Development and testing of an instrument to measure estuarine floc size and settling velocity \textit{in situ}

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A thesis submitted to the University of Plymouth in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY.

Institute of Marine Studies
Faculty of Science

In collaboration with
Plymouth Marine Laboratory

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Date 19.05.94
Abstract

Development and testing of an instrument to measure estuarine floc size and settling velocity in situ.

Michael Jim Fennessy

An instrument has been developed to observe the settling of individual flocs in turbid water in order to measure size and settling velocity spectra of estuarine cohesive suspended sediments. INSSEV - IN Situ SETtling Velocity instrument - is bed mounted and comprises a computer controlled decelerator chamber that collects a sample of water from which some of the suspended matter is allowed to enter the top of a settling column. The settling flocs are viewed using a miniature video system. Subsequent analysis of video tapes provides direct measurements of size and settling velocity of individual flocs down to 20 \( \mu m \). From this information floc effective density is estimated. The main feature of the instrument is its ability to video flocs in situ, irrespective of the concentration in the estuary, with as little disturbance to their hydrodynamic environment as possible. In addition to size and settling velocity distributions, data analysis developed for the instrument produces spectra of concentration and settling flux with respect to size, settling velocity or effective density. This is the first time that these parameters have been measured in situ. Field testing in the Tamar Estuary, South West England, and the Elbe Estuary, Germany, has given useful results in flow velocities up to 0.6 \( m \ s^{-1} \) and in concentrations up to 400 \( mg \ l^{-1} \). INSSEV was used in the 1993 Elbe Intercalibration Experiment where nearly all types of instrumentation for the in situ determination of estuarine floc size and/or settling velocity were deployed over several tidal cycles. From observations in the turbidity maximum of the Tamar Estuary, INSSEV data has shown significant changes in floc population characteristics during the tidal cycle, the most important being changes in floc effective density. A strong relationship between floc effective density and ambient turbulence characteristics is shown.
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Collaboration

The listing of Plymouth Marine Laboratory in the Declaration bears little testimony to the considerable co-operation and support that I received from Tony Bale during the course of this work. Over many weeks of fieldwork, where he cheerfully participated in some very early mornings and late evenings, his advice and assistance were generously and tactfully given. In addition to his direct support he has been a splendid mentor in the procedures for safe and efficient fieldwork practices and I am deeply grateful to have had such a valuable tutor in this important area of the work. Thanks also to Douglas Law for his diligent help with fieldwork and laboratory analyses, and to John Wood for his technical advice at the early stages of design of the underwater video system and control electronics.

Fieldwork

Preparations for fieldwork always proved challenging, ensuring that the equipment was ready and working. During the two years of the field trials I was fortunate to have the enthusiastic assistance of Jerry McCabe, Rica Constantinescu, and Malcolm Christie. I am grateful to them for their interest and hard work.

Boatwork

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This heading is well known throughout the campus and covers a range of skills and services that are invaluable to anyone designing and developing a new piece of equipment. The superlatives apply to all of the following, their expertise has not only been helpful to the project but their patience and interest has been an education in itself. I feel I have not only had tasks completed but I have gained considerable awareness of their particular specialisms. They are essential to any institution endeavouring to support scientific research. Much of the fabrication
of the main instrument was carried out by Brian Pateman, Adrian Matthews and Mike Byrnes of Central Workshops, W13. Adrian's many hours of careful machining proved essential for the project and his considerable patience and endurance in coordinating much of the construction are greatly appreciated. The electronics staff at Rowe Street operate an Aladdin's Cave of bits and pieces that quickly solved many of the problems I have had in trying to make something work or connect two components together.

IMS Technical Staff

Making things work in sea water is something which has taxed the skills of many inventors and engineers. Metals, electronics and saltwater are unhappy bedfellows. The combined experience of the Technical Support Staff in the Institute of Marine Studies provides a unique service to anyone trying to operate in such a technologically hostile environment. Special thanks to Ron Hill for never turning away a problem, but carefully following up all the tasks until completed; Andy Prideaux for a myriad of small and large tasks, often at short notice, that have enabled me to get experiments and fieldwork underway; Rod Jones for all his assistance in my use of the Marine Dynamics Laboratory, particularly his expertise in drying out immersed equipment; and Frank Burrell for his considerable help with electronic problems and my endless requests for small pieces of coloured wire.

Computing Staff

I can only assume that one of the requirements to work in Computing Services is to be able to memorise all the hardware and software reference manuals. It is a great relief to be able to take an apparently intractable problem to them and get a rapid solution. I am grateful to the many staff who have assisted me with my computing difficulties.

Video and Photography

Video was used both in recording experiments and compiling technical illustrative programmes. Nick Hill, of Library Media Services, provided valuable instruction and assistance with the former, and Dave Hurrell, of the Hoe TV Studio, has been instrumental in ensuring high production quality, as well as many useful suggestions, with the latter. Tony Smith of Media Services produced the high quality photographic prints used in presentations. Their assistance with these tasks has been invaluable.

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The Coffee Club at 4 Endsleigh Place

Although the acknowledgement of this institution has become somewhat a tradition it is, and long may it continue to be, a unique gathering of people with varied outlooks on life, but shared objectives. Like all institutions its membership is steadily renewed, but its influence on the individual remains unchanged. This list of thank you's would be incomplete if I did not acknowledge the friendship, humour and wit of all the 'members' of this supportive group.
AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the
author been registered for any other University award.

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and Engineering Research Council (Grants GR/F/88148 and GR/H/82310), and
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was partly supported by MAST 2 project G8M.

A programme of advanced study was undertaken, which included a final year hon­
ours course in sediment dynamics, supervised mainframe computer instruction, and
training in the use of an image analysis system.

Relevant scientific seminars and conferences were regularly attended at which work
was often presented. Two papers have been published, and two others are in
progress. External institutions were visited for consultation purposes and an ex­
tensive programme of fieldwork was undertaken, including a multinational intercal­
ibration exercise. These are detailed below.

Presentations and Conferences Attended

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<th>Conference Details</th>
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<tr>
<td>Sep 1990</td>
<td>UK Oceanography, 5 day conference (Asst Organiser)</td>
<td>Plymouth</td>
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<tr>
<td>Nov 1990</td>
<td>Suspended Matter in Estuaries, 3 day conference</td>
<td>Hamburg</td>
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<td>Sep 1991</td>
<td>Sediment Dynamics Discussion Group, 1 day meeting</td>
<td>London</td>
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<td>Sep 1992</td>
<td>Changes in Fluxes in Estuaries, 5 day joint ERF/ECSA conference (Assistant Organiser)</td>
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<tr>
<td>Sep 1992</td>
<td>UK Oceanography, 5 day conference, presented paper: A new Instrument to Measure Settling Velocity of Individual Flocs in situ</td>
<td>Liverpool</td>
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<td>Sep 1993</td>
<td>Particles in Estuaries and Coastal Waters, 5 day joint symposium ECSA/NVAE, presented paper: Size and Settling Velocity Distributions of Flocs in the Tamar Estuary during a tidal cycle.</td>
<td>Groningen, Netherlands</td>
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<tr>
<td>Mar 1994</td>
<td>Particulate Matter in Rivers and Estuaries, 5 day symposium (part of International Hydrological Programme); preceeded by a one day workshop on the Elbe Intercalibration Experiment – June 1993.</td>
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Publications


External Contacts

The need for specialist video equipment led to considerable investigation of underwater and surveillance, photography and video commercial organisations. This was in addition to library searches of underwater video and photography applications, which revealed that the particular specification required was not then available. Several companies were eventually approached for proposals and the development work was eventually placed with Custom Cameras of Wells, Somerset. Their ability and willingness to work closely with the project was pivotal in the success of the Instrument System.

Fieldwork

The main fieldwork programme was carried out on the Tamar Estuary, South West England, in collaboration with Dr A J Bale of Plymouth Marine Laboratory. Parallel work on Acoustic Backscatter Sensors was carried out by Dr C E Vincent and Dr A J Downing of the School of Environmental Sciences at the University of East Anglia during the part of the programme.

An additional opportunity arose towards the end of the project to join an inter-calibration experiment for settling velocity measurement techniques on the Elbe Estuary (June 1993), funded by the European Community Marine Science and Technology (EC MAST) programme and organised by Professor Eisma, NIOZ, Texel, The Netherlands, and Professor Dyer of Plymouth. This involved 40 scientists from 10 countries.

Signed

Date 19.05.1994
Chapter 1

Introduction

This study has focused upon one of the two problematic process areas in estuarine sediment transport: the settling velocity characteristics of cohesive suspended sediment. The other process area is resuspension.

The ability to produce mathematical models of estuarine sediment flux is highly desirable for various economic reasons. First is the monitoring and control of siltation. This has been recognised for many years, because of the need for navigable harbours and waterways. It has become an economic problem in the second half of the twentieth century as vessels become larger in order to compete efficiently. A second reason is the need for monitoring and prevention of accumulation of pollutants, a more recent concern, triggered by the growing recognition of the problems associated with 200 years of industrialisation and urbanisation in close proximity to estuarine environments. During the last ten years a third reason has become prominent, the possibility of global sea level rise. This would have a direct effect on all estuaries. If water depth increases, the dynamic characteristics of each estuary would change and modify the parameters which control sediment flux. If all sediment transport processes can be realistically modelled then predicting the consequences of such an event would be made considerably easier.

Although the existence of pollution in our estuaries has been evident for many years, local authorities have shown little effort in either monitoring or prevention. It has been the growth of green politics and, in North West Europe, the introduction of transnational legislation through the EC policies on the environment that has provided the motivation for attention to be paid to estuarine pollution. This change
in political will has come about at a time when improved techniques for quantifying chemical and organic composition of estuarine water and sediments have emerged. Large scale traditional sampling techniques, though expensive, mean that areal distribution of specific elements and compounds can be obtained, but this only provides a snapshot of the long term pollutant flux within an estuary.

Mathematical modelling of estuarine hydrodynamics allows the simulation of estuary flushing times from known tidal and fluvial inputs. Such computations already allow the flux of soluble compounds to be estimated. However, the movement of suspended particulate matter presents considerable additional problems to modellers, particularly the settling and entrainment of silt and clay sized particles, named cohesive sediments because of their variable aggregation characteristics during suspension. These fine particles, less than 63 \( \mu m \) in diameter, have a high surface area to mass ratio, amplified by the fact that few of them approach a spherical shape. As such they have a high propensity to adsorb pollutants. This link between sediments and pollutants has intensified the need to more fully understand the complex role of sediment transport processes. Horizontal transport of suspended particulate matter (SPM) is relatively simple to simulate using tidal flow algorithms. The problems involve knowing when the SPM is in suspension. Because cohesive aggregates change their size and density characteristics, even during the tidal cycle, there are considerable difficulties in accurately simulating the settling and resuspension of the material.

This thesis focuses upon one of the two major difficulties, the determination of settling velocity of cohesive sediments. It provides a method for obtaining, in situ, size and settling velocity distributions of flocculated suspended particulate matter, through the design, development and use of an In Situ Settling Velocity Instrument. The instrument is referred to in subsequent Chapters by the quasi-acronym INSSEV - IN Situ SEtting Velocity.
Chapter 2

Cohesive Sediments

This chapter provides background to the subject of estuarine mud and why its dynamics are so complex. It starts by defining some of the terms commonly used in the literature and continues under traditional scientific headings by looking at the physical, chemical and biological characteristics of cohesive sediments. The particular phenomena of tidal estuaries and the turbidity maximum are considered, and the remaining problems in estuarine research are briefly described. The chapter concludes with a section detailing the pursuit of more valid data on floc settling velocity over the past twenty years.

2.1 Definitions

The term cohesive sediments is commonly applied in oceanography to sediments that, during their suspended state, have a propensity to exist as aggregations of finer particles. In estuaries these fine particles are mainly clay sized minerals (Table 2.1) and the aggregations are referred to as flocs. In assembling such a definition it is easier to start with the purely inorganic form of cohesive sediments which have been prepared in laboratory conditions from clay minerals such as kaolin. However, in the natural environment such sediments are characterised by many types of organic material which can affect their physical properties.

It is important to stress that the term cohesive should not be confused with consolidated sediments on the floor of the sea, lake or estuary. Over time almost all particles will consolidate, but the processes which cause them to bind together in an
<table>
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<th>Description</th>
<th>$\Phi_{-\log_2(\text{mm})}$</th>
<th>Microns $\mu m$</th>
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<tr>
<td>SAND very coarse</td>
<td>-1</td>
<td>2000</td>
</tr>
<tr>
<td>coarse</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>medium</td>
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<td>500</td>
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<tr>
<td>COLLOIDS</td>
<td>+12</td>
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Table 2.1: Grain size (diameter) scales for fine sediments. After Wentworth, 1922.

apparently homogeneous layer are fundamentally different from the processes which result in cohesion while primary particles, and their aggregations, are suspended in the water column. The general term for all suspended material, mineral and organic, is suspended particulate matter, commonly abbreviated to SPM.

The processes which take place, over relatively short time scales (minutes to hours rather than days to years), to produce cohesive sediments are included in the term flocculation. The complementary term deflocculation refers to those processes which disaggregate flocs and are thus responsible for limiting the maximum size of flocs in the natural environment. Maximum floc size is critical to the prediction of settling flux, as individual floc settling velocity is proportional to the square of floc diameter. This thesis is concerned with processes that commonly occur in temperate climate estuaries.
2.2 Physical Characteristics

Physical processes are the primary cause of cohesiveness in sediments in estuaries. Horizontal movement of water due to fluvial discharge and tidal regime produces velocity shear and turbulence that results in continual mixing of the fluid at all scales, down to as small as 100 μm, even when the estuary gives the appearance of tranquil flow. This continual mixing allows primary particles to come into close proximity and interact electrostatically. Small dense flocs with higher settling velocities than clay sized primary particles exist in estuaries at all times and this causes differential settling which increases the opportunity of inter-particle collisions.

Laboratory particle size analyses of estuarine suspended sediments reveal clay size (0 - 4 μm) fractions ranging from 20% to nearly 100% (Eisma, et al., 1991). Such large variation is due partly to the geomorphological history of the drainage basin and the coastline, but also to the time (relative to tidal cycles) and depth of sampling as larger primary particles settle quickly towards the bed during times of low current velocity. At these relatively slack water times the background SPM will be composed of very small primary particles, the smaller low density aggregations, and buoyant organic material such as lignin (Reeves and Preston, 1991). The degree of incorporation of organic material into flocs within the permanently suspended fraction is not easily measured, but likely to be important for floc effective density. Although size distributions obtained by laboratory analysis are unlikely to preserve in situ aggregations, their techniques are useful when primary particle distributions are required.

Flocs are composed of thousands of primary clay and silt size particles (Table 2.1), but it is the clay size minerals which are considered to be the major players in flocculation processes. As flocs grow larger - sizes in excess of 125 μm are referred to as macroflocs (Eisma, 1986) - they tend to have lower densities, as the proportion of water to dry particulate matter increases. Water content (Porosity) in excess of 95% is normal for macroflocs. Microflocs - less than 125 μm in diameter - can vary a great deal in density and therefore porosity. Porosities greater than 90% are quite common for floc sizes down to 50 μm.

The highly porous, fragile structure makes the larger macroflocs particularly
susceptible to break up if water samples are removed from the estuary by traditional sampling methods for size analysis in laboratories (Gibbs, 1981, 1982; Gibbs and Konwar, 1982, 1983; Eisma et al., 1983, 1991a; van Leussen, 1988). The resulting reduction in real size distribution has even more serious implications for the settling velocity characteristics of a collected sample due to the power law relationship of floc settling velocity to floc size. This has been the main problem for the modelling of estuarine settling flux because, until recently, settling velocity spectra have been inferred from studies conducted with devices similar to the 'Owen Tube' (Owen, 1970), discussed in the last section of this chapter.

*In situ* photography (Edgerton et al., 1981; Eisma et al., 1983, 1990; Honjo et al., 1984; Kranck, 1984; Johnson and Wangersky, 1985; Asper, 1987; Wells and Shanks, 1987; Wells, 1989; Kranck and Milligan, 1992) and *in situ* laser particle sizers (Bale and Morris, 1987) are intended to measure the natural size of flocs, without damaging their fragile 'house of cards' structure. Many of these studies have shown that floc size distributions assembled from *in situ* data sources give greater proportions of large flocs than collected samples.

Why clay sized mineral particles flocculate when suspended in water is due to the ionic charges on their surfaces and the free ions of dissolved salts. Clay particles are platelike in shape with a thickness of the order of one tenth their diameter. The two faces usually carry negative charges due to exposed oxygen atoms in the broken bonds of the crystal lattice. Further negative charges may result from isomorphic substitution of positively charged cations of a low valency, within the lattice, for other principal structural cations of a higher valency. Around the edges the charge is positive because of the broken bonds of the silica tetrahedra. As might be expected from such an arrangement of ions on platelike shapes the overall charge for clay minerals is usually negative.

In water, the charges on each clay particle are modified by formation of an electrical double layer. This is due to free ions in the water being attracted to their opposite charge on the particle surface. In freshwater, the availability of free ions is low and the electrical double layer is not well developed. In estuaries, as salinity increases, the double layer is able to develop and has the effect, even at quite low salinities, of reducing the repulsive Coulombic force. This allows the molecular
attractive force, known as the London–van der Waals force, to dominate, resulting in flocculation. Both types of force become insignificant beyond particle separations of 50 nm which is relatively small for clay size particles with a range of 500 — 4000 nm. This is why the flocculation process requires micro-turbulent conditions to ensure that particle interactions take place. The degree of development of the electrical double layer as well as the mineralogy of the crystal lattice are responsible for the type of bonding: face to face, or face to edge; the latter being weaker than the former and theoretically likely to produce floe structures with higher porosity.

The implications of these electrostatic properties in the varying temperatures and salinities in estuaries are elucidated in Dyer (1986), but the essential points can be summarised as follows:

- Maximum bonding potential for most clay minerals is likely to occur at low salinities, generally less than 3 psu (Krone, 1978; Gibbs, 1983). This means that the landward regions of an estuary offer greater opportunities for flocculation than either the seaward end or the fluvial inputs.

- As water temperature rises increased thermal motion of the free ions reduces the development of the electrical double layer. This increases the number of particle interactions where repulsive forces exceed the attractive molecular forces, thereby reducing the number of successful bonds.

- Organic materials on the particles, such as bacterial films, have positive charges which modify the repulsive forces and enhance flocculation. The active stickiness of these films reinforces the inter-particle bonds making the flocs more resistant to break-up.

2.3 Chemical Characteristics

Clay sized particles are significantly different in their mineralogy to non-cohesive particles, like chemically inert quartz sand. Clay particles are chemically active in estuarine environments due in part to their mineral composition.

The clay particles which dominate, numerically if not always by weight, the primary mineral particle populations of estuarine suspended sediments, are an im-
portant area of research for marine chemists because of their ability to adsorb trace metals and organic compounds. This is mainly due to the large surface area and the excess negative surface charge of most clay particles, discussed in the previous section. The interest for chemists is the dynamic exchange of dissolved species with the surface coatings of the particulate phase. In terms of monitoring pollutant transport in estuaries this phase change is very important because soluble compounds are subject to the more easily modelled tidal excursion and diffusion processes whereas solids are subject to the significantly more complex sediment transport processes introduced in Section 2.5.

Although the upper limit for clay sized particles has been traditionally 4 μm (Table 2.1), many workers in this field now consider 2 μm as the upper limit, in terms of chemical behaviour. Sizing in this range is often performed with precision filters and in the case of the lower limit for clay particles the definition used by marine chemists to distinguish between the soluble and solid phases is whether or not material passes through a 0.4 μm membrane filter (e.g. Nuclepore) using a vacuum pump (Sholkovitz and Copland, 1981). This is an operational definition, and the material which passes through such filters is referred to as colloidal and dissolved. The quantification of the mass concentration of the colloidal and particulate material and the exchange rates between the two phases in natural environments has presented chemists with interesting problems (Honeyman and Santschi, 1992).

2.4 Biological Characteristics

Descriptions of biological, or organic, processes are more often qualitative than quantitative. Although they are numerous the combined effect of biological processes generally enhances and sustains the flocculated state in estuarine suspended sediments rather than initiating or destroying it.

Linley and Field (1982) have looked at the way in which biological processes enhance flocculation by bacterial activity and the formation of mucopolysaccharides. DeFlaun and Mayer (1983) found that although bacteria did not colonize the surfaces of clay size particles, preferring the irregular surfaces of grains greater than 10 μm, their mucus films were responsible for binding clay size particles. The way
in which the surface charge of primary particles is modified by adsorbed organic matter in the presence of varying salinities has been investigated by Hunter and Liss (1982). Reeves and Preston (1991) reported on how varying amounts and types of lignin affect the settling characteristics of suspended material in the Tamar estuary. Ten Brinke (1993) has made the first attempt at relating organic processes to settling rates of fine-grained suspended sediments in the Oosterschelde estuary (Netherlands). Two mechanisms were studied: aggregation and filter feeding. It was found that aggregation was stimulated most by primary produced organic matter, increasing floc sizes and hence settling velocities. Maximum aggregate size occurred during the phytoplankton spring bloom. Although this phenomenon requires other conditions such as calm weather and low turbulence in the water column it is concluded that primary production leads to a 'spring cleaning' effect within the estuarine waters, and that further studies of floc settling rates should look at the quality of the organic matter rather than just the quantity. The results of the investigations on filter feeders, specifically the mussel, did not show any strong influence.

Studies like these draw attention to complex interaction of organic materials with suspended particles. The interest for sediment transport is how the biological characteristics can be simulated with respect to time, seasonal and diurnal, and possibly to depth in the water column. Identification of the most significant biological factors in sediment transport is necessary so that work on quantification is appropriately channelled.

Although parts of this chapter appear to stress the remaining physical problems, it is unlikely that these will be solved unless future work considers the importance of organic constituents in flocculated material and how their impact can be quantified.

2.5 Tidal Estuaries

Estuaries are high energy environments, principally due to the tidal regime, but also the fluvial input. Tides are responsible for the change in water level by several metres, leaving many parts of an estuary's sediments uncovered at low water. The semi-diurnal cycle (in North West Europe) which itself is affected by many other astronomical cyclic variations, is complicated by local topography to produce an
environment that rarely exhibits kinetic symmetry.

When a particle of suspended sediment enters an estuary from a river it is subjected to a totally different dynamic regime. If an estuary were tidally symmetrical along its axis in terms of its ability to transport material it would be reasonable to assume that a small, permanently suspended particle would migrate seawards, but at a slower rate than during its passage down river. Among the factors that modify this simple concept are that many particles settle, particularly during the change in tidal flow at high or low water, and are then resuspended on the next ebb or flood, resulting in a partly oscillating partly stationary existence. This is why accurate data on particle size and settling velocity throughout the tidal cycle is crucial if these processes are to be successfully modelled. The settling and entrainment cycles within the tidal cycle are complicated by the fact that stream velocities vary along and across an estuary's course and, important for resuspension potential, the tidal asymmetry – stronger flood and weaker ebb velocities – is often accentuated towards the head of an estuary. Settled particles are not entrained until the new current at the bed has reached a threshold, or critical, velocity. This is illustrated in Figure 2.1. Thus the tidal asymmetry can be responsible for considerable preferential movement of sediments towards the head of an estuary. This is known as 'tidal pumping' and leads to a high concentration zone of suspended

Figure 2.1: Schematic diagram of the transport of sediment towards the head of a macrotidal estuary. After Allen et al., 1980.
sediment which itself migrates with the tides but achieves its highest concentration near the estuary head. This zone is known as the turbidity maximum. On the upper section of the Tamar, as with many estuaries, slack water is usually longer at high water than low water. With higher suspended sediment concentrations, due to the turbidity maximum, this enables a greater proportion of material to settle to the bed. The net result of these processes is that most macrotidal estuaries tend to accumulate sediments. However, the scale of this siltation is small with respect to time when compared to storm events which can cause exceptional peaks in river discharge and thereby dominate the estuarine sediment transport regime for several hours or days. These storm events cannot simply be viewed as sediment flushing because they also transport large volumes of fluvial sediment into the estuary, with a higher proportion of large particle sizes than at other times. The tidal pumping action of estuaries also means that suspended sediment of marine origin can enter the estuarine system, further complicating the analysis of sediment origin and calculation of sediment budget.

2.6 The Turbidity Maximum

In partially mixed meso- and macro-tidal estuaries, common in North West Europe, a region of high SPM concentration is maintained. This is known as the Turbidity Maximum and it is located towards the head of the estuary. Although the fluvial inputs dictate that there is a net seaward flux of water, sediment transport does not follow such a simple concept, due to the complex settling and resuspension behaviour of particulate material. The existence of the turbidity maximum at predictable locations is considered to be due to two processes: residual gravitational circulation of water and tidal asymmetry. In meso-tidal conditions, when estuaries can be quite well stratified, residual gravitational circulation is dominant, whereas at higher tidal ranges, and stronger horizontal tidal currents, tidal asymmetry becomes more pronounced and so controls the accumulation of SPM. This means that in the same estuary the formation of the turbidity maximum can be controlled by different processes during the spring-neap cycle.

Tidal asymmetry and its effect on erodable and suspended material was intro-
duced in the previous section. Residual gravitational circulation is the product of salinity, hence density, differences in the bodies of water in an estuary. Its effects are cancelled as an estuary becomes well mixed. Figure 2.2 shows the residual movement of water in an estuary after tidal and fluvial flows have been averaged over many tidal cycles. The effect on SPM is to move permanently suspended material towards the turbidity maximum. The cause is gravitationally induced flows which are considerably weaker than tidal flows. As sea water enters an estuary it will tend to sink towards the bed in relation to the less saline water. In low energy environments water masses of different densities do not mix readily and a freshwater-saltwater interface, or salinity interface, will form along the length of the estuary (depicted by the dashed line in Figure 2.2),

In addition to the two large scale processes which control the location and formation of the turbidity maximum, further local processes contribute to the high SPM concentration zone. Towards the head of the estuary, where salinity approaches zero, the salinity interface, with near vertical isohalines on the flood tide, will often develop a very shallow angle on the early ebb flow. This results in the ebbing fresh water overlying a near stationary salt wedge. This salt intrusion is then eroded downwards by the action of current shear at the interface producing turbulence and gradually mixing the high salinity water with the ebbing fresher water above.
Deposition of SPM on the bed within the turbidity maximum is from two sources. First, in the region below the shallow angled salinity interface, the landward flowing saline flood tide loses its velocity as it approaches high water slack. The ebb current velocity remains close to zero for some hours after high water, providing a longer period of time for near bed deposition than at low water. Second, as the fresher water overlying the salt wedge erodes and mixes with the more saline water, opportunities for flocculation are increased which leads to higher settling flux of the ambient SPM, towards the salinity interface. Many large floes can be of very low density and therefore may be unable to settle through the remaining higher density salt wedge. There are then two possible outcomes. They may be broken up into smaller and denser flocs which may be able to settle through the interface, or they will remain in suspension above or within the turbulent interface, probably being advected seawards, until such time as they can settle and therefore contribute to the seaward end of the depositional feature. As the salt wedge is eroded, and the ebbing current comes into contact with the bed, resuspension will occur from the recently deposited material, thereby increasing the turbidity maximum concentration. The amount of time that this ebb resuspension operates decreases seaward and is always of shorter duration than flood resuspension. This phenomenon is structurally enhanced at neap tides by a more clearly defined shallow angle salt intrusion, and because of lower tidal velocities and longer high water slack. However, the SPM concentration is higher at spring tides due to more resuspension from the bed, greater turbulent mixing generally and particularly during erosion of the the salt intrusion. This greater turbulence limits floc growth so that vertical settling flux is lower, relative to concentration, resulting in higher recorded SPM concentrations.

The longitudinal location and length of the turbidity maximum will vary with each semi-diurnal tide (landward at high water) and the spring-neap cycle (further landward on springs). It will also vary seasonally, mainly due to the freshwater discharge of the drainage basin (further seaward during Winter and Spring in North West Europe). The exact relationship of the turbidity maximum with the longitudinal salinity profile is debatable, but occurrence in the region of 0.5 psu at the surface is common.
2.7 Remaining Problems in Estuarine Research

The ever changing nature of suspended cohesive material presents considerable problems for mathematical modellers attempting to produce accurate simulations of estuarine sediment transport. Numerical models of the fluvial-tidal regime are approaching high levels of reliability and thus the simulation of solute phase material is now a realistic exercise. The problems for successful simulation of solid phase material transport largely revolve around knowing when material is in suspension, and at what depth in the water column. This can be viewed as two distinct problems, resuspension and settling, but the understanding of both processes cannot proceed without an appreciation of flocculation characteristics. The nature of processes in the near bed region are likely to be particularly important. The primary purpose of the instrument described in Chapter 3 is to investigate settling characteristics in the near bed region.

2.8 Determination of Settling Velocity

Many studies have shown that larger flocs generally have lower bulk densities than smaller flocs (Dyer, 1989). Large, low density 'macroflocs' are considered to be fragile, and sampling (eg. automatic water bottles) coupled with laboratory or shipboard analysis is highly disruptive (Gibbs, 1981, 1982; Gibbs and Konwar, 1982, 1983); so that many early studies of floc settling velocity almost certainly produced size distributions biased towards the smaller and stronger 'microflocs'.

The most widely used instrumentation in floc settling velocity investigation has been the 'Owen Tube' (Owen, 1970, 1971) which has also spawned many derivatives. It marked the start of attempts to gather in situ data, but it is now considered to modify its sampled floc population in a number of ways, both at sampling and during the settling process. A cylindrical tube, typically 50 mm internal diameter and 1 metre long, is lowered to the required depth in the horizontal position allowing the current to pass through. The ends of the tube are closed simultaneously using a messenger from the surface to activate spring loaded end seals. The tube is raised to the surface after sampling, still in the horizontal position. When recovered the
tube is rotated several times, then turned into the vertical position at the same time as a clock is started. At predetermined time intervals aliquots of sediment in suspension are drawn off at the base of the tube and their concentration is measured. The recovery and observation part of this procedure means that the floc settling characteristics cannot be considered to be genuinely in situ. The technique provides a coarse settling velocity spectrum but gives no direct information on the floc size spectrum. Hydrodynamic and methodological limitations of the 'Owen Tube' are discussed by Van Leussen (1988), and a method for correcting data, to account for post-sampling flocculation, is given by Puls et al. (1988). The use of median settling velocity, derived from 'Owen Tube' data, is limited as a parameter for the modelling of sediment flux in estuaries, due, in part, to its inability to represent the floc size or effective density spectra.

The first attempts at direct measurement of individual flocs came with in situ photography. This has shown that the floc size distribution varies within an estuary, both in time and space. Floc diameters of several hundred microns have been recorded by in situ photography (Edgerton et al., 1981; Eisma et al., 1983, 1990; Honjo et al., 1984; Kranck, 1984; Johnson and Wangersky, 1985; Wells and Shanks, 1987; Asper, 1987; Wells, 1989; Kranck and Milligan, 1992). However, an important further characteristic of the flocs is their settling velocity (Mehta and Lott, 1987). Size, density and settling velocity are linked, and each is likely to change during the tidal cycle in estuaries as the balance between the forces of aggregation and disruption varies. Until recently, most instruments have relied on Stokes' Law for estimating size from settling velocity, or vice versa. In either case the estimate is very crude because of unknown density.

The standard Stokes' settling velocity equation, with appropriate density subscripts for cohesive sediments is shown below.

\[ w_s = \frac{D^2 \rho_f - \rho_w g}{18 \mu} \]  \hspace{1cm} (2.1)

\( D \) is the floc horizontal diameter, the axis normal to the fall direction and therefore the appropriate length parameter for the equation. The bracketed term represents Effective Density, the difference between the floc bulk density (the mean of the
component particles and the interstitial fluid) and the water density. Effective den­sity has been referred to as excess density, differential density and density contrast. Viscosity, $\mu$, is a near constant, slightly altered between samples if the water temper­ature varies. The Stokes' Equation is valid for small spheres settling in the viscous Reynolds Number regime. As the Reynolds Number, $Re$, approaches unity corrections should be applied to cope with increasing inertia. Most estuarine flocs up to about 600 $\mu$m have $Re < 1$ and therefore the corrections have only a negligible effect. They are discussed in Chapter 6 but have not been used in the data analysis techniques described in Chapter 5.

For greater understanding of sediment dynamics there is a need to know the proportions of sizes that exist in estuaries during different conditions, and also the range of settling velocities for any given size, in order to provide more precise information on floc density. This then permits the estimation of mass settling fluxes. In situ photography and laser diffraction systems (Bale and Morris, 1987) now offer rapid techniques for obtaining particle size distributions, but until recently it has not been possible to obtain both the size and settling velocity spectra from in situ data.

Relatively rapid changes in settling velocity appear to occur in estuaries, prob­ably due to changes in floc size, which result in sudden decreases in turbidity at slack water. Such observations are corroborated by concentration profiles taken in parallel with 'Owen Tube' measurements, but with the former indicating considerably faster settling rates than the latter, possibly due to floc disintegration inside the 'Owen Tube' (Van Leussen, 1988).

Work on optical devices to measure concentration profiles by Bartz et al. (1985), Spinrad et al. (1989), Kineke et al. (1989), and McCave and Gross (1991) have sought to quantify the rate of water clearance, but they are unable, like all previ­ous instrumentation, to measure settling velocity spectra with respect to floc size directly.

The long term aim of settling velocity determination studies is improvement of the understanding of settling flux. This is the product of settling velocity and concentration. Although the mass concentration can be measured by other means, it is necessary to measure the spectral distribution of floc mass for assessment of
differential settling (Lick et al., 1993) and for the correct calculation of settling flux (Mehta and Lott, 1987) since the largest flocs contain the majority of the mass.

By obtaining size and settling velocity data on individual flocs it is possible to calculate their effective density and then use the three parameters to assemble concentration and settling flux spectra. The instrument described in the following chapter provides a method for obtaining such data.
Chapter 3

Instrument Development

Appendix 1 is a reprint of an article published in *Marine Geology* which gives a review of the working instrument. This Chapter looks at the background to the design decisions, the electronics and the control software. The reader who is unfamiliar with the instrument is recommended to read Appendix 1 before this Chapter, however the following paragraph provides a brief introduction.

The instrument system is known by the quasi-acronym INSSEV - IN Situ SETtling Velocity. It has been designed to operate on the estuary bed, mounted on a heavy frame, sampling at 0.5 metres above the bed. The instrument concept is shown in Figure 3.1. The decelerator samples about three litres of water. The closure of the flap doors, at each end of the decelerator, is performed at a rate proportional to the ambient current velocity so as to minimise induced turbulence. The current velocity is obtained from an Electromagnetic Current Meter (EMCM) which is mounted at sampling height. The control computer reads the velocity just prior to flap door closure. After a short delay to allow residual ambient turbulence to decay, a slide door in the centre of the decelerator floor is opened for a duration inversely proportional to the ambient suspended matter concentration, so that a controlled number of flocs enter the top of a stilled settling column containing filtered water of a predetermined salinity. Differential settling over a filming sequence of about 30 minutes allows faster falling flocs to be video-recorded first followed by slower falling flocs. This sorting means that accurate sizing and measurement of settling velocity can be performed on individual flocs. Shortly after the video-recording has been completed, a further sample sequence may be initiated.
3.1 Design Decisions

Early in the project it was envisaged that design refinement by software amendment would be quicker and cheaper than hardware modification. The early design of the hardware sought to keep to simple shapes that would accept hydrodynamic smoothing of components at later stages in the design development iteration process.

3.1.1 Dimensions

Because the instrument package would need to be deployed from small research vessels in relatively shallow estuarine environments there was always an unwritten requirement that it should be compact. There was also a requirement to be able to sample from close to the estuary bed, and this is one reason why the instrument is bed mounted.

In addition to the general principles outlined above, it was important to establish key dimensions that would accommodate the characteristics of the particles to be observed. The design concept was essentially a two chamber process in order to move the sampled flocs from the turbulent estuarine environment to one where their settling characteristics could be observed at high magnification, with minimum disturbance to their fragile structure. The range of floc settling velocities that could be expected was the main determinant of the length and height of the decelerator. If the length to height ratio is too great then most of the flocs will fall to the decelerator floor before they can be introduced into the top of the settling column. This problem will always be present for faster falling flocs in a slow moving ambient flow with a horizontal decelerator chamber. If the effects of turbulence are ignored, the vertical distance of fall, for any given settling velocity, can be calculated as follows:

\[ h = \frac{w_s l_c}{u} \]  

(3.1)

with \( h \) representing the vertical fall of the particle; \( w_s \) the settling velocity; \( u \) the ambient longitudinal flow velocity through the decelerator; and \( l_c \) the length of 'ceiling' from the front of the decelerator to a point directly above the object plane.
of the camera (all dimensions in millimetres). The 'ceiling' length is nominally 200 mm, but with the protrusion when the front flap is open (+42 mm) and the exact position of the camera object plane (+5 mm), the total length of the 'ceiling' is 247 mm. The available height, $H$, within the decelerator is 100 mm, so if the value obtained for $h$ in Equation 3.1 exceeds 100, then all particles of that settling velocity are lost to the floor before reaching the camera object plane. Assuming an even vertical distribution of particles with any given settling velocity, the value of $h$ also represents the percentage loss of particles for the specified settling velocity:

$$\%\text{loss}_{w, s} = \frac{h}{H} \times 100$$

Substituting Equation 3.1 for $h$ in Equation 3.2, and the specific value of 100 for $H$ gives the following equation:

$$\%\text{loss}_{w, s} = \frac{w_s l}{u}$$

(3.3)

However, except when the ambient current velocity, $u$, is below about 0.03 m s$^{-1}$, it is the programmed time interval between flaps closing and slide opening, which from fieldwork experience is set at 20 seconds, that most influences the theoretical
percentage loss of particles for any given settling velocity:

\[
%loss_w = w_s(t_{fc} + t_{td} + \frac{t_{st}}{2} + 3.4)
\]

(3.4) 

the three time values, in seconds, being the duration of the flap closure sequence, \(t_{fc}\), the interval mentioned above, \(t_{td}\), and the duration of the slide opening sequence until it is open directly above the camera object plane, \(t_{st}\). Figure 5.1 provides explanations of these symbols. By way of example, from a sample taken in a current velocity of 0.05 m s\(^{-1}\), there will be an approximate loss of flocs falling at 2 mm s\(^{-1}\) of 54 per cent. Chapter 5 explains how INSSEV data can be corrected to compensate for these losses.

The conclusion from these calculations is that any lengthening of the decelerator chamber would lead to greater loss of potential data, particularly of larger flocs which are important to this study. Shortening would be appear to be advantageous but would lead to problems with fitting components such as motors and door mechanisms.

### 3.1.2 Decelerator Doors

Theoretically, water passing through a square section tube that is aligned with a laminar flow will not produce eddy shedding, although minor turbulence due to velocity shear will be created at the boundary layers. Dye streaming experiments showed that boundary layer turbulence was operating in the first 2 – 3 mm above the decelerator floor at the front of the chamber, rising to approximately 6 – 8 mm in the vicinity of the slide door to the settling column. Unfortunately estuary flows are rarely laminar, nor stable in direction. The instrument sampling sequence is designed to operate only when the decelerator is reasonably aligned (within a few degrees) with the ambient flow.

Even if alignment difficulties could be ignored, closing the end of such a tube, whether round or square section, is problematic in terms of eddy formation and consequent additional turbulence. The type of closure hardware was chosen with the intention of creating as little turbulence or shock waves as possible in the water sample being decelerated. This aim was a direct response to the criticisms of the

The hydrodynamic characteristics of both the upstream and downstream doors in their 'open' position had to be considered and the method and rate of closing had to decelerate the water sample to zero whilst causing minimum additional turbulence. Controlled closure of the decelerator flap doors, at speeds varying with the ambient flow velocity, was the objective. The following equations were derived from extensive dyestream experiments in the wave/current tank of the Marine Dynamics Laboratory at the University of Plymouth. The duration of the flap closure, $t_{fe}$, can be obtained from either current velocity, $u$,

$$t_{fe} = 2.924(u + 0.0523)^{-0.495} - 2.01975$$

or, the control computer variable $SPS$, the motor starting speed.

$$t_{fe} = 2.924\left(\frac{SPS - 40.5}{262} + 0.0523\right)^{-0.495} - 2.01975$$

Dimensioning criteria, discussed in the previous section, also had a bearing on the angle between the open and closed positions of the doors. Thirty degrees would have increased the length to height ratio unacceptably, but sixty degrees would have increased the risk of eddy formation behind the front door (inside the decelerator) during the final stages of closure. Forty-five degrees was chosen for the prototype and dye streaming tests were performed on this configuration (see Figure 2 of Appendix 1). The doors are opened together using mechanical linkages. At the front door eddy shedding was noticeable from the dye streams, intermittent at first, if the doors were held stationary at angles greater than 17 degrees from the horizontal. However, when the doors were accelerated towards closure the eddy shedding was suppressed. This can be explained in two ways. First the horizontal velocity of the water parcel inside the decelerator is decreasing as soon as the doors begin to close. Second, the volume of water bounded by the narrowest points between doors and carcase is reducing during the closure routine. The effect of the latter, in flowing water, is to increase the velocity of the flow leaving through the back door but decrease the flow velocity under the front door. This situation continues until, at about 40 degrees from the horizontal, the flow direction under the front door is
reversed. This indicates that a null point exists within the decelerator.

The dye streaming experiments enabled the accelerating door closure routine to be refined and the motors programmed so that over the final 5 degrees the angular velocity of the doors decreases. This softens the sample deceleration process and also ensures that the flap door stepper motor does not run the risk of overshooting its precise angular position.

The configuration of the two flap doors was chosen to ensure that there was no significant difference between the top and bottom of the decelerator. It was decided to hinge the front flap door at the top so that the floor of the decelerator upstream of the slide door was always horizontal. If the front door had been hinged at the base of the decelerator it was considered that deposited sediment might be resuspended during the door closure routine. In addition, the flow axis of the water sample shortly before final door closure would be diagonally upwards and therefore suspended particles would have the gravity component assisting them to achieve zero horizontal velocity.

3.1.3 Slide Door to Settling Column

Ideally this component should be infinitely thin and possess frictionless surfaces. It is necessary in order to isolate the stilled water in the settling column from the turbulent estuary water passing through the decelerator prior to the sampling sequence. When the decelerator doors have been closed and the turbulence decay time, $t_{td}$, has elapsed the slide door is opened. The travel time, $t_{sl}$, to slide the 45 mm has been set to 2 seconds, although the control software allows it to be lengthened to 20 seconds. The column is effectively open above the video camera object plane approximately half way through the travel time sequence (this can be seen schematically in Figure 5.1). At a travel time setting of 2 seconds the stepper motor accelerates the slide door from a starting velocity of only $3 \text{ mm s}^{-1}$ to lessen the effect of shock waves in the water above and below the door. Similarly, near the end of its travel the motor decelerates before stopping.

The present door is made of stainless steel and is 1.5 mm thick with bevelled edges that locate it in the Perspex floor of the decelerator. In engineering terms, this was the thinnest section practical for considerations of rigidity and the machining of
the locating slide grooves. Because it has a real thickness and hence a volume, water has to move into its place as it slides. This water has to come from above because the column is far better sealed from the estuary water than is the decelerator with its doors closed. Provided the density (salinity) of the water in the stilled column is greater than that in the decelerator Rayleigh-Taylor instability should not occur. However, the interface between the two water bodies will be disturbed because of the shearing effect caused by both surfaces on the water in contact with them. During the design development stage thought was given to mounting the INSSEV video camera so that it could view the water movements during and after a slide door travel operation. Unfortunately this was deferred as the engineering requirements would have destroyed much of the prototype carcass. This is an area of the instrument’s operation that may yield important information on the behaviour of fragile low density flocs.

Operational Control

Throughout the laboratory and field trials the slide travel time has been left at 2 seconds, which is a practical minimum in terms of reliable motor control. The reason for this decision was to maximise the number of fast falling flocs entering the column rather than losing them onto the top surface of a slowly opening slide door. It was considered more beneficial to increase the turbulence decay time, $t_{td}$, rather than the slide travel time as this kept the column isolated from the residual turbulence in the decelerator for as long as possible.

The length of time that the slide door remains open, $t_{sd}$, is the only control available over the amount of SPM entering the column and appearing before the camera. Determination of $t_{sd}$ is made from measurement of total SPM concentration, usually by an optical instrument, just prior to sampling. The setting of this operating parameter has been determined empirically from many samples obtained in the field and is expressed as

$$t_{sd} = 1860.63C^{-0.80371}$$  (3.7)

where $C$ is SPM concentration in $mg l^{-1}$. The empirical assessment as to what con-
stituted the correct amount of flocs entering the column was based upon subjective analysis of video-tapes. Floc frequency at the camera decreases with elapsed time. This is because all large flocs fall quickly, as well as high density medium sized flocs and very high density small flocs. Only low density small flocs fall very slowly and therefore arrive at the camera late into the video-recording. The subjective decision as to what constitutes a good video-recording is based upon the following question. Can all flocs be seen separately on the video monitor for reliable measurement of size and settling velocity? Because of the foregoing it can be appreciated that the answer to the question is based upon the first few minutes of each recorded sample. In the 'optimum' samples over 200 flocs can be measured manually. Ongoing work with image processing software should result in the same level of video-tape processing. The above equation suggests that at a concentration of 1 g l\(^{-1}\) the slide fully open time will be about 7 seconds, resulting in a total time for the slide being open above the video camera object plane being a little less than 10 seconds. Fortunately this progressive limitation on the performance of the instrument system is less problematic for the larger flocs in any sample as they will always present before the camera a higher proportion of the total in the video object plane sample volume than the smaller sizes, due to the differences in settling velocity.

If there were no problems of turbulence transfer to the column that needed eliminating and the SPM concentration was always below 10 mg l\(^{-1}\), the slide door would be unnecessary. In this case all flocs in the video object plane sample volume, \(V_o\) (see Chapter 5 for definition), would be seen provided the tape was left running for long enough. These two idealised conditions do not exist in estuaries, which is why the careful timing of the sampling sequence is essential to the acquisition of good quality video-recordings.

Opening the slide door after a time delay (the turbulence decay time) means that some fast falling flocs are lost to the floor of the decelerator, more specifically they settle on the unopened slide door directly above the video object plane. Closing the slide door a relatively short time interval after it has opened means that some slow settling flocs are lost to the top surface of the side door. These two conditions are quantified in Chapter 5 where coefficients are developed which correct the calculated total dry mass of the flocs observed in each size band, so that they
are representative of the sample volume, \( V_s \). When INSSEV is used in high SPM concentration environments the slide door fully open time, \( t_{ad} \), is reduced to only a few seconds. This results in higher correction coefficients due to secondary losses (see Chapter 5) for flocs with slow settling velocities.

### 3.1.4 Column Stability

Laboratory experiments with settling columns to measure settling characteristics of flocs have shown that they are affected by residual currents, caused by either the passage of earlier large flocs or thermal instability (Gibbs, 1985).

In this project, the intention, from the outset, was to keep a low floc concentration in the column. This is achieved by controlling the length of time that the slide door to the column is open, as explained in the previous section. Thermal instability in laboratory conditions can be caused by temperature differentials in the lab itself together with uneven thermal energy exchange with different parts of the column. Powerful incandescent video camera illumination is an example of unpredictable heating due to the large amount of energy radiated in the infra-red part of the spectrum.

In the estuary environment, maintenance of a column temperature other than at ambient would be difficult. At the bed, changes in ambient temperature with time are slow, and changes in temperature with height, over the 180 mm of the column, are insignificant due to continual turbulent mixing. It was therefore decided that the column temperature would be controlled by the ambient conditions. As horizontal water flow barely reaches zero, there is always a relatively stable temperature background enveloping the column, which also serves as an effective heatsink for the small heat production inside the camera housing. Because this casing, painted black, is downstream of the column any heat radiated is theoretically advected away. The LED illumination is contained within the camera housing, behind an opal glass faceplate which is 12 mm thick. Because the light is of narrow bandwidth at approximately 650 nm very little of the energy output (6 x 130 mW) is absorbed by the column water or particles. This has been confirmed by laboratory observation.

Due to the in situ nature of the instrument, and the fact that the chamber
above the column acts as a decelerator, there is the possibility of turbulence transfer whenever the slide door is opened. This potential problem is greater during times of high turbulent intensity in the estuary.

The two principal methods of reducing instability from transferred turbulence are:

- increasing the time interval between flaps closing and slide opening, $t_{id}$, as this will allow more of the residual turbulence in the decelerator to decay, and

- maintaining a positive density contrast between the estuary water in the decelerator and the column water. This is achieved by charging the column with water of higher salinity than that expected in the estuary. A contrast of $6 \text{ psu}$ was found to be the optimum during early field trials, which gave a density difference of approximately $4.6 \text{ kg m}^{-3}$ at $15^\circ\text{C}$. If the salinity contrast was below $6$ there appeared to be a risk of instability. Later field trials have indicated that a lower salinity may be beneficial and this is discussed in Chapter 6. However, any positive contrast, although it assists stability, does mean that very low effective density flocs will not settle through the contrast interface. This is a phenomenon which may also be occurring naturally in estuaries, on ebb tides, when fresher water overlies a salt wedge. Its existence at the top of the instrument settling column could lead eventually to a build up of low density (fragile) flocs at the interface and a subsequent risk of collision with free falling higher density flocs. It is therefore important not to allow the salinity contrast to become too great.

An additional feature, the $\#$ shaped insert, which divides the column into nine smaller columns with the video object plane being located in the centre column, is believed to assist with turbulence dampening should any occur when the slide door is open. The main purpose of the insert is to prevent any sediment that has already settled to the decelerator floor, in the region of the slide door edges, from being introduced into the inner column if it is disturbed during slide door operation.
3.1.5 Video System

Video cameras for specialist applications are generally constructed from industry standard components, such as pick-up tubes or CCD (Charge Coupled Device) integrated circuits, and lenses. This is a simple economic decision. In the case of lenses, this means that some degree of compromise may have to be made with regard to optical design dimensions. With this instrument, a picture height of 3.3 mm was accepted instead of 3 mm, and a ‘through water’ focal length (faceplate to object plane) of 45 mm instead of 50 mm. This hasn’t significantly affected the design performance of the instrument.

Opting for a Pasecon tube has meant a higher image resolution than if a CCD camera had been used. Although the video market is moving rapidly towards sophisticated colour systems, for our purposes, a high resolution monochrome camera was more important, because it is able to operate from a considerably narrower bandwith of light than a colour system.

The willingness of the specialist video camera company, Custom Cameras of Wells, Somerset, U.K., to work closely to the design specification, particularly in dealing with the optical and engineering problems of the operating environment, was of great value to the project.

3.1.6 Perspex Construction

Early prototype components for the decelerator were made from clear Perspex acrylic sheet for ease of construction and the potential to permit flow visualisation experiments with coloured dye. Its use was retained for later versions as calibration experiments for flap door closure routines were repeated when closer tolerance components and a higher torque motor were fitted. In field use the Perspex construction offers many benefits during lift outs when checking, cleaning and column recharging are carried out. One disadvantage of acrylic sheet is its susceptibility to damage if rough handling occurs during field deployment.

Apart from the video camera casing (epoxy coated aluminium) all metallic components on the instrument are stainless steel in order to eliminate corrosion. This has proved beneficial for post fieldwork cleaning and overhaul, as well as maintai-
ing free movement of flap door linkages.

3.1.7 Stepper Motors

Despite early development problems in assessing the torque required to operate the flap and slide doors this type of electric motor has proved to be very suitable, largely because it satisfies the primary design criterion of being able to be completely controlled by the instrument computer software (Acarnley, 1984).

The early problems surrounded the need to operate two of these motors inside waterproof casings and therefore bring their rotary power out through shafts. To provide a satisfactory seal for these shafts over a range of water depths it was decided to use dynamic 'O' ring seals. Static 'O' ring seals are used extensively on oceanographic instrumentation where water ingress is completely unacceptable, but their use for dynamic seals requires significantly finer engineering tolerances and smoother surface finishes. Stepper motors have a relatively low power to weight ratio when compared to other DC electric motors and therefore choice of appropriate size is important. If they encounter a resistance greater than their torque capacity they miss steps, and therefore fail to complete their programmed task. The early problems over motor size selection were due to difficulty in calculating sufficient margins for the motors to cope with the resistance from the 'O' rings. Two are used on each shaft, spaced about 14 mm apart so that they also act as alignment bearings. They are lubricated with silicone grease on assembly and during consecutive tests they appear to offer quite low resistance to turning. However if they are allowed to remain stationary for about one hour or more, the torque required to start rotation increases by between two to three times. A possible explanation of this problem is that while stationary the pressure of the slightly deformed 'O' section forces the lubricant away from the contact surfaces and leaves them 'dry'. This hypothesis is supported by subsequent experiments, when the required starting torque decreases with more rotations of the shaft. The motor sizes now in use take account of this problem, and together with dry tests on board the vessel just prior to deployment, appear to have eliminated motor failure.
3.2 Electronics

As the instrument will be used in relatively shallow estuarine locations, it was decided to have cable links to the surface vessel both to collect and adjust the video signals and control the instrument sampling sequences. Sealed data logging systems were inappropriate for this type of instrument system and other methods of data transmission would have proved to be more expensive. In addition, using such equipment in high suspended sediment concentration requires frequent inspection and cleaning of the decelerator. As a lifting cable is always attached to the estuarine bed frame, cable links to the surface vessel are only a small additional inconvenience in shallow tidal waters. However, deployment in deep locations or with strong currents imposes considerable drag on the cable harness.

For the video system, cable connection means that only primary camera electronics, illumination LEDs and pick up tube need to be located in the camera housing. The video and illumination control circuits can be located on the surface vessel.

For the instrument motors and allied sensors it means that electrical power can be supplied through the cable. Cable selection was determined by the requirement to supply 24 volts at 2 amps for the Type 23 motors. The later change to a Type 34 motor for the flap door control raised the current demand to 3.5 amps, but fortunately the $12 \times 1.5 \text{ mm}^2$ cable is able to carry this current.

Figure 3 of Appendix 1 shows the general arrangement of the cable linkages for the whole system. Figure 3.2 shows the wiring connections between the circuit boards of the instrument control electronics.

3.3 Control Software

Development inertia has meant that a convenient and available BBC, model B, computer that was used for early experiments has become the main control computer for the whole instrument system. It is able to perform all the tasks required through its 8 bit user port and 4 channel Analogue to Digital Converter. In operation the user interacts with a menu display that includes incoming sensor information plus
Figure 3.2: Instrument Control Electronics: Wiring between Circuit Boards.
Planned change to an IBM type portable will permit significantly more digital data logging, enabling time series of ambient conditions at the height of the instrument to be constructed. High frequency logging of the Electromagnetic Current Meter (EMCM) data will allow turbulence characteristics to be analysed.

Apart from the routines to log more data, the software structure in Appendix 2 will not need to be significantly altered for an IBM machine. The bulk of the program is written in BBC Basic and operates through the Basic Interpreter ROM. This gives a comparatively slow program speed by 1994 standards, but it is able to run all the status management procedures and still sample the EMCM output at 2 Hz. The routines that provide the square wave pulses for the stepper motor driver board are written in assembly language, and can generate pulses at a much greater speed than the motors can physically operate. The technical details of this part of the program can be found in Bannister and Whitehead (1985) and Bray et al. (1983).

3.4 Future Hardware Developments

Depending on the nature of deployment sites there are provisional plans in the software structure for additional status sensing and instrument adjustment which would improve instrument control and performance. This is additional to the plans to log more master variable data discussed in the previous section.

A redesign of the estuarine bed frame is envisaged that will not only offer better protection for INSSEV but will also accommodate instrumentation being developed for other investigations. It is suggested that this redesign should take account of the possible additions and improvements to the current version (1.3) of INSSEV. If additional monitoring and control features are incorporated it is strongly suggested that the changeover from BBC to IBM type portable computer should be made at the same time. An IBM control computer will allow large scale logging of ambient conditions, particularly from the EMCM. In view of the foregoing the following order of priority is suggested:

1. New stainless steel bed frame without directional control option.
2. Change to IBM portable for control computer.

3. Two salinity sensors permanently mounted on the new deployment frame, one located at sampling height measuring ambient conditions, the other inside the column. These sensors to be interrogated by the computer prior to sampling, through the WTW LF196 Salinometer, in order to check the salinity contrast.

4. OBS or other concentration sensor directly interfaced with control computer so that SPM concentration can be evaluated prior to INSEV sample sequence, thereby ensuring that 'slide door fully open duration' can be more reliably programmed. The sensor is also very important if INSEV data is used to calculate settling flux.

5. Remotely operated pumps to recharge the settling column with an appropriate salinity, prior to obtaining a new sample.

6. Horizontal direction control of part of the deployment frame through remotely operated electric motors. Information from the EMCM to be used to align INSEV with the prevailing current direction prior to sampling.

7. Additional 200 metre cabling: instrument, video, EMCM, Salinity Sensors, OBS.

8. Cable rationalisation and batteries mounted on bed frame may be a better option if working with long cables in tidal currents (cable drag).

This higher level of instrument control would theoretically permit the instrument system to remain on the estuary bed for several changes in tidal flow direction, and would reduce the need for lift outs. However, as regular inspection and cleaning of the decelerator chamber is strongly recommended, the ability to leave the instrument system on the bed for as long as possible should not be the main objective.

If the current version of the main INSEV carcase is rebuilt, several engineering modifications could be made that would reduce construction costs and make the equipment more robust and easier to clean and maintain. These can be obtained from the author. They would not affect the sampling performance of the instrument system. A simple modification, at construction stage, that would allow more of the
slower settling velocity flocs to be observed, is the raising of the camera axis by up to 40 mm. If INSSEV were to be used in locations other than estuaries, with lower current velocities, then dimensional and possibly configuration changes should be considered.
Chapter 4

Fieldwork

This Chapter briefly describes the programme of field trials undertaken for the development of the Instrument System, and describes the ambient conditions for the Tamar Estuary, March 1993, and the Elbe Estuary, June 1993.

4.1 Programme of Field Trials

The project started in August 1990 with the aim of designing and developing a piece of equipment that would be able to measure the size and settling velocity of individual flocs in turbid estuarine environments. The early hydrodynamic work took place in the Marine Dynamics Laboratory at the Institute of Marine Studies, University of Plymouth. The first field trials took place 13 months after the start of the project and were successful in obtaining high quality video images, although the validity of the data in terms of volume reference had not been adequately addressed. These early trials were conducted in relatively low current velocities, due to neap tides, and the euphoria of initial success was somewhat damped as experiments were conducted in higher ambient current velocities. Table 4.1 provides an overview of the field trials programme. Much of the effort in 1992 went into improving the engineering design.

The choice of site during the Tamar trials was determined by the probable location of the turbidity maximum. The nature of the Estuarine Bed Frame (Figure 4.1) and its requirement for a laterally stable lifting vessel made deployment at more than one site during the day impractical. Additionally INSSEV requires about half
<table>
<thead>
<tr>
<th>MONTH &amp; YEAR</th>
<th>DATA DAYS</th>
<th>ESTUARY</th>
<th>SITE</th>
<th>NGR</th>
<th>TIDAL RANGE</th>
<th>VESSEL</th>
<th>LIFTING VESSEL</th>
<th>INSSEV version</th>
<th>Additional Features</th>
<th>TAPE Nos.</th>
<th>TAPE VALIDITY</th>
<th>Other Instruments</th>
<th>PERSONNEL</th>
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<td>Tamar</td>
<td>Calstock</td>
<td>SX436683</td>
<td>1.7H, 1.5</td>
<td>Tamaris</td>
<td>Barge</td>
<td>1.2</td>
<td></td>
<td>11</td>
<td>Unstable LPS</td>
<td>MJF AJB KRD DAH JMcC RC</td>
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<td>1.9H</td>
<td>Tamaris</td>
<td>Barge</td>
<td>12</td>
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<td>12</td>
<td>Good LPS</td>
<td>MJF AJB KRD JMcC RC</td>
<td></td>
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<tr>
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<td>Wed 28</td>
<td>Tamar</td>
<td>Calstock</td>
<td>SX436683</td>
<td>2.6L, 2.5H</td>
<td>Tamaris</td>
<td>Barge</td>
<td>1.2</td>
<td></td>
<td>18,19</td>
<td>Unst,Unst LPS</td>
<td>MJF AJB DAH Filmcrow</td>
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</tr>
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<td></td>
<td>Calstock</td>
<td>SX436683</td>
<td>3.1L, 3.2H</td>
<td>Tamaris</td>
<td>EMCM</td>
<td>19,20</td>
<td></td>
<td>21</td>
<td>Unst LPS</td>
<td>MJF AJB KRD</td>
<td></td>
</tr>
<tr>
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<td>Barge</td>
<td>1.3</td>
<td></td>
<td>25</td>
<td>Unst LPS</td>
<td>MJF AJB MC DL KRD CEV AD</td>
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<tr>
<td>OCT 92</td>
<td>Wed 21</td>
<td>Tamar</td>
<td>Calstock Boatyard</td>
<td>SX430687</td>
<td>2.6H</td>
<td>Tamaris</td>
<td>Barge</td>
<td>1.3</td>
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<td>Unst LPS,LT</td>
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<td></td>
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<tr>
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<td>Thu 18</td>
<td>Tamar</td>
<td>Below Halton Quay</td>
<td>SX412652</td>
<td>2.6H, 2.9</td>
<td>Tamaris</td>
<td>Catfish</td>
<td>1.3</td>
<td></td>
<td>None</td>
<td>-</td>
<td>LPS,LT,ABS</td>
<td>MJF AJB MC DL AD</td>
</tr>
<tr>
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<td>Mon 15</td>
<td>Tamar</td>
<td>Calstock Boatyard</td>
<td>SX436687</td>
<td>2.7L, 2.4</td>
<td>Tamaris</td>
<td>Catfish</td>
<td>1.3</td>
<td>Tiltmeter</td>
<td>26</td>
<td>Fair LPS,LT,FOS</td>
<td>MJF AJB MC DL PH AD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tue 16</td>
<td></td>
<td>Cotehele Chapel</td>
<td>SX425686</td>
<td>2.1H, 1.9</td>
<td>Tamaris</td>
<td>Catfish</td>
<td>27</td>
<td>Fair LPS,LT,FOS</td>
<td>28</td>
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<td>MJF AJB MC DL PH AD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wed 17</td>
<td></td>
<td>Cotehele Chapel</td>
<td>SX425686</td>
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<td>Tamaris</td>
<td>Catfish</td>
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<td>Good LPS,LT,ABS,FOS</td>
<td>30</td>
<td>Good various</td>
<td>MJF KRD MC AJB + ElbeCG</td>
<td></td>
</tr>
<tr>
<td>JUN 93</td>
<td>Fri 11</td>
<td>Elbe</td>
<td>SFB327 Pontoon</td>
<td>&quot;Sites&quot;</td>
<td>2.5L, 2.9</td>
<td>Pontoon</td>
<td>Pontoon</td>
<td>1.3</td>
<td>100m cable</td>
<td>30</td>
<td>Good</td>
<td>LPS,LT,FOS,ABS,FOS</td>
<td>MJF KRD MC AJB + ElbeCG</td>
</tr>
</tbody>
</table>

Sites (other information) Other Instruments Key Personnel Key

TAMAR South West England, into English Channel
    Current Direction: Flood - Ebb
    Calstock 160 340
    Calstock Boatyard 100 280
    Below Halton Quay 020 200
    Cotehele Chapel 345 165

ELBE Northern Germany, Into North Sea
    3 nautical miles upstream from Brunsbuttel near NE bank
    Latitude S3 52'59.2" N Longitude 9 13'58.3" E
    Current Direction: Flood 105 Ebb 285

Table 4.1: INSSEV Field Trials Programme.
an hour to satisfactorily complete a sample sequence. The intention was to select a site in mid-channel where the flooding tide brought the turbidity maximum up past the bed frame. After high water, as the tide ebbs, the salt wedge is eroded by the freshwater landward of the chosen site. The tidal regime for the Plymouth area produces high water at about midday during neap tides. There was an added convenience to pursue predominantly neap tide surveys of the turbidity maximum because the required daily pattern was observable during daylight hours. The early hydrodynamic problems working with higher current velocities meant that neap tides were more favourable for proving the instrumentation, and the nature of the turbidity maximum in the Tamar means that there is a greater chance of salinity stratification when the tidal range is lower.

4.2 Operating Criteria

INSSEV is mounted on an Estuarine Bed Frame (Figure 4.1) deployed from a surface vessel, which supplies power and houses the control computer and video electronics. Winching machinery is used to control a wire cable that lowers the frame
to the bed, and remains attached ready for retrieval. A cable harness connects the various instrument components to their respective monitoring, control and logging equipment in the surface vessel.

All instruments have been positioned on the frame such that they sample at the same height above bed (0.5 m) and that they do not interfere with each other's sampling criteria. INSSEV is mounted so that it receives ambient flow uninterrupted by other instruments or the bed frame structural members, for current directions up to 25 degrees from correct alignment. For reasons involving the hydrodynamic design of the INSSEV decelerator (see Chapter 3) samples should only be taken up to 15 degrees from correct alignment.

The total weight, in air, of the bed frame with all instruments is about 200 kg. Much of the weight is lead ballast to keep the frame stable on the estuary bed. The instrument video camera monitor gives immediate indication if the bed frame moves, because the settling column becomes unstable. The bed frame has worked successfully in current velocities up to 0.7 m s\(^{-1}\) before moving. However this was in shallow water. Much of the stress on the frame is caused by cable drag, and this becomes more problematic with deeper deployments.

To assist correct alignment with the current direction the bed frame is lowered with a detachable fin and sometimes, if the vessel is large enough, additional lines to control the frame's orientation. The EMCM, which continuously indicates relative current direction, and the integral tilt meter located in the INSSEV bed electronics casing are monitored during lowering and if the bed frame is not aligned or level when on the bed it is lifted and re-lowered.

### 4.3 Ambient Conditions - Tamar

The Tamar Estuary is often classified as partially mixed, macrotidal, and temperate. Figure 4.2 shows its position in the United Kingdom, and also demonstrates its recent geomorphological history by its dendritic shaped outline; that of a drowned river valley. Although one of the smaller estuaries of mainland Britain, it is one of the most studied. Uncles and Stephens (1993) provide a summary of the main hydrodynamic and sediment dynamic characteristics, specifically the nature of the
Figure 4.2: Location Map of the Tamar Estuary.
turbidity maximum. Salinity stratification is commonly observed during neap tide conditions. Seasonal variability of sediment dynamics is described in Uncles et al. (1994).

The Tamar River is the main tributary to, and the longest arm of the Tamar Estuary, which is approximately 31 km from its tidal limit near Gunnislake to Plymouth Sound. The freshwater discharge gauging station, see lower graph in Figure 4.3, is approximately 3 km above the tidal limit. The width of the estuary at high water at the four sites named in Figure 4.2 ranges between 40 to 100 metres. Low water depths are about 1 to 2 metres. The bed of the low water channel is composed of sands and gravels, as well as some cohesive material. The banks are predominantly cohesive mud.

The river is approximately 75 km from source to sea and the whole catchment above the freshwater gauging station drains 917 km² of mainly agricultural lowland with some moorland to 600 metres above sea-level. The former has a bedrock of Carboniferous shales and the latter chemically weathered granite. There is also a small complex region of contact metamorphism and gaseous mineralisation at the edges of the two small granite batholiths.

The background hydrodynamic conditions during the Tamar field trials are presented in the two graphs in Figure 4.3. The use of predominantly neap tide conditions was planned, but the occurrence of mainly low freshwater discharges is coincidental. Time series of Master Variables recorded at the site for Wednesday 17 March 1993 are presented in Figure 4.4. This is the date for which INSSEV data is analysed in Chapter 5. It can be seen that salinity and current velocity stratification are more pronounced after high water than before. The weather conditions during the Tamar field trials were varied, but rarely significant due to the sheltered position of the sites. On 17 March it was dry, cloudy and cool with only a light breeze.

4.4 Ambient Conditions – Elbe

The Elbe is a significantly larger temperate estuary than the Tamar. The total river length from source to sea is about 750 km. It rises in the western uplands
Tidal Range for Plymouth based upon Admiralty predictions

Tamar Discharge at 0600, 1200, 1800 hrs measured just above Tidal Limit

Figure 4.3: Hydrometric Data for the Tamar Fieldwork Deployments.
Figure 4.4: Master Variables Times Series – Tamar – Wednesday 17 March 1993.
of Czechoslovakia and flows through what was East Germany (1945-89), see Figure 4.5. This is significant for current work on estuarine pollution and sediment dynamics because approximately 90 percent of its freshwater catchment area was in Soviet controlled 'Eastern Europe' where standards of effluent discharge into the river system were considerably lower than those adopted in most countries of Western Europe. The length of the estuary from the barrage at Geesthacht to the sea is about 200 km. Previous hydrographical work on this estuary (Lucht, 1964) placed the seaward end some 30 km beyond Cuxhaven. This position also marks the extremity of extensive sand banks which characterize the south-eastern shore of the North Sea. The turbidity maximum migrates between just above Cuxhaven to just above Glückstadt. Since 1989 the University of Hamburg has maintained a research platform (moored barge) at the midpoint of this excursion, known as the SFB327 Pontoon. This is the pontoon used for the Elbe Intercalibration Ex-
periment in June 1993. The pontoon is moored 250 metres from the north bank, see Figure 4.5, in 17 metres water depth at low water springs. Near the pontoon (Brunsbüttel) the mean tidal ranges are 2.5 metres for neaps and 3.1 metres for springs. The estuary width at high water is 2700 metres. The Hamburg Port Authorities maintain a dredged main channel for shipping about 150 metres south of the site mooring. Many studies on the Elbe identify locations by stating the number of kilometres along the thalweg from the source. The Pontoon is located at 690 km on this longitudinal axis.

From inspection of the estuarine bed frame after retrieval sand and gravels, as well as cohesive material, are present on the bed. Divers reported that the bed was flat in the vicinity of the pontoon. The weather during the exercise was hot and mainly sunny, with generally light winds. Due to damage from other equipment being deployed from the pontoon only one sample sequence was suitable for the data analysis described in Chapter 5. This was taken on 11 June and the results are presented and discussed in Chapter 6. Master variable data was collected throughout the exercise by GKSS Forschungszentrum using a multiprobe sensor suspended from the pontoon, mainly at mid-depth, but also used to obtain through depth profiles at half-hour intervals. This data has been processed by GKSS and the time series for 11 June is displayed in Figure 4.6. GKSS is a German state research institute, based at Geesthacht near Hamburg, involved in aspects of water quality and sediment transport in the Elbe Estuary.

4.5 Deployment Conclusions

INSSEV has been used successfully in estuarine situations with current velocities up to 0.6 m s⁻¹; depths of 18 metres; and in concentrations up to 400 mg l⁻¹. All field trials have been conducted in the vicinity of turbidity maxima, mostly during neap to medium range tides.

Deployment in current velocities higher than 0.6 m s⁻¹ can probably be achieved with a redesigned bed frame, using structural members with lower drag coefficients and heavier ballast. Ground spikes are an additional possibility which need only be attached if severe conditions are expected. The problem of cable drag increases
Figure 4.6: Master Variables Time Series - Elbe - 11 June 1993. Prepared by Jens Kappenberg, GKSS, Geesthacht, Germany.
with increasing deployment depth. High current velocities at depth will increase the risk of bed frame movement. If this occurs at any time during video recording of floes settling in the column, the column will become unstable for several minutes, at least, and the sample will be of limited value for data analysis. In general, INSSEV will be easier to operate in lower current velocities.

Dynamic tests on the motor shaft seals have not been performed, although static tests in a pressure vessel have simulated a 100 metres water depth. If depths greater than 18 metres are expected, some additional work on shaft seals may be required.

INSSEV was designed to operate in much higher concentrations than experienced during the field trials up to June 1993. Electronic monitoring of the SPM concentration, just prior to sampling, at the same height above the bed as INSSEV, is essential to the acquisition of a good quality video-recording of the floc sample. This is to allow the use of the empirically (field trials) derived Equation 3.7 to set the time delay, $t_{ud}$, which is the slide door fully open time.

Concentrations up to 2 g l$^{-1}$ should not create significant problems, although the short duration of the slide door to the column being fully open (about 4 seconds) will reduce the number of small, low settling velocity floes actually observed and therefore places greater reliance on the volume correction coefficients described in Chapter 5.

Data analysis techniques developed in Chapter 5 have improved understanding of the performance of INSSEV as well as providing valuable data on floc characteristics. The field trial programme collected many recordings of floes settling in the column, but only the most recent deployments are presented as these are considered valid for the generation of volume referenced spectra. Other tapes contain recordings of samples that are sometimes unstable, although the floes observed are typical of the time/space continuum. Some samples contained floes that settled past the camera, but were then observed rising several minutes later. Although these samples were unstable at some periods during the video-recording, the rising floes appeared to be due to buoyancy effects rather than turbulence. It is thought that this may be a similar process to that reported by Riebesell (1992) for marine aggregates observed off Helgoland in the German Bight (southern North Sea), who showed that the phenomenon was due to gas bubble generation, within the aggre-
gate, due to oxygen production. These INSSEV samples will be closely examined as part of the programme of the further work.
Chapter 5

Data Analysis

The principal aim of developing the INSSEV Instrument System was to be able to measure the size and settling velocity distributions of individual floes. This was achieved early in the programme. During the development of the instrument it was considered that, provided the INSSEV sampling procedure met certain criteria, the additional aim of processing individual floc data from each sample to obtain mass settling flux spectra of suspended matter, could be achieved. This chapter looks at the data analysis techniques that have been used to achieve these aims, together with observations on the limits of the system and analysis. The chapter follows the logical sequence of data analysis of one day's field deployment in the Tamar Estuary on Wednesday 17 March 1993. The results are discussed in Chapter 6.

The system is able to provide direct measurements of both the size and settling velocity of individual floes. These two parameters, by calculation, can then be used to obtain the effective density of each floc. When the individual floc data for a Sample Sequence is integrated, estimates for concentration and mass settling flux can be made.

5.1 Field Data Formats

These can be grouped under two main headings: INSSEV data and conventional estuarine Master Variable data.
5.1.1 INSSEV data

The INNSEV Instrument System generates two types of data, Floe Data and a record of the system operation which is called the Operating Data.

Floe Data

The Floe Data are the video-taped images of individual flocs settling in the column for each Sample Sequence. The image quality of the tapes is high and they can be processed manually, or with an image analysis unit. Appendix 3 is a listing of a program that has been developed for a Cambridge Instruments (Leica) Quantimet 570 image processor. The computer program operates with the video tape being played at normal speed. Frames are grabbed and processed to obtain individual floc size and screen position. The floc position data are then processed to obtain settling velocity. The manual method involves stopping the tape repeatedly to make the size and settling distance measurements of individual flocs, the Camera Control Unit (CCU) frame counter, which is encoded onto the video tape, providing the time base for converting distance fallen to settling velocity.

Sampling Time is the start of motorised flap door closure, that decelerates the water sample, at the beginning of the INSSEV Sample Sequence. When the flap doors are closed, a short interval (the turbulence decay time) occurs before the flocs enter into the top of the settling column. The fastest falling flocs normally arrive at the video camera axis (110 mm below the decelerator floor) within one minute and the video recordings continue for about thirty minutes.

Operating Data

The Operating Data set is relatively small, but important for subsequent processing of the floc data. It comprises information about the Sample Sequence, such as timing, instrument status, and Electromagnetic Current Meter (EMCM) component values. Figure 5.1 shows how the definitions of elapsed time, e, after the start of Sampling, are assembled. The use of several small fixed programmed delays is necessary to allow the relays to stabilise before further signals are propagated down the instrument control cable.
Table 5.1: Definitions of Time (in seconds) at beginning of INSSEV Sample Sequence.

<table>
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<th>Time Event</th>
<th>$kh$</th>
<th>$fs$</th>
<th>$ff$</th>
<th>$vz$</th>
<th>$so$</th>
<th>$sc$</th>
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<tr>
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<td></td>
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</tr>
<tr>
<td>Sample Hit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Time</td>
<td>$t_{fe}$</td>
<td>$t_{td}$</td>
<td>$t_{st}$</td>
<td>$t_{sd}$</td>
<td>$t_{st}$</td>
<td>$t_{sd}$</td>
</tr>
</tbody>
</table>

| Fixed Delays $t_{fd}$ | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Variable Delays $t_{vd}$ | 0.1 | 0.1 | 1.0 | 0.1 | 0.1 | 0.1 |

- **Travel Time for Flap Doors to close (start to finish)**
  \[ t_{fs-ff} = t_{fe} \]
  [see Equation 3.5]

- **Turbulence Decay Time**
  \[ t_{fd} \]

- **Travel Time of Slide Door operation**
  \[ t_{st} \]

- **Duration of Slide Door being fully open**
  \[ t_{sd} \]

- **Duration of Slide Door being open above Video Object Plane**
  \[ t_{so-sc} = 2.0 + t_{sd} + t_{st} \]

- **Time from Key Hit ($kh$) to:**
  - Physical Start of Sampling (start of flaps closing - $fs$)
    \[ t_{kh-fs} = 1.1 \]
  - Video Frame Zero ($vz$)
    \[ t_{kh-vz} = 3.4 + t_{fe} + t_{td} \]

- **Time from physical start of Sampling, $e_{zero}$ (start of flaps closing - $fs$) to:**
  - Video Frame Zero ($vz$)
    \[ e_{vz} = t_{fs-vz} = 2.3 + t_{fe} + t_{td} \]
  - Slide Open above Video Object Plane ($so$)
    \[ e_{so} = t_{fs-so} = 3.4 + t_{fe} + t_{td} + t_{st} \]
  - Slide Closed above Video Object Plane ($sc$)
    \[ e_{sc} = t_{fs-sc} = 5.4 + t_{fe} + t_{td} + t_{sd} + \frac{3t_{st}}{2} \]

†Fixed Delays provide time for electromagnetic relays to stabilise before motor pulses are propagated along control cable.

Figure 5.1: Definitions of Time (in seconds) at beginning of INSSEV Sample Sequence.
<table>
<thead>
<tr>
<th>Computer Variable</th>
<th>Equation Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEQ. TIME</td>
<td></td>
<td>Sample Sequence Number</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local Time</td>
</tr>
<tr>
<td>SPS d1 st d2</td>
<td>$t_{sc}$ $t_{sd}$</td>
<td>Flap door starting speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turbulence Decay time (duration)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slide Travel time (duration)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slide Fully Open time (duration)</td>
</tr>
<tr>
<td>xBEF yBEF</td>
<td>$(t_{fe})^\dagger$</td>
<td>$z$ and $y$ components from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electromagnetic Current Meter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>producing ambient current velocity</td>
</tr>
</tbody>
</table>

$^\dagger$see Equations 3.5 and 3.6 for evaluation of Flap Door Closure time duration, $t_{fe}$

Table 5.1: Operating Data Set.

During the Turbulence Decay Time the control computer sends this instrument status data plus the ambient current velocity, derived from the electromagnetic current meter, to the video recorder. This digital information is also saved to disk by the computer. Table 5.1 gives a summary of the digital values saved for each Sample Sequence together with the symbols used in equations.

5.1.2 Master Variable data

Master variables are measured every thirty minutes at half metre depth intervals so that a profile time series can be obtained at the same site as the INSSEV deployment. Salinity, temperature and suspended matter concentration are recorded in this way. Current velocity and direction are also recorded as a profile time series, because the INSSEV electromagnetic current meter only samples at 0.5 metres above the estuary bed. Water sample bottles are used to obtain filtered samples of SPM from the surface water, and at 0.5 metres above the bed. These filtered samples are accurately weighed on return to the laboratory, the results being used to calibrate the profile time series data and the INSSEV mass concentration results.

The master variable profile time series are contour plotted using programs developed by McCabe (1992). The results are displayed in Chapter 4.
5.2 Floc Size and Settling Velocity Distributions

These are presented as scattergraphs of the individual floc data. Figure 5.2 shows the results for 17 March. The size (horizontal diameter as seen by the camera) and settling velocity of individual flocs for each Sample Sequence are loaded into the spreadsheet (Quattro Pro 4.0). Scaling factors, obtained from the millimetre grid scale placed before the camera and recorded on every video tape, are applied to change screen dimensions into real dimensions. At this point the scattergraph could be produced and would show a similar pattern of data points to those in Figure 5.2, but the actual velocities would be too low. Two corrections have to be applied to the individual settling velocity values. First, they are all multiplied by 1.03 to compensate for drag induced by the inner walls of the settling column (Allen, 1975). Second, effective density in relation to the column water, \( \rho_{\text{effective}} \), (the difference between the floc bulk density and the column water density) is calculated, using the rearranged Stokes' equation

\[
\rho_{\text{effective}} = (\rho_f - \rho_{\text{column}}) = \frac{18\mu(w_{\text{column}} \times 1.03)}{D^2g} \tag{5.1}
\]

so that the difference in density, \( \rho_{\text{diff}} \), due to higher salinity in the settling column than the ambient salinity, can be added. This is derived from the International Equation of State for Seawater, 1980, using the temperature data from the master variable profiles.

\[
\rho_{\text{ambient}} = \rho_{\text{effective}} + \rho_{\text{diff}} \tag{5.2}
\]

The settling velocity is then recalculated using the Stokes' equation

\[
w_{\text{ambient}} = \frac{D^2\rho_{\text{ambient}}g}{18\mu} \tag{5.3}
\]

to obtain the Ambient Salinity Settling Velocity, which is always slightly higher (provided the Column Salinity is higher than the Ambient Salinity). It is the Ambient Salinity Settling Velocity value which is used in the scattergraphs (Figure 5.2), and in Section 5.3 where it is used exclusively for the settling velocity term, \( w_s \).

The diagonal lines on each scattergraph are lines of constant calculated effective
Figure 5.2: Size and Settling Velocity Scattergraphs for seven samples, Tamar Estuary, near Cotehele Chapel, 17 March 1993. Dashed and dotted lines show instrumentation limits.
density. They are produced with the standard Stokes' settling velocity equation for all flocs in the sample.

The widespread use of the Stokes' equation in this work is considered valid as Reynolds numbers for most flocs up to about 600 μm are less than unity. The use of the Oseen modification (Schlichting, 1968; Graf, 1971) is discussed in Chapter 6.

5.2.1 Instrumentation Limits

Figure 5.2(h) provides a legend for instrumentation limit lines used on scattergraphs (a) – (g) of the seven samples taken on 17 March 1993. Four lines are generated which enclose the data. Strictly, data points should not occur outside these boundaries. The fact that they do in all samples is due to turbulence, particularly in the decelerator. The degree to which this turbulence is affecting the flocs observed varies greatly across the seven samples. The four limit lines are produced as follows:

Maximum Settling Velocity

This is the Maximum Ambient Salinity Settling Velocity of each sample, \( w_{\text{MAX\cdotLIM}_{\text{amb}}} \). Because it is an ambient value it is the same across the size range. It is due to the faster falling particles settling to the floor of the decelerator before the slide door to the settling column is opened. It is obtained by dividing the height of the decelerator by the elapsed time, \( e_{so} \), which is from the start of the flap doors closing to when the slide door is open above the video camera object plane (Figure 5.1).

\[
w_{\text{MAX\cdotLIM}_{\text{amb}}} = \frac{100}{e_{so}} \quad (5.4)
\]

The value can be increased by reducing the turbulence decay time, \( t_{td} \), the programmed interval between flap doors closing and slide opening, but this may cause more residual turbulence transferring to the top of the settling column. Consequently, although more fast falling flocs may be observed, a greater proportion may be recorded above the limit line.
Minimum Settling Velocity

This is simply due to the duration of the video recording observation after the slide door to the settling column is open above the video camera object plane, \( t_{rec} \). The value calculated is the minimum column settling velocity, \( w_{\text{MIN-LIM}_{col}} \), because it is a calculation based upon the velocity of the slowest particle that could fall the 109 mm through the column salinity water to appear on the video image in the time of the video recording. In some cases this may be the time until the instrument is disturbed on the estuary bed, causing the water in the column to become unstable.

\[
 w_{\text{MIN-LIM}_{col}} = \frac{109}{t_{rec}} \tag{5.5}
\]

This minimum column settling velocity cannot be plotted as a horizontal line on the y-axis, because the scattergraph plots the ambient salinity settling velocity of the observed floes. In all the scattergraphs with a density difference the limit line is plotted as an ascending curve. This curve is generated by calculating an ambient salinity settling velocity value for all floes observed, using the following equation:

\[
 w_{\text{MIN-LIM}_{amb}} = \left( \frac{18\mu w_{\text{MIN-LIM}_{col}} \times 1.03}{D^2 g} + \rho_{\text{eff}} \right) \frac{D^2 \rho_{\text{eff}} g}{18\mu} \tag{5.6}
\]

\[
 = (w_{\text{MIN-LIM}_{col}} \times 1.03) + \frac{D^2 \rho_{\text{eff}} g}{18\mu} \tag{5.7}
\]

By definition, this line will always be above the Density Limit Line.

Floc Size Resolution

This is always 20 \( \mu m \). The detection level of the video system is in the region of 7 - 10 \( \mu m \) but the arbitrary figure of 20 was chosen to maintain the integrity of size measurements for smaller particles.

Density Limit

This is due to the settling column being charged with a higher salinity water than the ambient salinity of the estuary. It is plotted as a diagonal line on the scattergraphs in the same way as the calculated constant effective density lines, using the
density difference, $\rho_{diff}$, in the standard Stokes' settling velocity equation.

$$w_{st,lim} = \frac{D^2 \rho_{diff} g}{18 \mu}$$ (5.8)

Figure 5.2(d), Sample 4 on 17 March, did not have a density difference, so the limit does not apply and does not appear on the log scaled scattergraph.

5.2.2 Backtracking

Backtracking is a technique developed to check the validity of the individual floe data. It traces each floe back up the column into the decelerator using the individual settling velocity and elapsed time data. If the flocs can be shown to be within the vertical height of the decelerator just after sampling, and just before the slide door opens, then that indicates a low level of turbulence in the decelerator and upper parts of the column. This procedure is useful for assessing the validity of in situ floe size and the volume referenced spectra: SPM concentration and settling flux.

The Camera Control Unit frame counter, recorded onto the video tapes, provides a time base that gives every floe in the sample a unique time reference as it passes the camera axis (a horizontal plane in the middle of the video monitor). This time reference is converted to seconds, but retains the frame counter resolution of 0.04 second. It is modified by addition of the following Operating Data Set time variable

$$e_{oz} = t_{fz-oz} = 2.3 + t_{fc} + t_{id}$$ (5.9)

(see Figure 5.1 for definitions of symbols) to Elapsed Time since Sampling. The Column Settling Velocity (uncorrected) is used to calculate the time that a floe passed the level of the decelerator floor. This Decelerator Floor Time is then multiplied by the Ambient Salinity Settling Velocity to 'backtrack' the floe to its vertical positions at the time of sampling, the time of opening the slide door to the settling column, and the time of closing the slide door. These three positions are plotted in Figure 5.3.

A full statistical interpretation of this procedure has not been attempted, but Table 5.2 shows the percentages of flocs in each sample that have been 'backtracked'
Figure 5.3: 'Backtracked' vertical positions of individual flocs in Tamar Samples, 17 March 1993. Elapsed time is time since sampling.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Sample Sequences:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of flocs in 'correct' position at time of:</td>
<td></td>
<td>1  2  3  4  6  7  8</td>
</tr>
<tr>
<td>- Sampling ($e_{\text{zero}}$)</td>
<td>$Q_b^{\text{Sampling}}$</td>
<td>48  60  57  36  3  9  76</td>
</tr>
<tr>
<td>- Slide Open ($e_{\text{so}}$)</td>
<td>$Q_b^{\text{so}}$</td>
<td>48  70  43  36  4  13  62</td>
</tr>
<tr>
<td>- Slide Close ($e_{\text{sc}}$)</td>
<td>$Q_b^{\text{sc}}$</td>
<td>20  70  93 100 98 100 66</td>
</tr>
<tr>
<td>Mean Percentage</td>
<td>$\bar{Q}_b$</td>
<td>38  67  64  57 35 41 68</td>
</tr>
</tbody>
</table>

Table 5.2: 'Backtracking' Percentages.

to their 'correct' vertical position at the time of sampling, $e_{\text{zero}}$, slide open, $e_{\text{so}}$, and slide closed, $e_{\text{sc}}$ (see Figure 5.1 for definitions). This backtracking validity check may prove to be a valuable diagnostic tool for the instrument operation as well as a quality check on the raw floc data. Figure 6.3 in Chapter 6 shows the relationships between the percentage of flocs in the correct position, and various operating parameters and master variables. Generally the relationships do not show high levels of significance. The implications of all the validity checks for data quality and future instrument operation are discussed in Chapter 6.

During the fieldwork trials, however, more importance was placed upon the stability of the video images at all times during each sample sequence, as being the most effective method of ensuring the stability of the water in the column in the vicinity of the camera axis. This is determined by observing very small particles that are often neutrally buoyant. If any turbulence is present in the column these 'background' particles will move rapidly across the monitor screen at any angle. The most critical time for performing this visual check is when the slide door to the column is opened. There is nearly always a slight movement observable on the monitor but with a 'good' sample stability returns within a few seconds. Column stability was very good for all sample sequences in Figure 5.3. The presence of low density, fragile flocs in the samples was taken as encouraging evidence that residual turbulence was not a significant problem.
5.3 Size Banding of the Individual Floc Data

During the field trials of INSSEV, samples were taken at the same time as the In Situ Laser Particle Sizer developed at Plymouth Marine Laboratory (Bale and Morris, 1987). This is an adaptation of a Malvern Instruments' laser diffraction instrument which, for estuarine use, employs a 300 mm lens. This generates the size bands that have been used for the Size Band Histograms of INSSEV floc data in Figures 5.5, 5.6 and 5.7. This size band format was chosen for convenience because of ongoing intercalibration work with the Laser Particle Sizer. Initial intercalibration results are discussed in Chapter 6.

The lower size limit for INSSEV is 20 μm. In some of the histograms, extrapolation to the lower size fractions can be visualised, except when samples are bi-modal. For the estimates of concentration and particularly settling flux it is, as might be expected, the larger size bands that are the most significant, so the absence of INSSEV data in the lower size bands is less important.

The following sections detail the sequence of processing the floc data in spectral formats.

5.3.1 Dry Mass

The mass of Suspended Particulate Matter (SPM) can be calculated for each size band by totalling the dry mass of all recorded flocs. The total mass for each size band then requires a correction coefficient, $b_s$, because of the INSSEV mode of operation. The main INSSEV derived parameter used to obtain the dry mass is the Ambient Salinity Floe Effective Density, $\rho_e$. This is derived from Equations 5.1 and 5.2. The Stokes' Equation density notation is appropriate when dealing with single grains composed of single density matter and which have no interstitial water, eg. quartz spheres. For aggregates, in this case estuarine flocs, which may be composed of mineral and organic particulates as well as interstitial water, the definitions of density and effective density need to be more specific. For the remainder of this Chapter, the definitions listed in Table 5.3 will be used.

McCave (1975) provides a definition of the various components of Floc Density, which was used to obtain dry mass (the first term) of particle aggregates (flocs) in
The total volume of the floe, $V_{\text{tot}}$, or $V_f$, is defined as the volume of both the mineral, $V_m$, and organic, $V_o$, components of the SPM and the volume of the interstitial water, $V_w$. One of McCave’s implicit assumptions is that the density of floe interstitial water is the same as the density of the surrounding, or ambient, water. This assumption is retained in this work because of the length of time that floes are falling through the INSSEV settling column water, and will therefore adjust to the column salinity by diffusion. However, the modified subscript notation shown in Equation 5.11 recognises the potential existence of a difference by using $\rho_{iw}$ to represent floe interstitial water.

$$V_{mo}\rho_{mo} + V_w\rho_w = V_{\text{tot}}\rho_f$$  \hspace{1cm} (5.10)$$

McCave’s (1975) original subscript notation, $om$, for the dry matter volume and density have been reversed to acknowledge that in estuarine floes the mineral fraction of SPM is higher than the organic fraction. McCave made the generalisation that deep ocean aggregates had a 60:40 mineral:organic ratio, producing a mean dry density of 1591 $kg\ m^{-3}$. This was based upon the assumption that the mineral dry density was 2500 $kg\ m^{-3}$ and the organic dry density was 1030 $kg\ m^{-3}$. Calculation reveals that the 60:40 ratio was in fact a mass ratio, which translates into a volume ratio of 38:62, mineral to organic. Estuarine floes have typical mass ratios of 90:10, mineral to organic, which translates into a volume ratio of 78:22. This

| $\rho_e$ | Floc Effective Density derived from ambient settling velocity |
| $\rho_{pw}$ | Density of Water through which Floc is falling |
| $\rho_f$ | Floc Bulk Density ($\rho_e + \rho_{pw}$) |
| $\rho_m$ | Dry Density of Mineral Component of SPM |
| $\rho_o$ | Dry Density of Organic Component of SPM |
| $\rho_{mo}$ | Mean Dry Density of SPM – see Equation 5.12 |
| $\rho_{iw}$ | Density of Floc Interstitial Water, $\rho_{iw} = \rho_w$ unless otherwise stated |
| $\rho_{e,sp}$ | Mean Effective Density for solid (non-porous) aggregate ($\rho_{mo} - \rho_w$) |

Table 5.3: Density subscript symbols used in equations.
A typical example is based upon a mineral dry density of 2600 \( kg \ m^{-3} \) and an organic dry density of 1030 \( kg \ m^{-3} \), and results in a mean dry density, \( \rho_{mo} \), of 2256 \( kg \ m^{-3} \).

When mineral to organic ratios are known, such as those derived from loss on ashing during gravimetric analysis, the constituent volumes and densities can be calculated using the following mass equation.

\[
V_{mo}\rho_{mo} = V_{m}\rho_{m} + V_{o}\rho_{o}
\]  
(5.12)

Extending equation 5.11 gives the full floc mass equation.

\[
V_{m}\rho_{m} + V_{o}\rho_{o} + V_{iw}\rho_{iw} = V_{f}\rho_{f}
\]  
(5.13)

Although loss on ashing was not performed on the filtered samples collected on 17 March this paragraph is included here for completeness and to demonstrate that it is possible to divide the final settling flux totals and size band distributions into mineral and organic components.

An approximation of floc dry mass can be made by multiplying the Floc Effective Density by the floc volume. Because the Effective Density term, \( \rho_e \), is derived from the Stokes' Equation the volume is defined as spherical and therefore the dry mass estimate will take the following form.

\[
M_{dry, (approximation)} = \frac{\pi D^3 \rho_e}{6}
\]  
(5.14)

Although this is a reasonable approximation for low density flocs where the volume of floc interstitial water, \( V_{iw} \), is approaching the total floc volume, \( V_f \), it is not correct and becomes less accurate with increasing effective density. This is because Equation 5.14 uses \( \rho_e \), which is \( (\rho_f - \rho_w) \) in calculating dry mass, i.e. \( V_f\rho_f \) minus \( V_f\rho_w \), whereas the equation required is one that calculates the floc bulk mass minus the mass of interstitial water only, \( V_f\rho_f \) minus \( V_{iw}\rho_{iw} \) (see Table 5.3 for subscript definitions).

The error in Equation 5.14 is due to the fact that \( V_{iw} \) never equals \( V_f \) and decreases with increasing effective density. A more accurate calculation of floc dry mass can therefore be made by reducing the volume, and hence mass, of the water...
to be deducted. This can only be done with INSSEV data by estimating the volume ratio of SPM to interstitial water from the floc effective density. If flocs are highly consolidated aggregates, with hardly any interstitial water, then \( V_{iw} \) approaches zero. If they have an extremely low effective density, then \( V_{iw} \) approaches \( V_f \). Thus there is an inverse linear relationship between \( \rho_e \) over \( \rho_{en} \) and \( V_{iw} \) over \( V_f \), which can be used to define \( V_{iw} \). A value is required for \( \rho_{en} \), which is the difference between the mean dry density of mineral and organic components of the SPM, \( \rho_{mo} \), and the ambient water density, \( \rho_w \). In estuaries \( \rho_{mo} \) will range between about 2000 - 2600 \( \text{kg m}^{-3} \); 2256 \( \text{kg m}^{-3} \) has been used for the 17 March data. An accurate value for \( \rho_{mo} \) can be obtained from gravimetric analysis but the following equations are not very sensitive to the typical diurnal variation found in most estuaries.

\[
V_{iw} = (1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \frac{\pi D^3}{6}
\]  

(5.15)

At this point, floc porosity, \( P_f \), can be obtained by taking a ratio of the volume of floc interstitial water to total floc volume.

\[
P_f = \frac{V_{iw}}{V_f} \times 100
\]

(5.16)

\[
P_f = \frac{(1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \frac{\pi D^3}{6} \times 100}{(1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \times 100}
\]

(5.17)

\[
P_f = (1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \times 100
\]

(5.18)

Returning to the calculation of Floc Dry Mass, Equation 5.15 can be incorporated into a re-arranged Equation 5.11.

\[
M_{dry} = V_{mo} \rho_{mo}
\]

(5.19)

\[
= V_f \rho_f - V_{iw} \rho_{iw}
\]

(5.20)

\[
= \frac{\pi D^3}{6} \rho_f - (1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \frac{\pi D^3}{6} \rho_{iw}
\]

(5.21)

\[
= \frac{\pi D^3}{6} ((\rho_e + \rho_{iw}) - (1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)}) \rho_{iw})
\]

(5.22)

Taking \( \rho_{iw} \) to be the same as \( \rho_w \), the following equation is then solvable with
INSSEV and Master Variable data.

\[ M_{dry, f} = \frac{\pi D^3}{6} \left( \rho_e + \rho_w \right) - \left( 1 - \frac{\rho_e}{(\rho_{mo} - \rho_w)} \right) \rho_w \]  \hspace{1cm} (5.23)

\[ = \frac{\pi D^3 \rho_e \rho_{mo}}{6 (\rho_{mo} - \rho_w)} \]  \hspace{1cm} (5.24)

5.3.2 Concentration

To obtain the uncorrected dry mass of SPM for each size band requires the individual floc dry masses to be summed.

\[ M_{dry,s} = \Sigma_{ab} M_{dry, f} \]  \hspace{1cm} (5.25)

Before the summed value can be converted into a Concentration value, the nature of the INNSEV sampling system has to be evaluated so that the volume of water from which the flocs have been collected can be specified and appropriate correction coefficients applied.

Volume Correction

The representative volume of water from which the individual floc data have been obtained is termed the video object plane sample volume, \( V_{os} \). This notional volume is illustrated in Figure 5.4. However, it is difficult to quantify precisely due, in part, to the almost certain fact that there is at least a small amount of residual turbulence in the decelerator while the flocs are settling into the column, but mainly due to the imprecision in recognising the focal boundaries of the depth of field of the video camera (nominally 1 mm) whether the flocs are measured manually or with the image processor. The assumption made for the volume, \( V_{os} \), from which the sample of floc data originates is 400 mm\(^3\). This is derived from a practical screen width of 4 mm, the nominal 1 mm depth of field and the 100 mm height of the decelerator.

Even if all residual turbulence could be discounted, there are still two corrections that need to be made to the dry mass of flocs observed in each size band, \( M_{dry,s} \). Before the corrections can be evaluated the mean settling velocity of all the
individual flocs in each size band, \( w_{sb} \), has to be determined.

\[
w_{sb} = (\bar{w})_{sb} \tag{5.26}
\]

The first correction is due to the current velocity at the time of sampling, which determines the duration of the flap door closure, \( t_{fc} \), and the duration of the Turbulence Decay Time, \( t_{td} \). These two time intervals (see Figure 5.1 for definitions) cause a proportion of the settling flocs in any size band to reach the decelerator floor before reaching a position above the camera object plane, or settling on the slide door before it is opened. This is discussed in Chapter 3, resulting in Equation 3.4 (repeated below) defining the primary loss for any size band mean settling velocity.

\[
primary\ loss_{sb} = w_{sb}(t_{fc} + t_{td} + \frac{t_{st}}{2} + 3.4) \tag{5.27}
\]

The result has units of length, specifically height, in \( mm \) and can be visualised in Figure 5.4. Because the height of the decelerator is 100 \( mm \) the result can also be
expressed as a percentage loss.

The second correction is necessary because the slide door is closed after a time interval, $t_{sd}$, which is relatively short for the slower falling floes, and therefore a proportion of those falling down through the decelerator when the slide door opens will not reach the top of the column before the slide door closes. In order to evaluate this secondary loss a value is required for each size band to represent the remaining height of a notional column containing floes, within that size band, still in suspension, $h_{rem,b}$. This is obtained using the result from Equation 5.27.

$$h_{rem,b} = h_{decelerator} - primary\ loss_{sb}$$
$$= 100 - primary\ loss_{sb}$$

The calculation for secondary loss is only shown for explanatory purposes.

$$secondary\ loss_{sb} = \frac{h_{rem,b} - (t_{sd} + t_{st} + 2.0)}{h_{rem,b}} \times 100$$

$$= \frac{w_{sb} (\frac{h_{rem,b}}{w_{sb}} - (t_{sd} + t_{st} + 2.0)) \times 100}{h_{rem,b}}$$

Again, units are length in mm, but can be considered as a percentage loss from the 100 mm column height. The two variables, $t_{sd}$, slide fully open time, and $t_{st}$, slide travel time, are obtained from the Operating Data Set for each Sample Sequence (see Table 5.1). Clearly these losses vary significantly with settling velocity and the processing of data by size band is an effective method of correcting for the sampling characteristics of the Instrument.

The equation required for data processing is that of cumulative loss, and gives the same result as the sum of the primary and secondary losses.

$$cumulative\ loss_{sb} = w_{sb} (\frac{h_{rem,b}}{w_{sb}} - (t_{sd} + t_{st} + 2.0))$$

As before, units are length in mm, and can be considered as the percentage cumulative loss from the 100 mm column height.

The processing needs to be modified within a spreadsheet by ensuring that a 100% primary loss is recognised by an IF... THEN... ELSE condition in the correc-
tion coefficient equation. Such a condition will be due to one of the causes postulated in Section 5.3. For the volume corrected histograms produced in Figures 5.5 (right hand column), 5.6 and 5.7, if any flocs were recorded in a particular size band the largest percentage primary loss accepted was 70%. The equation, without the limiting check, to correct the total Dry Mass of SPM in each size band produces a coefficient, $b_{ab}$.

$$b_{ab} = \frac{100}{100 - w_{sab} \left( \frac{h_{max}}{w_{sab}} - (t_{ed} + t_{et} + 2.0) \right)}$$ (5.33)

The correction coefficients, $b_{ab}$, for each size band are applied to the totalled dry mass values of the recorded flocs in the size band, $M_{dry,ab}$, to obtain the Volume Corrected Dry Mass values of SPM within each Size Band, $M_{dry,cor}$:

$$M_{dry,cor} = M_{dry,ab} b_{ab}$$ (5.34)

Histograms of the two Dry Mass Size Band Distributions are presented in Figure 5.5.

This last section has described the development of the size band correction factor, $b_{ab}$, using the size band mean settling velocity, $w_{sab}$. This is because the data was being assembled for inter-comparison with a particle sizer whose output is always in discrete bands. A term, $b_f$, can be evaluated for every observed floc, based upon its own settling velocity. In this case each floc dry mass is ‘volume corrected’ and these individual floc data are then processed as required. The difference in the total dry mass calculated by the two methods is small, but the decision as to which method to use needs to be made early in the data analysis spreadsheet planning.

Unit Correction

The Volume Corrected Dry Mass values of SPM within each size band are strictly a size band concentration value of $kg$ per 400 $mm^3$. This value is transformed into the SI units $mg$ $l^{-1}$ by multiplying first by $10^6$, to change $kg$ into $mg$, then by $25 \times 10^3$, to increase the volume reference to $10^6$ $mm^3$ (one litre). Combining the two unit transformations results in a multiplication factor of $25 \times 10^8$ which is applied to the Volume Corrected Dry Mass values of SPM in each size band, to
Malvern Size Bands

<table>
<thead>
<tr>
<th>Malvern Size Band No.</th>
<th>Ranges (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.8 - 7.2</td>
</tr>
<tr>
<td>2</td>
<td>7.2 - 9.0</td>
</tr>
<tr>
<td>3</td>
<td>9.0 - 11.4</td>
</tr>
<tr>
<td>4</td>
<td>11.4 - 14.5</td>
</tr>
<tr>
<td>5</td>
<td>14.5 - 18.5</td>
</tr>
<tr>
<td>6</td>
<td>18.5 - 23.7</td>
</tr>
<tr>
<td>7</td>
<td>23.7 - 30.3</td>
</tr>
<tr>
<td>8</td>
<td>30.3 - 39.0</td>
</tr>
<tr>
<td>9</td>
<td>39.0 - 50.2</td>
</tr>
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<td>10</td>
<td>50.2 - 64.6</td>
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<tr>
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<td>84.3 - 112.8</td>
</tr>
<tr>
<td>13</td>
<td>112.8 - 160.4</td>
</tr>
<tr>
<td>14</td>
<td>160.4 - 261.6</td>
</tr>
<tr>
<td>15</td>
<td>261.6 - 564.0</td>
</tr>
<tr>
<td>16</td>
<td>&gt; 564.0</td>
</tr>
</tbody>
</table>

Figure 5.5: Histograms of Floc Dry Mass by Size Band, Tamar Samples, 17 March 1993.
Calibration of Total Concentration

Totalling the Concentration values for all the size bands gives the INSSEV Concentration, \(C_{\text{inssev}}\)

\[ C_{\text{inssev}} = \sum C_{ab} \]  

(5.36)

which can then be compared with the filtered sample concentration, \(C_{\text{filtered}}\), taken at the same time. Taking a ratio of the two independent results, \(C_{\text{inssev}}\) over \(C_{\text{filtered}}\), gives another measure, \(Q_c\), of the INSSEV system's data validity.

\[ Q_c = \frac{C_{\text{inssev}}}{C_{\text{filtered}}} \]  

(5.37)

Three of the seven samples processed for 17 March give \(Q_c \approx 1\). There is no reason why \(Q_c\) has been always greater than unity other than the difficulty in accurately defining the video object plane sample volume, \(V_o\). When \(Q_c\) is plotted against the main operating variables for the seven Sample Sequences (Figure 6.4 in Chapter 6) it is apparent that the clearest relationship is that with Relative Current Direction. This has implications for the way in which the instrument system is deployed rather than the generation of a further correction factor. The consequences of this validity check are discussed in Chapter 6.

Because of the difficulties of precision in determining the volume of water from which the sample flocs settle, \(V_o\), discussed earlier in this section, and the inherent problems of turbulence, it is not realistic to claim that the total concentration values for each Sample Sequence are absolute. However, the distribution across the size bands is more likely to be representative, so a percentage in size band is calculated:

\[ \%C_{\text{inssev},ab} = \frac{C_{\text{inssev},ab}}{C_{\text{inssev}}} \times 100 \]  

(5.38)

This INSSEV concentration percentage is then applied to the concentration value from the filtered sample \(C_{\text{filtered}}\) (taken at the same time as the INSSEV sample) in
the Master Variable Data Set, to obtain the absolute, or calibrated, concentration in each size band:

$$C_{\text{filtered}_{i,b}} = \frac{\%C_{\text{inssec}_{i,b}} \times C_{\text{filtered}}}{100}$$  \hspace{1cm} (5.39)

Histograms of Concentration by Size Band, derived from equations 5.35, 5.38 and 5.39 are presented in Figure 5.6.

The calibration technique described here assumes that INNSEV data includes the very small size fractions. Its lower limit of size resolution is 20\(\mu\)m and therefore a modification is required to take account of the mass of material not observed by INSSEV. How this is performed depends on the available other data. Chapter 6 describes methods employed when spectral data were available from a laser particle sizer and a settling tube.

### 5.3.3 Settling Flux

The settling velocity term used to calculate the settling flux values is the mean of all the individual floc settling velocities for the flocs recorded in each size band, \(w_{s,b}\), discussed in Section 5.3.2.

Settling flux for any given size band is the product of the size band mean settling velocity, \(w_{s,b}\), and the size band concentration, either \(C_{\text{inssec}_{i,b}}\) or \(C_{\text{filtered}_{i,b}}\). The latter is the recommended parameter, but if a filtered sample is not available the following equation will have to be employed which only uses INSSEV data.

$$F_{\text{inssec}_{i,b}} = w_{s,b} C_{\text{inssec}_{i,b}}$$ \hspace{1cm} (5.40)

Using a filtered sample to calibrate the INSSEV Concentration data permits use of the recommended equation.

$$F_{\text{filtered}_{i,b}} = w_{s,b} C_{\text{filtered}_{i,b}}$$ \hspace{1cm} (5.41)

The values generated from this equation are used to construct the histograms of settling flux size band distributions for 17 March shown in Figure 5.7. The total settling flux for any given sample sequence is the sum of the size band values, either
Figure 5.6: Histograms of Concentration by Size Band, Tamar Samples, 17 March 1993.
Figure 5.7: Mean Settling Velocity and Settling Flux by Size Band, Tamar Samples, 17 March 1993.
the non-preferred parameter:

\[ F_{tot_i} = \Sigma F_{inssev_{i,b}} \]  \hspace{1cm} (5.42)

which uses the uncalibrated INSSEV Concentration data; or the recommended parameter.

\[ F_{tot_{fi}} = \Sigma F_{filtered_{i,b}} \]  \hspace{1cm} (5.43)

which uses a total concentration value derived from a filtered sample to calibrate the INSSEV concentration spectrum. The last four equations produce flux values in \( mg/m^2/sec \), or \( mg \cdot m^{-2} \cdot s^{-1} \), without the need for a unit correction factor.

5.3.4 Size Banding Summary

Most of this chapter has dealt with the processing of raw INSSEV floe data into size band distribution, through to settling flux. One day's data can be contained within a single spreadsheet, thus simplifying the copying of equations. The data processing is carried out in the order of this chapter. Table 5.4 provides a summary of the symbols used in the size band analysis, presented in their logical order of calculation. It is possible to use the same procedures for analysing data in either Settling Velocity or Effective Density bands. All symbols in the equations then have the subscript \( wb \) or \( pb \) instead of \( sb \). The data from the Elbe Estuary discussed in Chapter 6 has been analysed in both size bands and settling velocity bands.

5.4 Sample Parameters

It is possible to generate many 'average' parameters of INSSEV sample data, and this is of value for comparison with other instrumentation, or where a simulation procedure is only able to accept a single value. This immediately removes any spectral information that has been obtained from the sample and therefore removes much of the importance of the INSSEV technique. Some single parameters are of value and can be considered valid. They are particularly valuable when correlating with other variables in the estuarine regime.
Table 5.4: Summary of symbols used in size banding calculations.

Mean Max 4

This is an abbreviation of: the arithmetic mean of the individual floc data of the four largest flocs in a sample. It can be calculated for size, settling velocity or effective density. The choice of the largest four flocs was arbitrary and constrained mainly by the fact that in the Tamar samples, obtained on 17 March, sample 1 had only 10 flocs, whereas sample 7 had 207. Therefore if a sub-population greater than 5 had been used to obtain ‘mean’ values there would have been the problem that the results would not have been representative of the upper fraction of the size distribution. Averaging less than 4 would present difficulties for the validity of the parameter. The justification for taking a mean at the upper end of the size distribution is that this part is less affected by the instrumentation and sampling limits imposed by INSSEV, and the spread of settling velocities (and effective densities) is generally at its smallest in this part of the size distribution (see Figure 5.2). Also, trend lines calculated for the size/settling velocity scattergraphs pass through, or very close to, the Mean Max 4 values. In terms of settling flux the main interest is...
in the characteristics of the largest floes. Mean max 4 parameters have been used in the discussion of the time series of floc characteristics in Tamar turbidity maximum on 17 March 1993.

**Sample Mean Effective Density**

This is obtained by dividing the total dry mass of all observed floes in a sample by their total Stokes' equivalent sphere volume, with the correction for the mass of the interstitial water, explained in Section 5.3.1 of this Chapter.

\[
\rho_{\text{sample}} = \frac{\Sigma M_{\text{dry},i}(\rho_{\text{mo}} - \rho_w)}{\Sigma V_i \rho_{\text{mo}}} \quad (5.44)
\]

The method produces a value dominated by the larger, and therefore lower density floes. A median value can be generated which will be higher. Many existing instruments assume a fixed effective density in their algorithms (Malvern Particle Sizer and Owen Tube), and the generation of this mean value from the INSSEV data allows intercomparison between instrumentation, such as the comparison with the Plymouth Marine Laboratory in situ Laser Particle sizer discussed in Chapter 6.

**Median Settling Velocity by Mass**

This parameter is generated solely for comparison with 'Owen Tube' type instruments which employ a bottom withdrawal method for the determination of a cumulative mass curve against settling velocity. The fiftieth percentile on the cumulative mass plot is taken as the Median Settling Velocity. INSSEV data can produce the same type of cumulative mass frequency curve by sorting the floc dry mass data in ascending order of individual floc settling velocity, then plotting the cumulative mass against settling velocity. This has been done for the one sample obtained on the Elbe Intercalibration Experiment 1993. The result is shown in Chapter 6.
Chapter 6

Discussion

This Chapter looks at four aspects of the development work with INSSEV:

1. Performance of the Instrument System,

2. Interpretation of the Tamar data for 17 March 1993,

3. Interpretation of the Elbe data for 11 June 1993,

4. The role of INSSEV in estuarine sediment dynamics research.

6.1 Instrument Performance

This section follows on from points raised in Chapter 3 and data analysis validity checks in Chapter 5.

6.1.1 Settling Velocity adjustment

Settling velocity data is increased by a factor of 1.03 to take account of the drag induced by the settling column walls (Allen, 1975). Allen’s equations are considered to be more relevant to this work than those of Lovell and Rose (1991) because they deal with individual particles rather than mass settling.

The Stokes’ relationship (Equation 2.1) has been used without use of any modification for higher inertia in the faster falling aggregates. Ten Brinke (1993), and others, recommend use of the Oseen Modification (Schlichting, 1968; Graf, 1971)
for particles with Reynolds Numbers between 0.5 and 5. The modification takes the form:

\[
\omega_s = \frac{D^2(\rho_f - \rho_w)g}{18\mu} \frac{1}{1 + \frac{3}{16} Re}
\]  

(6.1)

which, re-arranged for effective density, gives the following.

\[
\rho_{e_{\text{eff}}} = \frac{18\mu \omega_s D^2 g}{D^2 g} \left(1 + \frac{3}{16} Re\right)
\]  

(6.2)

The effect is to produce higher effective densities, than with the standard Stokes' form (Equation 2.1), for increasing Reynolds Numbers. This means a higher effective density as floc size or settling velocity increases, as shown in Figure 6.1 (scattergraphs A and B), because these two parameters are the main variables in the dimensionless Reynolds equation:

\[
Re = \frac{\rho_w \omega_s D}{\mu}
\]  

(6.3)

The others, fluid density, \(\rho_w\), and viscosity, \(\mu\), vary little in relative terms. Below \(Re = 0.1\) the effect of the modification is insignificant, but becomes important as \(Re\) approaches unity. The Reynolds Numbers for all the Tamar particles measured on 17 March 1993 is shown in Figure 6.2A. Two populations can be detected in this scattergraph, The high Reynolds Number population is composed of the high settling velocity single grains from samples 6 and 7 (Figure 6.2C) whose provenance is discussed in Section 6.2. Samples 1,2,3,4 and 8 (Figure 6.2B) contain only the low Reynolds Number population, all of which are taken as being flocs, because of their lower calculated effective densities. Only a few of these flocs, those larger than 300 \(\mu m\), fall within the recommended boundaries for use of the Oseen Modification. Figure 6.2C shows that the modification is appropriate for about half the observed mineral grain population, the particles larger than about 45 \(\mu m\). In both cases the boundaries should not be regarded as 'cut offs', rather that they mark the point where very slight differences in effective density can begin to be calculated.

Because INSSEV measures settling velocity directly it is only the calculated effective densities that are altered by use of the Oseen Modification. However, as effective density is used to calculate floc dry mass, the modification will affect
Figure 6.1: Calculated effective density comparisons, using pure Stokes' Equation and Stokes' with the Oseen Modification, for all Tamar Samples, 17 March 1993.
Figure 6.2: Reynolds Numbers for Tamar Samples, 17 March 1993.
estimates of concentration and settling flux. Settling flux determination is clearly dominated by larger, fast falling particles and as these are the ones affected by inertia modifications to the standard Stokes' equation, it will be valuable to study their magnitude effects. Since INSSEV measures both size and settling velocity directly, individual floc Reynolds Numbers can be produced for the Oseen Modification to be used. Future work, particularly studies at sites of changing water density with depth in the water column, will be able to investigate the effect of performing data analysis with, and without, the Oseen Modification.

### 6.1.2 Instrument Limits on the Sample Scattergraphs

These are displayed graphically in Figure 5.2 and explained in Section 5.2.1 (Chapter 5).

Particles observed above the Maximum Settling Velocity Limit in samples 6 and 7 are thought to be due to remaining turbulence in the decelerator, causing faster falling particles to have been prevented from settling to the floor until the slide door to the settling column had been opened. This is consistent with the 'backtracked' floc positions shown in Figure 5.3. The source of the turbulence may be either ambient or generated from the side wall of the decelerator entrance when the instrument is not aligned with the ambient flow direction. In some cases it may be a combination of both. Whereas the dye streaming tests showed that the INSSEV door closure sequence does not generate turbulence (when correctly aligned with the flow), it cannot remove ambient turbulence from the collected water sample, other than by allowing the turbulence to decay. Unfortunately it is not realistic to increase the Turbulence Decay Time above about 20 seconds as this would cause the Maximum Settling Velocity Limit Line to be even lower than 3 to 4 mm s\(^{-1}\) and would therefore prevent measurement of some of the floc population under investigation.

The flocs observed below the Minimum Settling Velocity Limit could be due to any, or a combination, of the following reasons.

1. They may be slow settling flocs from an earlier sample, still falling slowly through the upper section of the column, above the camera axis, when a new
sample is taken. This overlapping of sample recording could be the case for Samples 3, 4 and 7, (notice the time intervals, 29, 32 and 17 minutes respectively since the start of the previous sample) but not for Sample 6, because Samples 1 and 6 were the first samples taken with a new charge of filtered column water. Backtracking the individual flocs below the ‘minimum’ line in Samples 3, 4 and 7 indicates a strong possibility that they could have originated from the previous samples. For small low density flocs in particular, the problem of how rapidly the original interstitial water is replaced by the higher density water of the column has not been investigated. If the replacement takes tens of minutes rather seconds, then the risk of small flocs remaining high in the column between samples becomes greater. This increases the risk of sample overlap and reduces the accuracy of the ‘backtracking’ validity checks.

2. They may have broken off a larger floc at sometime during their passage down the column. Although this is likely in the more micro-turbulent regions of the decelerator, particularly when the slide door is operating, it is less likely as the flocs settle further into the stilled column. Disaggregation in the decelerator can be discounted as the observed very low settling velocity flocs would not arrive at the camera axis. Disaggregation within the stilled column is considered unlikely simply on the basis that no occurrences of floc breakup or aggregation have been observed in the many hours of recording, with one exception: a copepod was observed eating small flocs and spitting out pieces not required.

3. Turbulence from the decelerator may give some flocs an assisted passage down the upper section of the settling column when the slide door is first opened. The micro-turbulent characteristics of the slide door opening procedure has not been observed on the scale necessary to evaluate these type of phenomena, so this reason is quite possible. The backtracking evidence in the following section certainly supports this theory.

The main conclusions from the limit line checks are that undecayed turbulence from the ambient water conditions almost certainly causes the very high velocity
particles to be suspended long enough to gain entry to the column. This turbulence may also be causing some of the very slow settling flocs to be included in the sample, but there is a real possibility that sample overlap is responsible for occurrences of settling velocities well below the minimum line. Overlap can be avoided by increasing the time interval between successive samples or recharging with filtered water between samples. The latter is impractical due to the time required, but could be achieved by an in situ pumping system proposed in the last section of this Chapter. Increasing the interval between sampling is desirable and it is suggested that 50 minutes should be sufficient. This would mean that if any very slow material was observed, it would form an identifiable population on the size/settling velocity scattergraph. In terms of settling flux calculations these 'overlap' flocs are insignificant, even if they are unsightly on the scattergraphs. Partial digestion and regurgitation by aquatic organisms is not problematic because it is an in situ process.

For integrity of the floc data sets, the problem of particles above the maximum limit line, assumed to be due to turbulence, is more important than the problem of flocs below the minimum limit line.

6.1.3 Backtracking of individual flocs

This technique uses the observed floc data, time at camera and settling velocity, to backtrack each floc to its position at three time points in the INSSEV sampling sequence: the physical start of sampling; the moment that the slide door to the settling column is open above the camera object plane, and the moment it closes. These three time points are defined in Figure 5.1 and referred to in the following text and figures as sampling, slide open and slide close.

At sampling and slide open all flocs should be above the decelerator floor and below the decelerator ceiling. At slide close all flocs should be below the level of the decelerator floor. These are the definitions of 'correct' position. 'Backtracking' percentages are a measure of the flocs in the 'correct' position at the three time positions on the 'Backtracking' graphs in Figure 5.3. They are more fully explained in Chapter 5 where the Tamar values are displayed in Table 5.2. The samples used in these correlations are the seven from the Tamar, plus one from the Elbe.

Because the flocs have a higher settling velocity in the ambient water than they
do in the settling column water, due to the salinity difference, the backtracking calculations have to use the ambient salinity settling velocity when the individual floc is being backtracked in the decelerator, whereas the uncorrected column settling velocity is used to backtrack them up the column. These calculations make the assumption that the density interface occurs exactly at the level of the decelerator floor for the whole time that the slide door remains open, and that the pycnocline is infinitely thin. The calculations also assume that the floc interstitial water density is always identical to the density of the water through which the floc is falling. These assumptions are more problematic for lower density flocs and probably account for some of the discrepancies of the 'backtracking'.

Figure 5.3 is the main diagrammatic result of the 'backtracking' technique. Ideally, if there were no residual turbulence after sampling, no further floculation due to differential settling, no disturbance to flocs or the stability of the water when the door slide door opens and closes, and a stable interface between the ambient and column salinities, then all flocs would appear in their correct positions on the graphs in Figure 5.3 (boxes and plus signs within the decelerator and crosses below the decelerator floor). Clearly, this is not the case for all flocs in each sample.

Theoretically, low settling velocity flocs, on the right hand side of each graph (Fig.5.3), are the most susceptible to any disturbance in the water and this can be seen in all seven graphs. Table 5.2 shows that generally a higher percentage of flocs in their 'correct' position is observed at slide close than at slide open or sampling. This is to be expected as the further back in time the 'backtracking' is taken the more chance of events causing individual flocs to be out of their 'correct' position. An event that affects all observed flocs is their passage through the zone of water at the level of the slide door. Problems may arise in this zone from either negotiating the density interface or the action of the slide door, or both. Although a great deal of engineering design went into the current thin section slide door, it is thought that the horizontal sliding action is probably causing local disturbance to the water at the position of the salinity interface. It is suggested that the slide door travel time, $t_{sd}$, be increased from 2 seconds to possibly 10 seconds, to investigate whether this has any effect on the 'backtracking' results. However, any such variation must also take account of the delay before flocs are able to enter the column, the turbulence
decay time, $t_{td}$, because of the problem of premature settling onto the top of the slide door by the faster falling flocs.

The irregularities on the left hand side of the graphs, associated with the flocs that arrive at the camera within the first few minutes, are almost all due to residual turbulence within the decelerator after sampling. It is apparent that even small amounts of residual turbulence inhibit floc settling and this can be seen in some of the early, high settling velocity flocs positioned well above the decelerator ceiling. Backtracking calculations assume that flocs are always falling when, in fact, they could be kept in suspension by residual turbulence. In Figure 5.3, sequences 6 and 7 present much less irregularity for flocs that arrive at the camera after the slide door has closed, indicating that residual turbulence was present in the decelerator.

The cause of residual turbulence is difficult to attribute. From the dye streaming experiments, conducted to set the closure speed of the flap doors, it is assumed that the sampling sequence does not create additional turbulence. If that assumption is accepted, it leaves the following:

- vertical axis eddy shedding from the side wall when the decelerator has not been completely aligned with the current direction at the time of sampling, and

- ambient turbulence in the estuary water.

Fortunately, these two problems can be quantified. First the relative current direction is obtained continuously from the $x-$ and $y-$axes of the EMCM. Second the current shear, or turbulent intensity, are obtained from the current velocity profiles, or the EMCM, respectively.

Figure 6.3 shows some of the 'backtracking' percentages (Table 5.2) against operating parameters and master variables that have the highest correlation coefficients. Many of the correlation coefficients produced from the linear regressions are well below 0.5. Only those demonstrating significance, and therefore a possible causal link, are presented in Figure 6.3. Generally, higher correlation coefficients are obtained when the mean of the three 'backtracking' percentages, $Q_b$, is tested against the operating parameters and master variables. Even these coefficients are not high, but when some of the variables are combined to simulate the probable
Figure 6.3: 'Backtracking' Percentages against significant Operating Parameters and Master Variables, with Correlation Coefficients. Tamar (1-4,6-8) and Elbe (E) samples.
residual turbulence in the decelerator the correlations increase.

In the following paragraphs the eight scattergraphs are referred to by their key capital letter. The first six, A - F, plot $\bar{Q}_b$ against variables; the bottom two, G and H, plot the $Q_b$ percentage at sampling. The latter should be the most sensitive to any form of residual turbulence because it is a measure of the longest 'backtracking'.

Graph A is one of the highest correlation coefficients, 0.6. The significance of this result is interesting, because it suggests that the higher the current velocity, the greater the percentage of flocs in their correct positions. This correlation needs further sample data to test whether it is sustained.

A weak relationship is shown with $Q_i$ and Relative Current Direction (graph B), indicating that higher percentages are generally obtained when INSSEV is aligned with the ambient flow.

A slightly stronger relationship, $r^2 = 0.35$ for $\bar{Q}_b$ is shown in graph C where it is plotted against the slide fully open time, $t_{sd}$. The indication is that the longer the slide remains open the greater the opportunity for any turbulence to affect the upper part of the settling column. This line of investigation is pursued in graphs D to F by testing the relationship of $\bar{Q}_b$ with combinations of turbulence parameters and the slide fully open time. The reasoning for the investigation is that the magnitude of the residual turbulence, from whatever sources, multiplied by the slide open time should represent a measure of the disturbance to the upper part of the column. When correlation coefficients are computed for two sources of turbulence (graphs D and E), individually multiplied by slide open time, they are considerably higher, although not significant, for $\bar{Q}_b$ than with $Q_{b_{s\, sampling}}$. The method for calculating Misalignment Turbulence is explained in the following section. Graph F tests $\bar{Q}_b$ against total turbulence, the product of current shear and misalignment turbulence, multiplied by slide open time. Again the correlation is not significant, $r^2 = 0.45$, but these relationships represent the highest correlations for $\bar{Q}_b$.

The best relationships occur in the bottom two graphs, G and H. These are the tests for $Q_{b_{s\, sampling}}$ and represent the only ones to exceed 0.27. Graph G clearly provides support for the result in graph C, that the longer the slide door is left open the greater the transfer of turbulence to the upper part of the settling column. Graph H supports the line of investigation culminating in graph F.
It would be reasonable to conclude that the tests illustrated in graphs B to H provide an indication of how turbulence may be affecting the progress of individual flocs through the instrument, but coefficients are not particularly significant. Relationships have been identified, however, that may benefit from further analysis when further samples are available. The need for careful monitoring of current velocity, both at the instrument level and with regular through-depth profiles in essential in future deployments.

6.1.4 Concentration Ratios

This is another validity check using the ratio of INSSEV calculated SPM concentration over that derived from a filtered sample. It is the parameter $Q_c$, defined in Equation 5.37. INSSEV concentration is calculated by referencing the total floc dry mass, with corrections, to the notional video object plane sample volume which is defined in Chapter 5 and illustrated in Figure 5.4. For reasons explained in Chapter 5, it is unrealistic to expect $Q_c = 1$, but in ideal conditions it should be close to unity. It is assumed that a high value for $Q_c$ is indicative of turbulence continuing within the decelerator while the slide door is open. This is because additional SPM is brought to a position just above the open slide door, allowing it to fall into the column. Figure 6.4 shows $Q_c$ for the eight samples, seven from the Tamar and one from the Elbe, against operating parameters and master variables, together with correlation coefficients.

If $Q_c$ is indicative of continuing turbulence in the decelerator then investigation of the relationship with possible turbulence sources should confirm the assumption. As discussed in the two previous sections, the principal sources are considered to be ambient turbulence, and that generated from the side wall at the front of the decelerator if the instrument is not correctly aligned with the current flow. In any sample the degree of residual, or continuing turbulence, should be proportional to the product of the two sources. Both these are recorded: the first as current shear, and turbulent intensity; the second as relative current direction.

Current shear for the water column 1 metre above INSSEV is taken as the measurement for ambient turbulence. This agrees rather weakly ($r^2 = 0.35$) with turbulent intensity calculated from the EMCM data. A close correlation should not
Figure 6.4: Concentration Ratios against significant Operating Parameters and Master Variables; with Correlation Coefficients. Tamar (1–4, 6–8) and Elbe (E) samples.
be expected because current shear is a measure of turbulence in the vertical plane, whereas the two-axis EMCM is measuring fluctuations in the horizontal plane.

The instrument generated turbulence is quantified by taking the Sine of the relative current direction multiplied by the current velocity. This parameter is termed the Misalignment Turbulence. The product of current shear and the misalignment turbulence are termed the Total Turbulence. The relationship of $Q_c$ with total turbulence is shown in Figure 6.4E. The higher the total turbulence parameter, the longer it will take to decay. To obtain a measure of how much additional SPM can be swept into the column by the total turbulence requires the duration of the slide door being open to be included. This is done by calculating the product of total turbulence and the slide fully open time, $t_{sd}$. Figure 6.4F shows the relationship of $Q_c$ with this time referenced turbulence parameter. The correlation coefficient of 0.91 for the log-linear relationship is highly significant. $Q_c$ was correlated with all other possible combinations of turbulence parameters, multiplied by the slide fully open time. Coefficients ranged between 0.73 and 0.90. Coefficients derived when $\log_{10}Q_c$ was correlated, ranged between 0.68 and 0.86. The consistently significant relationship between $Q_c$ and turbulence is an important result from these validity checks. Together with the clear relationship found between effective density and current shear, discussed in the next section, and the concluding remarks for the 'backtracking' technique, in the previous section, the importance of obtaining through-depth current velocity profiles and high frequency current velocity component measurements, at the sampling level of INSSEV, is clearly demonstrated.

Looking at relationships for $Q_c$ with other instrument operating parameters, there is an interesting correlation with water density difference (Figure 6.4G), suggesting that provided turbulence is not excessive (i.e. leave out samples 6 and 7 from the Tamar) there is some evidence that $Q_c$ approaches unity if the density difference is not too great. This suggests that although creating a large density contrast in the settling column may assist with turbulence damping, and help to reduce visible movement on the video monitor, it may not necessarily improve the integrity of the sample. This lends support to the recommendation that turbulence should be avoided whenever possible. Correct alignment of the instrument with prevailing current direction is the most important operational consideration, as demonstrated
in Figure 6.4B when samples 6 and 7 (the high ambient turbulence samples) are removed from the regression, and this is supported by Figure 6.4F.

The relationship with current velocity (Figure 6.4C) is shown because it generates a very low correlation coefficient, when all samples are included. This could be taken as encouraging evidence that the rate of door closure, empirically derived from the dye-streaming experiments, is effective. Indeed, if samples 1, 6 and 7 are removed from the regression analysis, the remaining 5 samples indicate only a very small increase in $Q_e$ with increasing current velocity. This regression analysis with only 5 observations, producing a coefficient of 0.71 and relatively small slope, is not sufficient evidence to alter the relationship of flap door closure speed with current velocity (Equation 3.5). It is, however, worthy of re-investigation when a larger number of stable samples have been analysed, particularly as it contradicts the relationship established between $Q_b$ and current velocity (Figure 6.3A) in the previous section.

On the basis of correlation coefficients, it appears that $Q_e$ may offer greater opportunities for evaluating the instrument's *modus operandi* and data quality than 'backtracking'. The use of concentration ratios for validity checks is highly recommended and places additional emphasis on the obtaining of a filtered sample from as close to INSSEV as possible whenever a sample sequence is initiated.

### 6.2 Tamar Data for 17 March 1993

The aim of this fieldwork was to gather several samples during part of the tidal cycle at a location where the advance and retreat of the turbidity maximum would be observed. These floc data are presented in Chapter 5 using the data analysis techniques developed for INSSEV video-recordings.

Of the eight samples obtained in this experiment seven were stable in the column and these are the data produced here (sample 5 taken at HW+0.10 was unstable and found to have a negative salinity contrast; no reliable settling velocity data could be obtained).
6.2.1 Time series variations during the tidal cycle

It should be noted that this time series represents events, in an Eulerian frame, during the advance and erosion of the turbidity maximum.

Results

The main interest is in the variation of the large, high settling velocity floes over the tide, as these are likely to govern the mass flux towards the bed (Eisma et al., 1991b). In order to provide representative single parameters, for comparative purposes, the four largest floes of each INSSEV sample were taken to provide a mean value (referred to as 'Mean Max 4' in Chapter 5) of size, settling velocity and effective density. This method is less valid for the mean size parameter due to large differences in floc numbers and the possibility that the INSSEV sampling procedure may not be always bringing the largest flocs before the camera. The method is much more valid for settling velocity and effective density as these data show temporal variability (Figure 5.2) and the sampling procedure is not considered to alter these characteristics. Figure 6.5 shows, as a time series, the three 'Mean Max 4' parameters together with Median Settling Velocity and the Sample Mean Effective Density. Mean size produces the least variation in magnitude but the settling velocity and effective density parameters show similar significant variations, particularly before high water. The very close correspondence between the two methods for determining settling velocity is very marked, particularly before high water. The correspondence for the two methods of determining effective density is again very marked before high water, but does not exist after high water. By whichever method a single parameter settling velocity is determined there is a closer correspondence with effective density than with size.

Figure 6.6 shows the relationship, over time, between mean settling velocity of the four largest flocs in each sample with SPM, salinity and current velocity. Each of these three graphs shows just the surface and near bed time series for the master variable, although profile data were obtained at 0.5 m vertical intervals. The relationship of mean settling velocity with salinity is inconclusive, but significant with SPM and current velocity until high water.
Figure 6.5: Time series of single parameters, Tamar Estuary, 17 March 1993.

Figure 6.7 shows the relationship, again as a time series, of mean effective density with current shear measured over the total water depth and in the layer of water one metre above INSSEV. There is a strong correspondence between the density variation and current shear, indicating the controlling influence of turbulence on floc structure.

Figure 6.8 is a time series of INSSEV calculated total settling flux, $F_{tot,4}$; settling flux derived from the product of SPM and INSSEV median settling velocity; SPM; and 'Mean Max 4' settling velocity and effective density. The single parameter for settling flux is the term $F_{tot,4}$, the total of the size band settling flux calculations. As such it is more sensitive to the effective density spectrum of each floc sample than the product of SPM concentration and the single parameter median settling velocity. There is relatively good agreement between these two trends, but the same would not be true if the median settling velocity term was obtained from an 'Owen Tube'. There is agreement between SPM and the flux trends up to High Water, then considerable divergence, at similar times to the changes in effective density of the four largest flocs.
Figure 6.6: Time Series of Mean Settling Velocity of four largest flocs in each sample, and Master Variables. Dotted lines represent surface values; solid lines represent 0.5 m above bed.
Figure 6.7: Time series of Mean Effective Density of the four largest flocs in each sample (■) and Current Shear. Full depth shear shown by dotted line; one metre above INSSEV by solid line.

Figure 6.8: Time series of settling flux and other variables. Dashed parts of settling flux lines are inferred.
Discussion

The master variable data (Figure 6.6) obtained in this study indicates three flow phases: declining surface flood resulting in declining current shear in the upper part of the water column; apparent high water slack tide but with slow salt wedge intrusion continuing in the near bed region; and surface ebb flow where increasing current velocity over a near stationary salt intrusion is responsible for high current shear at the freshwater-saltwater interface.

Of the three master variables plotted in Figure 6.6, salinity, graph (b), shows the least significant relationship with the mean settling velocity of the four largest flocs in each sample, although the density gradient produced by the salinity stratification is clearly associated with the high current shear produced along the saline interface. Although salinity is known to exert controls over the physical processes of flocculation (Gibbs, 1983; Al Ani et al., 1991), other studies have shown the importance of organic coatings and other factors on the properties of the particle surfaces (Hunter and Liss, 1982; Van Leussen, 1988).

The SPM graph, (a), shows a similarity to current velocity, (c). Before high water, when the suspended matter concentration was slightly higher at the bed than the surface, both surface and bed suspended matter concentrations lagged behind the current velocity, probably due to the time required for the higher settling velocity material to settle out of the water column. After high water the surface SPM appeared to respond quite quickly to the increasing ebb current, but this response will have been due to resuspension where the freshwater current was in contact with the bed, upstream of the deployment site and of the salt intrusion. The ebbing bed current at the deployment location was delayed by nearly two and half hours due to the presence of the salt intrusion. However the rise in SPM near the bed did not occur until the bed velocity increase. Consequently, the population of particles near the bed over the period following high water was derived by vertical settling.

Before high water the mean settling velocity of the four largest flocs in each sample appears to show a relationship with the surface and bed SPM time series. After high water, although the mean settling velocity of the four largest flocs was
reflected in increasing suspended matter concentration, the concentration continued to rise during the middle of the ebb tide, whereas the mean settling velocity dropped back to the pre high water values. This suggests that although SPM may have a controlling influence on floc settling velocity during times of decreasing turbulence, its effect during times of strong velocity shear is reduced.

It was evident that samples 6 and 7 were taken when the interface, and the zone of high current shear, was above the instrument, and flocs had settled through this zone. Sample 8 was taken when the salt interface had eroded to below the sampling height. The size and settling velocity distributions in sample 8 (HW+3.12) then returned to pre high water patterns (Figure 5.2). It is suggested that the presence of lower density flocs in sample 8 (Figure 6.7) is due to these flocs settling only through the freshwater and not the freshwater-saltwater interface, at least to within half a metre above the estuary bed, and therefore able to retain their fragile structure. Flocs in samples 6 and 7, however, probably experienced considerable break-up because they had settled through the turbulent freshwater-saltwater interface.

The variations in calculated effective density, particularly the absence of very low density flocs in samples 6 and 7 (Figure 5.2) is particularly marked. This strongly suggests that the velocity shear, and consequent turbulence, during the period following high water is responsible for the break up of larger, lower density aggregations into their constituent primary particles and microflocs. Figure 6.7, the time series of mean effective density of the the four largest flocs in each sample with current shear, shows a stronger correspondence than either settling velocity or floc size, and the strongest correspondence with any of the measured master variables. Figure 6.9 shows this relationship and the results of linear regression. This scattergraph includes a plot for the Elbe sample, discussed in Section 6.3 of this Chapter. Although the highest correlation coefficient is only 0.56 it is considerably higher than any other regression analyses of floc characteristics with master variables. Removing Tamar sample 1 from the regression increases $r^2$. This was the sample taken when INSSEV was not correctly aligned with the ambient current flow. In addition, hysteresis may prevent higher correlations. How long does it take an increase in current shear to convert a fragile low density floc population to a higher density? Although Al Ani et al. (1991) has studied this problem in laboratory conditions, no
in situ data is yet available. If further experiments show the relationship between effective density and current shear to be sustained, it offers considerable possibilities for the improved performance of cohesive sediment transport modelling. The Tamar and Elbe results from INSSEV are consistent with those of van Leussen (1994) using another type of in situ video system, discussed in Section 6.4 of this Chapter.

The very high individual settling velocities plotted for samples 6 and 7 were interesting, particularly when effective density values were calculated to be in excess of 10,000 kg m\(^{-3}\) (a spherical quartz particle has an effective density of about 1,600). Microscopic examination of filtered samples of suspended material from the near bed region at the same time showed the particles to be heavy minerals such as tourmaline and hornblende. They occurred as rod-like crystals with a length to diameter ratio of up to 10:1. Particle shape data from the video tape analysis also confirm that many of the fast falling small particles were rod-like and settling with their long axis in a vertical orientation. Consequently, particularly with the smaller sizes, the very high calculated effective densities in samples 6 and 7 (Figure 5.2), need to be corrected for non-sphericity. These particles would seem to be
constituents of the larger flocs at other times during the tidal cycle.

Previous studies of the turbidity maximum at the same location in the Tamar (McCabe et al., 1992) have shown similar variation, by weight, in the floc size distribution over the neap tide high water. They show that during the period following high water, floc size distribution is compatible with the concept of flocs being disrupted in the shear at the freshwater-saltwater interface. Because INSSEV data provides size, settling velocity and effective density for individual flocs, when the through depth water density variation is known at the time the sample is obtained, changes in settling velocities as flocs settle through stratified regions can be estimated. Where the vertical rate of erosion of the freshwater-saltwater interface is close to the settling velocities of the flocs such calculations will indicate whether flocs will achieve neutral buoyancy, and therefore risk break up as they are suspended in the high shear zone, or whether they will continue to settle. This change in settling velocities is very important for very low density flocs, but almost insignificant for primary mineral particles and higher density flocs, such as those identified in samples six and seven. Changes in salinity for these would make virtually no difference at all to their settling velocity.

The ability to observe settling velocity as well as size of individual flocs, enabling effective density to be estimated, allows causal factors to be more strongly confirmed. It would appear that the large variations in floc effective density observed in this study are more significant than the small variations in maximum floc size, since the floc density spectrum is an important determinant in the mass settling flux.

Conclusions

Because salinity determines water density it is important for the adjustment of settling velocity when stratification is present, but the effect of changes in salinity for floc growth and eventual size is inconclusive.

Although SPM concentration in this study was relatively low for a neap tide, even for the Tamar, declining concentration during the period leading up to high water slack was reflected in both floc settling velocity and effective density. This relationship was not sustained after high water when increasing current velocity
and current shear appear to be more significant.

From the results presented, changes in floc effective density are more significant than changes in floc size distribution in controlling settling velocity. Current velocity shear appears to be the greatest influence on floc effective density, and consequently upon settling velocity and settling flux. Time series current velocity profiles offer the opportunity of tracking regions of high current shear which appear to be destructive of lower density flocs and therefore exercise a controlling influence on flocculation processes.

Data on individual flocs obtained with INSSEV are able to portray important changes in the characteristics of floc populations across major changes in the estuary velocity and salinity regime. Although the maximum floc size did not vary greatly, the mean settling velocity of the larger flocs showed significant variation during the tidal cycle due to large changes in floc effective density. It is these changes in effective density that probably offer the most promising area for future investigation, and support the claim by Dyer (1989) that floc characteristics are controlled by the turbulent microscale resulting from shear stress.

6.2.2 Intercomparison with Laser Particle Sizer

This has been undertaken on INSSEV Sample 2 (HW-1.23). The *in situ* Malvern Laser Particle Sizer (Bale and Morris, 1987) was deployed alongside INSSEV throughout the day, but owing to optical difficulties this was the most appropriate sample to use for comparative purposes. The sample times were identical, to with a few seconds. Figure 6.10 shows the size band results. The top histogram has been truncated below the INSSEV size threshold of 20 $\mu$m to produce the middle histogram; percentages are proportionately increased but the distribution in bands 6 - 15 is the same. The INNSEV histogram does not register any concentration in bands 6 - 9 but this is probably due to the small size of the observed population, or the minimum settling velocity limit. The shape characteristics are similar, but with INSSEV showing a slightly larger proportion of larger floc sizes. The absence of material in size band 11 of the INSSEV histogram is reflected in the distribution shape between bands 9 - 12 of the Particle Sizer.

With only one sample for comparison it is not valid to comment on the fact that
Figure 6.10: Comparison of INSSEV Percentage Concentration Distribution with similar output from *in situ* Malvern Laser Particle Sizer, Tamar Estuary, 17 March 1993.
INSSEV observes a higher proportion of larger flocs than the Particle Sizer.

6.3 Elbe Data for 11 June 1993

Due to damage to INSSEV described in Chapter 4, only one complete sample was obtained during this experiment. No time series results can therefore be presented, so this section looks at the results of an intercomparison with a settling tube deployed at the same time as INSSEV.

The data have been processed using the techniques described in Chapter 5, with an additional analysis using settling velocity bands. This second analysis was performed in order to compare INSSEV data with that derived from the University of Wales - Bangor (UWB) QUISSET Tube data. The QUISSET Tube (McCave, personal communication) is a development of the Owen Tube (Owen, 1970). This comparison forms part of the University of Plymouth contribution to the Elbe Intercalibration Experiment Workshop held in Reinbek, Hamburg on 20 March 1994. The full results of this workshop are to be published.

6.3.1 INSSEV Results

The size and settling velocity distributions are presented in Figure 6.11. All flocs in focus were measured. Column stability was good for the first 15 minutes of video-recording, but then the bed frame was disturbed. During the previous 6 minutes only two flocs were observed, the last nearly 3 minutes prior to the disturbance. This suggests that few, if any, low settling velocity flocs (less than 0.1 mm s\(^{-1}\)) were present in the sample.

Figure 6.12 shows histograms of concentration and settling flux produced with respect to Malvern size bands. The histograms on the left use individual floc effective density in the calculations, those on the right use the sample mean effective density. The variation in spectral shape illustrate the importance of using individual floc data, although the spectra produced for this sample are clearly dominated by particles over 261 \(\mu m\) (Size Bands 15 and 16), accounting for 89% of INSSEV observed settling flux. Extrapolating to the lower, unobserved, size bands is only likely to reduce this percentage to 88%.
Figure 6.11: Scattergraphs of Size and Settling Velocity, Elbe Estuary, 11 June 1993.
Figure 6.12: Concentration and Settling Flux Spectra, Elbe Estuary, 11 June 1993.
Figure 6.11 includes data on the height:width ratio of the INSSEV observed flocs, producing a mean ratio of 1.335 : 1. Other observations, mainly photographic, have shown that estuarine flocs are rarely spherical. Large flocs, particularly, can have very irregular shapes and are often joined into 'stringers' by threads of biological origin (Eisma, 1986; Fennessy et al., 1994a). However, Alldredge and Gotschalk (1988) found that organic aggregates whose shapes varied from spherical, including long 'comets', had values of a settling factor very similar to those of nearly spherical particles. Similarly, Gibbs (1985) showed that flocs from Chesapeake Bay had a mean height:width ratio of 1.6 : 1, giving a settling factor of 0.91. Thus, the spherical approximation and use of the Stokes' Equation, using the diameter normal to the direction of fall, would appear to be reasonable under most circumstances.

6.3.2 Intercomparison with QUISSET Sampling Tube

Unlike the Tamar deployments, a water bottle sample was not taken, so the total SPM concentration from the UWB QUISSET tubes has been used to estimate total SPM for the time/position. The absolute values of the GKSS contour plots shown in Figure 4.6 (assembled from transmissometer data) do not agree with UWB's total concentrations, but combining the latter's values with the trends shown by GKSS it seems reasonable to assume that total SPM at the INSSEV time/position was similar to the UWB QUISSET Tube, 1 metre above bed sample. However, in taking the UWB value of 291.6 mg l\(^{-1}\) to scale the INSSEV concentration data by settling velocity band we need to acknowledge that INSSEV can only measure particle size down to about 20 \(\mu m\), and for the Elbe sample the smallest size was 50 \(\mu m\). Figure 6.13 shows concentration by Settling Velocity bands for both INSSEV and the QUISSET tube. It is apparent that INSSEV data, processed into the same settling velocity bands, indicates a right shift from the UWB spectrum of about one order of magnitude. Applying this assumption to the concentration values in each of the UWB settling velocity bands, it has been assumed that INSSEV has not observed the first eight settling velocity bands of the QUISSET tube data. Therefore the concentration in these columns (51.7 mg l\(^{-1}\), about 18% of total) has been deducted from the UWB total of 291.6 mg l\(^{-1}\). The remaining 239.9 mg l\(^{-1}\) has been used as the absolute value upon which the four settling velocity bands
Figure 6.13: Concentration spectra with respect to settling velocity. Comparison of INSSEV and QUISSET data for Elbe sample, 11 June 1993.
observed by INSSEV have been scaled. The lower histogram in Figure 6.13 shows the INSSEV concentration, with respect to settling velocity, spectrum result scaled to absolute values by the UWB concentration, with respect to settling velocity, spectrum.

Although the INSSEV histogram is a composite of INSSEV and QUISSET data, the spectral shapes indicate that a higher proportion of SPM in the higher settling velocity bands is observed by INSSEV than by QUISSET. This suggests that QUISSET destroys the higher settling velocity flocs and consequently is destroying at least some of the larger sizes.

Conclusions

Although there were small differences in sampling time and sample elevation, these difference are offset by only small changes in the SPM time series profile. It is suggested that these results demonstrate a significant difference in measurement technique and support the claim (van Leussen, 1988) that sampling tubes probably destroy larger floc sizes.

6.4 The role of INSSEV in estuarine sediment dynamics research

This section looks at the present state of knowledge on floc settling velocity in estuarine sediment dynamics, and the contribution of the INSSEV Instrument System to future developments.

Since 1970, floc settling velocity has been determined mainly by ‘Owen Tube’ (Owen, 1970) type devices, discussed briefly in Chapter 2. Such instruments have traditionally generated a single parameter for floc settling, the median settling velocity. This is derived from the fiftieth percentile on a cumulative plot of percentage weight against settling velocity. The cumulative weight is obtained from the dry mass of sediment, filtered from aliquots of SPM which are taken from a bottom withdrawal tap at increasing time intervals after the sampling tube has been placed in the upright position. There is currently a debate among 'Owen Tube' users as to
whether it is more valid to use a 'mean' settling velocity rather than the median. It is also possible to present the filtered aliquot dry mass data as a concentration spectrum with respect to settling velocity, as shown in Section 6.3 of this Chapter (Figure 6.13). However, the validity of all parameters obtained from such instruments is strongly questioned because of the general criticisms of bottom withdrawal tubes, summarised by van Leussen (1988). The need to obtain more valid data on floc settling processes has been the principle motivation for in situ devices.

Much effort has focused on the nature of undisturbed flocculated material in estuaries during the last decade. Until recently the most important contribution has been in the form of in situ measurements of floc size. Two methods have been successful in producing data on floc size distributions: the photographic systems (principal among which have been Eisma et al., 1983, 1990); and laser particle sizers (Bale and Morris, 1987). These in situ floc sizing instruments are intended to eliminate the opportunities for floc disruption and re-flocculation, which alter the size and effective density spectra of the floc population. Whether any instrument can observe such small delicate structures without modifying them is difficult to substantiate unequivocally, but the fact that in situ systems produce different size distributions to those inferred from settling tube systems is clear evidence that sampling procedures modify results. In situ floc sizing systems claim that greater proportions of larger flocs (above about 250 μm) are detected, than with settling tubes deployed at the same time, and this is one reason why higher average settling velocity parameters are obtained. This has strengthened the case for in situ suspended particle studies which aim for minimal disruption of the fragile macrofloc structure. Mehta and Lott (1987) stressed the need for studies of both size and settling velocity of estuarine flocs; the two parameters enabling effective density to be calculated.

Video systems for the determination of individual floc settling velocity

There are now two proven systems that measure size and settling velocity of individual flocs in situ, INSSEV, the subject of this thesis, and VIS, Video In Situ, developed in The Netherlands (van Leussen and Cornelisse, 1993). Both systems use video to obtain images of flocs settling, the images being processed on return
from field deployment. Comparisons are listed in Table 6.1. Apart from technical differences in obtaining the video images, the most significant difference between the two systems is that INSSEV captures and decelerates a known volume of estuarine water and observes all floes above its limit of resolution (20 μm) from a representative proportion of the suspended sediment sample in a closed column, whereas VIS is continually moving with the body of estuarine water, allowing floes to fall into its settling tube apparently at random.

Because INSSEV obtains its floes from a known volume of water it enables calculation of the spectra of concentration and settling flux, in addition to producing size and settling velocity distributions. VIS is able to produce size and settling velocity distributions of its observed floes, but cannot claim to be able to produce spectra from a known volume, only that the floes observed may be typical of its Lagrangian track. To what extent these randomly captured floes are typical is dependent on the characteristics of the top of the settling tube and how it interacts with the turbulence of the water below the scale at which the neutrally buoyant instrument responds.

INSSEV uses a water salinity in its closed column which is slightly higher than ambient, to assist column stability when the slide door is opened to allow floes to enter the top of the column. The salinities are carefully measured to make appropriate density corrections to the observed settling velocities (see Chapter 5). VIS observes its floes in the ambient salinity water and therefore requires no density cor-

<table>
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<th>Features</th>
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<th>VIS</th>
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<td>Lagrangian</td>
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<td>Deployment</td>
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<td></td>
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<tr>
<td>Sampling Height</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>Settling Column</td>
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</tr>
</tbody>
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Table 6.1: System Comparison.
Figure 6.14: Floe data comparison with VIS. Short diagonal indicates trend line of VIS data.

rection to its floe data; however, it sometimes requires corrections to the observed floe settling velocities due to the vertical oscillations in the open ended settling tube. INSSEV floe settling velocities are those of a non-turbulent regime, whereas those derived from VIS are of a pseudo non-turbulent regime.

Because of the differences in deployment, precise location intercomparison of INSSEV with VIS was not possible during the Elbe Intercalibration Experiment (June 1993), but from observations performed at similar times there was good agreement on maximum floe size and mean effective density as shown in Figure 6.14 (van Leussen, personal communication). The data produced by both systems on floe size and settling velocity distribution are already helping to explain some of the major changes noticeable within the tidal cycle, particularly the existence of large, high settling velocity flocs at high water slack (ten Brinke, 1993; van Leussen and Cornelisse, 1993; Fennessy et al., 1994b).

The different sampling modes - Eulerian (INSSEV) and Lagrangian (VIS) - each offer opportunities for specific research objectives. INSSEV has already shown its potential for observing changes in floe characteristics during the passage of
hydrodynamic features such as the freshwater-saltwater interface (Fennessy et al., 1994b). Conceptually VIS follows floc populations and is therefore better placed to consider floc disruption and formation.

According to the Stokes' relationship (Equation 2.1), individual floc settling velocity is a function of size and effective density. Recent results from the video systems have indicated that it is not sufficient to infer mass settling velocity from just floc size distributions, due to the wide variations in floc effective density. Turbulent characteristics have been shown to have significant controlling influences on floc effective density spectra, and it is likely that further work on seasonal variations will highlight the importance of considering organic content of flocs and other biological parameters, as co-determinants of effective density.

The greatest single contribution of in situ video systems to estuarine fine suspended sediment transport is likely to be the opportunity the floc data offer for the calculation of individual effective densities. Until now, this parameter has not been available from in situ observations and it is likely to provide useful information for the improved understanding of flocculation and break-up processes, not least the strong indication that effective density is controlled by current shear, as demonstrated in Figure 6.9.

Advantages of INSEEV

In addition to producing size and settling velocity distributions and enabling the calculation of effective density, INSEEV floc data can be processed in a number of ways. The data analysis techniques detailed in Chapter 5 describe how the floc data can be referenced to water volume, thereby allowing the spectra of concentration and settling flux to be calculated. This is the first instrument able to produce such spectra. Although total concentration and total settling flux can be obtained by relatively simple oceanographic procedures such as automatic water bottles and sediment traps (the use of the latter is problematic in high current velocities), until now the spectra of such parameters have been unknown. INSEEV spectral bandwidths can be selected, the resolution being proportional to the number of flocs in the sample. Spectra can be assembled with respect to size, settling velocity or effective density, thus enabling changes in floc characteristics with respect to
time to be studied. Examples of SPM concentration spectra with respect to floc size (Figure 6.10) and floc settling velocity (Figure 6.13) are presented in this Chapter in comparison with output from other types of instrument.

INSSEV settling velocity data are determined from observations which relate to a specific water density, that is determined mainly by salinity. Relating settling velocity to a known water density is particularly important for the low density flocs as these change their settling velocity significantly with small changes in estuarine water density. These density changes are often quite marked, with respect to height in the water column, in the vicinity of the freshwater saltwater interface, especially during the early ebb flow. This is the time in the tidal cycle, just after the high water slack, when large low density flocs are now known to be common. The INSSEV settling velocities should be considered as still water settling velocities, to which the turbulent characteristics of the estuary should be applied. This is because there will hardly ever be conditions within a natural estuary where current velocities will slacken long enough for all turbulence to decay so that small particles will be able to fall vertically at a constant velocity with respect to the estuary bed.

Mathematical models of estuarine sediment transport will benefit from INSSEV data for their vertical flux algorithms because the method of settling velocity determination means that they are free of turbulence effects, and they are related to a known water density. This allows models to apply turbulence parameters independently, and vary the settling velocities with depth changes in salinity. With the data available in spectral format, as opposed to just average values, modelling the effect on sediment fluxes, horizontal and vertical, of changes in floc population characteristics has been brought a step closer.

Because INSSEV spectra, and measures of central tendency, are assembled from individual floc data they are able to closely replicate the numerical techniques used for the instrumentation with which intercomparison is required. This is a valuable characteristic of the system for the validation of its data with existing and future instruments.

INSSEV is well placed to pursue the field investigations that are needed to improve understanding of cohesive suspended particulate matter flocculation characteristics.
Chapter 7

Conclusions

This Chapter is divided into three sections:

1. Floc characteristics in the turbidity maximum.

2. INNSEV performance against other instrumentation.

3. Recommendations for use of the present INSSEV system.

4. Suggested modifications to the INSSEV system to improve data integrity and ease of handling.

7.1 Floc characteristics in the turbidity maximum

Changes in effective density within the tidal cycle are more significant for variations in individual floc settling velocity and total settling flux than changes in floc size.

Turbulent characteristics appear to be exerting the greatest control over floc density structure, and, to a lesser extent, maximum floc size.

Floc settling velocity and total settling flux both show evidence of a relationship with SPM concentration during times of declining turbulent energy, approaching High Water slack, but this may be due to faster settling material falling out of the floc population. In times of increasing turbulent energy there is no relationship between floc settling velocity and SPM concentration.
7.2 INSEEV performance

The instrument system has shown that it is able to produce data from observations of individual floe size and settling velocity. When such data for a whole sample are processed, the means and trend lines agree well with earlier published studies of parameters produced by other techniques (McCave, 1984; van Leussen, 1994; ten Brinke, 1993).

INSSEV data sets are able to quantify other parameters not yet attainable with other systems; individual floe effective density and porosity; sample mean effective density and porosity; spectra of floe dry mass, concentration and settling flux with respect to size, settling velocity or effective density.

Intercomparison with other ‘Owen Tube’ type instrumentation has shown that INSSEV data produces higher settling velocities. This is possibly due to changes in the effective density spectrum caused by the ‘Owen Tube’ method of operation (van Leussen, 1988).

7.3 Recommendations for the use of INSEEV

Deployment in association with instrumentation recording master variables is essential for the interpretation of INSEEV results. SPM concentration and current velocity should be sampled at high frequency, at the instrument sampling height, and full-depth profile data should be made at a minimum of thirty minutes intervals. Full-depth temperature and salinity profiles should also be made every thirty minutes. Filtered sample SPM concentration data should be obtained from the same height and at the same time as every INSEEV sample.

The time between successive INSEEV samples should not be less than fifty minutes, and video recording of each sample should be at least thirty minutes.

A campaign of sampling should be undertaken with the Turbulent Decay Time in the instrument software reduced from 20 to 10 seconds, and the Slide Travel Time increased from 2 to 10 seconds. Depending on the success of such a campaign,
measured by validity checks described in Chapter 5 and evaluated in Chapter 6, other time combinations should be attempted.

Sampling should be avoided if the relative current direction exceeds 10 degrees. This requirement places a demand for careful setting of the 'zero offsets' on the EMCM.

Use in current velocities greater than 0.6 m s\(^{-1}\) should be avoided, and where water depths exceed 5 metres the maximum operating current velocity should be reduced by 0.05 m s\(^{-1}\) for every additional 2 metres depth, in order to reduce the effects of cable drag.

The settling column should be charged with filtered water with a positive salinity difference that will be within the range of 1 – 4 psu. Wherever possible the charging water should be refrigerated and attempts should be made to prevent the charged column from ambient heating prior to lowering into the estuary.

A 'dry' sampling sequence should be made at the beginning of each deployment day to spread the lubricant on the motor shaft 'O' Ring shaft seals.

### 7.4 Modifications to INNSEV instrument design

Attention should be paid to the design of suitable deployment frames, so that flow and vertical settling of SPM are unimpeded by the structural members or other instrumentation. Directional control of the frame on lowering, or remote control on the bed, should be given a high priority.

Dimensions should be retained for floc investigation in tidal estuaries, except that the camera axis could be raised by up to 40 mm. Use in low current velocities would benefit from major dimensional changes, which will need to be visually tested in a flume. These changes could include shortening the length of the decelerator and raising its height, but both of these have consequences for the closed flap door angle. Deep ocean deployment should consider some other form of primary chamber.
REFERENCES


Proceedings of Specialty Conference on Advances in Understanding of Coastal Sediment Processes, American Society of Civil Engineers, New York, pp.348-362.


Appendix 1

'MARINE GEOLOGY' Article

A reprint of:


will be found inside the back cover of this Thesis. It is referred to as 'Fennessy et al., 1994a' in the main text.
Appendix 2
Instrument Software

The program listing on the following 12 pages is written in BBC BASIC. This is a machine specific, interpretative form of BASIC stored in a Read Only Memory (ROM) integrated circuit.

To ensure correct screen spacing of messages and data when the program is running it is important that any specified spaces in the PRINT statements are produced correctly. Lines of dashes have been added in this listing to assist identification of PROCEDURES, which are structurally the same as subroutines. These should not appear in the executable listing. Indentation shows the various levels of FOR...NEXT and REPEAT...UNTIL loops. BBC BASIC accepts spaces used for indentation.

There is an assembly language routine called RAMP in the early part of the listing that controls one of the internal timers producing the square wave signals which operate the stepper motors.
10 REM "T3ELBE"
20 REM With Tiltcheck + auto: vel + vid
30 REM Mike Fennessy
50 REM up to 090693
60 REM *FX4,1 Disable 4,0 Reset Cursor Keys
70 REM *FX11,0 Disable 12,0 Reset AutoRepeat
80 REM *FX21,0 Flush Keyboard Buffer
90 REM *FX220,5 Ctrl/E to Esc 220,27 Reset Esc Key
110 ON ERROR GOTO 1310
120 DIM PROG 170
130 ?&FE62=&FF
140 ?&FE60=0
150 T1=6=FFE64
160 T1CH=FFE65
170 T1LL=FFE66
180 T1LH=FFE67
190 ACR=FFE68
200 IER=FFE6E
210 FOR I=0 TO 2 STEP 2: PROG
220 |OPTI
230 .RAMP
240 LDA #40: STA IER
250 LDA ACR: ORA #60: STA ACR
260 .STCNT
270 LDA 470: STA T1CL
280 LDA 471: STA T1CH
290 LDX 74
300 .ACCEL SEC
310 LDY 77
320 .AREV
330 LDA 470: SBC 472
340 STA 470: STA T1LL
350 LDA 471: SBC 473
360 STA 471: STA T1LH
370 CLC
380 JSR CHECK
390 DEY
400 BNE AREV
410 DEX
420 BNE ACCEL
430 LDY 75
440 .CONST
450 LDY 77
460 .CREV
470 LDA 470: STA T1LL
480 LDA 471: STA T1LH
490 JSR CHECK
500 DEY
510 BNE CREV
520 DEX
530 BNE CONST
540 LDX 76
550 ASL 72
560 ASL 72
570 .DECEL CLC
580 LDY 77
590 .DREV
600 LDA 470: ADC 472
610 STA 470: STA T1LL
620 LDA 471: ADC 473
630 STA 471: STA T1LH
640 JSR CHECK
650 DEY
660 BNE DREV

131
670 DEX
680 BNE DECEL
690 LDA #0:STA T1LL
700 LDA #0:STA T1LH
710 LDA #&C0:EOR ACR:STA ACR
720 RTS
730 .CHECK LDA #&40
740 BIT &FE6D
750 BEQ CHECK
760 LDA &FE64
770 RTS
780 }
790 NEXT
800 MODE7
810 *FX4,1
820 *FX220,5
825 key%=0
830 turbd%=20
835 aut$="off"
840 cfsps%=100
845 tin%=250000
850 tlc%=tin%/cfsps%
860 fplsus$=" CLOSED":fposus$="CLOSED "
870 splsus$=" CLOSED"
873 out$=""
875 angoff%=194:infsoff$=STR$(angoff%)
880 cfinc%=1
890 slidet%=2
900 sopen%=10
910 seq%=0
915 lseqts$="00:00:00":ltct$s="00:00:00":tg$s="00:00:00"
918 pitch%=0:mipi%=2250:piden%=12
920 roll%=0:mirl%=2070:roden%=12
922 lp%=0:lr%=0
924 lud$="":lps$=""
928 par%=0
930 menu%=0
935 haz%=0
937 fsr%=1:sr$=""
940 xoff%=1913:yoff%=1990
942 x%=xoff%:y%=yoff%
943 midx$=STR$(xoff%):midy$=STR$(yoff%)
944 vcal%=740:initvc3=STR$(vcal%)
950 *FX11,0
955 PROCsetup
960 PROCsite
970 PROCsettime("DATE/TIME ENTRY")
980 filename$="D"+dm$+h$+m$
990 IF log%=0 W=OPENOUT filename$
1000 CLS:PRINT TAB(1,15)"Switch ON power to Surface Electronics"
1010 PROCdelay(2)
1012 IF log%=0 W=OPENOUT filename$
1024 PROCdelay(2)
1020 REPEAT
1030 menu%=1
1040 PROChead
1050 PROCmain
1130 PROCinfo
1140 PROCclock
1150 IF key%=49 PROCsoption
1160 IF key%=50 PROCsampseq
1170 IF key%=51 PROCfreset
1180 IF key%=52 PROCadjust
1190 IF key%=53 PROCtiltchk

132
IF key%=54 PROCexitcheck
1195 IF key%=56 PROCvideo
1200 UNTIL key%=1
1310 *FX4,0
1320 *FX12,0
1330 *FX220,27
1340 MODE7
1350 IF log%=0 CLOSE#W
1360 IF NOT key%=1 REPORT:PRINT " Line No "; EOL
1370 PRINT:PRINT "You are now back in BASIC"
1380 END
1385 DEF PROCsetup
1387 PROChead
1388 PRINTTAB(5,4)" SETUP QUESTIONS ";
1389 PRINTTAB(7,8)"If 'Y' insert Data Disk first ";
1390 PRINTTAB(1,6)"Disk log this run ? Y/N ";
1391 PROCyn
1392 IF suq$="Y" log%=0 ELSE log%=1
1394 PRINTTAB(1,11)"Enter last sample number ? Y/N ";
1396 PROCyn:IF suq$="Y" INPUTTAB(23,13)"Enter digits "seq%;
1397 PROCn2s
1398 ENDPROC
1400 DEF PROCyn
1401 suq$=GETS
1402 IF suq$="Y" PRINT"YES" ELSE PRINT"NO"
1403 ENDPROC
1405 DEF PROCsettime(titles)
1410 nienu%=0
1415 REPEAT
1420 PROChead
1430 PRINTTAB(5,4);title$;CHR$(135)
1440 PRINTTAB(1,6)"You will be asked for:");
1450 PRINT:PRINT" Year (93,94,etc) ";
1460 PRINT" Month (1 to 12) ";
1470 PRINT" Day (1 to 31) ";
1480 PRINT" Hours (0 to 23) ";
1480 PRINT" Minutes (0 to 59) ";
1500 PRINT" Seconds (0 to 59) ";
1510 PRINT:PRINT" Press RETURN after each of the ";
1520 PRINT" six entries; the clock is set ";
1530 PRINT" when you press RETURN after ";
1540 PRINT" entering seconds. ";
1560 VDU23.1,1;0;0;0;
1570 PROCcheck(8,92,99):yr%=t%:yr$=t$
1580 PROCcheck(9,1,12):mn%=t%:mn$=t$
1590 PROCcheck(10,1,31):dm%=t%:dm$=t$
1600 PROCcheck(11,0,23):H%=t%:H$=t$
1610 PROCcheck(12,0,59):M%=t%:M$=t$
1620 PROCcheck(13,0,59):S%=t%:S$=t$
1630 TIME=H%*360000+M%*6000+S%*100
1634 cg$=H$+":"+M$+":"+S$
1636 dats$=dm$+"."+mn$+"."+yr$+
1640 VDU23,1,0;0;0;0;
1650 PRINTTAB(1,15)"Date Entered is ";CHR$(135)
1660 PRINT"Clock is now running - see top right ":PRINTSPC(36)
1670 PROCone2mnud9,"date/time")
1675 REPEAT
1680 PROCclock
1690 UNTIL key%=49 OR key%=50
1700 UNTIL key%=50
1710 ENDPROC
1720 DEF PROCclock
1730 REPEAT
1740 ©%t=&00002
1750 VDU23,1,0;0;0;0;
1760 key%=0
1770 *FX21,0
1780 s%=(TIME DIV 100) MOD 60
1790 m%=(TIME DIV 6000) MOD 60
1800 h%=(TIME DIV 360000) MOD 24
1810 IF h%<10 PRINTTAB(30,4)''0";h% ELSE PRINTTAB(30,4) h%
1820 IF m%<10 PRINTTAB(35,4)"0";m% ELSE PRINTTAB(35,4)":";m%
1830 IF par%=1 PROCpandr
1840 IF menu%=1 PROCemcm:IF par%=0 PROCfsens
1850 key%=INKEY(10)
1860 UNTIL key%>26 AND key%<58
1870 *FX21,0
1880 ©%=10
1890 ENDPROC

1900 DEF PROCsoption
1910 REPEAT
1920 menu%=0
1930 PROChead
1940 PRINTTAB(2,4) ;CHR$(134) /"SAMPLING OPTIONS MENU";CHR$(135)
1950 PROCsomenu
1960 PROCclock
1970 IF key%=49 PROCalter(6,"spcs",40,350):cfsp%-%t%:tcf%-%ln%/cfsp%$%
1980 IF key%=50 PROCalter(9,"",0,2):cfinc%-%t%
1990 IF key%=51 PROCalter(12,"secs",0,30):turbd%-%t%
2000 IF key%=52 PROCalter(15,"secs",2,20):slidet%-%t%
2010 IF key%=53 PROCalter(18,"secs",0,300):sopen%-%t%
2014 IF key%=54 aut$="off"
2016 IF key%=55 aut$="on 
2020 UNTIL key%>27
2030 key%-%0:*FX21,0
2040 ENDPROC

2042 DEF PROCmain
2044 PRINTTAB(8,4)CHR$(131) "MAIN MENU"CHR$(135)
2045 PRINT" 1. Sampling Options Menu";SCPC(14)
2046 PRINT" 2. Sampling Sequence autovel ":aut$
2047 PRINT" 3. Reset after sampling"SCPC(15)
2048 PRINT" 4. Adjustment Menu"SCPC(20)
2049 PRINT" 5. Check Tilt Sensors"SCPC(17)
2050 PRINT" 6. Exit to Basic 8. Video Text";
2052 IF haz%>0 PROCadvice ELSE PROCready
2055 ENDPROC

2060 DEF PROCsampseq
2080 IF fplsus$=" CLOSED" PROCabort("NOT RESET","press 3 to reset"):haz%=1:ENDPROC
2085 IF fsr%=1 AND flang%=45 PROCabort("FAILED","check flap door angle"):haz%=2:ENDPROC
2090 PROCtgrab
2100 IF aut$="on " PROCauto
2110 seq%-%seq%+1:PROCn2s
2120 PRINTTAB(0,14);CHR$(134);"This",CHR$(135);"Sampling Sequence No",CHR$(134);seq$;CHR$(131);tg$
2150 PROCmotor(&41,tlcf%,cfinc%,24,152,24,8,17,"CLOSING"," CLOSED")
2160 fplsus$=out$
2165 PROCdelay(l):PROCfsens:PROCfsens
2170 IF fsr%=l AND flag%=0 PROCabort("FAILED","check flap door angle"):haz%=3:seq%=seq%+1:PROCn2s:ENDPROC
2172 zcft%=TIME
2174 PROCvideo
2176 REPEAT UNTIL TIME>zcft%+turbd%*99
2178 PROCmain
2180 VDU
2190 PROCmotor(&03,tln%/200*slidet%,1,80,120,40,4,18,"OPENING"," OPEN ")
2200 splsus$=out$
2210 PROCdelay(sopen$)
2220 PROCmotor(&43,tln%/200*slidet%,1,80,120,40,4,18,"CLOSING"," CLOSED")
2230 splsus$=out$
2240 IF log%=0 PROCdisk
2250 1setq$=tg$
2260 ENDP d
2270 DEF PROCn2s
2272 IF seq%<10 seq$="0"+STRS(seq%) ELSE seq$=STRS(seq%)
2274 ENDP D
2280 DEF PROCdelay(secs)
2290 LOCAL now$
2300 now%=TIME
2310 REPEAT
2320 UNTIL TIME>now%+secs*99
2330 ENDP D
2340 DEF PROCmotor(bit%,tlatch%,inc%,accel%,const%,decel%,revs%,v%,
ing$,end$)
2350 REM bit &41=cf &03=of &43=cs &01=of
2360 !(&70=tlatch%
2370 !&72=inc%
2380 ?&74=accel%
2390 ?&75=const%
2400 ?&76=decel%
2410 ?&77=revs%
2420 IF outS$=" SCOUR " GOTO 2450
2430 2440 PROCdelay(.5)
2445 ?&FE60=bit%
2447 PROCdelay(.5)
2450 PRINTTAB(12,v%);ing$
2460 CALL RAMP
2468 PROCdelay(.5)
2469 IF end$=" SCOUR " GOTO 2480
2470 ?&FE60=bit%
2471 PROCdelay(.5)
2472 ?&FE60=0
2480 PRINTTAB(12,v%);end$
2490 out$=end$
2500 ENDP D
2510 DEF PROCdisk
2520 PRINT#W,seq$,tg$,cf,spst%,cfinc%,turbd%,slidet%,sopen%,xt%,y$
2530 PROCemcm:PROCemcm:PROCemcm
2540 PRINT#W,x%,y%
2550 PROCdelay(2)
2560 ENDP D
2580 DEF PROCadjust
2590 *FX 21,0
2600 CLS:PRINTTAB(16,10)"PASSWORD"
2620 pass$=INKEY$(300):PROCdelay(1)
2630 IF NOT (pass$="M") ENDPROC
2640 REPEAT
2650 menu%=1
2660 PROChead
2670 PRINTTAB(5,4);CHR$(134);"ADJUSTMENT MENU";CHR$(135);PRINT
2690 PRINT" 1. Flap Doors"
2700 PRINT" 2. Slide Door"
2710 PRINT" 3. Current Meter"
2720 PRINT" 4. Flap Sensor"
2730 PRINT" 5. Reset Date/Time"
2735 PROCesc("MAIN")
2740 PROCready
2750 PROCinfo
2760 PROCclock
2770 IF key%=49 PROCfdoors
2780 IF key%=50 PROCslidoor
2790 IF key%=51 PROCcm
2800 IF key%=52 PROCpotsfsadj
2805 IF key%=53 PROCsettime("RESET DATE/TIME")
2810 UNTIL key%=27
2820 *FX 21,0
2830 key%=0
2840 ENDPROC
2850 DEF PROChead
2860 CLS:PRINT
2880 PRINTCHR$(141);CHRS(157);CHR$(132);"INSSEV IN Situ SEttling Velocity"
2890 PRINTCHR$(141);CHRS(157);CHR$(132);"INSSEV IN Situ SEttling Velocity"
2910 PRINT:PRINT" ********••****•**••**•*•*";CHR$(131)
2920 ENDPROC
2930 DEF PROCwait
2940 PRINTTAB(0,12);CHR$(135);CHR$(157);CHR$(131);CHR$(132);"WAIT";
CHR$(137);"menu disabled until";CHR$(132);key%-48;
CHR$(129);"complete"
2950 PRINTTAB(15,5);CHR$(135);CHR$(157);CHR$(132);"CLOCK DISPLAY PAUSED"
2960 PRINTTAB(0,key%-43);CHR$(134)
2970 ENDPROC
2980 DEF PROCinfo
2990 PRINTTAB(1,14)"Last Sampling Sequence No";CHR$(134);seq$;
CHR$(131);lseq$;
3000 PRINTTAB(0,16)"ProgramLogic PositionSensor"
3010 PRINTTAB(0,17)CHR$(135);CHR$(157);CHR$(132)"Flaps";CHR$(133)
TAB(12);fplss$;
3020 PRINTTAB(10,18)CHR$(135);CHR$(157);CHR$(132)"Slide";
CHR$(133)TAB(12);splsus$STAB(29)CHR$(132)sr$s"active"
3022 @%=&000002
3024 PRINTTAB(1,19)"Pitch ",lp%;lud$;" Roll ",lr%;lp$s;" ";
CHR$(131);ltct$;
3025 @%=10
3026 PRINTTAB(1,20)"Cm X ";midx$STAB(23,20)"Y ";midy$;
3030 PRINTTAB(0,21)CHR$(135);CHR$(157);CHR$(132)
"Relative Current Velocity m/sec"
3040 PRINTTAB(0,22)CHR$(135);CHR$(157);CHR$(132)"Relative Current Direction"
3050 IF log$=0 PRINTTAB(1,23)"Data Filename ";filename$
ELSE PRINTTAB(1,23)"No Log"
3055 PRINTTAB(30,23)date$
3070 DEF PROCcheck(v%, lo%, hi%)
3080 PRINTTAB(0, v%); CHR$(134)
3090 INPUTTAB(24, v%); t%
3100 IF t% < lo% OR t% > hi% PROCsound: PRINTTAB(24, v%) SPC(16): GOTO 3090
3110 IF t% < 10 t$ = "0" + STR$(t%) ELSE t$ = STR$(t%)
3120 PRINTTAB(24, v%); t$
3130 PRINTTAB(0, v%); CHR$(135)
3140 ENDPROC
3150 DEF PROCsomenu
3160 PRINTTAB(1, 6) "1. Flap Doors" SPC(12) "autovel "; aut$
3170 PRINT" Starting speed in steps per second"
3180 PROCline(cfsp%", " sps", 40, 350)
3190 PRINT" 2. Flap Doors"
3200 PRINT" Acceleration increment"
3210 PRINT" 3. Turbulence decay time"
3220 PRINT" Between flaps closing/slide opening"
3230 PRINT" 4. Slide"
3240 PRINT" Duration of open and close routines"
3250 PRINT" 5. Slide open"
3260 PRINT" Duration of slide being fully open"
3270 PRINT" 6. Slide"
3280 PRINT" READY to accept menu number"
3290 PROCesc("MAIN"); PROCready
3300 PRINT"PRINT" Last Sampling Sequence No"; CHR$(134); seqS;
3310 PRINT: PRINT" SAVED "; sav%; u$; " VALID RANGE "; lo%; " to "; hi%"
3320 ENDPROC
3330 DEF PROCready
3340 PRINTCHR$(13); "READY to accept menu number"
3350 ENDPROC
3360 DEF PROCCalter(v%, u%, lo%, hi%)
3370 VDU23, 1.1; 0; 0; 0;
3380 PRINTTAB(0, v%); CHR$(130): PRINT; CHR$(130): PRINT; CHR$(130)
3390 REPEAT
3400 PRINT" ENTER new value"; CHR$(133); " and press RETURN"
3410 PRINTCHR$(133); " valid range "; lo%; " to "; hi%"
3420 VDU23, 1, 0, 0, 0, 0;
3430 PRINTTAB(0, v%); CHR$(130): PRINT; CHR$(130); PRINT; CHR$(130)
3440 REPEAT
3450 PRINT" ENTER new value"; CHR$(133); " and press RETURN"
3460 PRINTCHR$(133); " valid range "; lo%; " to "; hi%
3470 PRINTCHR$(133); " valid range "; lo%; " to "; hi%
3480 IF t% < lo% OR t% > hi% PROCsound ELSE q% = 1
3490 UNTIL q% = 1
3500 VDU23, 1, 0, 0, 0, 0;
3510 PRINT: PRINT" SITE NAME ENTRY"
3520 VDU23, 5, 4; CHR$(130); PRINT; PRINT; PRINT" Use any keyboard characters,"
3530 PRINT" except commas, to enter the site name"
3540 PRINT" max 24 characters - "
3550 PRINT" and press RETURN"
3560 VDU23, 131, 157, 132, 31, 28, 10, 156, 31, 3, 10; INPUTsite$
3585 IF LEN(site$) > 24 PROCsound: site$ = ""
3590 UNTIL ASC(site$) > 0
3600 VDU31, 0, 10, 135, 157, 132: PRINTsite$; ";CHR$(156); SPC(23)
3610 VDU23, 1, 0; 0; 0;
3620 REPEAT
3630 PROCone2mnu(14, "site name")
3640 key%= GET
3650 IF key% < 49 OR key% > 50 VDU7
3660 UNTIL key% = 49 OR key% = 50
3670 VDU23, 1, 1; 0; 0;
3680 UNTIL key% = 50
3690 ENDPROC
3700 DEF PROCtgrab
3710 IF h% < 10 HR$ = "0" + STR$(h%) ELSE HR$ = STR$(h%)
3720 IF m% < 10 MIN$ = "0" + STR$(m%) ELSE MIN$ = STR$(m%)
3730 IF s% < 10 SEC$ = "0" + STR$(s%) ELSE SEC$ = STR$(s%)
3735 tg$ = HR$ + ":" + MIN$ + ":" + SEC$
3740 ENDPROC
3750 DEF PROCone2mnu(v%, enters)
3760 PRINTTAB(0, v%) " ****"; CHRS(134); "OPTION MENU"; CHRS(135); "*****"
3770 PRINT "PRINT" 1. Re-enter "; enters$
3780 PRINT " 2. O.K. to continue"
3790 PROCready
3800 ENDPROC
3810 DEF PROCabort(f1$, f2$)
3820 PROCsound
3830 warn$ = fIS: adv$ = f2$
3850 ENDPROC
3852 DEF PROCadvice
3853 PRINTTAB(25, 7) CHR$(135); CHR$(137); CHR$(129); CHR$(136); warn$
3854 PRINTTAB(0, 12) CHR$(135); CHR$(137); CHR$(129); "ADVICE - "; adv$
3855 PROCready
3856 PRINTTAB(30, 13) "s except 2"
3857 ENDPROC
3860 DEF PROCemcm
3870 xem% = ADVAL(1)/16
3880 yem% = ADVAL(2)/16
3890 x% = (x% + xem% - xoff%) DIV 2
3900 y% = (y% + yem% - yoff%) DIV 2
3910 IF x% = 0 x% = 1
3920 angle% = ABS(DEG(ATN(y%/x%)))
3922 IF x% > 0 AND y% < 0 angle% = ABS(angle%)
3924 IF x% < 1 angle% = 180 - angle%
3930 rawv% = SQR(x% ^ 2 + y% ^ 2)
3940 vel = rawv% / vcal$
3950 sies$ = "STBD"
3960 IF y% > 0 sies$ = "PORT"
3990 IF angle% = 0 AND x% = 0 sies$ = ""
4024 @%= &00005
4026 PRINTTAB(10, 20) xoff% TAB(16, 20) x% TAB(29, 20) yoff% TAB(35, 20) y%
4030 @% = &20204
4032 PRINTTAB(29, 21), vel
4035 @% = &00003
4040 PRINTTAB(30, 22), angle%; "; side$ 4050 ENDPROC
4100 DEF PROCFsens
4110 fs% = ADVAL(3)/16
4112 flag$ = (fs% - angoff%) / 80
4114 IF flag% < 1 fposus$ = "CLOSED "

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4115 IF flang$>44 fposus$="OPEN"
4116 IF flang$=44 "AND flang$<44 fposus$="ANGLE=
4120 @%=600003
4130 PRINTTAB(26,17)fposus$,flang%
4170 @%=600002
4180 ENDPROC

---

4200 DEF PROC freset
4205 IF flang$>0 AND fsr%=1 PROCabort("FAILED", "De-act.Sensor OR Adjust"):haz%=4:ENDPROC
4210 PROCmotor(&01,tln%/100,1,24,12,24,8,17,"OPENING"," SCOUR ")
4215 PROC fsens
4220 PROCdelay(10)
4230 PROCmotor(&01,tln%/100,1,24,92,24,8,17,"OPENING"," OPEN ")
4240 fpl sus$=out$
4245 haz%=0
4250 ENDPROC

---

4300 DEF PROC tiltchk
4310 ?&FE60=&05
4312 PRINTTAB(0,10)CHR$(134)TAB(24,10)"PITCH ROLL": PRINTSPC(28)
4320 PRINTTAB(0,12)CHR$(135);CHR$(157);CHR$(129);CHR$(136);
"Press ESCAPE key to exit Tilt Check"
4340 PROCdelay(.2)
4350 par%=1
4370 REPEAT
4390 PROC clock
4400 UNTIL key%=27
4410 *FX 21,0
4420 Key%=0
4430 park%=0
4440 ?&FE60=0
4450 PROC tgrab
4455 ltct$=tg$
4457 lp%=ABS(pitch%)
4458 lr%=ABS(roll%)
4460 ENDPROC

---

4500 DEF PROC pandr
4510 pitch%=(ADVAL(3)/16-mipi%)/piden%
4520 roll%=(ADVAL(4)/16-mirl%)/roden%
4525 lud$=" LEVL"
4530 IF pitch%>0 lud$=" UP "
4540 IF pitch%<0 lud$=" DOWN"
4545 lps$=" LEVL"
4550 IF roll%>0 lps$=" PORT"
4560 IF roll%<0 lps$=" STBD"
4570 @%=600002
4580 PRINTTAB(22,11)CHR$(131),ABS(pitch%);lud$;ABS(roll%);lps$
4590 @%=10
4600 PRINTTAB(1,7)"ADval","ADval(3)/16,ADval(4)/16
4680 ENDPROC

---

4700 DEF PROC esc(ret$)
4710 PRINT "ESC Return to ",;ret$;" MENU"
4720 ENDPROC

---

4800 DEF PROC doors
4810 IF fsr%=0 PROCabort("FAILED","Activate the Flap Sensor"):
PROCadvice:ENDPROC
4820 *FX21,0
4830 REPEAT
4835  menu%=1
4840  PROChead
4843  PRINTTAB(5,4)CHRS(134);"FLAP DOOR MENU";CHRS(135):PRINT
4846  PRINT"  1. Open Flap until angle = 45"
4850  PRINT"  2. Close Flap until angle = 0"
4853  PROCesc("ADJUSTMENT"):VDU31,0,12:PROCready
4856  PROCinfo
4860  PROCclock
4861  ubs%=((3600-fs%-angoff%) DIV 18)-4
4862  IF ubs%<2  ubs%=2
4863  dbs%=(fs%-angoff%) DIV 18)-3
4865  IF key%=49 PROCmotor(&01,tln%/100,0,2,ubs%,2,8,17,"SENSADJ","NowTry2"):fplsusS=outS
4870  IF key%=50 PROCmotor(&41,tln%/100,0,2,dbs%,2,8,17,"CLOACHEC"," CLOSED"):fplsusS=outS
4875  UNTIL key%=27
4880  haz%=0
4882  *FX21,0
4884  key%=0
4890  ENDPROC

4890  DEF PROCslidoor
4905  *FX21,0
4910  REPEAT
4920  menu%=1
4930  PROChead
4940  PRINTTAB(5,4)CHRS(134);"SLIDE DOOR MENU";CHRS(135):PRINT
4950  PRINT"  1. Open Slide"
4960  PRINT"  2. Close Slide"
4965  PRINT"  3. Close Flaps"
4970  PROCesc("ADJUSTMENT"):VDU31,0,12:PROCready
4980  PROCinfo
4990  PROCclock
5000  IF key%=49 PROCmotor(&03,tln%/200*slidet%,1,80,120,40,4,18,"OPENING"," OPEN "):splsusS=outS
5020  IF key%=50 PROCmotor(&43,tln%/200*slidet%,1,80,120,40,4,18,"CLOSING"," CLOSED"):splsusS=outS
5032  IF key%=51 PROCmotor(&41,tln%/l00,1,24,152,24,8,17,"CLOSING"," CLOSED"):fplsusS=outS
5040  UNTIL key%=27
5050  *FX21,0
5060  key%=0
5070  ENDPROC

5200  DEF PROCcm
5210  *FX21,0
5215  REPEAT
5220  PROChead
5230  PRINTTAB(6,4)CHRS(134);"CURRENT METER";CHRS(135):PRINT
5240  PRINT"  1. Zero X Offset"
5245  PRINT"  2. Zero Y Offset"
5250  PRINT"  3. Enter X Mid-value"
5254  PRINT"  4. Enter Y Mid-value"
5256  PRINT"  5. Increment Calib. Denominator ":initvcs$
5260  PRINT"  6. Decrement Calib. Denominator"
5270  PROCesc("ADJUSTMENT")
5275  PROCready
5285  @%=&00004
5290  PRINTTAB(34,11):vcal%
5295  @%=10
5300  PROCinfo
5310  PROCclock
5320  IF key%=49 xoff%+xoff%+x%
5325  IF key%=50 yoff%=yoff%+y%
5330 IF key%=51 PROCinpmid:xoff%=b%
5334 IF key%=52 PROCinpmid:yoff%=b%
5336 IF key%=53 vcal%=vcal%+1
5340 IF key%=56 vcal%=vcal%-1
5350 UNTIL key%=27
5360 *FX21,0
5370 key%=0
5380 ENDPROC

5500 DEF PROCpotfsadj
5505 REPEAT
5510 PRINTTAB(26,6)CHR$(131);"0":CHR$(134);"inactive"
5515 PRINTTAB(26,7)CHR$(131);"1":CHR$(134);" active"
5520 PRINTTAB(0,9)CHR$(134)TAB(16,9)"Offset":CHR$(135)
5530 PRINTCHR$(134);" \nNOW ":angoff$;
5540 PRINTCHR$(134);" \nTO RESET\"TAB(30):CHR$(135)
5550 PRINTCHR$(134);" \nPress ESCAPE key to return to MENU"
5560 PROCclock
5570 IF key%=56 angoff(fs%-3600)-40
5574 IF key%=48 fsr%=0:sr$="in"
5576 IF key%=49 fsr%=1:sr$=" "
5580 PRINTTAB(30,18)sr$
5590 UNTIL key%=27
5595 *FX21,0
5600 key%=0
5610 ENDPROC

5690 DEF PROCvideo
5700 PRINTTAB(8,4)CHR$(131)"VIDEOTEXT":CHR$(135)
5705 PRINT:PRINTTAB(1,6)"Site: site$;
5710 IF LEN(site$)<18 PRINTSPC(20-LEN(site$)) ELSE PRINT
5715 PRINTSPC(23):PRINTSPC(25)
5720 PRINTCHR$(141)" FLOC SAMPLE THAT FOLLOWS IS No. ";seq%
5725 PRINTCHR$(141)" FLOC SAMPLE THAT FOLLOWS IS No. ";seq%
5730 PRINTCHR$(39)
5735 PRINTCHR$(15)" Open Flaps to exactly horizontal"
5740 PRINTCHR$(15)" then press key";CHR$(131);"8";SPC(12)
5745 PRINTCHR$(15);CHR$157);CHR$(129);CHR$(136);
5750 "Press ESCAPE key to return to MENU"
5755 PROC-delay(1)
5760 c%=turbd
5765 REPEAT
5770 c%=c%-l
5775 PRINTTAB(27,12),c%
5780 PROC-delay(1)
5785 UNTIL c%<1
5790 @%=0
5795 UNIL key%=27
5800 *FX21,0
5810 key%=0
5820 ENDPROC

5820 DEF PROCvauto
5820 cfsps%=262*vel+41
5830 IF cfsps%>224 cfsps%=224
5835 IF cfsps%<42 cfsps%=42
5840 tlcf%=tln%/cfsps%
5850 ENDPROC

5850 DEF PROCsound
5860 SOUNDl,-15,173,30:q%=0
5870 ENDPROC

5880 DEF PROCIpmid
5860 \texttt{b\%=2047: c\%=0: j\%=key\%=43}
5870 \texttt{REPEAT}
5875 \texttt{c\%=c\%+1: IF c\%>1 PROCsound}
5877 \texttt{VDU23,1,1,0;0;0;0;}
5880 \texttt{VDU31,0,j\%,134,31,24,j\%,131,157,132,9,9,9,9,156,127,127,127,127}
5882 \texttt{INPUTTAB(27,j\%)b\%}
5885 \texttt{VDU23,1,0;0;0;0;}
5900 \texttt{UNTIL b\%>0 AND b\%<4096}
5910 \texttt{VDU31,0,j\%,135,31,24,j\%,131,157,156}
5920 \texttt{ENDPROC}

---

6000 \texttt{DEF PROCexitcheck}
6010 *FX21,0
6020 \texttt{PROChead}
6030 \texttt{PRINTTAB(1,4)'Are you sure you wish to leave the"}
6040 \texttt{PRINT" INSEEV Control Program ?" : PRINT}
6050 \texttt{PRINT" Press key 'Y' if you wish to leave."}
6060 \texttt{PRINT" Press any other key to take you back"}
6070 \texttt{PRINT" to the MAIN MENU."}
6080 \texttt{PRINTTAB(1,19)'If 'Y' switch OFF power to Surface":}
6090 \texttt{PRINT" Electronics."}
6090 \texttt{exit\%=GET$}
6100 \texttt{IF exit\%="Y" OR exit\%="y" key\%=1}
6110 \texttt{ENDPROC}

---

END OF PROGRAM
Appendix 3
Image Processing Software

The two program listings on the following 7 pages are written in types of BASIC. "ACQ2.QBA" can only be run with a Cambridge Instruments (Leica) Q570 system. "SWS3.BAS" will operate on any IBM compatible running MS-DOS and GW-BASIC. The purpose of these two programs is to obtain size and settling velocity data for individual flocs from INSSEV video tapes. This is achieved in three stages:

Stage One

Using program "ACQ2.QBA" frames are grabbed from a video taped sample sequence of flocs settling in column, at a rate proportional to the expected settling velocities. This requires rapid frame grabbing (up to 8 frames a second) at the start of the sample sequence and considerably slower (about 1 frame every 18 seconds) after about 30 minutes of video tape playback. The tape is played at normal speed. The acquired frames are processed to obtain a binary image of anything in the frame. The binary image is saved to the Hard Disk, because Stage Two cannot always be completed before it is necessary to grab the next frame.

Stage Two

In the latter part of the same program the binary images are retrieved in turn and all features are measured and positioned in relation to the screen pixel grid. These floc size and floc position data sets for every grabbed image are saved to floppy disk with the elapsed time.

Stage Three

Using program "SWS3.BAS" the floc data are retrieved from floppy disk into a large array. The array is then processed to find each recorded floc in subsequent grabbed images for which the elapsed time since sampling is known. When the same floc has been found in more than one grabbed image it is possible to calculate the settling velocity. This is achieved using screen position data for the floc and the elapsed time data from two grabbed images to calculate the time interval. The output data from this program consists of size (various parameters), settling velocity and time that individual flocs are at mid screen height.
10 REM "ACQ2.QBA"
20 REM 160893 at 12.00
30 REM written by Mike Fennessy and Paul Russell
40 REM Q570 QUCbasic program for INSSEV
50 REM A two stage Image Processing procedure
60 REM STAGE ONE - ACQUIRE, THRESH, binary image held in RAM; loop 135
70 REM STAGE TWO - MEASFEAT and Image Data sent to disk
80 REM --- BUT not tested or complete ---
90 REM Output from this program requires STAGE THREE processing
100 REM by SW3.BAS run on GWBASIC
110 REM Configure Pix 6, Data c:\mike
120 REM Elbe Gain 40.6 Offset 31.6 Pre Elbe Gain 27.7 Off 30.5
130 cmax=135
140 DIM imfrm(cmax),nof(cmax)
150 PRINT
160 PAUSETEXT 1 'Program now running .........'
170 PAUSETEXT 2 'Image Processor settings have to be confirmed,'
180 PAUSETEXT 3 'by clicking on CONTINUE, or adjusted.'
190 qmenu 'image_setup'
200 qmenu 'calibrate'
205 riasettings 'cal_value' x
210 mframe 30 0 444 509
220 iframe 0 0 512 512
230 qmenu 'shading'
235 PAUSETEXT 1 ''
240 PAUSETEXT 2 ''
245 PAUSETEXT 3 ''
250 REM DIMENSIONING FOR BINARY IMAGES
260 REM use only the Grey Image Memories in the Data list:
270 DATA 3,4,8,9,10,11,12,13,15,16,17,18,19,20,21
280 REM total of 15 grey images giving 120 binary images
290 FOR z=116 TO 235 STEP 8
300 READ grim
310 FOR s=0 TO 7
320 bbox=z+s
330 BINDGREY grim bbox
340 NEXT s
350 NEXT z
360 PRINT
370 PRINT
380 PRINT
390 PRINT
400 PRINT
410 PRINT
420 PRINT
430 PRINT
440 REM spare space for any changes to memory control
450 PRINT
460 PRINT
470 REM ----------------- SETUP DATA FILE
480 PRINT
490 r$=""
500 PRINT "Please enter the following information for the FEATURE DATA FILE"
510 PRINT "-- all stored as strings for assembly of filename .FEA"
520 PRINT "(NB 2nd line - FW DATE - enter days and year as digit(s),)"
530 PRINT "( months in letters, NO SPACES, eg 13june93)"
540 PRINT
550 INPUT "SITENAME ",site$
560 INPUT "FIELDWORK DATE ",fwdate$
570 INPUT "SAMPLE SEQUENCE No. ",samno$
580 INPUT "DATA GRAB Letter ",dgrab$
590 PRINT
600 id$=LEFT$(site$,3)+LEFT$(fwdate$,3)+LEFT$(samno$,1)+LEFT$(dgrab$,1)
610 feafil$=id$+.FEA'
620 PRINT "FEATURE DATA FILE filename is -- ";feafil$
630 PRINT:print "Press r to re-enter these four lines,"
640 PRINT "or any other key to continue."
PRINT: PRINT "Your choice is activated only when you press <Enter>"

PRINT

INPUT r$

IF r$ = "r" GOTO 480

PRINT

PRINT "The Dimension File keeps a record of the ACQUIRED IMAGE number"
PRINT "together with the video frame counter number."
PRINT "In order to achieve synchronisation YOU have to input"
PRINT "an appropriate frame number, start the Video Tape,"
PRINT "and hit the <Enter> key when the number"
PRINT "appears on the Image Monitor; the Tape must then be left to run."
PRINT: INPUT "Frame Number ",frmbeg

REM

REM STAGE ONE STAGE ONE

co=0

start=0

old=frm beg

q$=""

REM

t$=TIMES REM TIMEGRAB centisecs
hrs=VAL(MID$(t$,1,2))
min=VAL(MID$(t$,4,2))
sec=VAL(MID$(t$,7,2))
dec=VAL(MID$(t$,10,2))
cs=(hrs*360000)+(min*6000)+(sec*100)+dec

IF co=0 THEN start=cs-(frm beg*4)

co=co+1: PRINT

elap=cs-start

frn=INT(elap/4)+frm beg

imfrm(co)=frn

ACQUIRE 1

THRESH 1 1 0 200

PRINT "Count ";co; " Elapsed seconds ";elap/100; " Frame No. ";frn;
PRINT " FrmInt ";frn-old

old=frn

REM space for saving binary image to RAM

IF co>15 GOTO 1060

REM

BINMOVE 1 co+1

GOTO 1110

IF co>100 GOTO 1060

REM

q$=INKEYS: IF q$="q" GOTO 1150

REM

IBLEEP 25000 INT(elap/10-(frm beg/3)) REM used as msec int timer

REM

IF co<135 GOTO 840

PRINT "BINARY IMAGE ACQUISITION finished":GOTO 1170

PRINT "BINARY IMAGE ACQUISITION stopped by operator after ";co;" IMAGES"

REM

PRINT: PRINT "Enter the Frame Number at FINISH ",lastfr

REM

REM STAGE TWO STAGE TWO

PRINT

PRINT "Program now executing SECOND stage":PRINT

PRINT "--- Measuring the features identified on the Binary Images"

OPEN #1 "c:/mike/+feafil$ REM -- OPEN FEATURE DATA FILE

PRINT #1:DATES,TIMES,site$,fwdate$,samno$,dgrab$,
FROMBEGLASTFR,ELAP/100

PRINT #1: "ImFrmNo","FeatNo","xFCP","yFCP","Wide","High","Area","Round"
1280 REM-----------------------------------------------
1290 CLEAR
1300 SETFTRPAR "1,2,3,4,5,15,63"
1310 lnf=0:tlines=0
1320 FOR co=1 TO cmax
1330 PRINT co;
1340 REM---get binary image---
1350 IF co>15 GOTO 1380
1360 BINGET 23 co+1
1370 GOTO 1400
1380 BINGET 23 co+100
1390 REM
1400 MEASFEAT 23 1 6 270000
1410 REM
1420 RFEATNRM n(1)
1430 nof(co)=n(1)
1440 IF n(1)>lnf THEN lnf=n(1)
1450 REM
1460 FOR f=0 TO n(1)-1
1470 RFEATRES f 1 area(1)
1480 RFEATRES f 2 xfcp(1)
1490 RFEATRES f 3 yfcp(1)
1500 RFEATRES f 4 wide(1)
1510 RFEATRES f 5 high(1)
1520 RFEATRES f 15 round(1)
1530 REM
1540 REM
1550 REM
1560 tlines=tlines+1
1570 REM
1580 PRINT#1:imfrm(co),f+1,xfcp(1),yfcp(1),wide(1),high(1),area(1),round(1)
1590 PRINT TAB(6)imfrm(co)TAB(16)xfcp(1)TAB(21)yfcp(1)Tab(26)wide(1)Tab(31)high(1)Tab(36)area(1)Tab(43)round(1)
1600 NEXT f
1610 REM
1620 NEXT co
1630 CLOSE #1
1640 REM-----REM-so that DATA on Grey Image Stores can be READ again
1650 RESTORE REM---so that DATA on Grey Image Stores can be READ again
1660 FOR z=1 TO 15
1670 READ grim
1680 GREYDISP grim
1690 NEXT z
1700 PRINT:PRINT
1710 OPEN #2 "c:\mike\"+id$+.DIM"
1720 PRINT #2:cmax,lnf,tlines,x
1730 FOR dd=1 TO cmax
1740 PRINT #2:nof(dd)
1750 NEXT dd
1760 PRINT #2:ProcDate","ProcTime","Site","FWDate","SamSeqNo","DGrab","frmbeg","lastfr","ProcDur"
1770 Print #2:DATES,TIMES,sites,fwdate$,sammo$,dgrab$,frmbeg,lastfr,elap/100
1780 PRINT #2:ImFrmNo","FeatNo","xFCP","yFCP","Wide","High","Area","Round"
1790 CLOSE #2
1800 REM-----------------
1810 REM
1820 PRINT TAB(10)"TOTAL NUMBER OF BINARY IMAGES ";co
1830 PRINT TAB(10)"TOTAL NUMBER OF FEATURE DATA LINES ";tlines
1840 PRINT TAB(10)"HIGHEST NO OF FEATURES COUNTED IN ONE IMAGE ";lnf
1850 PRINT
1860 PRINT TAB(10)"FEATURE DATA FILENAME - ";feafil$
1870 PRINT TAB(10)"DIMENSION DATA FILENAME - ";id$+.DIM
1880 PRINT
1890 PRINT TAB(10) "SITENAME - - - - - - - ";sites
1900 PRINT TAB(10) "FIELDWORK DATE - - - - - ";fdate
1910 PRINT TAB(10) "SAMPLE No. - - - - - - ";samno
1920 PRINT TAB(10) "DATA GRAB Letter - - - - ";dgrab
1930 PRINT
1940 PRINT
1950 PRINT ". . . . . . . . . . . . . . . . . . . . . . . . . . END OF RUN"
1960 END
REM "SWS3.BAS" save as LIST,"a:sws3.bas"
REM
10 REM 170893 © 17:30
20 REM written by Mike Fennessy as a prototype data array checking
30 REM routine for the FEATURE DATA from ACQ2.QBA.
40 REM For use on GWBASIC.
50 REM This is the THIRD STAGE of the Image Processing of Video Tapes
60 REM
70 OPTION BASE 1
80 PRINT:PRINT"SWS3.BAS now running.................. . . .
90 PRINT
100 INPUT"Enter Data Filename from Stage 2 (without extension) ",IDS
110 OPEN"I",#1,"a:"+ID$+.DIM"
120 INPUTSl.MAXCO,LNF,TLINES,CALIB
130 DIM NOF(MAXCO)
140 IF LNF=0 THEN LNF=1
150 REM
160 FOR CO=1 TO MAXCO
170 INPUT#1,NOF(CO)
180 NEXT CO
190 INPUT#1,H1S,H2S,H3S,H4S,H5S,H6S,H7S,H8S,H9S
200 INPUT#1,D1S,D2S,D3S,D4S,D5S,D6S,D7,D8,D9
210 CLOSE#1
220 PRINT
230 PRINT H1S,D1S
240 PRINT H2S,D2S
250 PRINT H3S,D3S
260 PRINT H4S,D4S
270 PRINT H5S,D5S
280 PRINT H6S,D6S
290 PRINT
300 PRINT H7S,D7
310 PRINT H8S,D8
320 PRINT H9S,D9
330 PRINT
340 BELOW=.7:ABOVE=1.3
350 DIM FRN(MAXCO), DFEANO(MAXCO), WIDE(LNF,MAXCO), HIGH(LNF,MAXCO)
360 DIM XFCP(LNF,MAXCO), YFCP(LNF,MAXCO)
370 DIM AREA(LNF,MAXCO), ROUN(LNF,MAXCO), USED(LNF,MAXCO)
380 OPEN"I",#2,"a:"+ID$+.FEA"
390 INPUT#2,FD1S,FD2S,FD3S,FD4S,FD5S,FD6S,FD7,FD8,FD9
400 INPUT#2,FH1S,FH2S,FH3S,FH4S,FH5S,FH6S,FH7S,FH8S
410 CHECK=0
420 PRINT
430 FOR CO=1 TO MAXCO
440 IF NOF(CO)=0 GOTO 415
450 FOR FI=1 TO NOF(CO)
460 IF EOF(2) THEN 440
470 INPUT#2,FRN(CO),DFEANO(CO),XFCP(FI,CO),YFCP(FI,CO),WIDE(FI,CO)
480 INPUT#2,HIGH(FI,CO),AREA(FI,CO),ROUN(FI,CO)
490 CHECK=CHECK+1
500 NEXT FI
510 PRINT "###":CO,NOF(CO);"
520 PRINT ";"
530 NEXT CO
540 PRINT:PRINT
550 IF CHECK< TLINES THEN PRINT "Not all FEATURE DATA lines have been READ"
560 CLOSE#2
570 REM
580 PRINT "FrameNo (pixels) (microns) (microns) (um^2) (C=1000) (mm/sec)
590 REM
600 PRINT "Camera Screen Width Height Mean Roundness Settling"
610 PRINT "Axis Position Area Index Velocity"
620 PRINT
630 IF TLINES>0 THEN GOSUB 1141
530 REM----------------------------------------
540 FOR CO=1 TO MAXCO-1
545 IF NOF(CO+1)=0 GOTO 1020
546 IF NOF(CO)=0 GOTO 1020
550 FOR FEATNO=1 TO NOF(CO)
560 REM
570 KFLAG=0
580 IF USED(LOOKBLOB,CO+1)=1 GOTO 990
585 IF XFCP(LOOKBLOB,CO+1)<(XFCP(FEATNO,CO)-40) GOTO 990
590 IF YFCP(LOOKBLOB,CO+1)<(YFCP(FEATNO,CO)-40) GOTO 990
595 IF YFCP(LOOKBLOB,CO+1)<(YFCP(FEATNO,CO)+40) GOTO 990 REM eqn
600 IF YFCP(LOOKBLOB,CO+1)<(YFCP(FEATNO,CO)+3) GOTO 990 REM eqn
605 IF YFCP(LOOKBLOB,CO+1)<(YFCP(FEATNO,CO)+40) GOTO 990 REM eqn
610 IF WIDE(LOOKBLOB,CO+1)<(WIDE(FEATNO,CO)*BELOW) GOTO 990
615 IF WIDE(LOOKBLOB,CO+1)<(WIDE(FEATNO,CO)*ABOVE) GOTO 990
620 IF AREA(LOOKBLOB,CO+1)<(AREA(FEATNO,CO)*BELOW) GOTO 990
625 IF AREA(LOOKBLOB,CO+1)<(AREA(FEATNO,CO)*ABOVE) GOTO 990
630 REM
635 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*BELOW) GOTO 990
640 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
645 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
650 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
655 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
660 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
665 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
670 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
675 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
680 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
685 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
690 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
695 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
700 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
705 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
710 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
715 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
720 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
725 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
730 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
735 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
740 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
745 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
750 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
755 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
760 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
765 IF ROUN(LOOKBLOB,CO+1)<(ROUN(FEATNO,CO)*ABOVE) GOTO 990
770 GOSUB 1040 REM goes to do an assemble
775 IF DISTFAL*2+YFCP(FEATNO,CO)>505 GOTO 1000
780 IF CO=MAXCO-1 GOTO 1000
785 IF NOF(CO+2)=0 GOTO 1000
790 FOR A2NDLOOK=1 TO NOF(CO+2) REM goes to do a re-assemble
795 IF USED(A2NDLOOK,CO+2)=1 GOTO 970
800 IF XFCP(A2NDLOOK,CO+2)<(XFCP(FEATNO,CO)-40) GOTO 970
805 IF XFCP(A2NDLOOK,CO+2)<(XFCP(FEATNO,CO)+40) GOTO 970 REM eqn
810 IF XFCP(A2NDLOOK,CO+2)<(XFCP(FEATNO,CO)+40) GOTO 970 REM eqn
815 IF XFCP(A2NDLOOK,CO+2)<(XFCP(FEATNO,CO)+5) GOTO 970 REM eqn
820 IF WIDE(A2NDLOOK,CO+2)<(WIDE(FEATNO,CO)*BELOW) GOTO 970
825 IF WIDE(A2NDLOOK,CO+2)<(WIDE(FEATNO,CO)*ABOVE) GOTO 970
830 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*BELOW) GOTO 970
835 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*ABOVE) GOTO 970
840 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*ABOVE) GOTO 970
845 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*ABOVE) GOTO 970
850 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*ABOVE) GOTO 970
855 IF AREA(A2NDLOOK,CO+2)<(AREA(FEATNO,CO)*ABOVE) GOTO 970
860 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*BELOW) GOTO 970
865 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
870 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
875 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
880 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
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900 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
905 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
910 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
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925 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
930 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
935 IF ROUN(A2NDLOOK,CO+2)<(ROUN(FEATNO,CO)*ABOVE) GOTO 970
940 GOSUB 1040 REM goes to do an assemble
945 IF KFLAG=1 THEN GOSUB 1150 REM goes to write to floclist
950 KFLAG=1
955 GOTO 1000
960 GOTO 1000
965 NEXT A2NDLOOK
970 IF KFLAG=1 GOTO 1000
975 NEXT LOOKBLOB
980 IF KFLAG=1 THEN GOSUB 1150 REM goes to write to floclist
990 NEXT CO
1000 GOTO 1230 REM goes to END
1005 HEIGHT=(HIGH(FEATNO,CO)+HIGH(LOOKBLOB,CO+PEEP))/2*CALIB
1010 WIDTH=(WIDTH(FEATNO,CO)+WIDTH(LOOKBLOB,CO+PEEP))/2*CALIB
1015 MNAREA=(AREA(FEATNO,CO)+AREA(LOOKBLOB,CO+PEEP))/2*(CALIB*2)
1020 IROUND=(ROUN(FEATNO,CO)+ROUN(LOOKBLOB,CO+PEEP))/2
1025 DISTFAL=(YFCP(LOOKBLOB,CO+PEEP)-YFCP(FEATNO,CO))
1030 XAX256=XFCP(FEATNO,CO)
1035 FALFRMS=FRN(CO+PEEP)-FRN(CO)
1040 KMRRSM=(DISTFAL/FALFRMS/25)+6/1000
1045 CAMAXF=INT((256-YFCP(FEATNO,CO))/DISTFAL)*FALFRMS+FRN(CO)
1050 XAX256=XFCP(FEATNO,CO)
OPEN "O", #3, "a:\"+IDS+".DAT
PRINT #3, D1$, D2$, D3$, D4$, D5$, D6$, D7$, D8$, D9
PRINT #3, "Camera Screen Width Height Mean Roundness Settling'
PRINT #3, "Axis Position in in Area Index Velocity"
PRINT #3, "FrmNo pixels microns microns um^-2 c=1000 mm/sec"
RETURN
PRINT #3, USING "#####"; CAMAXF; XAX256;
PRINT #3, USING "#####.#"; DWIDTH; HEIGHT;
PRINT #3, USING "########"; MNAREA; IROUND;
PRINT #3, USING "#####.###"; USMMS
REM
PRINT USING "#########"; CAMAXF; XAX256;
PRINT USING "#########.#"; DWIDTH; HEIGHT;
PRINT USING "##########"; MNAREA; IROUND;
PRINT USING "##########.###"; USMMS
REM
REM
IF TLINES > 0 THEN CLOSE #3
PRINT
PRINT ". . . . . . . . . . . . . . . . . . . . . . Program ENDED"
END