position of Owen Tube during sub-sampling procedure

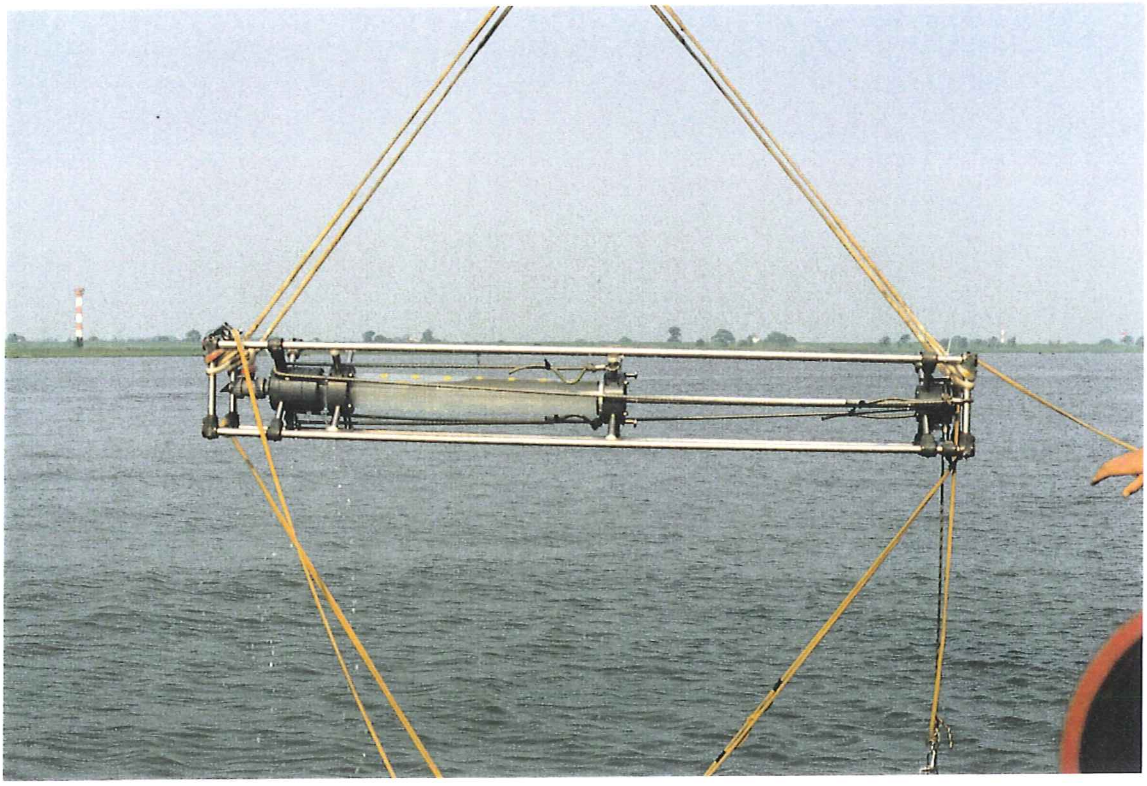

Plate 7 QUISSET tube

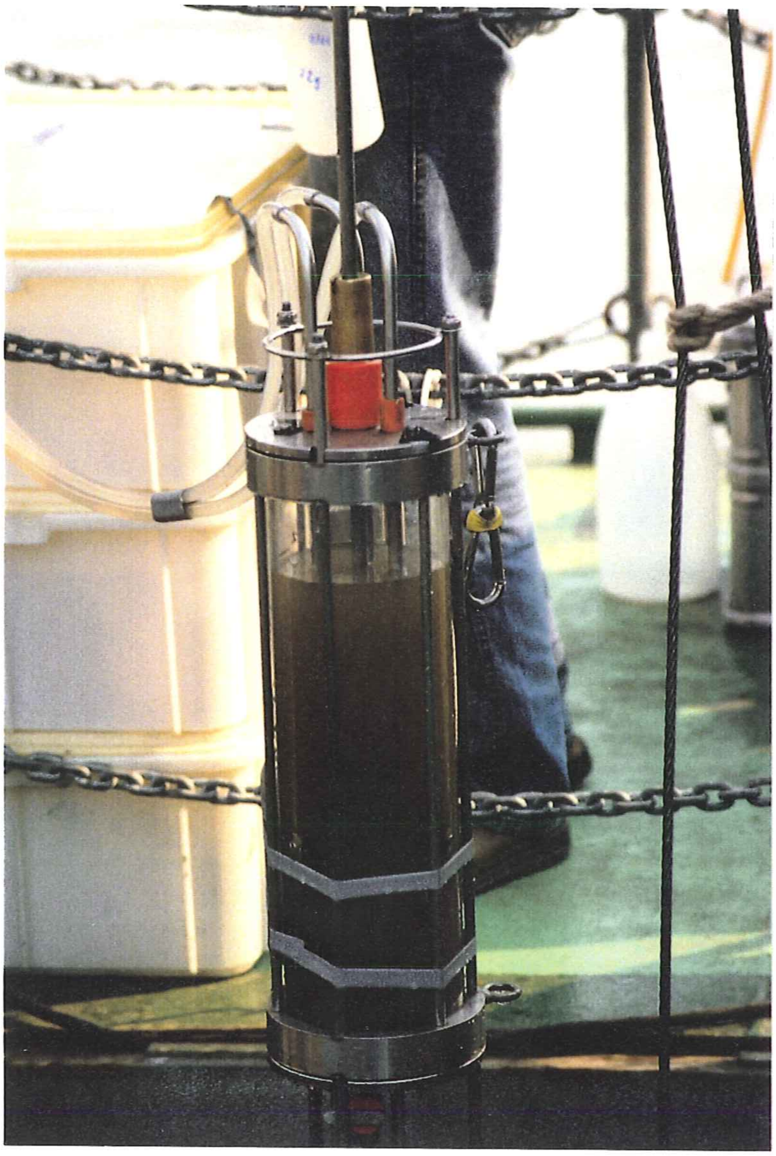

Plate 8 BIGDAN Settling Tube

Plate 9 Cambridge University Settling Box

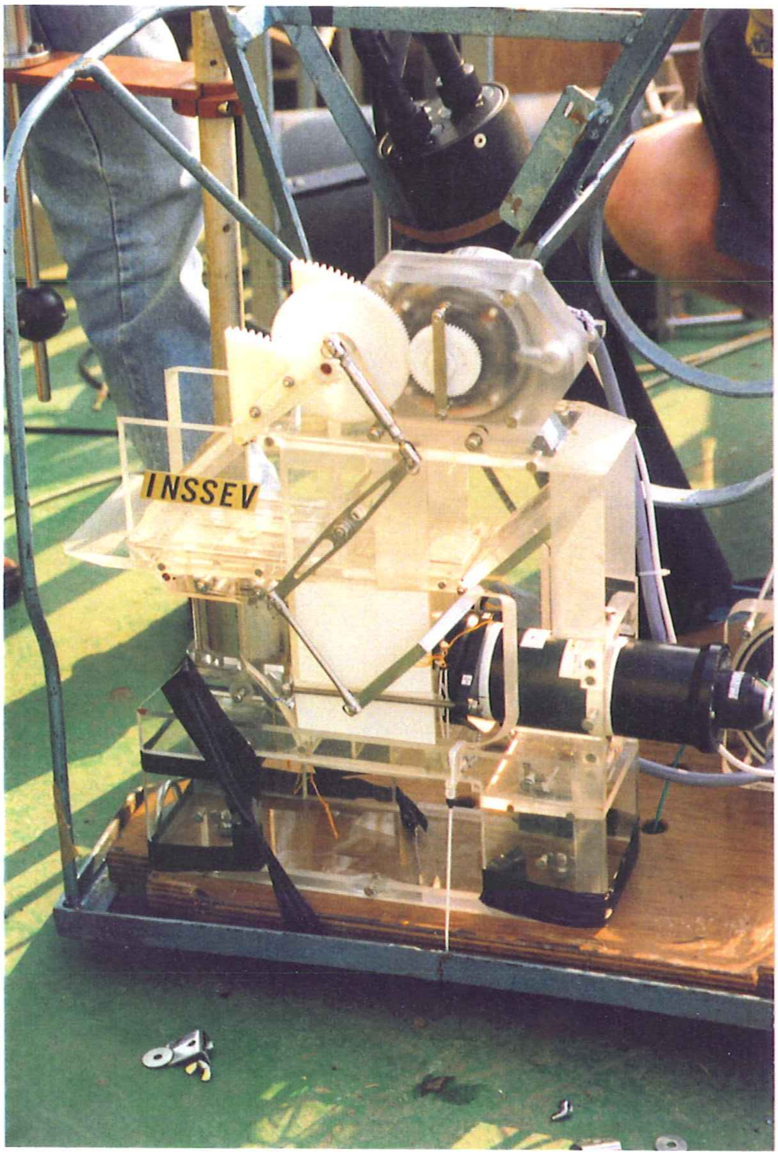

Plate 10 INSSEV device

Plate 11 NIOZ Camera

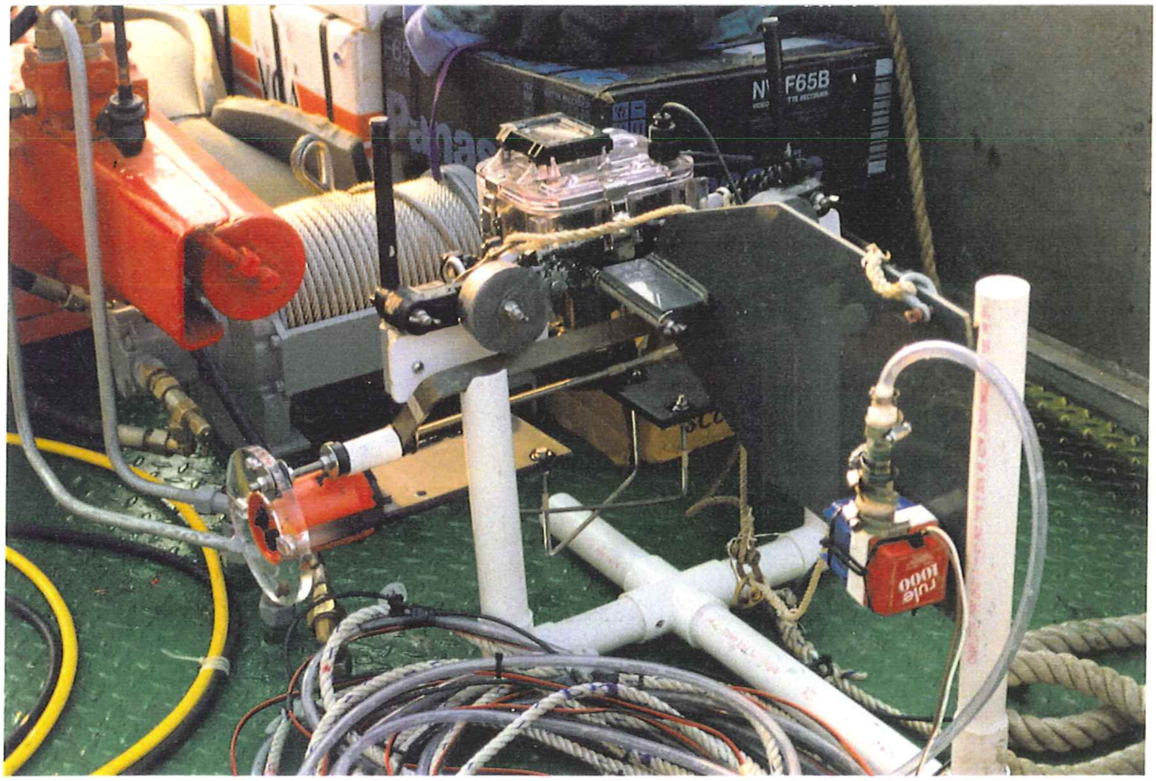

Plate 12 ISAAC device