COAST3D

MEASUREMENT ERRORS OF INSTRUMENTS FOR

VELOCITY, WAVE HEIGHT, SAND CONCENTRATION

AND BED LEVELS IN FIELD CONDITIONS

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1.   Introduction

Field measurements of hydrodynamics (fluid velocities and wave height), sediment dynamics (sand concentrations) and morphodynamics (bar behaviour) as performed during the COAST3D campaigns at the Egmond site in 1998 and at the Teignmouth site in 1999 inevitably involve the problem of the accuracy of the measured variables.

The measurement errors are related to:
- the physical size of the instrument including supports, cables, housing for electronics, etc.;
- the measurement principle including electronic instability, drift, offset, calibration procedure, sampling size and applicability and validity ranges of the instrument concerned;
- the conversion principle including assumptions of applied theories (for example: conversion from fluid pressure to wave height; errors in position of pressure sensor above bed).

Information of the measurement errors involved can be obtained by comparing instruments based on different measurement principles under controlled conditions. Recently several studies focussing on hydrodynamics and sand transport in the large scale wave tanks of Delft Hydraulics (The Netherlands) and of the 'Forschungszentrum Küste' in Hannover (Germany) have been carried out. Various types of instruments have been used to measure fluid velocities, wave heights and sand concentrations during the experiments in the wave tanks. In addition data sets from various field experiments are used to evaluate the performance of the instruments considered.

In this note some results of instrument intercomparisons are presented. Furthermore, information of instrument characteristics are given.

2.   Velocity measurements

2.1   Instruments

The instruments used during the COAST3D campaigns are:
- electromagnetic velocity meters;
- acoustic Doppler velocity meters ADV and ASTM;
- acoustic Doppler current velocity profiler ADCP.

2.1.1   Electromagnetic velocity meters
Various types of sensors have been used.
The EMF sensors used by University of Utrecht are manufactured by Delft Hydraulics. The instruments are accurate to ± 3% of measured value. The calibration curve is linear (correlation coefficient > 0.99). The offset is smaller than |0.03| m/s.
Timeseries of EMF are decomposed into longshore and cross-shore components using the compass readings. Accuracy of compass reading is of the order of a few degrees, < 2-3 degrees.
The S4 sensors used by HR Wallingford and University of Caen are manufactured by InterOceans Systems, Inc. The applicability range is 0 to 350 cm/s with resolution of 0.2 cm/s. The accuracy is about ±2% of the reading. The compass, used to transform the components measured into northward and southward or longshore and cross-shore components, has an accuracy of 2 degrees with a resolution of 0.5 degrees. The S4 performance will be affected by breaking waves in shallow water, where considerable aeration is produced around the instrument. The effect will be a 'noisy' signal, which will be apparent on a time-series plot.
The University of Caen (tripod deployed at station 2) has used three electromagnetic current meters of Marsh Mc Birney type 512 OEM. The resolution of these instruments is 0.15 cm/s and the precision better than 2 cm/s. A magnetic compass is also used to convert the two components of the horizontal current into northward and southward or longshore and cross-shore components. The precision of this compass is 1.4 degrees.

2.1.2   Acoustic Doppler velocity meter ADV
Basically, the ADV measures the velocity of particles (sediments) in the water column from the Doppler shift in frequency of the emitted and received acoustic signals (without calibration). The accuracy is of the order of ±3% of the reading, if sufficient particles are present in the measurement volume. Often, insufficient

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particles are present at low velocity conditions resulting in loss of signal and rather inaccurate velocities. An important source of error is the presence of air bubbles in the water column (breaking wave conditions).

2.1.3   Acoustic Doppler Current Profilers ADCP

ADCP instruments are being used as bottom mounted or as ship mounted instruments.

The accuracy of the bottom mounted 1500 kHz standalone ADCP of HR Wallingford is 1% of measured value and +/-0.5cm/s at maximum output rate. In the Teignmouth main deployment 1999 with 40 seconds averaging and 0.5m cells the precision (p) is given as +/-2cm/s.

The accuracy (precision) of the 1500 kHz downward-looking ship mounted ADCP of HR Wallingford is given as: precision = sqrt(p^2 + boat variance) cm/s. The boat variance can be estimated as: 25(cm/s)^2 for typical DGPS speed input to software. This gives: precision = +/-5.3cm/s for 10 second averaging (1.0 m cells) and precision = +/- 5.1cm/s for 30 second averaging (1.0 m cells).

The boat variance will depend on weather conditions; the rougher the weather the more swinging around the boat will do and the greater the amount of wave-induced velocity that must be smoothed out. No moving vessel ADCP surveys were conducted in truly bad weather.

2.2   Comparison of velocity derived from Electromagnetic velocity meter EMF and Laser Doppler velocity meter in wave tunnel LOWT

A disc-type (diameter of about 0.04 m) Electro-magnetic velocity meter (EMF) manufactured by Delfts Hydraulics has been used to measure the orbital velocities in the Large Oscillating Water Tunnel (LOWT) of Delft Hydraulics (Walstra et al., 1998). The EMF consisted of a 2-axis, 4 cm diameter, ellipsoid probe with an inaccuracy of 0.01 m/s (± 1% of the measured value) and a zero stability (offset) of less than 5 mm/s. The EMF measures the water velocity along two perpendicular horizontal axes. The sampling frequency generally is 2 Hz. The EMF was calibrated at Delft Hydraulics before and after the experiments by towing the EMF at different constant speeds through a tank. The calibration was performed in the range 0-2.5 m/s. The calibration curves are linear with a high correlation coefficient ($r^2 \approx 0.99$).

The EMF was positionned at about 0.03 m above the top of the sand bed in the wave tunnel. Comparison of the calibration results performed before and after the wave tunnel experiments did not show significant changes in calibration. In the present experiments the x-axis of the EMF was oriented parallel to the wave tunnel. The EMF was placed at approximately 3 cm above the sand bottom.

The oscillating water tunnel has the shape of a vertical U-tube with a long rectangular test section (length= 14 m, width= 0.3m, height= 1.1 m). The oscillating water motion is generated by the motion of a pistion operated in one of the vertical legs of the U-tube. The range of velocity amplitudes is 0.2 to 1.8 m/s with periods of 4 to 15 s. The standard instrument to measure the fluid velocities in the vertical plane (horizontal and vertical velocities) in the water tunnel is a forward scattering Laser Doppler velocity meter (LDA). The height and length of the measurement volume are approximately 0.22 mm; the lateral width is 6.5 mm (perpendicular to main orbital motion). The standard range of the velocities is 0.001 to 2 m/s. No calibration is required. The LDA is mounted in a movable frame standing over the tunnel; the laser beams penetrate through the glass windows of the tunnel. The measurement position of the LDA was about 0.2 m above the top of the sand bed present in the tunnel.

The EMF velocity signals have been compared with the velocity signals from the LDA for two tests B7-3 and E2-2.

The basic characteristics of these tests are:
- B7-3; $U_{max,forward}$= 1 m/s, $U_{max,backward}$= 0.5 m/s and period= 6.5 s, plane sand bed;
- E2-2; $U_{max,forward}$= 1.8 m/s, $U_{max,backward}$= 1.3 m/s and period= 7.2 s, plane sand bed.

Results of these comparisons are given in Figures 2.1 and 2.2. It can be observed that the general trend of the LDA signal is quite well followed by the EMF signal. Discrepancies are as follows:
- Test B7-3; the peak forward velocity of the EMF is about 15% smaller than that of the LDA; the peak backward velocity of the EMF is about 10% smaller than that of the LDA;
- Test E2-2; the peak forward velocity of the EMF is about 10% to 15% smaller than that of the LDA; the peak backward velocity of the EMF is about 5% to 10% larger than that of the LDA.
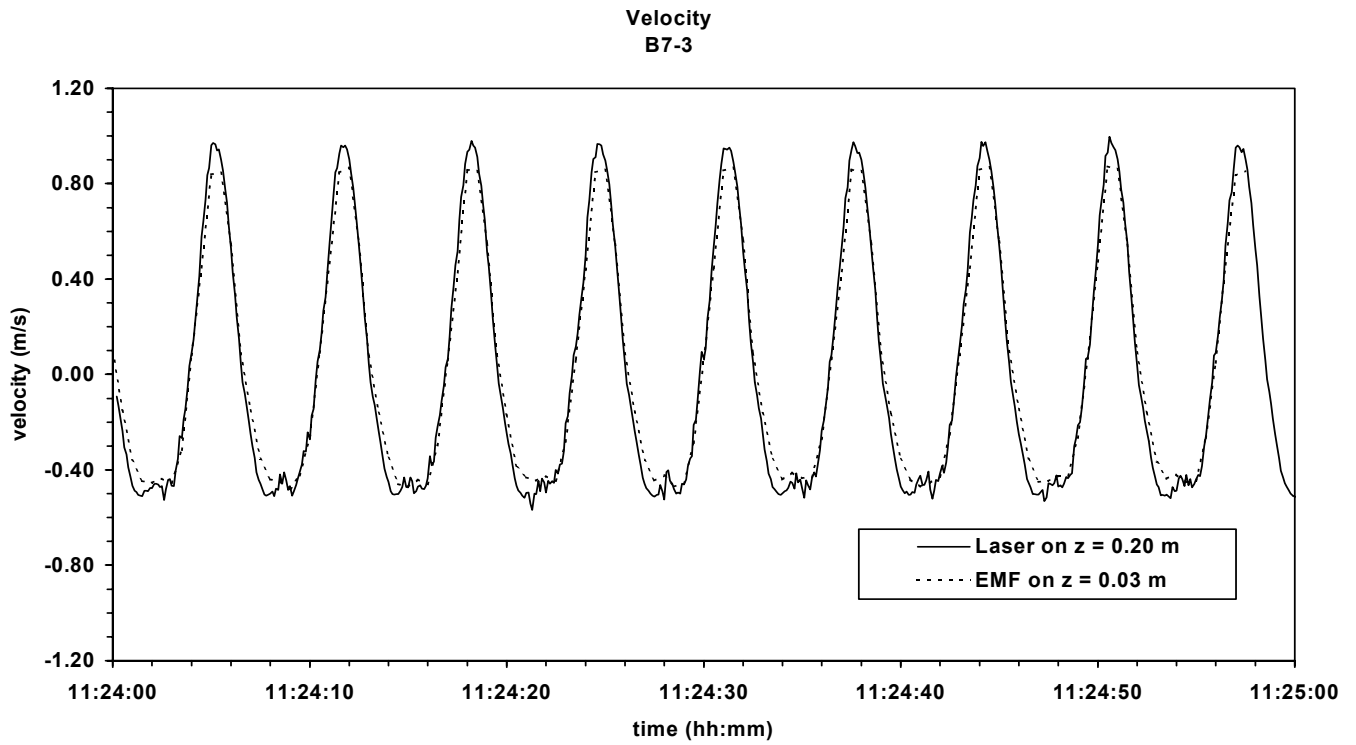
**Velocity
B7-3**

Figure 2.1
Orbital velocity in water tunnel measured by Laser Doppler velocity meter and by Electro-magnetic velocity meter; Test B7-3
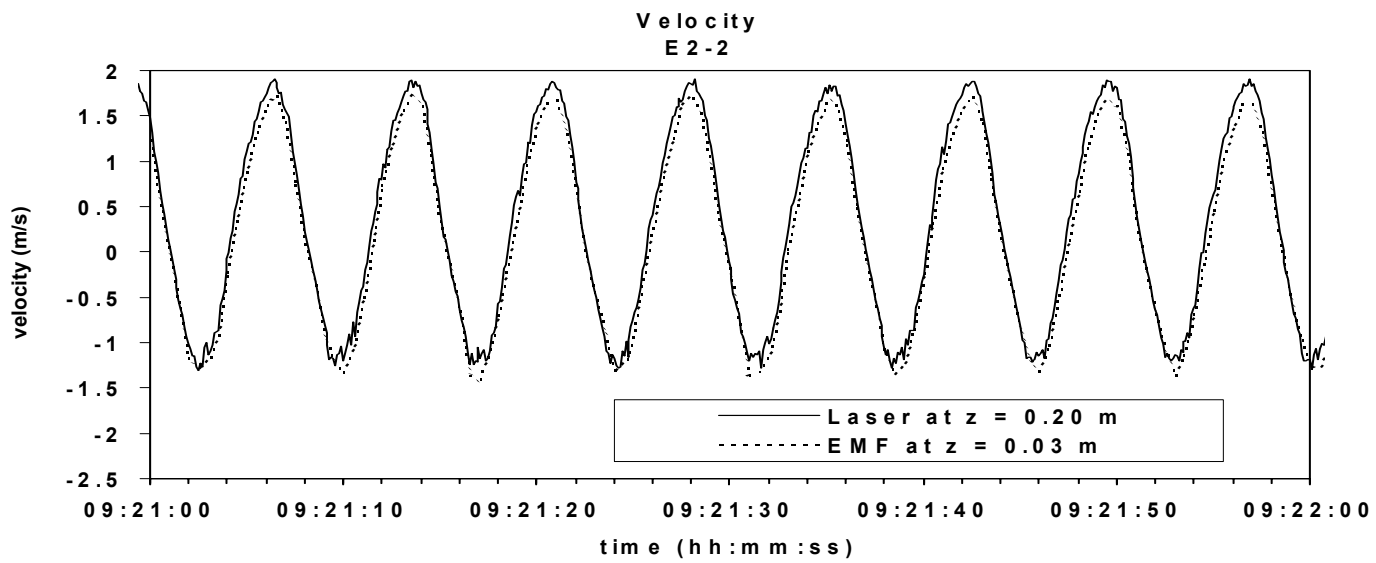
**V e l o c i t y
E 2 - 2**

Figure 2.2
Orbital velocity in water tunnel measured by Laser Doppler velocity meter and by Electro-magnetic velocity meter; Test E2-2

2.3 Comparison of velocity derived from Acoustic Doppler velocity meter ASTM and Electro-magnetic velocity meter EMF in wave tank and in surf zone of Egmond, The Netherlands

A tripod (of University of Utrecht) with various instruments (velocity meters and pressure sensors) was deployed in the wave tank during experiments on hydrodynamic and sand transport processes (De Boer et al., 1997a,b). The tripod was deployed on a horizontal sand bed placed on the bottom of the wave tank (length= 200 m, height= 7 m, width= 5 m) of Delft Hydraulics. The water depth was about 4.5 m. The acoustic velocity meters (ASTM or ADV) were mounted in the middle of the tripod. The ASTM instrument consists of five acoustical velocity meters arranged in a vertical array between about 0.1 m and 1 m above the sand bed. The ASTM is attached to a movable arm for accurate positionning of the sensors with respect to the local sand bed. Basically, the ASTM measures the horizontal velocity of the sand particles from the doppler shift in frequency of the emitted and received acoustical signals. The measurement volume is about 0.2 m (horizontally) from the transducers. Irregular waves with a peak period of 5 s were generated in the tank.

The velocity signals have also been measured by various Electro-magnetic velocity meters (EMF) attached to the wall of the wave tank and attached to the tripod. The EMF measures the fluid velocities.

Figure 2.3 shows an example of simultaneously recorded velocity signals of the ASTM and an EMF attached to the wall (at the same height as the ASTM sensor). It can be observed that the velocity signal of the ASTM and the velocity signal of the EMF are quite similar with the exception of the peak orbital velocities. Peak values measured with the ASTM are on average 10% to 20% smaller compared to the peak values measured with the EMF on the wall.

Figure 2.4 shows an example of simultaneously recorded velocity signals of the ASTM and an EMF attached to the tripod (at the same height as the ASTM sensor). Peak values measured with the ASTM are on average 10% to 25% smaller compared to the peak values measured with the EMF on the tripod.

The differences between the ASTM and EMF results can be attributed to:

- influence of the wall on the velocities measured near the wall,
- disturbance of the flow field caused by the ASTM transducers,
- disturbance of the flow field caused by the tripod in which the ASTM and EMF are mounted,
- the different measurement principles (measuring *sediment* velocity by ASTM versus *water* velocity by EMF).
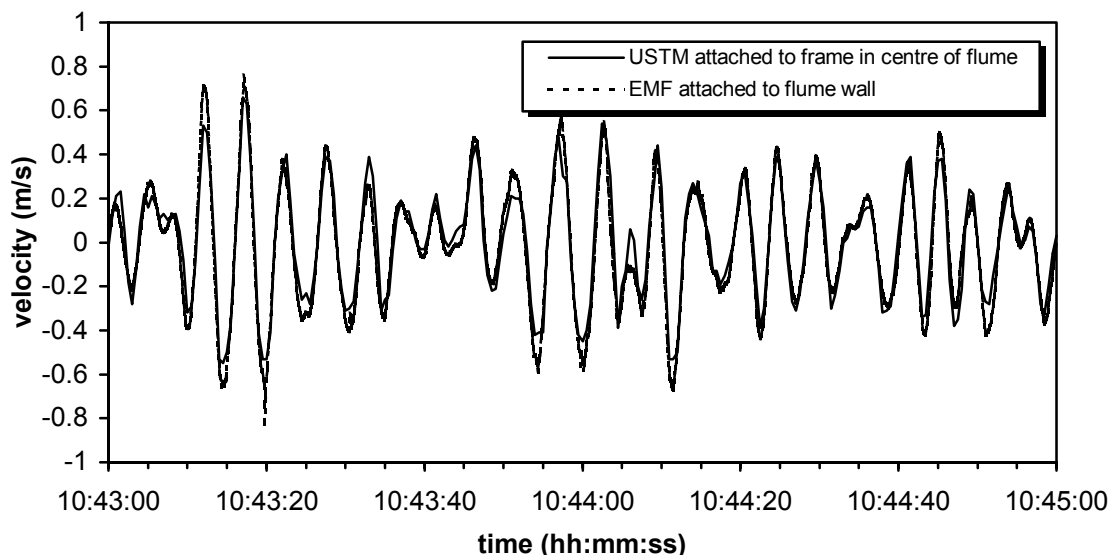

Figure 2.3
Example of simultaneously recorded time-series of velocity measured with ASTM (or USTM) and velocity measured with EMF attached to the wall at approximately 0.25 m above the bed level
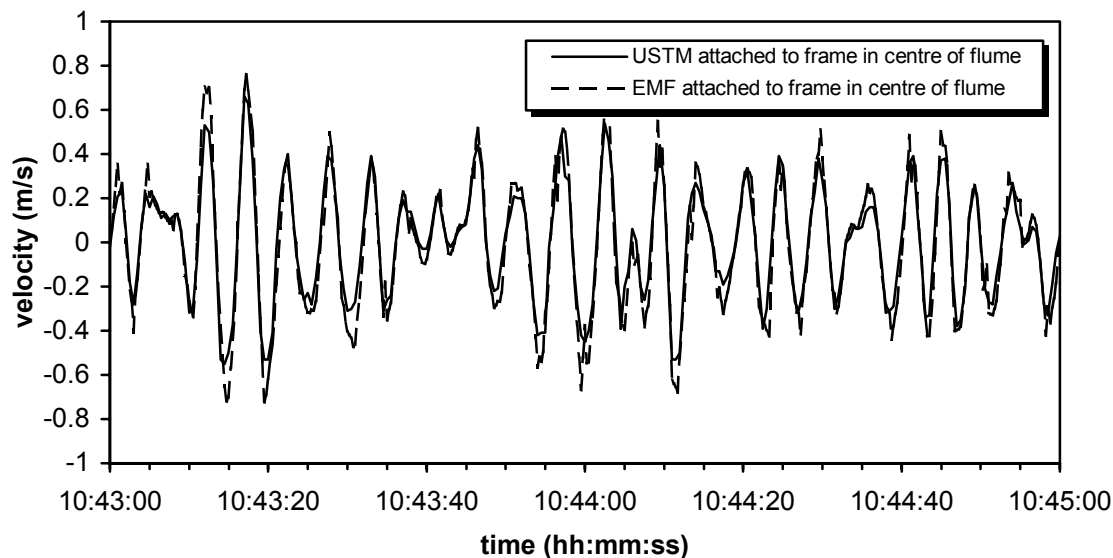
Figure 2.4
Example of simultaneously recorded time-series of velocity measured with ASTM (or USTM) and velocity measured with EMF attached to the tripod (frame) at approximately 0.25 m above the bed level

Comparison of time-averaged velocities (in the range of -0.05 to 0.05 m/s) derived from the instantaneous velocity signals of the ASTM and EMF shows relatively large differences.

Figure 2.5 shows time-averaged velocities of the ASTM, time-averaged velocities of the EMF instrument attached to the tripod and time-averaged velocities of the EMF instrument attached to the wall, in case of irregular waves with a significant wave height of 1.0 m. Near the bed the time-averaged values measured with the ASTM are onshore-directed, while the EMF velocities tend to be offshore-directed. At higher elevations above the bed ($z > 0.25$ m) the ASTM velocities are offshore-directed, while the EMF velocities are onshore-directed. In case of a larger significant wave height (Figure 2.6) the same tendency was found for the ASTM velocities and the EMF velocities measured near the tripod. The EMF velocities measured near the wall were offshore-directed at each elevation above the bed.

It is concluded that the relatively small time-averaged velocities (<0.05 m/s) of the orbital motion near the bed derived from the EMF or the ASTM velocity signals are rather inaccurate (up to 100%) due to uncertainties of 10% to 20% in the peak values of the orbital motion. The accuracy of the time-averaged velocities will increase if relatively strong external currents (tide, wind or wave-driven) are present (superimposed on the wave motion).

Similar measurements have been performed in the surf zone of Egmond (The Netherlands). The ASTM and EMF sensors were mounted on a trailer positionned in the surf zone close to a minitripod equipped with an EMF (De Boer et al., 1997a). The time-averaged velocities were in the range of 0.15 to 0.3 m/s and showed maximum differences of about 30%. The time-averaged velocities based on the EMF were generally larger than those based on the ASTM. This latter instrument becomes inaccurate in conditions with relatively small velocities, when there is not sufficient sand in suspension for accurate signal detection.

The effect of breaking waves on the performance of the EMF has been studied in a small-scale wave-current flume by Grasmeijer and Sies (1996). The vertical distribution of the time-averaged velocities was rather irregular in tests with breaking wave conditions. Local time-averaged velocities are sometimes 30% smaller than expected according to the trend of the velocity profile over the water depth.
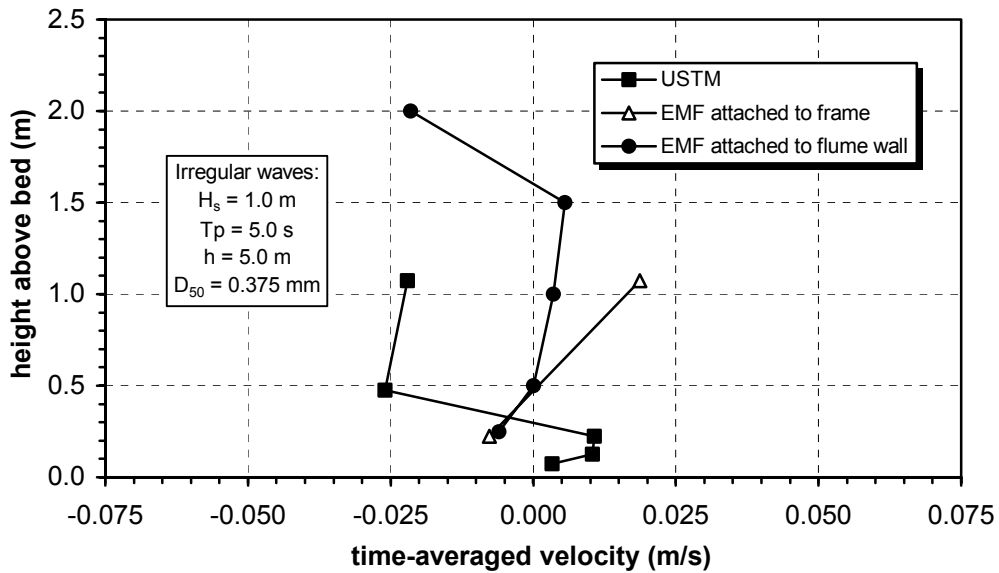
Figure 2.5
Time-averaged velocities measured with ASTM, EMF attached to tripod (frame) and EMF attached to wall;
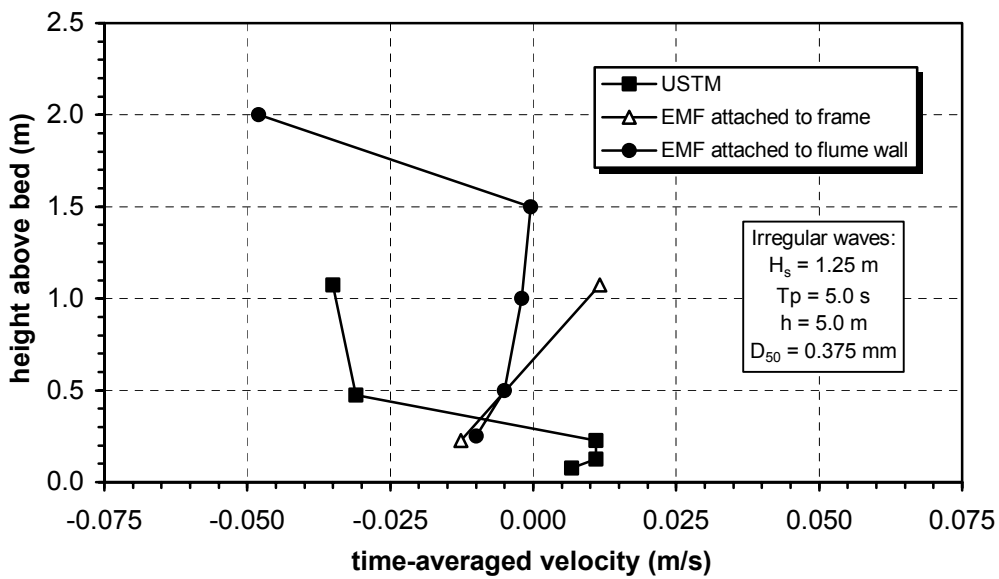*irregular waves: Hs = 1.0 m*

Figure 2.6
Time-averaged velocities measured with ASTM, EMF attached to tripod (frame) and EMF attached to wall;
irregular waves: Hs = 1.25

2.4   Conclusions

The following conclusions are given:
- peak orbital velocities of Electromagnetic velocity meters may have an uncertainty of maximum 15%; Acoustic Doppler velocity meters yield peak orbital velocities which are somewhat smaller (about 15%) than those of Electromagnetic velocity meters;
- time-averaged velocities smaller than 0.05 m/s may have an inaccuracy of maximum 100%;
- time-averaged velocities in the range of 0.15 to 0.3 m/s may have an inaccuracy of maximum 30%;
- time-averaged velocities larger than 0.5 m/s are assumed to have an inaccuracy of maximum 15%.

The inaccuracies of Acoustical Doppler velocity meters are caused by:
- air bubbles in the water (breaking wave conditions);
- insufficient suspended matter in the water during low velocities; insufficient signal detection;
- velocity of suspended matter is measured and not fluid velocity;
- practical working range for velocity range is 0.3 to 2 m/s.

The inaccuracies of Electromagnetic velocity meters are caused by:
- offset values (zero drift stability);
- air bubbles in the water (breaking wave conditions);
- wearing and fouling;
- practical working range for velocity range is 0.03 to 2 m/s.

3. Wave height measurements

3.1 Instruments

Water level fluctuations have been measured by various pressure sensors.

The University of Caen (tripod-arrangement) has used Paroscientific 2100-A pressure sensors. The precision of this instrument is 0.015 % i.e. 1 cm for a maximum range of 0-70 m (0-100 psi). The resolution is 0.0015 % (0.1 cm).
The pressure sensor of Univ. of Cean used on the S4 system has a precision of ±0.15% of the full scale (±10 cm for range of 0 to 70 m). The resolution is 4 mm.
Sources of errors in water depth and wave height derived from pressure sensors are: application of linear wave theory, variations of the water density, variations in the height of the sensor above the local bed and variations in barometric (air) pressure.

The largest contribution to the inaccuracy of the total water depth is assumed to be caused by the unknown height of the sensor above the bed related to (sometimes quite large) erosion/sedimentation near the tripod. For the Egmond main campaign (1998) the height above the bed was estimated using known water levels from permanent tidal gauges, WESP bed level soundings, and EMF burial/re-appearance data observed in the velocity time series records. Estimated accuracy of water depth is about 5 to 15 cm, occasionally up to 50 cm on steep slopes (e.g., station 1A at the Egmond site during the onset of the main campaign). Tests indicate that the uncertainty in water depth does not affect the computed wave height by more than about 10% (Ruessink, 1999). For wave height measurements in future it is recommended to install an acoustic altimeter on each tripod for continuous bed level readings.

The atmospheric pressure influence was eliminated (Univ. of Caen) by fitting a linear function between the atmospheric pressure and the height recorded by the pressure sensors above water. After compensation, residual errors (difference between the corrected height measured by the pressure sensor above water and the theoretical value that should be zero) of up to ±5 cm were observed during the main experiment at the Teignmouth site 1999. This value may be considered as a realistic order of magnitude for the accuracy of this compensation process. It nevertheless depends on the number of readings of the atmospheric pressure during the measurement period.

The pressure transducers used by the University of Utrecht have the following characteristics: ± 0.25% of measured value; linear calibration curve (correlation coefficient> 0.99). The instrument offset is determined in the laboratory prior to deployment and taken into account by the calibration curve. Afterwards, barometric (air) pressure (measured in the field every 10 minutes), is taken into account (accurate to ±1 cm).

Bird (1993) has made a review of the available literature on the accuracy of wave height measurements based on pressure sensors. Based on analysis of results from various field sites, he has concluded that a modern well designed pressure transducer system in combination with proper analysis techniques can give estimates of surface wave height to within +/-10%.

3.2 Inaccuracy related to the application of linear wave theory

Within the COAST3D project, time series of near bed pressure are routinely converted to the sea surface elevation with a depth correction using linear theory. The pressure at a distance z above the bed, p_z, is related to the pressure at the sea surface elevation, p_{sse}, as

$$\frac{p_z}{p_{sse}} = \frac{\cosh(kz)}{\cosh(kh)} \text{ for } z \geq 0 \, \text{m} \tag{3.1}$$

and

$$\frac{p_z}{p_{sse}} = \frac{e^{kz}}{\cosh(kh)} \text{ for } z < 0 \, \text{m} \tag{3.2}$$

Here, k is the frequency dependent wave number and h is the total water depth. The accuracy of the wave height computed from a time series of the sea surface elevation based on linear wave theory, will depend on (among other factors):
- the use of linear wave theory itself,
- the inaccuracy in z (and thus h), and
- the maximum frequency for which equations 3.1 and 3.2 can be applied.

The first point, linear wave theory itself, is discussed in Sections 3.3, 3.4, 3.6 and 3.7, presenting comparisons between wave height derived from pressure signals and from time series derived from direct water surface readings.

The second point, inaccuracy in z, was already briefly mentioned in Section 3.1. Based on various sensitivity tests of COAST3D, Ruessink (1999) suggested that the estimated uncertainties in water depth did not affect the wave height computations by more than about 10%. The remainder of this section will focus on the applied maximum frequency.

The maximum frequency for which Equations 3.1 and 3.2 can still be applied is often referred to as the cut-off frequency, f_c. Above f_c, amplification factors between p_z and p_{sse} become unrealistically large. The choice of f_c is related to the ratio p_z/p_{sse}, although there is no general consensus on the minimum value of this ratio to which the depth conversion using linear wave theory may be applied. However, a value of $p_z/p_{sse} = 0.1$ seems to be most commonly used. When analyzing a large data set, one could choose to compute f_c for each burst. Alternatively, one could also define a fixed f_c to be used for all bursts and all positions. This latter option has been applied within the COAST3D project. The choice of f_c is then defined by the sensor located closest to the bed in deepest water. The value $f_c = 0.33$ Hz was adopted, based on a bottom-mounted array of pressure sensors in 6 to 8 m water depth. Ruessink (1999) re-evaluated this choice for the UU tripods deployed in much shallower depth, typically 1 to 4 m. He found that, based on $p_z/p_{sse} = 0.1$, f_c for these tripods could be raised to 0.4 Hz. However, the increase in wave height caused by increasing f_c from 0.33 to 0.4 Hz was small, generally between 5 to 10%.
Obviously, the inaccuracy in wave height will increase if a considerably amount of energy is located above f_c, but cannot be reconstructed with a pressure sensor and linear wave theory. Thus, f_c should be well above typical peak frequencies that can be expected in the field. The mere 5 to 10% increase in wave height by changing f_c from 0.33 to 0.4 Hz indicates, that this condition was satisfied for the COAST3D data.

3.3   Comparison of wave height derived from pressure sensor and capacity wire in wave tank of Hannover, Germany

The experiments have been carried out in the 'Grosser Wellenkanal' (GWK; length= 300m, depth= 7 m, width= 5 m) in Hannover, Germany. Irregular waves with a peak period of 6 s have been generated in a water depth of 3.5 m (Grasmeijer, 2000).
A tripod (of University of Utrecht) with various instruments (velocity meters and pressure sensors) was deployed on a sand bed (d_{50}= 0.23 mm) in the wave tank during these experiments. The water depth above the sand bed was about 3.5 m. The pressure sensor was at 0.6 m above the sand bed.
The standard instrument to determine the wave height is a capacity wire attached to the wall of the wave tank at about 5 m seaward of the tripod location. Furthermore, the measurement period of the capacity wire was about 6 minutes longer than that of the pressure sensor.
Data are available for one wave height: H_s=1.25 m, T_p= 6 s.

The computed wave heights based on the pressure sensor (cut-off frequency of 0.4 Hz; linear wave theory) are within 5% to 10% of the wave heights based on the capacity wire system, see Table below.

Parameter	$H_{1/3}$	$H_{1/10}$	H_{rms}	H_{m0}
	(m)	(m)	(m)	(m)

Capacitance wire	1.23	1.55	0.87	1.21
Pressure sensor with correction based on linear wave theory	1.22	1.43	0.91	1.27

3.4 Comparison of wave height derived from pressure sensor and surface following wave gauge in wave tank of Delft Hydraulics

A tripod (of University of Utrecht) with various instruments (velocity meters and pressure sensors) was deployed on a horizontal sand bed in the wave tank during experiments on hydrodynamic and sand transport processes (Chung and Grasmeijer, 1999). The water depth above the sand bed was about 4.5 m. The pressure sensor was at 2 m above the bottom of the sand bed. Irregular waves with a peak period of 5 s were generated in the tank.

The standard instrument used by Delfts Hydraulics to determine the wave height is a water surface following gauge, which is operated from a (movable) bridge over the tank.

Data are available for two wave heights: H_s= 1 and 1.25 m, T_p= 5 s.

Analysis showed that a cut-off frequency of 0.5 Hz is an appropriate value to be used for converting the pressure time series to surface elevation (see Figures 3.1 and 3.2). Using a cut-off frequency of 0.4 Hz, the computed wave heights are about 2% smaller.

The computed $H_{1/3}$-wave heights based on the pressure sensor (cut-off frequency of 0.5 Hz) are about 5% to 10 % smaller than those according to the surface following gauge system, see Tables below.

Test H_s=1 m, T_p= 5 s

Type of instrument	$H_{1/3}$ (m)	H_{rms} (m)	H_{m0} (m)
pressure sensor with correction based on linear theory	0.94	0.67	1.00
surface following wave gauge 1	1.03	0.73	1.03
surface following wave gauge 2	1.03	0.73	1.02

Test H_s=1.25 m, T_p= 5 s

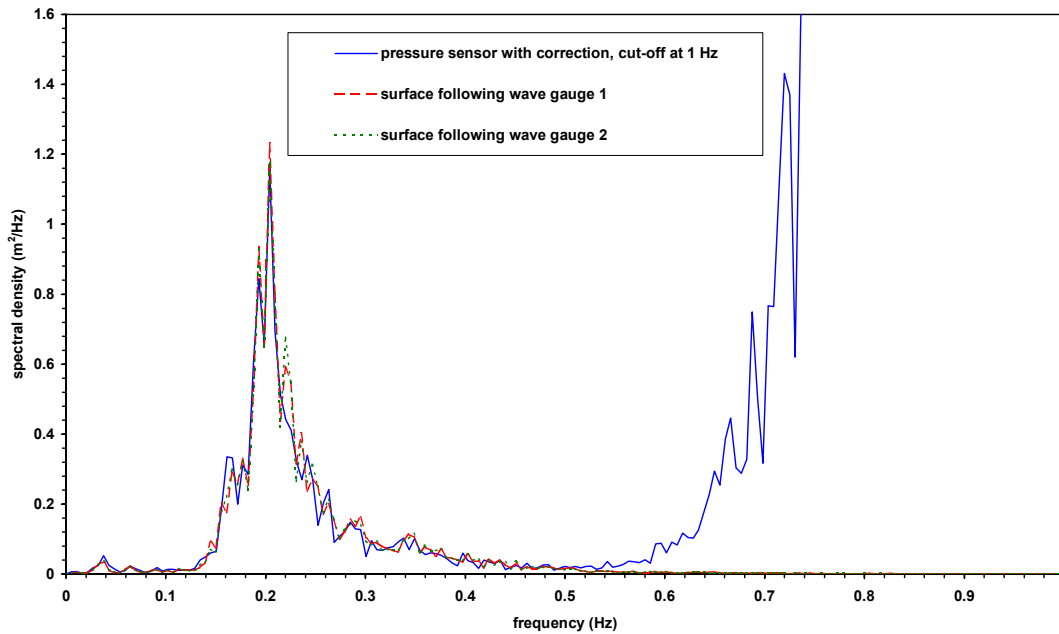| Type of instrument	$H_{1/3}$	H_{rms}	H_{m0}
pressure sensor with correction based on linear theory	1.20	0.86	1.27
surface following wave gauge 1	1.34	0.96	1.31
surface following wave gauge 2	1.32	0.94	1.30

Figure 3.1
Energy density spectrum measured in the wave tank with a pressure sensor (location x = 118 m) and two surface following wave gauges (location x = 118 and 120); pressure time series is converted to surface elevation based on linear wave theory with a cut-off frequency of 1.0 Hz.
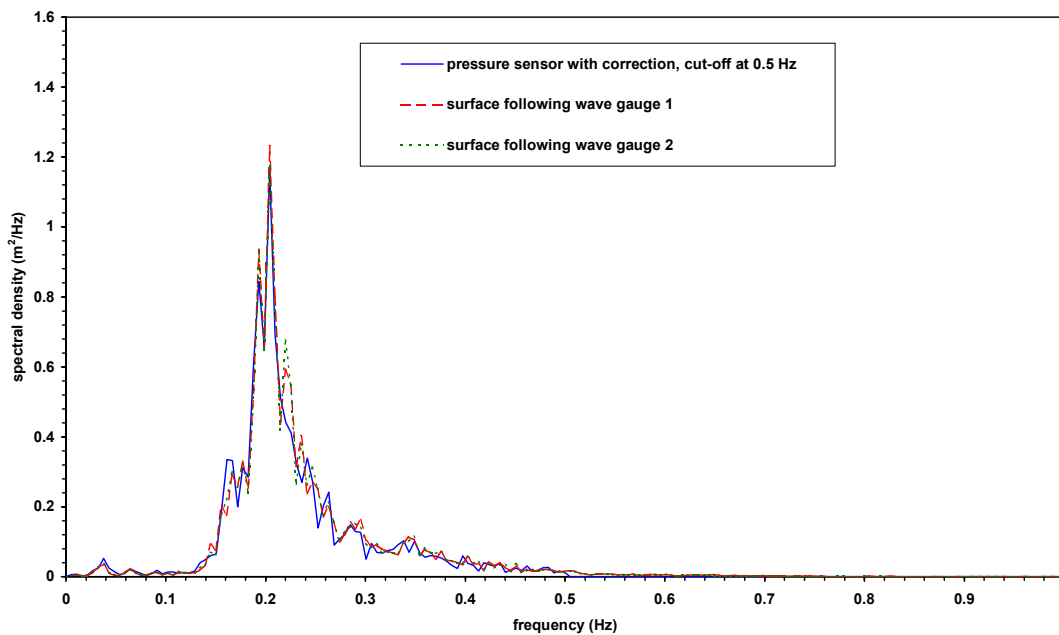

Figure 3.2
Energy density spectrum measured in the wave tank with a pressure sensor (location x = 118 m) and two surface following wave gauges (location x = 118 and 120); pressure time series is converted to surface elevation based on linear wave theory with a cut-off frequency of 0.5 Hz.

3.5 Comparison of wave height derived from pressure sensor on tripod and on Cris in surf zone of Egmond, The Netherlands

Field measurements have been carried out in the surf zone of Egmond beach (The Netherlands) within the COAST3D project (April-May, 1998 and October-November, 1998). The Egmond site is located in the central part of the Dutch North Sea coast and consists of a sandy beach (about 0.3 mm sand). The local morphology is 2.5 dimensional exhibiting two longshore bars intersected by local rip channels; the bars are

aligned parallel to the shore most of the time, but crescentic bar forms do also occur. The wave climate is dominated by sea waves with a mean annual significant offshore wave height of about 1.1 m. The tidal range varies between 1.4 m (neap) and 2 m (spring). The tidal peak currents in the offshore zone are about 0.5 m/s; the flood current to north is slightly larger than the ebb current to south. Wave height measurements (pressure sensor) have been carried at various locations (1A, 1B, 1C and 1D; around the crest of the inner bar) along the main transect using stand-alone tripods of the University of Utrecht (Grasmeijer, 2001). Wave heights have also been measured by use of a pressure sensor at the CRIS trailer connected to the WESP (of Rijkswaterstaat). The WESP is an approximately 15 m high amphibious 3-wheel vehicle; the CRIS is a 3.5 m square and 2.5 m high trailer. The instruments on the CRIS are attached to a movable arm at the seaward end of the CRIS. The CRIS was positionned as close as possible (within 10 m) to the tripod locations 1A and 1B. The measurements have been carried out in water depths varying between 1 and 5 m. The wave heights ($H_{1/3}$) were in the range up to 1.35 m (peak periods of 5 to 10 s). Relative wave heights (H_s/h) were as large as 0.4. Breaking waves were present during most measurements. Time series of the wave heights measured at tripod locations 1A and 1B and at the CRIS location are given in Figure 3.3. Analysis of the data shows that the significant wave height at the tripod locations 1A and 1B is on average about 10% larger than at the CRIS location (neglecting wave heights smaller than 0.5 m). This shows that the results of pressure sensors on different nearby stations give comparable values; the relatively small deviations are most probably caused variations in local hydrodynamics and bathymetry.
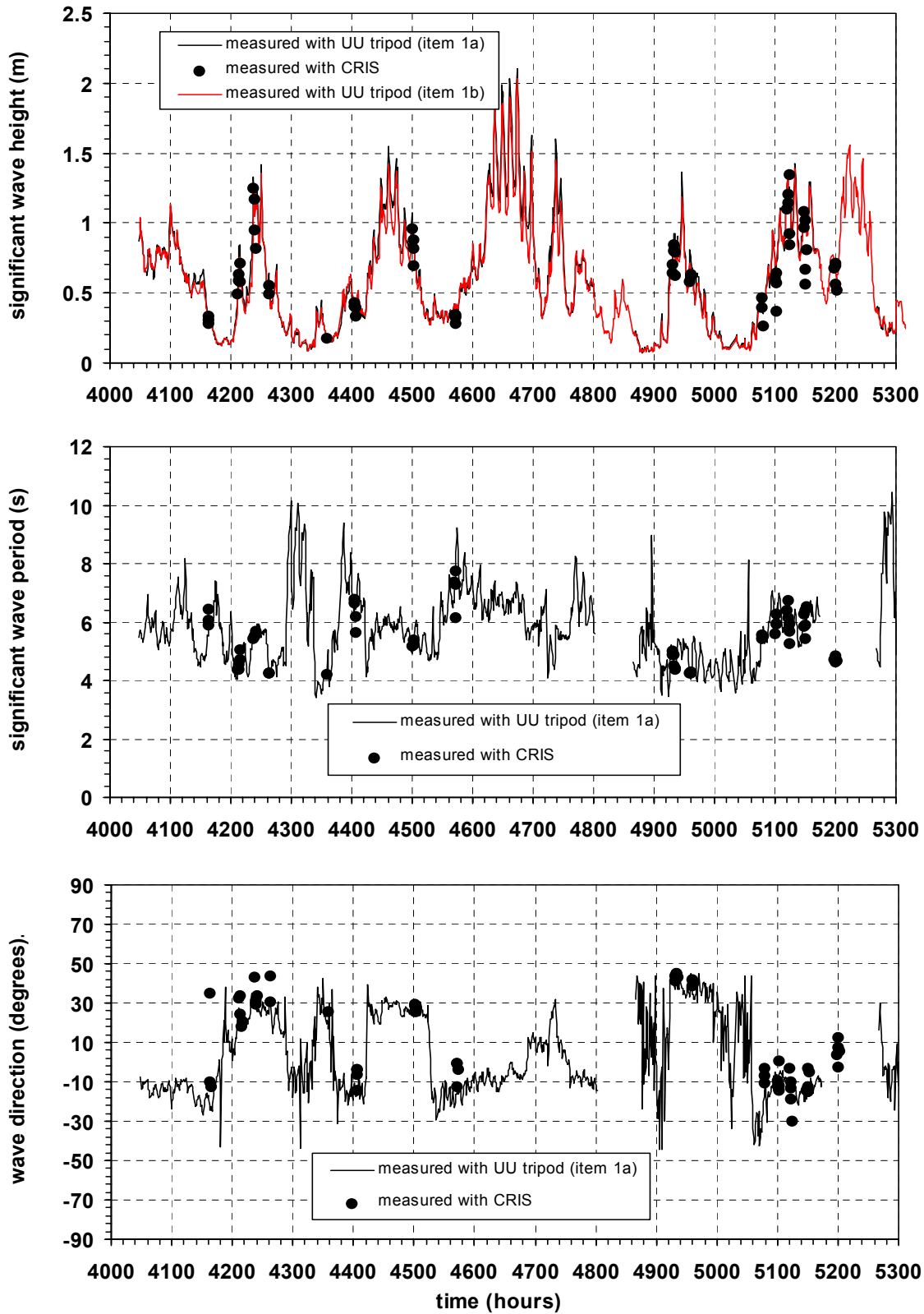
Figure 3.3
Significant wave height, wave period and wave direction measured at tripod locations 1A, 1B and at CRIS location, surf zone of Egmond, The Netherlands

3.6 Comparison of wave height derived from velocity sensor, fluid pressure sensor and capacity wires at Torry Pines Beach, California (USA)

Guza and Thornton (1980) used pressure sensors (Stathem temperature-compensated, dynamic range of 912-2316 or 912-3720 g/cm^2), electro-magnetic current meters (Marsh-McBirney, spherical, diameter of 0.04 m, three-pole output filter at 4 Hz) and wave staffs (dual resistance wires) to measure the hydrodynamics at Torrey Pines Beach, San Diego, California in the USA. All instruments were mounted on pipes which had been fluidized in the bed. Data were retrieved from the sensors by telemetering the data to the shore. Velocity and pressure spectra measured by the instruments have been related to sea surface elevation, using linear wave theory. The significant wave height is defined as $H_s=4(\sigma^2)^{0.5}$ with σ^2 = total variance of the surface elevation with frequencies between 0.05 and 0.3 Hz for a burst of 34 minutes. The data represent eight different days with rather different incident wave conditions varying from narrow banded to very broad banded spectra.

Guza and Thornton show plots of the ratio $H_{s,u}/H_{s,p}$ and $H_{s,u}/H_{s,\eta}$ as a function of water depth (between 0.5 and 6 m) at the measurement stations involved; $H_{s,u}$= significant wave height derived from measured velocity signal using linear theory, $H_{s,p}$== significant wave height derived from measured pressure signal using linear theory, $H_{s,\eta}$= significant wave height derived from measured surface elevation (wave staffs).

Analysis of the results show the following features:

- the $H_{s,u}/H_{s,p}$ and $H_{s,u}/H_{s,\eta}$ ratios usually show a discrepancy less than 10% for non breaking wave conditions in shallow and deeper water (0.5 to 6 m);
- the ratios have as much as 20% disparity for breaking wave conditions near the breakpoint of the waves;
- the significant wave heights based on direct water surface elevation measurements are systematically larger than those derived from the velocity and pressure measurements using linear wave theory;
- the relatively good agreement between H_s derived from direct measurement of surface elevation and H_s based on velocity or pressure data using linear wave theory suggests that local nonlinearity effects are not extremely strong (across all frequency bands);
- the results are valid for H_s-values in the range between 0.2 and 1.3 m in depth between 0.5 and 6 m.

3.7 Comparison of wave height derived from pressure sensor and resistance wave staff at field site Felpham, UK, 1993

Two measurement systems for wave height (Ilic, 1994) owned by the University of Plymouth and University of Brighton have been compared using data collected in water depths of 0.5 to 3.5 m (due to tidal variation). Relatively low waves have been measured (H_{mo} is 0.3 to 0.7 m in depths of about 3.5 m; and 0.3 to 0.4 m in depths of about 1 m). The measurement systems consist of:

- Plymouth pressure transducer system: the system consists of six transducers and a data recorder unit, which are held in position on the sea bed in specially fabricated supports; the output signal is in the range of 4 to 20 mA corresponding to a pressure range of 0 to 4 bar; sampling frequency was 2 Hz.; sampling cycle was 11 minutes in every three hour period;
- Brighton resistance wave staff system: the wave staff system measures instantaneous water surface elevation directly and simultaneously at four sensor positions; each sensor consists of 6 metre resistive device mounted on an alumimium scaffold held vertically from the sea bed, on a triangular base frame; a cable is used to connect the sensor array to a base station on the beach; all wave data with frequencies less than 0.75 Hz are sampled; sampling frequency was 4 Hz.

Analysis of the data show the following results (see also Table below):

- the mean water depths based on the transducer system are systematically larger than those based on the wire system; the maximum difference was about 15% for depths smaller than 1 m and about 5% for depths larger than 1 m; variations in atmospheric pressure were not taken into account and the wire system was subject to a small drift in the zero voltage offset related to temperature variations;
- the energy density spectra of transducer system do not show frequencies higher than 0.4 Hz, which is the cut-off frequency in the filter method used in the transformation of the data from pressure to water elevation levels; thus the pressure transducer system is not accurate for relatively small waves with periods smaller than about 2.5 s; large errors may occur when relatively small waves (<0.5 m) are of importance within the wave spectrum;

- for the spectra of relatively low waves with clear defined peaks, the Brighton system (after filtering) generally yields the highest total spectral energy density values (maximum difference of 15% in m_o-values; less than 10% in $H_{mo} = 4(m_o)^{0.5}$);
- for broad-banded spectra of relatively low waves without clear peaks (18 june 14.26), the Plymouth pressure transducer system yields the largest m_o-values (m_o-value is about 40% larger than that of filtered Brighton wave staff data; H_{mo} is 20% larger);
- the application of various filter methods (Welch-window, Hanning-window or Cosine-bell window) to produce energy spectra resulted in differences of about 5% for the same dataset;
- the H_{mo} derived from both instruments (after filtering) show differences of 10% for peaked spectra and up to 20% for broad-banded spectra; the H_{m0} of the unfiltered wave staff is about 25% larger than the H_{mo} of the pressure transducer for relatively small waves (<1 m), which is caused by the presence of waves with frequencies larger than 0.4 Hz (cut-off frequency for pressure transducer signal).

Date	Mean water depth (m)	$H_{mo,\text{wave staff}}$ (m)		$H_{mo,\text{pressure transducer}}$ (m)
		unfiltered time series	filtered using spectral windows	filtered using cut-off frequency and spectral windows
11 june 17.26	3.55	0.33	0.27	0.25
18 june 14.26	1.07	0.35	0.25	0.31
18 june 11.26	3.38	0.74	0.64	0.59
14 june 11.26	0.82	0.42	0.32	0.32

3.8   Conclusions

The following conclusions are given:

- rms and significant wave height in non-breaking conditions derived from direct measurement of surface elvation by use of capacity wires or derived from pressure sensors using linear wave theory may have an uncertainty of maximum 10%;
- rms and significant wave height in breaking conditions (surf zone) derived from direct measurement of surface elvation by use of capacity wires or derived from pressure sensors using linear wave theory may have an uncertainty of maximum 15%;
- significant wave heights derived from pressure sensor measurements (using linear wave theory) are systematically somewhat smaller (maximum about 15%) than those derived from direct wave elevation (capacity/resistance wires) measurements;
- wave heights derived from direct water surface elevation measurements and from pressure data using linear wave theory are in reasonably good agreement (within 15%) suggesting that local nonlinearity effects are not extremely strong;
- the energy density spectra of a pressure transducer system do not show frequencies higher than about 0.4 Hz, which is the cut-off frequency in the filter method used in the transformation of the data from pressure to water elevation levels; thus the pressure transducer system is not accurate for relatively small waves with frequencies larger than about 0.4 (wave periods<2.5 s); large errors may occur when relatively small waves (<0.5 m) are of importance within the wave spectrum.

The inaccuracy of the water depth derived from pressure sensors is strongly dependent on the inaccuracy of the vertical position of the sensor above the bed; this latter parameter should be measured continuously (acoustic depth sounder) in conditions with rather large bed level changes. The inaccuracy of the wave height is much less affected by inaccuracies of the position of the pressure sensor (except in shallow water).

4.   Sand concentration measurements

4.1   Introduction

Results of various instruments for the measurement of sand concentrations are presented.
The instruments considered are:
- pump sampler (PS);
- Optical Back Scatterance sensor (OBS);
- Acoustical Sand Transport Meter (ASTM).
Instrument characteristics are given in Section 4.2.
Comparisons of measured values by different instruments are given in Sections 4.3, 4.4, 4.5 and 4.6.

4.2   Instruments

4.2.1   Pump sampler

The pump sampler consists of a pumping system with 5 to 10 intake tubes. The intake tubes of 3 mm internal diameter are connected by means of plastic hoses to the (peristaltic) pumps. The intake openings generally are placed in a direction transverse to the plane of orbital motion. The intake velocity is about 1 to 1.3 m/s, satisfying sampling requirements. The water-sand samples are collected in calibrated buckets. The pump sampler generally is operated for 15 minutes giving an average concentration over the measurement period. The maximum inaccuracy of the pump sampling concentrations is estimated to be about 30% (Van Rijn, 1992).

4.2.2   Optical Backscatterance Sensor OBS

Instrument
The OBS is an optical sensor for measuring turbidity and suspended solids concentrations by detecting infrared light scattered from suspended matter. The response of the OBS sensors strongly depends on the size, composition and shape of the suspended particles. Hence, each sensor has to be calibrated using sand from the site of interest. The measurement range for sand particles (in water free of silt and mud) is about 1 to 100 kg/m^3. The sampling frequency generally is 2 Hz.
The OBS sensors consist of a high intensity infrared emitting diode (IRED), a detector (four photodiodes), and a linear, solid state temperature transducer. The diameter of the sensor is about 0.02 m; the length is about 0.05 m, see Photographs 1, 2 and 3 below. The IRED produces a beam with half power points at 50° in the axial plane of the sensor and 30° in the radial plane. The detector integrates IR-light scattered between 140° and 160°. Visible light incident on the sensor is absorbed by a filter. Sensor components are potted in glass-filled polycarbonate with optical-grade epoxy.
The sensor gain of the OBS has to be adjusted in order to match the highest output voltage expected from the OBS during the measurements with the input span of the data logger. Undesirable results will be obtained if the gain is not correctly adjusted. When the gain is too high, data will be lost because the sensor output is limited by the supply voltage and will "saturate" before peaks in sediment concentration are detected. If the gain is too low, the full resolution of the data logger will not be utilized.
Experiments have shown that the sensor gain varies with particle size. Ranging from mud (< 10 μm) to sand (> 200 μm) the gain decreases approximately by a factor 10.
The OBS sensors are about the same size (or larger) as the length of gradients in the sand concentration being measured. This may cause hydrodynamic noise in the output signal because the turbulent flow around the sensor redistributes the particles in the water and increases the variation of sediment concentration above natural levels. Furthermore, the volume sampled by the OBS sensors depends on how far the IR beam penetrates into the water. This decreases as sediment concentration increases and so the sample volume is constantly varying with concentration which may also cause random noise in the output signal. From limited tests performed by the manufacturer it appeared unlikely that the random noise would exceed 30% of the mean signal in situations with high concentrations of coarse sediment. The manufacturer recommends post processing the data with a low-pass filter to reduce the random noise in the output signal.
Other noise in the output signal may be caused by electronic noise or environmental conditions. According to specifications, the electronic noise is insignificant for most applications. Some causes for environmental

noise are: biofouling, excess in suspended sediment resulting from scour around instrument structures and cables moving in front of the OBS sensor with the currents.

Calibration results from Utrecht University

A detailed description of the calibration of OBS sensors is given by Van de Meene (1994). The OBS sensors were calibrated in a calibration tank of the Physical Geographic Laboratory at Utrecht University. Water is circulated in a closed circuit by a strong slurry pump. The sediment is added from above in a large perspex cylinder. The circulating water-sediment mixture is jetted into the cylinder, where the flow expands and decelerates. A flow straightener is present to make the flow as smooth as possible. The water sediment mixture flows undisturbed along the sensors with a velocity of approximately 0.25 m/s, which is large enough to suppress inhomogeneities due to settling and small enough to prevent inhomogeneities due to turbulence. Two OBS sensors can be calibrated simultaneously. A suction tube is present near the sensors to draw concentration samples. The calibrations were carried out using c_{input} (=mass of sand in system divided by volume of water) as the actual concentration. According to Van de Meene (1994) the sediment distribution across the horizontal plane in the measurement region appeared reasonably homogeneous. Variations were in the order of 5 to 10% of the mean concentration.

Figure 4.1 shows examples of the calibration curves for the OBS sensors used for the experiments carried out in the GWK, Hannover (grain size characteristics are $D_{10} = 0.14$ mm, $D_{50} = 0.23$ mm, $D_{90} = 0.34$ mm).
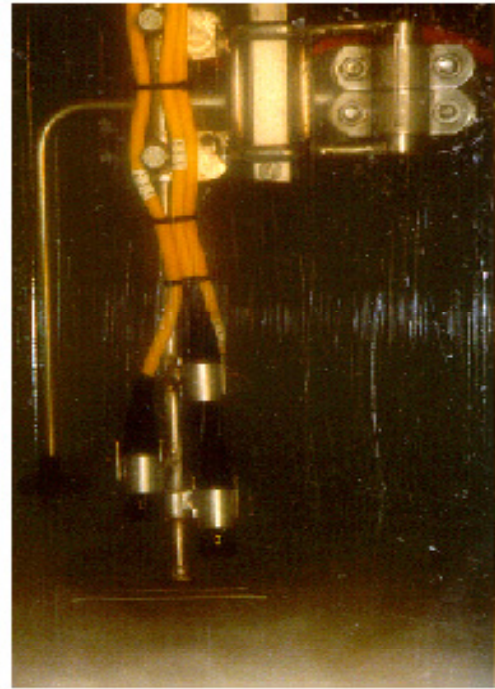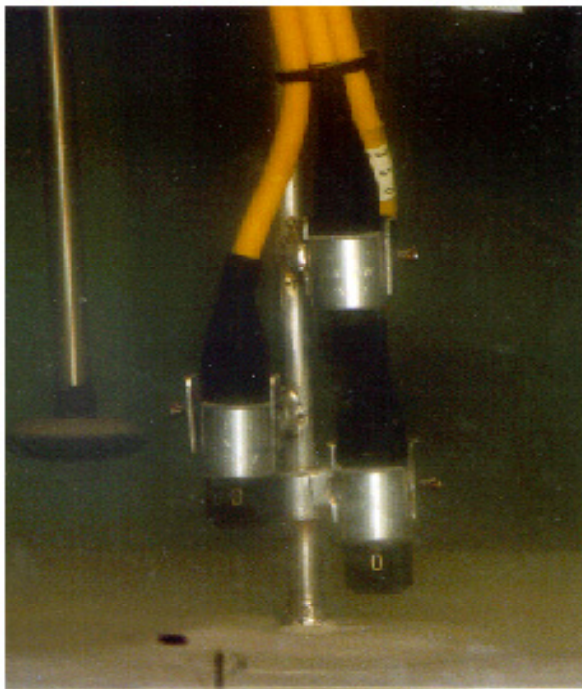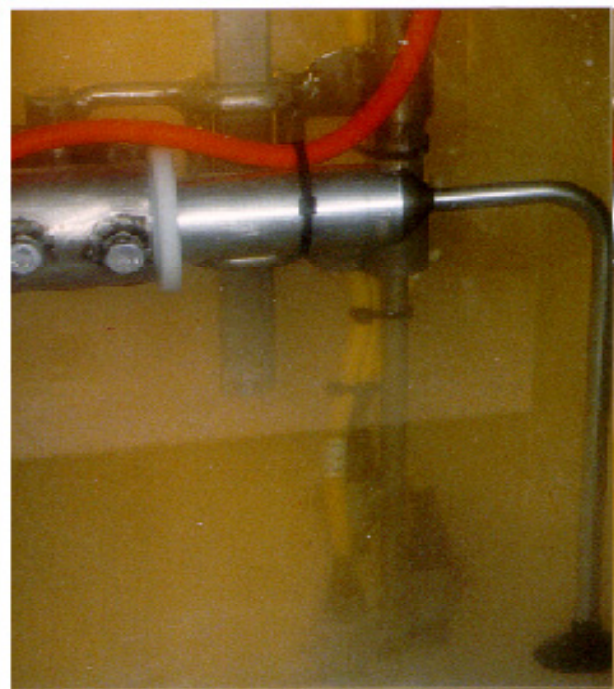
Photo 1

Photo 2

Photo 3

Photo 4

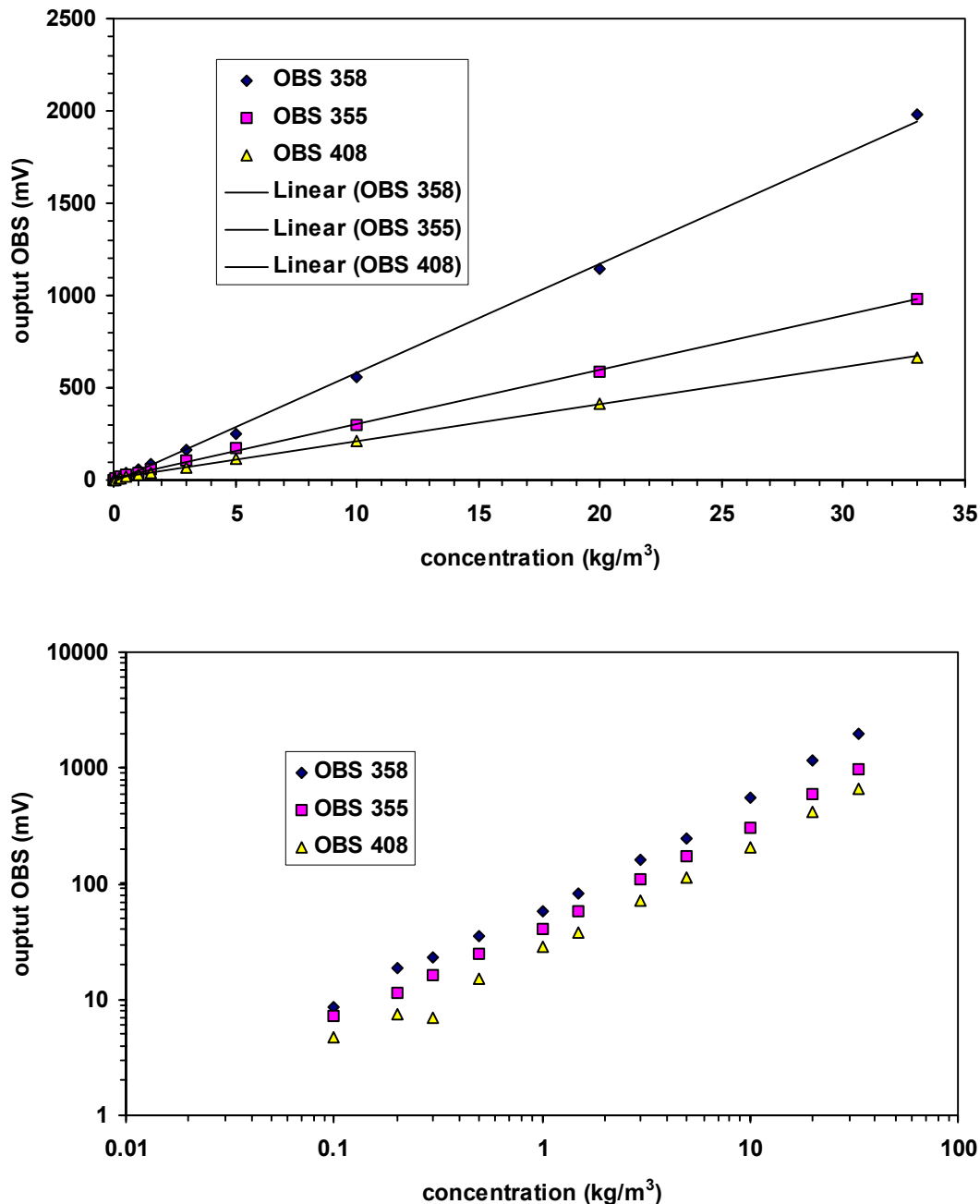| | 11-03-'98 | |
| OBS - Transportmeter
($U_{max, on}$ = $U_{max, off}$ = 1,3 m/s) Test H5 | | |
| wL \| delft hydraulics | Z 2378 | FIG. 5.2.8 |

Figure 4.1
Calibration of OBS sensors used during GWK Hannover experiments

Figures 4.2 to 4.4 show calibration results using the bed material from tests in the LOWT (two types of sand: D_{50} = 0.12-0.13 mm and 0.19-0.21 mm; d_{50} varied slightly based on samples before and after the tests). The different response of the OBS sensors to the two different grain sizes is reflected by the different slopes of the calibration curves. Figure 4.3 shows this influence of the grain size on the calibration factor (slope of calibration curve). It can be observed that the calibration coefficient is 2 to 3 times smaller when the grain size decreases with 30%.

Figure 4.4 shows the OBS concentrations measured in the calibration tank compared to the sand concentrations from a pump sampler. It can be seen that the OBS concentrations show favorable comparison to pump concentrations larger than 1 kg/m^3. OBS values significantly deviate from pump concentrations smaller than 1 kg/m^3. A systematic overestimation of the measured values can be observed for concentrations below 1 kg/m^3.
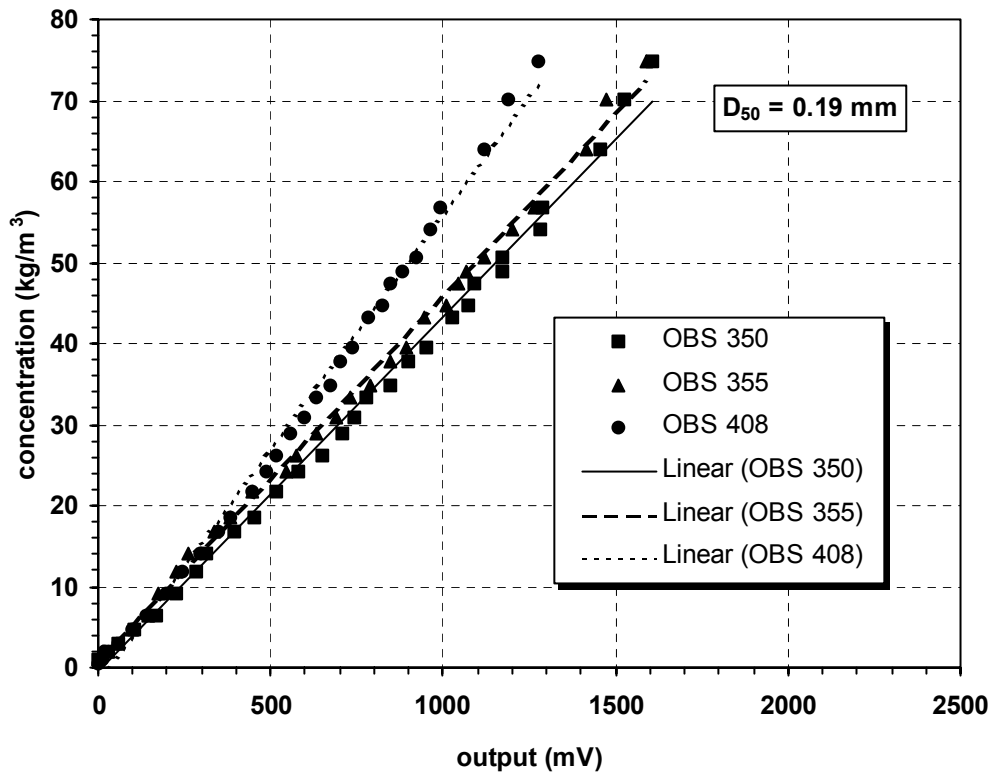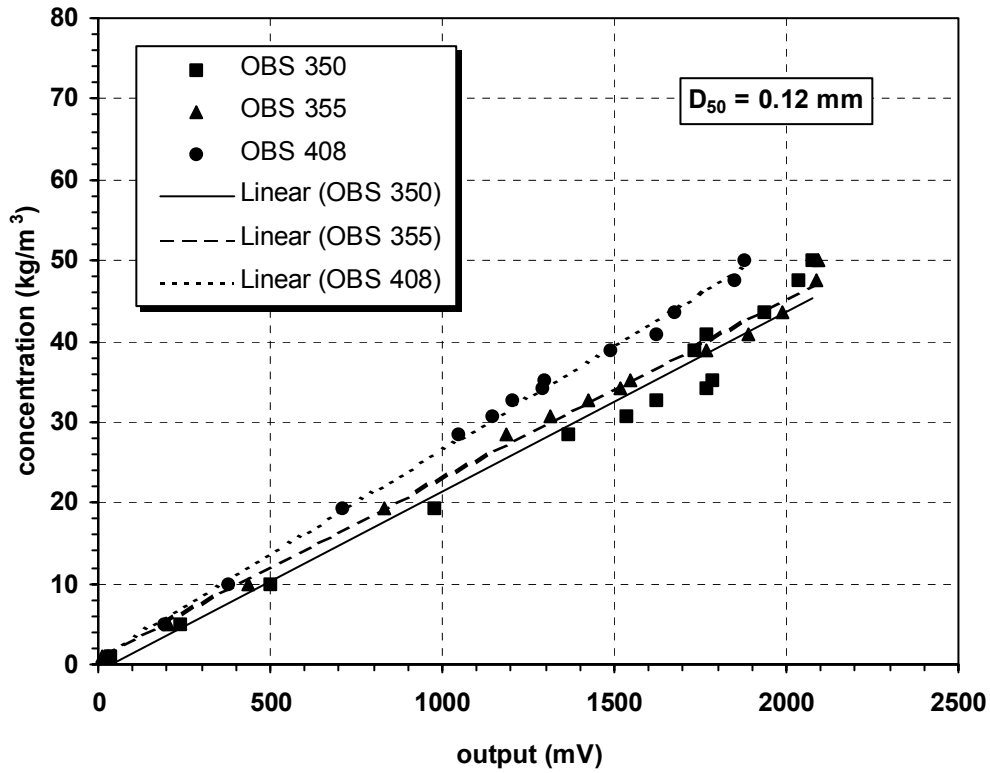
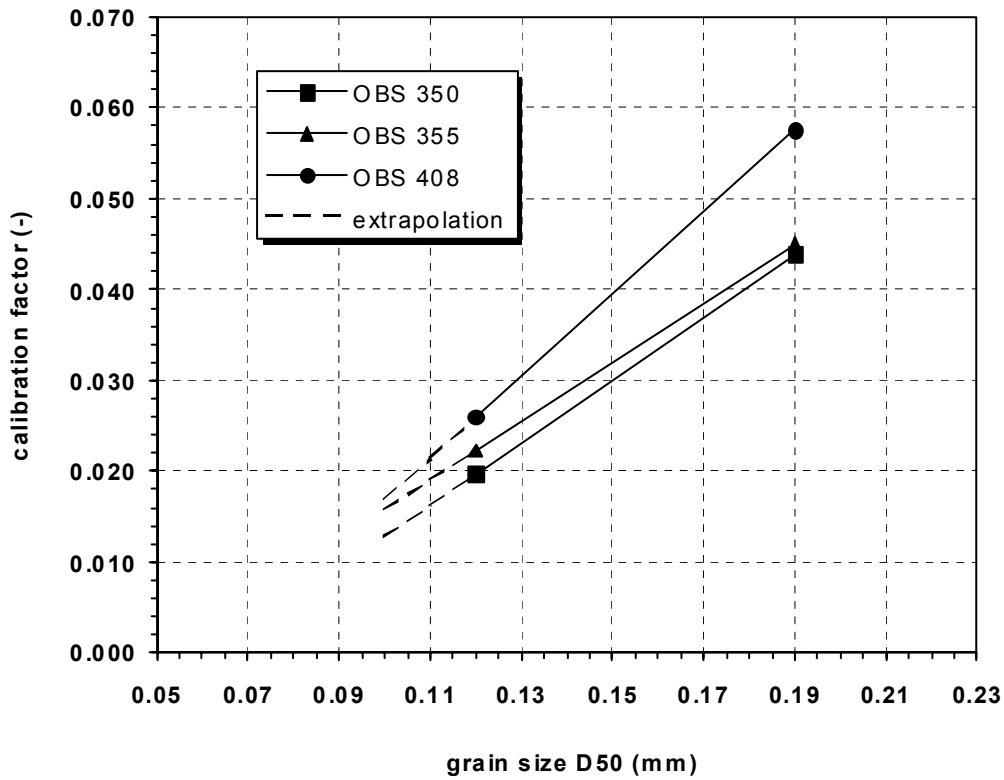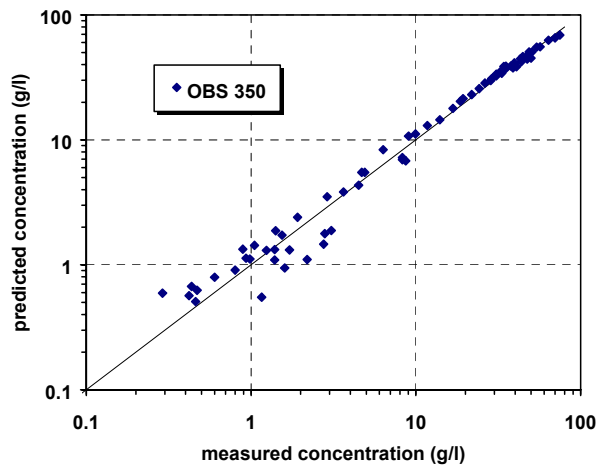*Figure 4.2*
Calibration of OBS for LOWT experiments

Figure 4.3
Influence of sediment grain size on slope of OBS calibration curve, Oscillating Water Tunnel Experiments; calibration factor is slope of calibration curves (in kg/m^3 per millivolt)
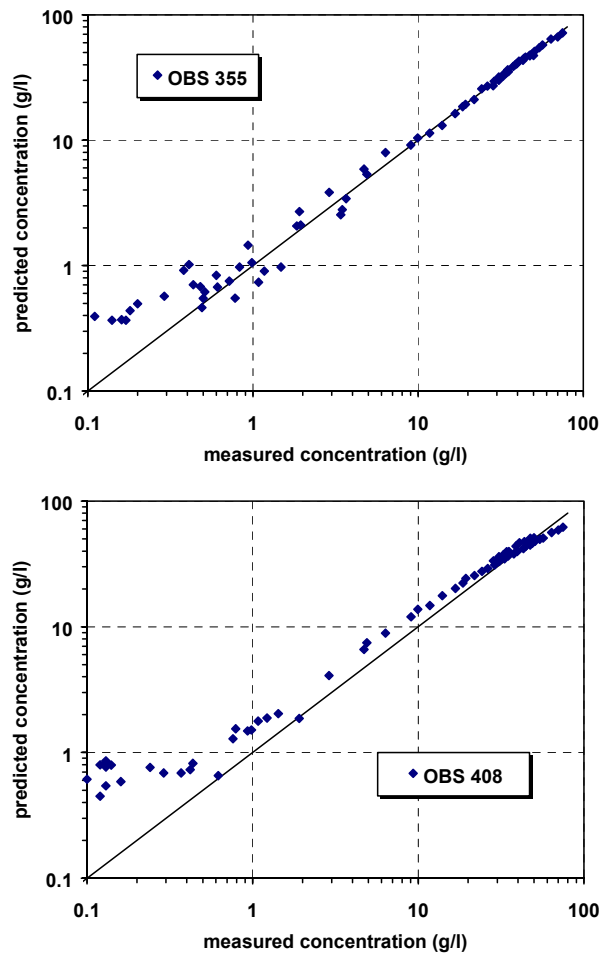
Figure 4.4
OBS concentration based on calibration curves as a function of time-averaged pump concentration in the calibration tank; two calibration curves with different sediment sizes (D_{50} = 0.12-0.13 and 0.19-0.21 mm) were used.

The OBS sensors often show a reasonably steady offset concentration, which is related to the background concentration of relatively fine sediments (silt and mud). It is common practice to subtract this offset value from the original time series data. The offset can be defined as the mimimum value of the data record (burst) or as the 1% to 5% lowest value of the signal. For example, Battisto et al (1999) found that the most appropriate cut-off voltage at the Duck site (USA) was 1% to 5% of the signal values.

Figure 4.5 shows time series values of two OBS sensors and one ASTM sensor (see Section 4.2.3) for experiment M2 carried out in the large scale wave tank of Delft Hydraulics (Chung and Grasmeijer, 1999). The time-averaged ASTM-concentrations were about 1.3 kg/m³ at 0.115 m above the bed and 0.6 kg/m³ at 0.215 m above the bed. The OBS signal shows a background voltage of about 50 mV, which is equivalent to a concentration of about 0.5 to 1 kg/m³. Hence, the background concentration to be subtracted from the record is of the same order of magnitude as the sand concentration, which makes the application of the OBS sensors rather dubious in the sand concentration range below 1 kg/m³. The acoustical ASTM sensor (see Section 4.2.3) does not show a background cocncentration due to fine sediments. This instrument is not sensitive for fine sediments (<0.05 mm; smaller than the sand range).
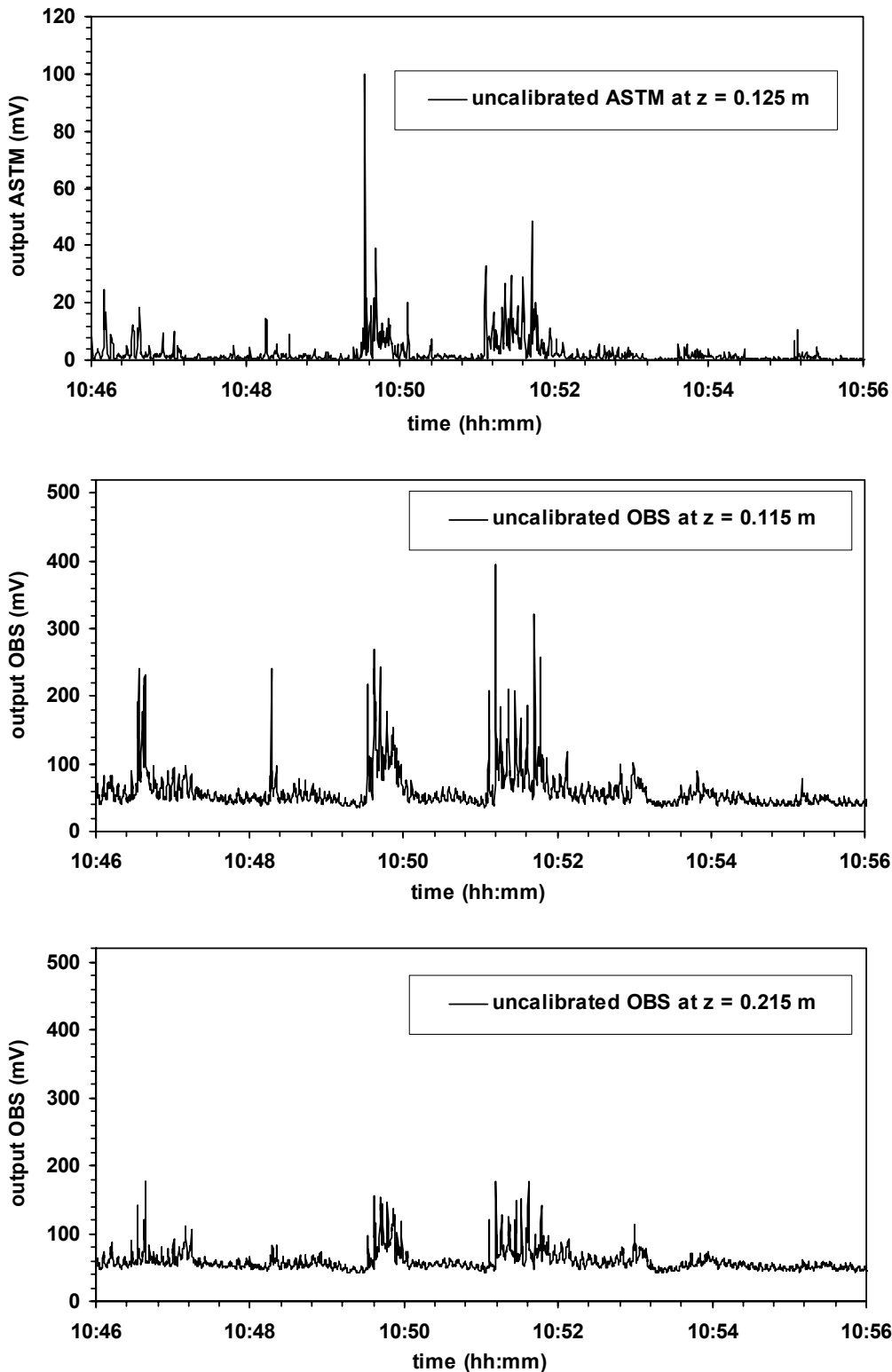
Figure 4.5
Comparison of uncalibrated ASTM (or USTM) and OBS signals.
Delta flume M2, $H_{m0} = 1.5$ m, $T_p = 5.0$ s, $h = 4.55$ m, $D_{50} = 0.16$ mm.

Calibration results from Duck site, USA

Battisto et al (1999) have made a comparison between OBS and pump sampler concentrations measured in the surf zone at the Duck site (USA) during October 1997. For this study, OBS sensors were calibrated separately using sand and mud collected at the Duck site. OBS voltage gain associated with mud was found to be an order of magnitude larger than that for sand. Based on this calibration, Battisto et al show that the

concentration of particles smaller than 0.063 mm pumped at the Duck site during October 1997 correspond to the lowest 1% to 5% of the output voltage recorded by the OBS sensors (background turbidity). The intake tubes of the pump sampler were positioned approximately 0.1 to 0.2 m above the bed.

Calibrated OBS response above this background turbidity level was consistent with pumped sand concentration as long as corrections were made for 1) varying size of suspended sand, 2) the precise time of pump sampling, 3) apparent noise in the OBS records. Corrections for the smaller size of the suspended sand relative to that used during calibration resulted in a decrease of the OBS sand concentration by about 50%. Accounting for signal noise resulted in a decrease of the OBS sand concentration by about 0.05 to 0.2 kg/m^3. Despite these corrections the OBS concentrations are considerably larger (factor 2 to 5) than the pump concentrations for sand concentrations smaller than 1 kg/m^3. Hence, OBS data are unreliable for c<1 kg/m^3.

4.2.3   Acoustic Sand Transport Meter ASTM

Instrument

The USTM or ASTM (Figure 4.6) is an acoustical instrument for measuring the flow velocity and the sand concentration. The *fivefold two-dimensional* ASTM consists of five identical sensors. Each sensor consists of one transmitter and two receivers in a horizontal arrangement (measurement volume is about 0.2 m from transmitter). The transmitter produces a 4.4 MHz signal, which is scattered by the sediment in suspension in front of the transmitter. This signal is subsequently sampled with a frequency of 2 Hz. The backscattered signals are analysed to obtain the signal intensity and the frequency shift (Doppler effect). The velocity of the sand particles can be derived (without calibration) from the frequency shift. The signal intensity is a measure of the sand concentration and also depends on local sediment characteristics such as the texture, the angularity and the density of the sediment (calibration curve). The measurent range for the sand concentration is about 0.1 to 10 kg/m^3. According to the manufacturer (Delft Hydraulics) the maximum error amounts to about 3% of the measured velocity value and 30% of the measured concentration value.
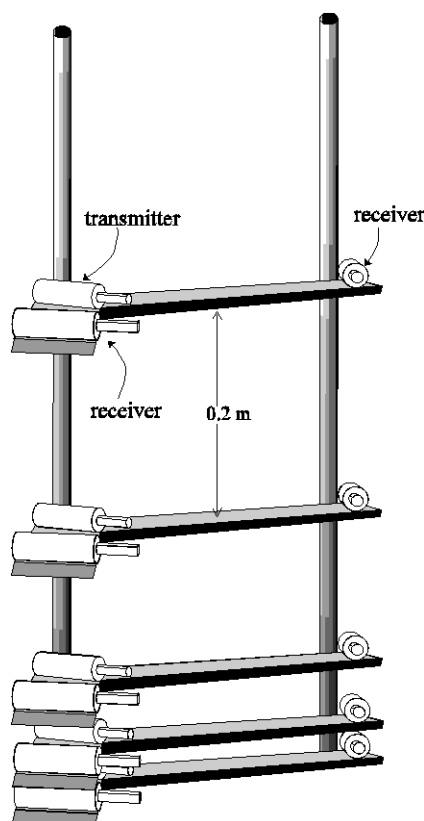

Figure 4.6
The fivefold two-dimensional ASTM (or USTM)

Calibration curve

The ASTM has been calibrated using pump sampling concentrations obtained during experiments in the Deltaflume (Chung and Grasmeijer, 1999). The five intake openings of the pump sampling equipment were positionned close to the acoustic sensors. Details are described in Section **4.4.**

The time-averaged sand concentrations measured by the five intake tubes of the pump sampler near the acoustic sensors have been used to determine the calibration curve of the ASTM. The time-averaged (over about 15 min) sand concentrations are between 0 and 3.7 kg/m^3 for the coarse sediment (0.33 mm sand) and between 0 and 2.7 kg/m^3 for the finer sediment (0.16 mm sand). The results are shown in Figure 4.7. It can be observed that for concentrations larger than $\pm$ 0.05 g/l the output of the ASTM varies linearly with the sediment concentration. For smaller concentrations (< 0.05 g/l) the ASTM output is larger than may be expected for a linear relationship. This is in agreement with the measuring range of the ASTM according to technical specifications (0.1 < c < 10 kg/m^3).

The calibration curve can be represented by: Concentration$_{ASTM}$ = 0.257*Output$_{ASTM}$. The effects of particle size (d_{50}= 0.16 mm and d_{50}= 0.33 mm) can not be detected.
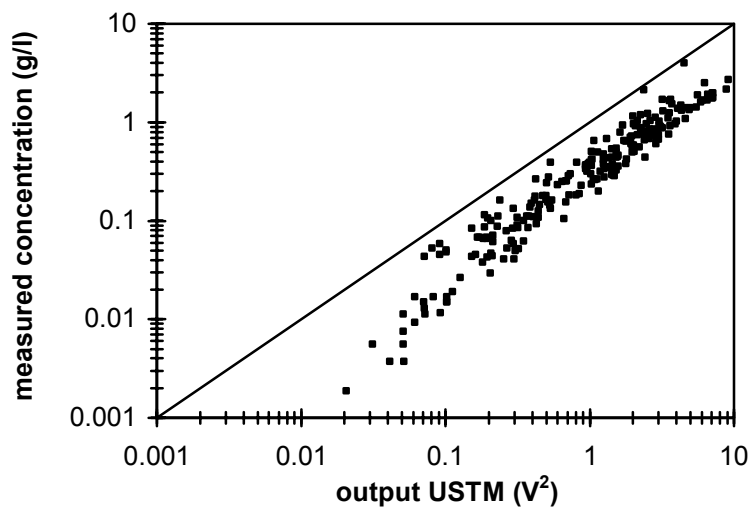

Figure 4.7
Time-averaged output of ASTM sensors plotted against the sediment concentration measured with the pump sampling system

4.2.4   Acoustic Backscatter Sensor ABS

The ABS system produces instantaneous vertical profiles of sand concentrations, which are inferred from the backscatter signal of acoustic transducers mounted at around 1 m above the sand bed looking vertically downward. Generally, three transducers operating at about F_1= 1, F_2= 2 and F_4= 4 MHz are used (Thorne et al., 1991; Vincent et al., 1998). Vincent and Green (1999) described an arrangement with a pulse-repetition rate of 80 Hz; each profile recorded consisted of an average of 16 pulses (5 Hz). The vertical resolution is 1 cm. The concentration range is about 0.1 to 20 kg/m^3. The system was calibrated in a laboratory recirculating suspension tank using sand from the deployment site (0.33 mm sand).

The mass concentration at range r from the acoustic transducer is estimated from a function, depending on the voltage V measured at range r, the sediment density, the speed of sound in water and the attenuation of sound by water and sediment of radius a. The attenuation is a complex form function of ka, which describes the efficiency with which sediment of radius a backscatters sound of acoustic wavenumber k. Three different acoustic frequencies are used to simultaneously determine the size and concentration of the suspended sediment involved.

The strongest acoustic echoes are used to identify the position of the sand bed. Close to the bed, the bed echo dominates the backscattered signal. The concentration at 1cm above the bed is defined at the height at which the first uncontaminated echo occurs, which is identified from a break-in-slope in the concentration profile close to the maximum backscattered signal in the burst-averaged profile. The uncertainty in height is about ±0.5 cm.

The concentration profiles measured by the three transducers should be identical, if the calibration conditions are perfect, which means that the suspended sand has the same size distribution at all heights in the water coloumn at the field site and in the laboratory tank. Vincent and Green (1999) show examples of concentration profiles based on the three frequencies, which have relatively large differences (factor 3, see Figure 4.8) in concentrations. The concentration profiles were calculated using the results of the calibration tank (based on 0.33 mm sand from the bed at the field site). The concentration profiles differ systematically with F_1 concentration < F_2 concentration < F_4 concentration. When the backscatter data are re-processed using F_1 simultaneously to obtain concentration and size, the sand concentrations are between those of F_2 and F_4 concentration, and the suspended sand size varies between 0.25 and 0.15 mm. It is assumed that the suspended sand has a Gaussian distribution at every height and that the width of the distribution is constant. When the F_1 and F_4 frequency pair is used, the suspended sand sizes become smaller and the concentrations become larger; the latter show a discontinuity due to the shape of the form function yielding ambiguous results for F_1-F_4 pair. This latter combination of frequencies is very sensitive to small errors in backscatter intensity. These analysis results suggest that the sizes of the suspended sand at the field site differ significantly from that of the bed material used in the calibration procedure. The concentrations derived from the F_1-F_2 pair were found to be the most reliable. Vincent and Green concluded that the applied form function is not quite right and should be reconsidered.

Another problem is the elimination of the effects of air bubbles in the water column, if the ABS system (highly sensitive to air bubbles) is used in the surf zone with breaking waves (Huck et al., 1999). This can be done by analysis of the time-averaged concentration profiles, which should show a decreasing concentration with increasing height above the bed. If large amounts of bubbles are present, the concentration profiles derived from the ABS will show an increase of concentration at higher levels. These data records should be excluded from the analysis.

The optimum conditions for the ABS system are: rather uniform fine sand (0.1 to 0.3 mm) in non-breaking wave conditions.
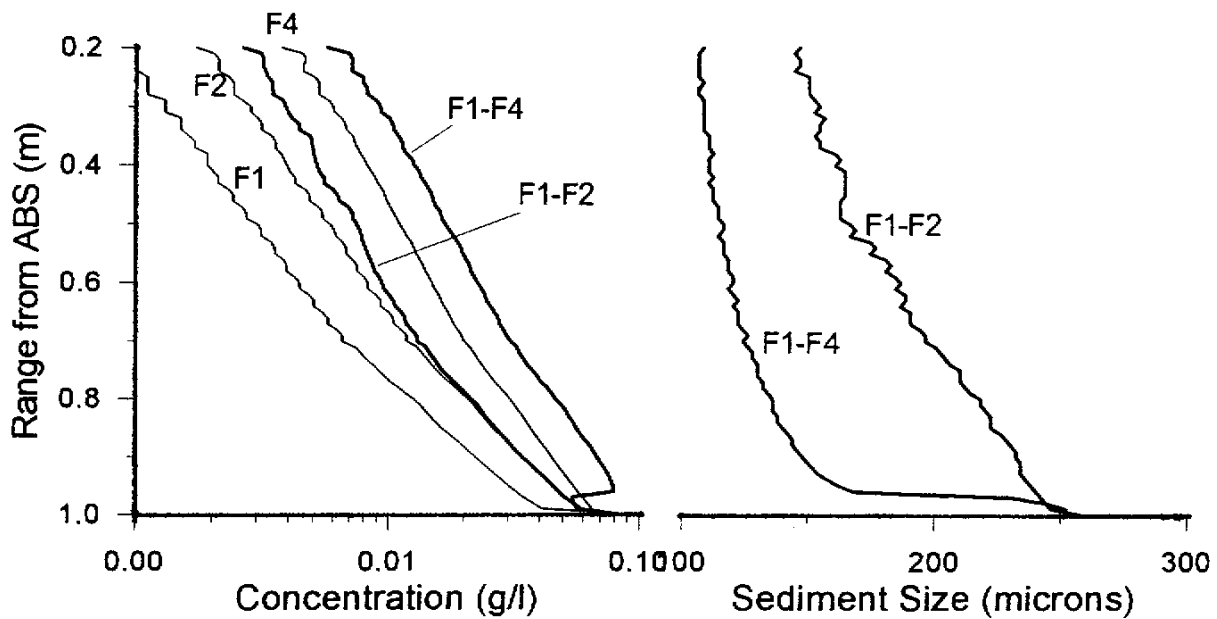
Figure 4.8
Left: *Time-averaged sand concentration profiles calculated for F_1, F_2, F_4, F_1-F_2 pair simultaneously and*
          F_1-F_4 pair simultaneously based on a mean sand size of 0.33 mm; Pacific East Coast New Zealand
Right: *Time-averaged values of suspended sand size derived from F_1-F_2 signals and from F_1-F_4 signals*

4.3   Comparison of OBS and pump sampler in large scale wave tunnel LOWT

Instruments
Grasmeijer (in Walstra et al, 1998) did measurements over a sand bed in the Large Oscillating Water Tunnel
(LOWT) of Delft Hydraulics using the OBS and a pump sampling system. The LOWT is described in
Section 2.2. The OBS sensors were calibrated using the sand bed material in the LOWT (D_{50} = 0.12-0.13 mm
and 0.19-0.21 mm; D_{50} varied slightly based on samples before and after the tests). Three OBS-sensors have
been attached to a vertical rod on a footplate (see photographs above); an EMF velocity probe is also
connected to the rod. The footplate is resting on the bed and can move downwards (due to the movable
instrument arrangement) when the bed surface is eroding. Using this arrangement, an approximately constant
distance can be maintained between the bed and the measurement elevations of both EMF and OBS-sensors
during a short measurement period of say 15 to 30 minutes The EMF-sensor is placed at 0.05 m above the
upper side of the footplate. The OBS-sensors are placed at distances of 0.03, 0.05 and 0.1 m above the upper
side of the footplate. The effective measurement elevations of the OBS-sensors with respect to the
surrounding bed surface are approximately 0.025, 0.045 and 0.095 m, as the instrument will sink down into
the bed over about 0.005 m (due to local erosion).
The pump sampler consisted of a vertical array of 10 intake tubes of 3 mm internal diameter connected to the
pumps by plastic hoses. The lowest intake tubes were placed at about 0.01 m above the bed, with the intake
openings placed in a direction transverse to the plane of orbital motion. The intake velocity was about 1 m/s,
satisfying sampling requirements. The 10 liter samples were collected in calibrated buckets. The pump
sampler was operating for 15 minutes giving an average concentration over the measuring time. In case of
fast bed level variations due to large transport rates the operation time of the pump sampler was reduced to 8
minutes giving 5 liter samples. The suspended sand samples at each level above the bed were analyzed to
determine the size composition of the sand.
It was found from the suspended sand samples that in case of relatively coarse bed material (D_{50} = 0.19-0.21
mm), the median diameter of the suspended sand at z = 0.025 m and z = 0.095 m above the bed is
approximately 20%, respectively 30% smaller than the median grain size of the bed material. In case of
relatively fine bed material (D_{50} = 0.12-0.13 mm) the vertical sorting was less pronounced. For nearly all
tests with fine sand and at all three heights above the bed the median diameter of the suspended sand was
approximately 10% smaller than the median grain size of the bed material.

To take the effect of a varying grain size with height above the bed into account, the OBS concentrations were determined from the calibration curve using the particle size of the suspended sand at the same level as the OBS.

Experimental programme

Two different test series were performed using two different sediment sizes with a median diameter of 0.19-0.21 mm and 0.12-0.13 mm respectively. Regular asymmetric wave motion (second order Stokes) and irregular wave motion were generated. Orbital velocities were measured by means of a Laser Doppler velocity meter at about 0.1 m and 0.2 m above the bed. Most tests were repeated twice to determine the variation related to small differences in bed arrangement (refilling of sand in the tunnel).

The test procedure was as follows:
- positioning of OBS transport meter on bed; foot plate flush with bed surface;
- positioning of vertical array of intake tubes with lowest intake tube at 0.01 m above bed;
- generation of oscillatory flow during 10 to 20 min.;
- establishment of equilibrium bed conditions during about 10 min.;
- sampling of water-sediment mixture through each intake tube after establishment of equilibrium conditions;
- separation of water and sand; determination of wet and dry sand volumes of samples.

Comparison of OBS and pump sampler

Figures 4.9 and 4.10 show examples of time-averaged concentration profiles measured with OBS sensors and the pump sampler in the Large Oscillating Water Tunnel. It can be observed that the concentrations measured with the OBS and the concentrations measured with the pump sampler are of the same order of magnitude. On average, the OBS sensors gave values that were 15% larger (two largest deviations are 250% and -70%) in case of coarse sand (0.19-0.21 mm) and 30% larger (two largest deviations are 150% and -50%) in case of fine sand (0.12-0.13 mm) than the values determined with the pump sampler. The largest differences were found for test B2 and H2 in which the concentration gradient is relatively large (fine sand, small orbital velocity and weak current compared to other tests).

Values from the OBS sensors showed favorable comparison to values from the pump sampler in case of relatively large sand concentrations (larger than about 1 kg/m^3, see Figure 4.9).
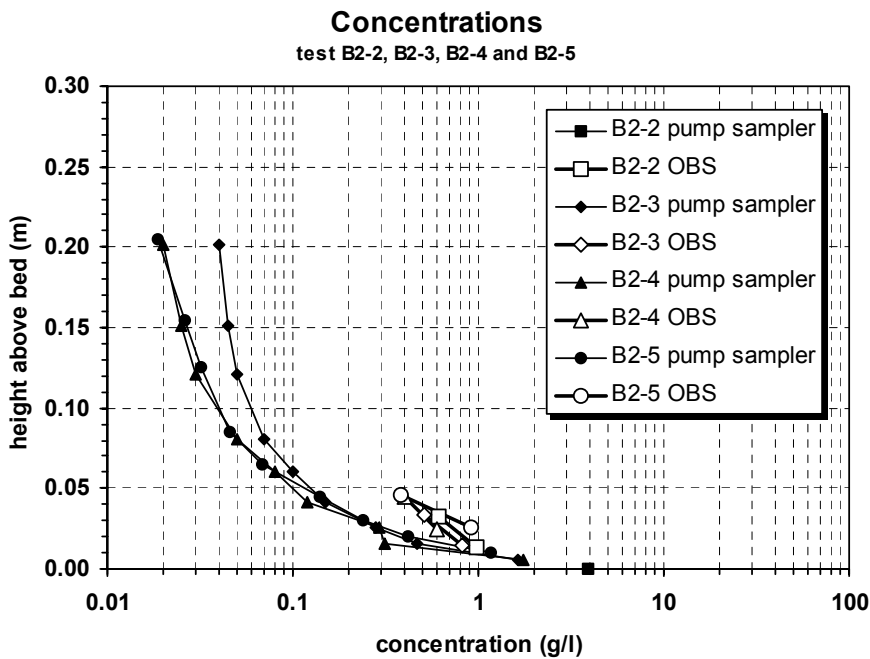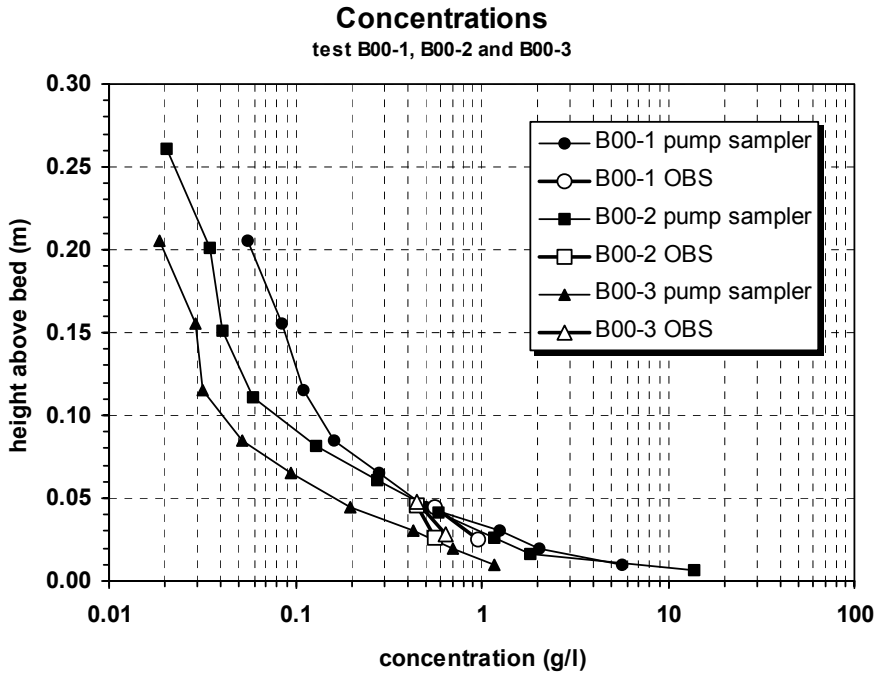
Figure 4.9
OBS concentrations and pump concentrations in Large Oscillating Water Tunnel.
B00: reg. asym., $U_{1/3,on}$ = 0.52 m/s, $U_{1/3,off}$ = 0.33 m/s, D_{50} = 0.19-0.21 mm
B2: irreg. asym, $U_{1/3,on}$ = 0.84 m/s, $U_{1/3,off}$ = 0.48 m/s, D_{50} = 0.19-0.21 mm

Concentrations
test H5-1, H5-2 and H5-3

Concentrations
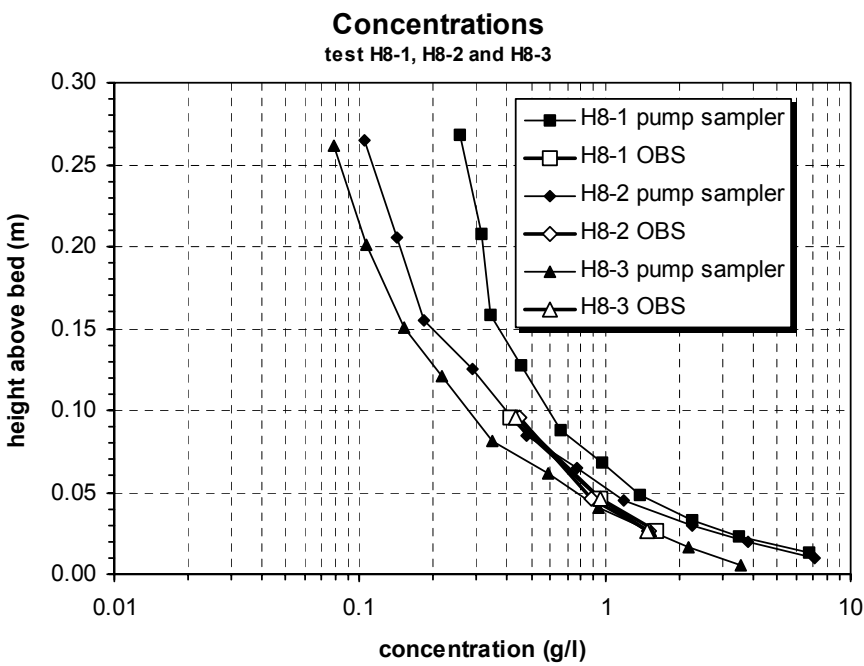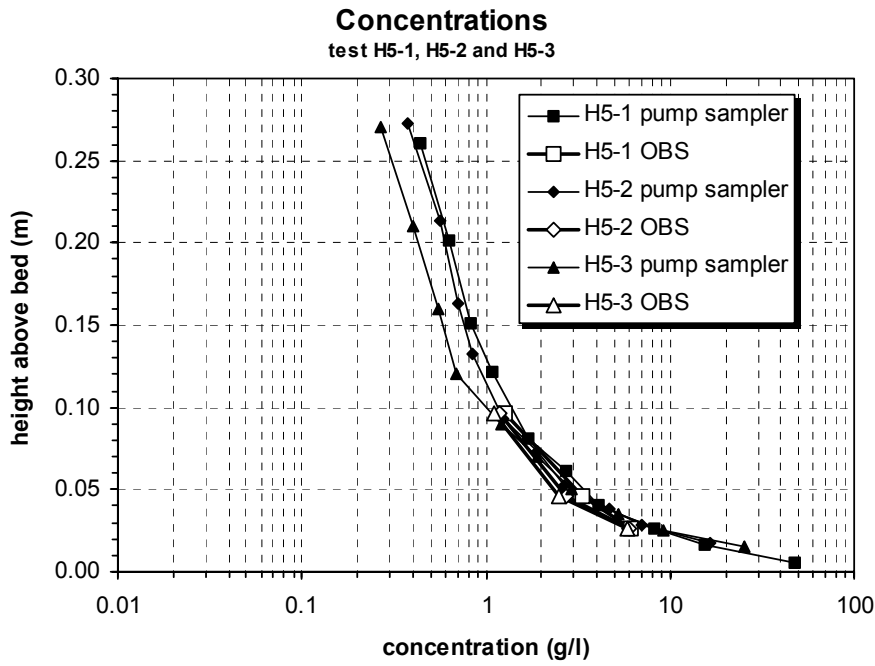**test H8-1, H8-2 and H8-3**

Figure 4.10
OBS concentrations and pump concentrations in Large Oscillating Water Tunnel.
H5: reg. symm, $U_{max} = 1.30$ m/s, $D_{50} = 0.12$-13 mm
H8: reg. symm, $U_{max} = 0.67$ m/s, $D_{50} = 0.12$-0.13 mm

4.4 Comparison of ASTM and and pump sampler in large scale wave tank (Deltaflume) of Delft Hydraulics

Special experiments (Chung and Grasmeijer, 1999) have been performed in a large-scale flume of Delft Hydraulics, in which a horizontal sand bed was placed over a length of about 40 m (Figure 4.11). The Flume has a total length of 233 meters, a depth of 7 meters and a width of 5 meters. A piston activated wave board on one side of the flume generates the waves.

A sand bed ($\pm$ 0.5 meter high) was placed in the Delta flume from position x = 100 meters to x = 140 meters. During the first test series (July 1997) this sand bed had a D_{50} of 0.33 mm, and during the second test series (August 1997) the D_{50} was 0.16 mm. The waterdepth was 4.55 m in all experiments.

The ASTM was mounted in a tripod, which was placed on the sand bed at location x = 125 m (Figure 4.11). The ASTM was used to measure the instantaneous fluid velocities and sand concentrations at five points above the bed simultaneously. The ASTM was attached to an in vertical direction movable arm to position the sensors at a known level above the bed. In most tests the measurement levels were: z= 0.075, 0.125, 0.225, 0.475 and 1.075 m above the bed. A pump sampler (PS) was used to determine the time-averaged concentrations and to get suspended sand samples at the same levels. Five intake tubes of the pump sampler were attached at the ASTM sensors (horizontally within 0.2 m; vertically within 0.01 m from the measurement volume of ASTM) and five other intake tubes were attached to a supporting rod outside the tripod on the upwave side of it to study the effect of the tripod and ASTM arrangement on the sand concentrations. These latter intake nozzles of the pump sampling unit were within 2 m of the ASTM sensors (at the same levels above the bed). During each test the instruments were operated for about 15 minutes to sample over a representative wave record.
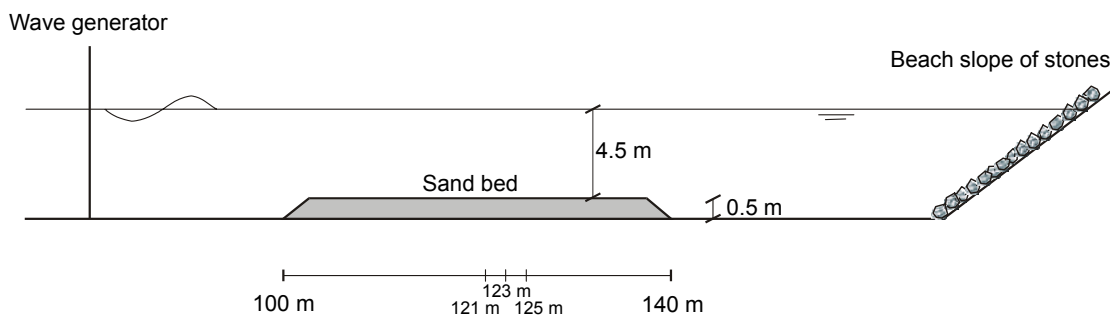

Figure 4.11
Sketch of experimental setup

Sand concentration profiles based on the pump sampler near the ASTM sensors inside the tripod and the pump sampler outside the tripod are presented in Figure 4.12 and 4.13 for the tests over a sand bed of 0.16 mm. The concentrations measured with the pump sampling system were averaged over 7 to 9 tests. Only results for conditions with irregular waves are shown. Standard deviations in concentration are represented by x-error bars and possible deviations in bed level (due to ripple migration) are represented by y-error bars. The ripple height was found to be approximately 0.07 m.

All measured concentrations are within a factor 2 of each other without the presence of systematic differences, which is a remarkably good result. Differences in concentrations can be caused by:
- scour and extra turbulence induced by the supporting structure and footplate of the pump sampling system outside the tripod,
- extra turbulence induced by ASTM sensors and supports of tripod,
- small local variations in bed forms and bed level inside and outside the tripod.

Turbulence related to the presence of the tripod and the ASTM sensors may produce larger concentrations near the bed (more sediment is being stirred up). Also, larger concentrations at higher elevations above the bed may be expected because of an increased turbulent mixing (sediment is distributed more easily by vortices induced by the presence of the sensors).

Figure 4.14 and 4.15 show sand concentration profiles based on the pump sampler near the ASTM sensors inside the tripod and the pump sampler attached to the flume wall for the tests over a sand bed of 0.33 mm. The concentrations near the ASTM sensors are systematically larger (factor 2) than the concentrations

measured near the flume wall. Higher up in the water column these effects are supposed to be related to some extra turbulence induced by the instrumental arrangement. In the near-bed region the observed differences in concentrations are most likely be caused by differences in bed levels and differences in bed form dimensions between the location of the pump sampler near the flume wall and the tripod location in the centre of the flume. From visual observations of the sand bed after draining of the flume it became clear that the presence of the pump sampling system near the flume wall had caused a scour hole at that location. At locations more landward and more seaward of the pump sampler near the wall (approximately 1 m from the pump sampler), an increase in bed level was found (local bump). In the centre of the flume near the ASTM sensors inside the tripod location, scour effects were much less pronounced. Moreover, well-developed vortex ripples were found near the ASTM sensors in the centre of the flume while no ripples were found near the pump sampler attached to the flume wall.

The comparison of the sand concentrations measured by the pump sampler near the ASTM sensors inside the tripod and measured by the other pump sampler outside the tripod shows that the sand concentration profiles inside and outside the tripod generally are within a factor 2 of each other. The deviations between the ASTM and pump sampling concentrations are most probably caused by variations in morphodynamic (bed) conditions at the measurement locations (presence or absense of scour holes and/or ripples) rather than by instrumental errors and instrumental arrangement. The ASTM concentrations higher up in the water column may be somewhat too large due to extra turbulence produced by the tripod (effect of instrumental arrangement).

Overall, the effect of the instrumental arrangement (ASTM sensors and supports within the tripod) on the concentrations measured by the ASTM is assumed to be sufficiently small.
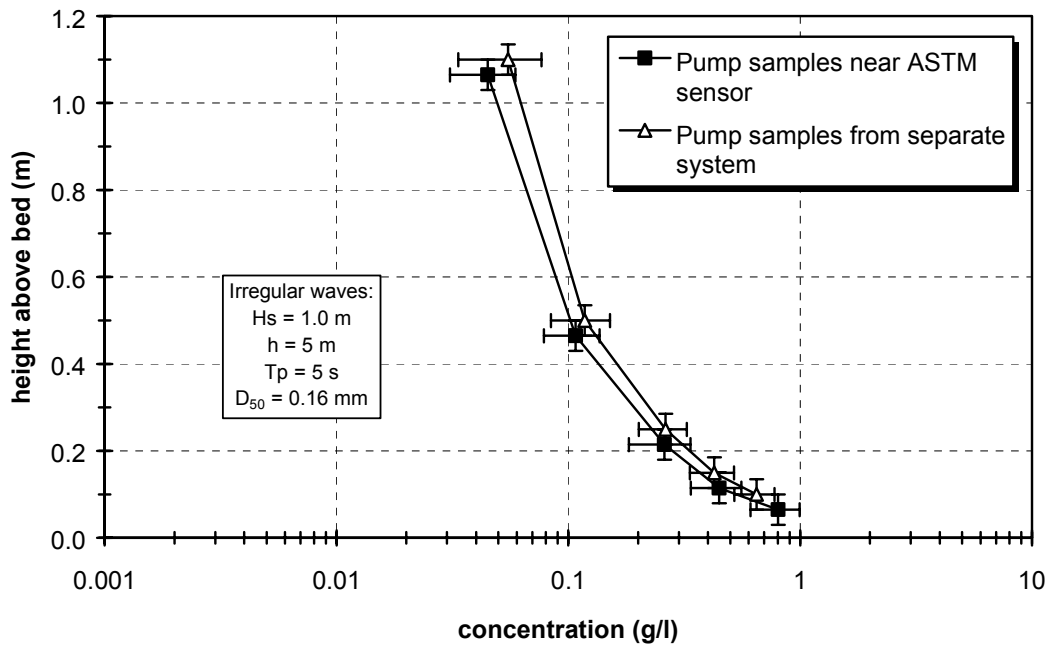
Figure 4.12
Pump concentrations near ASTM sensors inside tripod and outside tripod (separate system) in case of irregular waves H_s = 1.0 m and fine sand bed (0.16 mm); average values and standard deviations derived from 7 tests
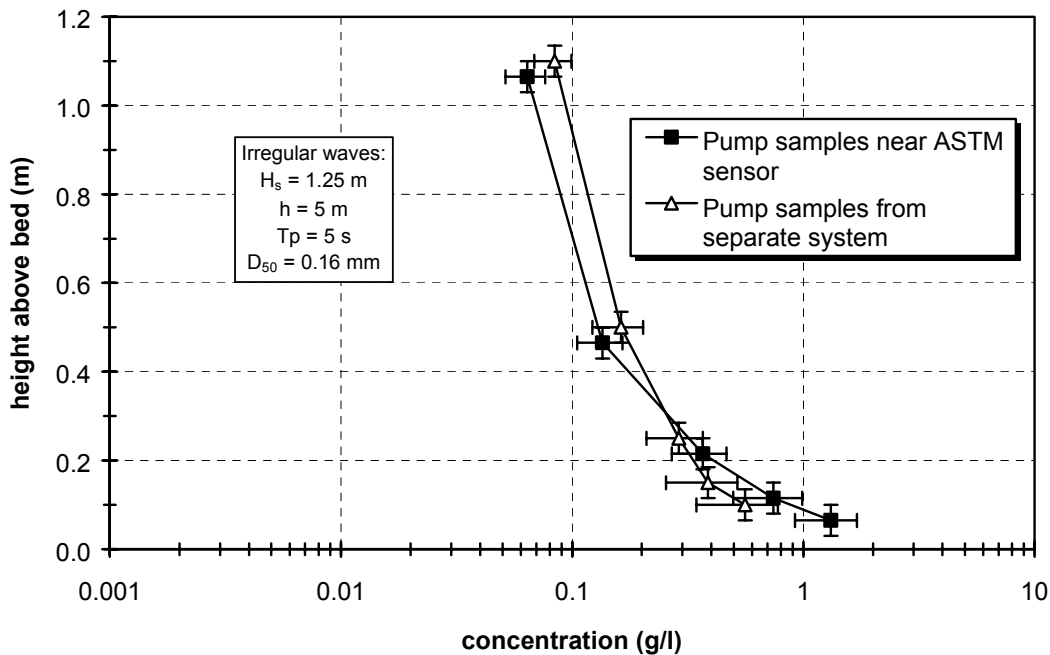

Figure 4.13
Pump concentrations near ASTM sensors inside tripod and outside tripod (separate system) for irregular waves H_s = 1.25 m and fine sand bed (0.16 mm); results from 9 tests
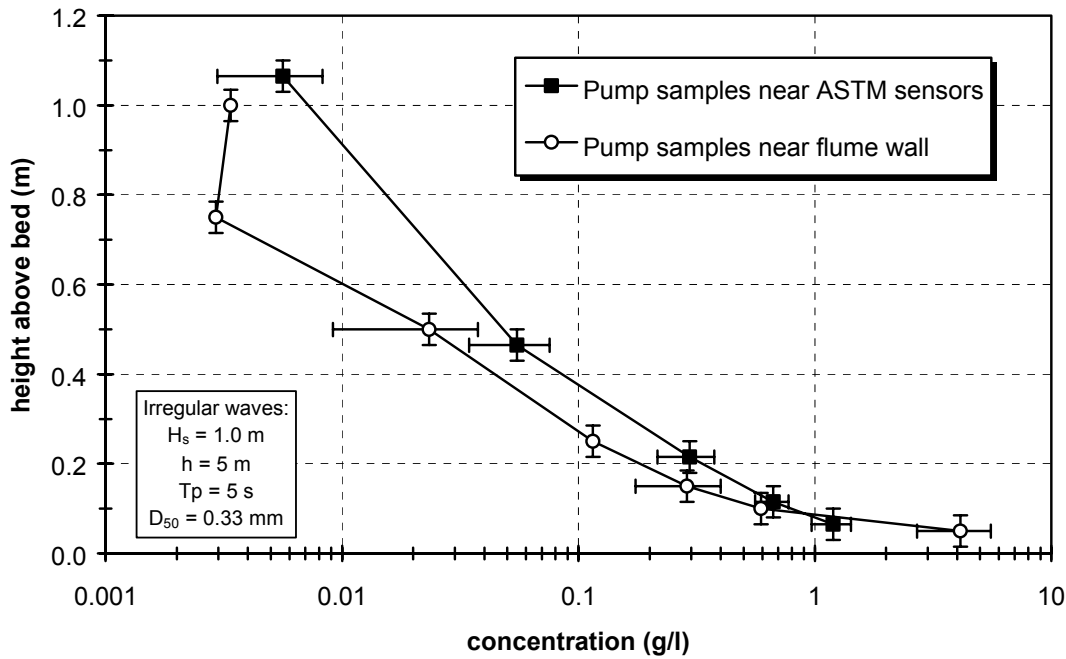
Figure 4.14
Pump concentrations near ASTM sensors inside tripod and near flume wall in case of irregular waves H_s = 1.0 m and coarse sand bed (0.33 mm); results from 4 tests

Figure 4.15
Pump concentrations near ASTM sensors inside tripod and near flume wall in case of irregular waves H_s = 1.25 m and coarse sand bed (0.33 mm); results from 4 tests
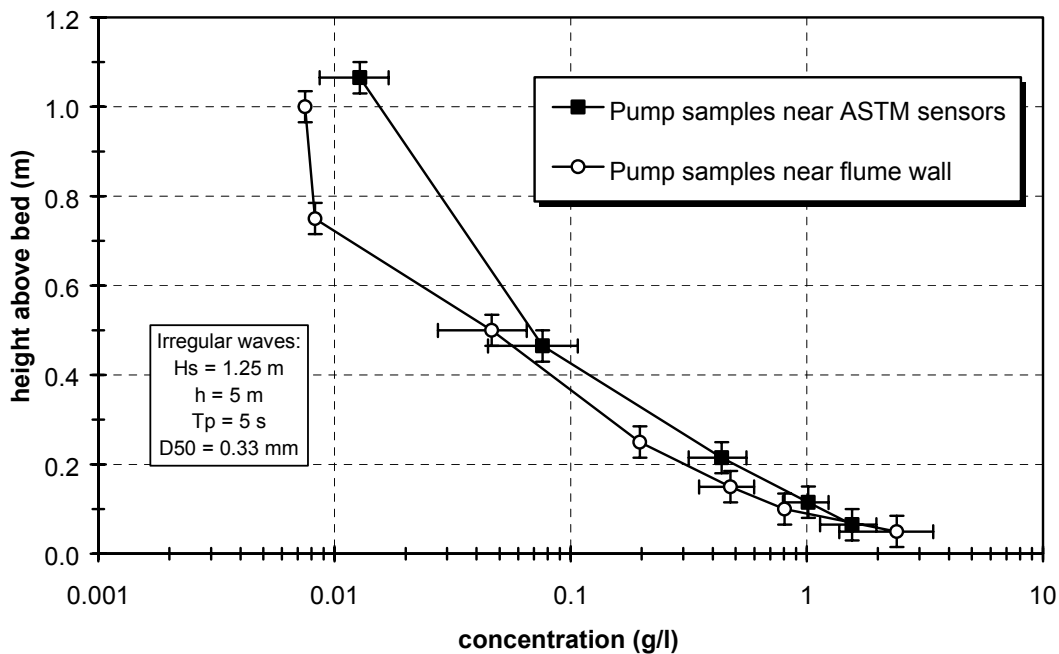
4.5   Comparison of ASTM, OBS and pump sampler in large scale wave tank of Hannover

Experimental setup

The experiments have been carried out in the 'Grosser Wellenkanal (GWK)' in Hannover, Germany. It has a length of about 300 m, a depth of 7 m and a width of 5 m. The piston-type wave generator can produce regular or irregular waves with periods between 1 and 15 s and heights up to 2.5 m. The wave reflections from the beach are compensated directly at the wave paddle. For the present experiments irregular waves

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were generated with a significant wave height of $H_{1/3}$ = 1.25 m and a wave spectrum peak period of T_p = 6.0 s. In addition, two tests with regular waves (H = 1.6 m, T = 6.5 s) were done. The water depth was kept constant at a value of 4.2 m in front of the wave generator. The water depth at the test section was 3.5 m. A sand bed with a length of approximately 50 m was constructed in the flume (Figure 4.16).

Measurements have been done using an instrumented tripod designed and build by the Laboratory for Physical Geography of the University of Utrecht, the Netherlands. The tripod was placed in the center of the flume at x ≈ 113 m (Figure 4.16). Instruments mounted on the tripod included a five-fold acoustic sediment transport meter (ASTM), three optical backscatterance sensors (OBS), six pump sampling intake tubes, three electromagnetic velocity meters (EMF), a pressure sensor and a ripple profiler.

The ASTM is connected to an arm, which can be moved in vertical direction by an electromotor. A sensor to detect the bed surface was attached to the lower end of the arm. Using the movable arm, the ASTM sensors can be placed at pre-selected elevations above the bed. The OBS and EMF sensors are also attached to the movable arm. Three Optical Backscatterance Sensors (OBS) were used during the present experiments. Two sensors (serial number 455 and 458) were installed on a supporting rod at about 0.03 m above the sand bed. One OBS sensor (serial number 408) was placed at about z = 0.10 m (near the lowest ASTM sensor for comparison). The lowest EMF sensor (velocity) was positioned at about 0.05 m above the bed. The pump sampler consisted of a pumping system with 6 intake tubes. Five intake tubes were attached to the five ASTM sensors at about 0.10 m, 0.15 m, 0.25 m, 0.50 m and 1.0 m above the sand bed. One intake tube was mounted near two OBS sensors at about 0.03 m above the bed. The intake tubes of 3 mm internal diameter were connected by plastic hoses to the pumps. The intake openings were placed in a direction transverse to the plane of orbital motion. The intake velocity was about 1.3 m/s, satisfying sampling requirements. The 8-liter samples were collected in calibrated buckets. The pump sampler was operating for 15 minutes giving an average concentration over the measurement period.
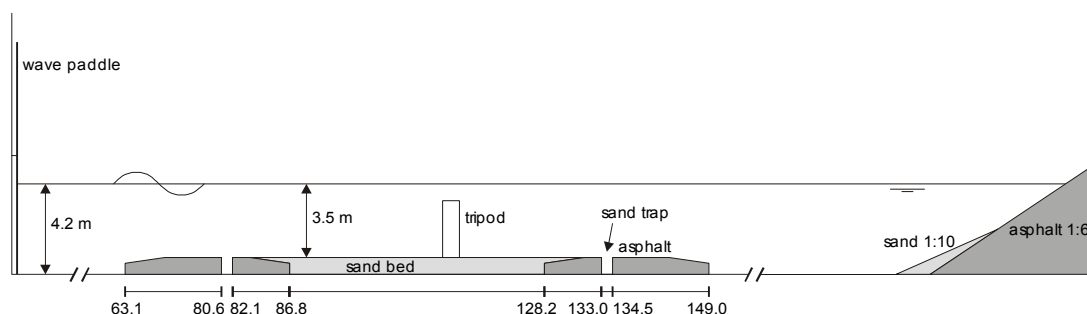

Figure 4.16
Sketch of Grosser WellenKanal

Sand was used with grain size characteristics: D_{10} = 0.14 mm, D_{50} = 0.23 mm, D_{90} = 0.34 mm. The sand bed was ended by asphalt constructions in which sandtraps were build. The sandtraps were intended for determining the sediment transport rates based on volumetric changes. Previous experiments showed that this approach was unsuccessful.

Comparison of OBS and pump sampler
Figure 4.17 shows a comparison between time-averaged concentrations measured with the pump sampler and those measured with OBS sensors. Relatively large OBS concentrations were observed on each day during the first tests, which was caused by resuspension of fine muddy and silty materials that had settled onto the bed during the night. These relatively large OBS values were removed from the data set. Most OBS concentrations are smaller than the pump concentrations. The maximum discrepancy is a factor 2.
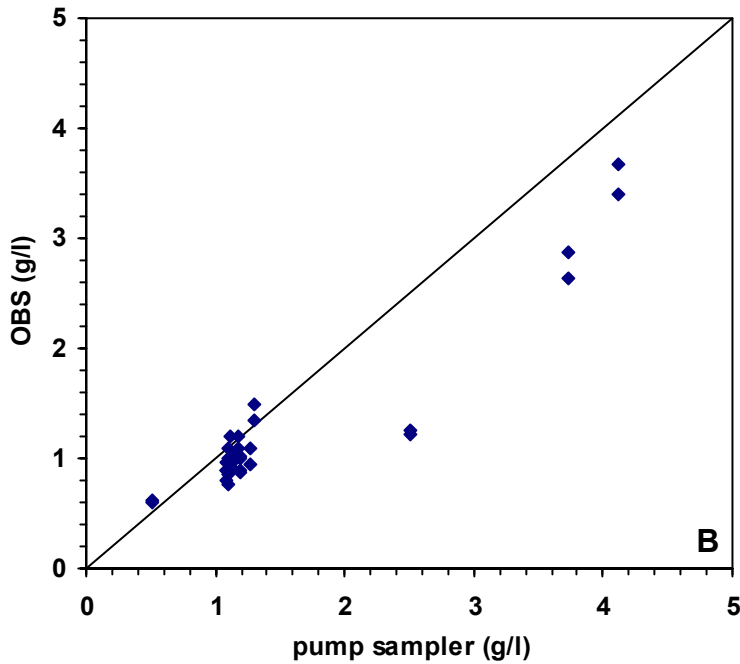
Figure 4.17
Comparison of time-averaged OBS concentrations and pump concentrations

Comparison of ASTM and pump sampler
Figure 4.18 shows a comparison between time-averaged concentrations measured with the ASTM sensors (based on standard calibration curve; concentration$_{ASTM}$ = 0.257*Output$_{ASTM}$) and the pump sampler. The ASTM values have been interpolated to compare concentrations from the ASTM and the pump sampler at the same height above the bed. For concentrations smaller than 1 kg/m^3 the ASTM concentrations and the pump concentrations agree very well (ASTM on an average 5% smaller). For concentrations larger than 1 kg/m^3 the ASTM conccentrations are slightly smaller than the pump sampler conccentrations (ASTM on an average 22% smaller).
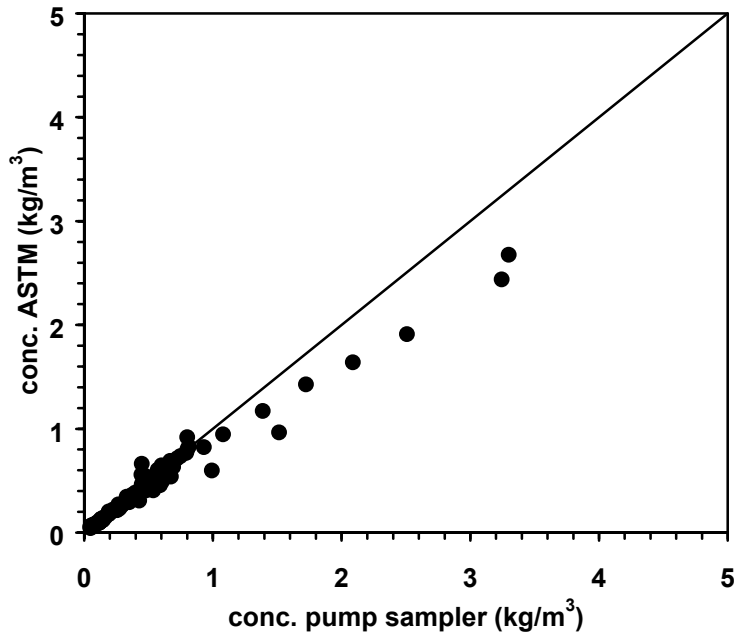

Figure 4.18
Comparison of time-averaged ASTM concentrations and pump concentrations

4.6   Comparison of ABS and pump sampler

Thorne (personal communication) tested the ABS system in the large-scale wave tank of Delft Hydraulics (Williams et al., 2000). The ABS was mounted in a tripod of Proudman Oceanographic Laboratories, which was placed on the sand bed (0.33 mm sand; rippled bed). A pump sampling system was used to determine the sand concentrations at 10 points above the bed surface. The intake nozzles were installed at a horizontal separation distance of 0.3 m from the vertical ABS beam. Figure 4.19 shows a comparison of time-averaged pump and ABS concentrations (over about 15 min) at various levels based on results of tests with regular and irregular waves (no current). The sand concentrations were processed from the ABS signal between 0.01 and 1 m with a vertical resolution of 0.01 m. The sand concentration at one height and the suspended sand sizes over the depth were assumed to be known from the pump sampling results to calibrate the ABS concentrations. Hence, the ABS concentrations were not independently determined. The deviations between the results of both instruments are up to 30%.

Figure 4.20 shows a comparison of pump concentrations P_c and ABS concentrations A_c for a site in a British estuary (0.16 mm sand bed; bed covered with sand waves; tidal current; no waves). The horizontal separation distance between the intake nozzles (at 4 heights) and the ABS beam was 0.5 m. The ABS concentrations were determined independently of the pump concentrations. The deviations between the results of both instruments are up to 20%.
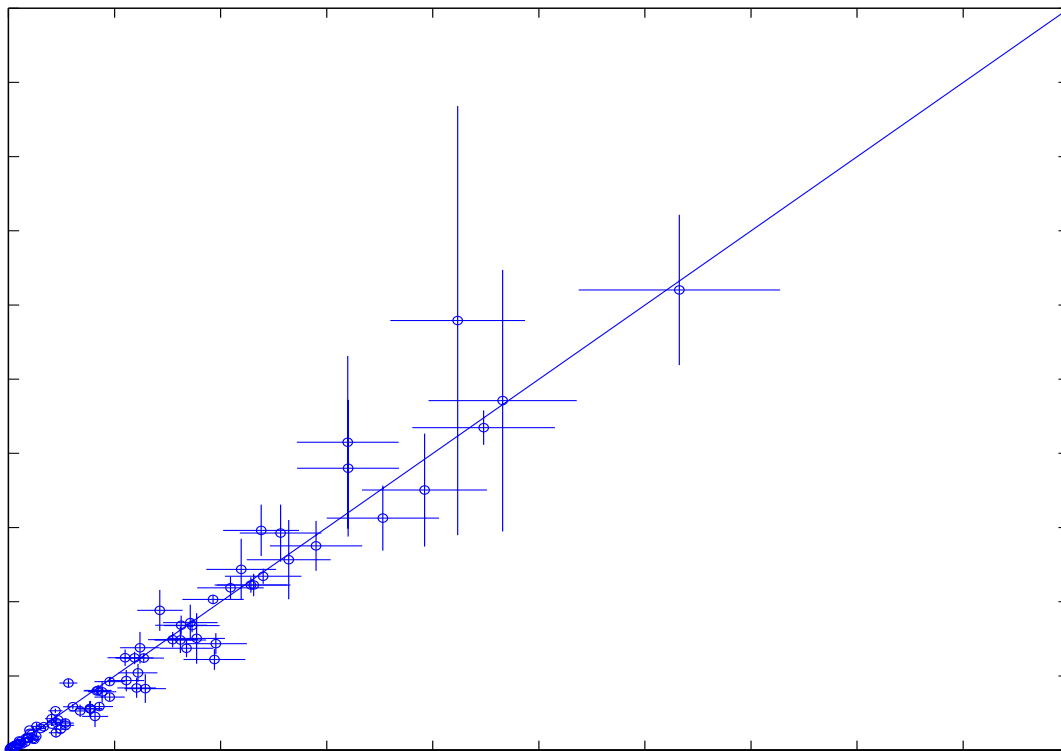

Figure 4.19
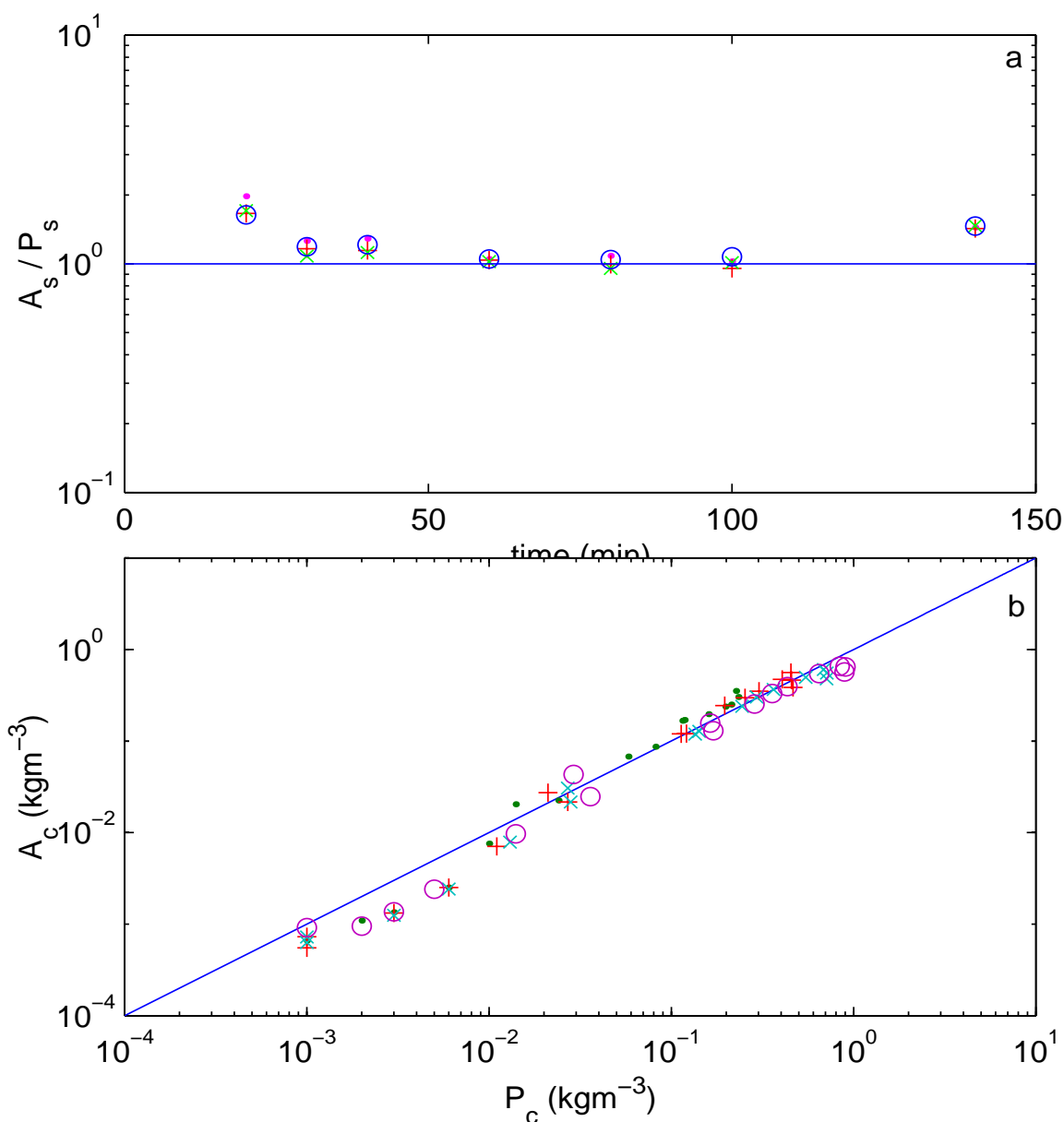*Comparison of pump C_p and ABS C_a concentrations in large scale wave tank of Delft Hydraulics*

Figure 4.20

Top: *Comparison of suspended sand size; A_s=particle size derived from ABS signal; P_s= particle size derived from pump samples*

Bottom: *Comparison of suspended sand size; A_c=concentration derived from ABS signal; P_c= concentration derived from pump samples*

Rose and Thorne (2000) tested the multi-frequency (1, 2.5 and 5MHz) ABS-system mounted in a tripod in conditions with tidal flow velocities between 0.6 and 1 m/s and water depths between 2 and 3 m (River Taw Estuary, UK). The bed was composed of fine sand with d_{50}=0.17 mm and d_{90}= 0.2 mm. Ripples were present with approximate wave heights of 0.025 m and wave lenghts of 0.2 m. Figure 4.21 shows four ABS-concentration profiles and pumped concentrations at 4 heights (= 0.1, 0.2, 0.4 and 0.8 m) above the bed. The agreement between the concentrations of both instruments is quite good with maximum deviations of about 15% near the bed and 30% higher up in the water column. The magnitude of the acoustically derived suspended sediment estimates were slightly adjusted (factor 0.8 to 1.1) to optimise the agreement with the direct pumped sampling measurements. The 5 MHz data was not utilised owing to inversion difficulties at periods of high concentrations when sediment attenuation of the MHz signal resulted in problematic concentrations.
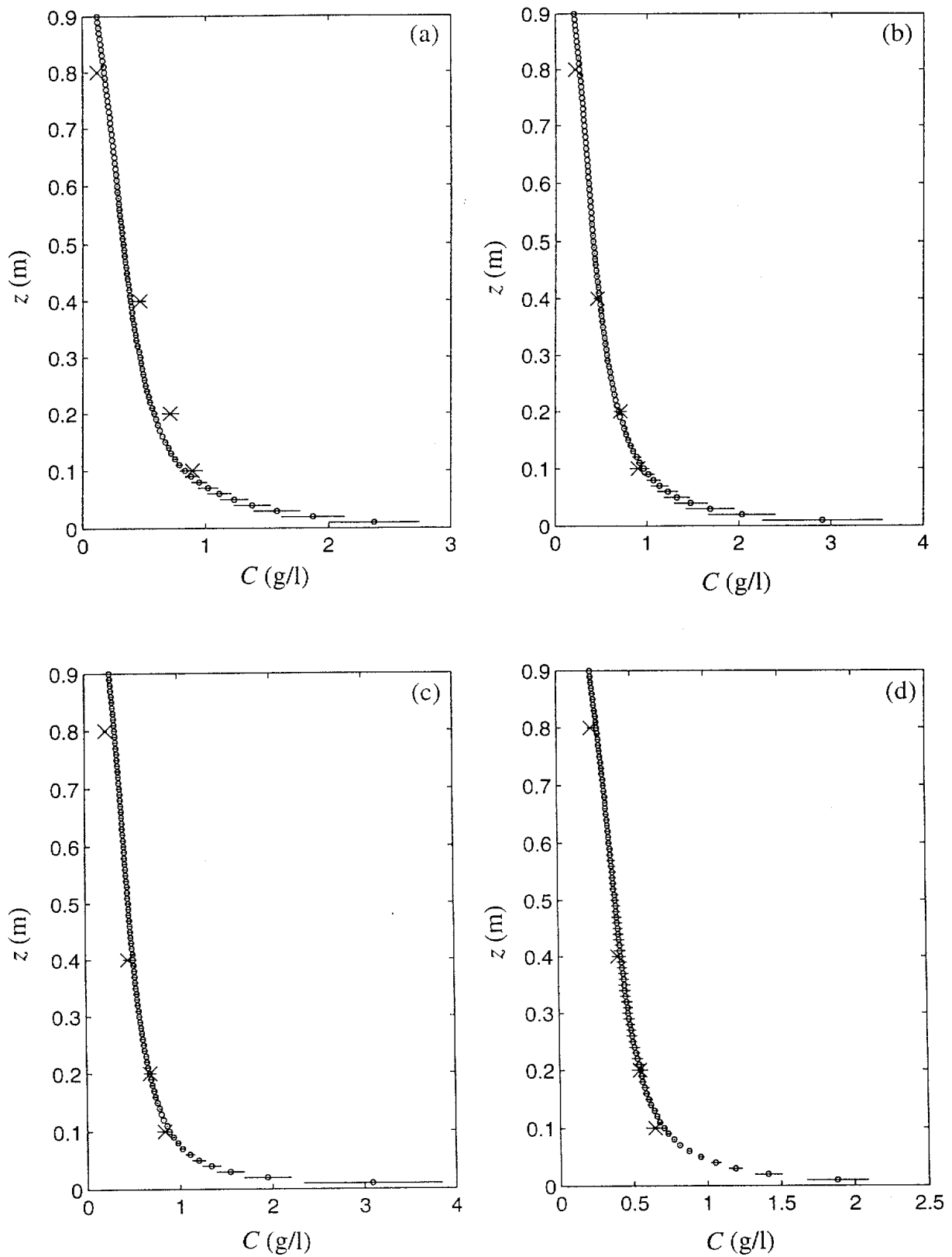
Figure 4.21
Sand concentration profiles of ABS system (circles) and pumped concentrations (crosses); River Taw Estuary (UK)

4.7   Conclusions

The following conclusions are given:
- the OBS sensors are highly sensitive to particle size;
- the OBS concentrations should be corrected for the smaller size of the suspended sand relative to that of the sand bed material used during calibration; this requires samples of suspended sand during field measurements;
- the effective concentration range for OBS sensors is 1 to 100 kg/m^3; concentrations measured within this range have an inaccuracy of about 50%;
- the OBS sensors often show a reasonably steady offset concentration, which is related to the background concentration of relatively fine sediments (silt and mud), which should be subtracted from the original time series data; if the background concentration to be subtracted from the record is of the same order of magnitude as the sand concentration, the OBS concentrations will be rather inaccurate;
- OBS concentrations below 1 kg/m^3 are not accurate (inaccuracy larger than factor 2) and should not be used;
- Acoustic concentration sensors (ASTM) for point measurements are not very sensitive to particle size; the effective measurement range is 0.1 to 10 kg/m^3; concentrations measured by sensors mounted in a tripod have an inaccuracy of about 50%;
- Acoustic concentration sensors (ABS) for profile measurements are sensitive to particle size; the effective measurement range is 0.1 to 20 kg/m^3; three different acoustic frequencies are used to simultaneously determine the size and the concentration of the suspended sediment involved; the sand concentration profiles can be determined with an inaccuracy of about 30% if the suspended sand size is known and some pump concentrations are available for calibration; the optimum conditions for the ABS system are: rather uniform fine sand (0.1 to 0.3 mm) in non-breaking wave conditions;
- the mass concentration at range r from the ABS transducer is estimated from a complex function, depending on the voltage V measured at range r, the sediment density, the speed of sound in water and the attenuation of sound by water and sediment of radius a; this function is not yet properly defined resulting in relatively large inaccuracies (factor 2 to 3) of the measured concentration, if calibration samples of concentration and sediment size are not available;
- the ABS system is rather sensitive for the presence of air bubbles in the water column (surf zone conditions with breaking waves) resulting in an increase of the concentration.

5. Bed level measurements (bathymetry)

5.1 Accuracy of echo soundings from ship surveys

The accuracy of echo soundings from ship surveys has been evaluated by Rijkswaterstaat, The Netherlands (Westlake et al., 1996).

Survey errors can be divided into systematic and stochastic errors. The former affect the whole survey data set, whereas the latter are random and cancel out from survey to survey (e.g., difference plots). The accuracy of ship surveys is therefore essentially related to systematic errors. For the Terschelling nourishment site, the following error sources were considered to be of most importance:
- determination of the water level at the moment of sounding,
- setting 'zero' on the echo sounder (= depth of the transducer below the water surface),
- squat of the ship (= decreased water level around a moving ship, only of importance in shallow water, say, < 6 m),
- ship specific characteristics, such as the ship's weight,
- the surf riders effect (= effect of waves on survey accuracy), and
- the accuracy of the positioning in the horizontal plane (x,y).

For the Terschelling site, the total effect of these errors in water depths less than 6 m was –0.01 to –0.25 m, or in water deeper than 6 m the errors are -0.05 to +0.10 m. The larger error in shallower water is caused by the ship's squat. Negative errors indicate that the true depth is underestimated by the survey, whereas a positive notation means that the depth is overestimated.

These numbers are not directly applicable to the Egmond site in 1998. For instance, the distance between the Egmond study site and the nearest tidal station is different than for Terschelling site. Egmond surveys were always done in depths larger than 6 m, so the error by squat will be negligible. Overall, it would appear safe to suggest that an error range of +/- 0.10 m on survey values is appropriate for the COAST3D site near Egmond, The Netherlands.

5.2 Accuracy of WESP surveys

The WESP is an approximately 15 m high amphibious 3-wheel vehicle, which is used for bed level soundings in the surf zone in depths up to -6 m. It is equipped with a DGPS positionning system (De Hilster, 1998).

The measuring accuracy of the WESP depends on:
- the location of the DGPS antenna,
- the accuracy of the DGPS (KART) system, and
- the accuracy of the attitude (tilt) sensor.

The antenna is situated over the middle of the wheelbase of the WESP. The bed level at the location of the WESP is calculated straight down from the antenna in the middle of the wheelbase. This means that certain morphology wavelengths are measured partially or not all. Theoretical considerations suggest that this error source especially affects morphological features with a wavelength smaller than about 10 times the wheelbase. For the bars at Egmond, the errors in the vertical co-ordinate because of the location of the antenna are estimated at about 3 cm at the inner bar and about 1 cm at the outer bar.

The vertical accuracy of the applied DGPS (95%) is estimated as 0.05 to 0.07 m. A small difference of about 0.01 m should be added because of non-constant difference of the ellipsoid and geoid in the study area.

At present, the tilt of the WESP over a sloping sea bed is not accounted for in the computations of the horizontal and vertical co-ordinates. Typical bed slopes at Egmond vary between zero to six degrees. The latter may cause a height error of about 0.08 m. The squat of the wheels into the sand has not been taken into account due to a lack of knowledge on this subject.

Overall, it is fair to say that the WESP survey accuracy is 0.10 to 0.15 m, or less, depending on the precise settings of the DGPS, the bed slope and the degree of compaction of the bed under the weight of the wheels. This error does not account for small unresolved bed forms with wave lengths of O(1 m) and heights of O (0.1 m).

5.3   Accuracy of bed level soundings at beach

Beach level soundings are often done by DGPS receivers mounted on small vehicles. The DGPS receiver used during the COAST3D studies at the Egmond and Teignmouth sites in 1998 and 1999 was mounted on a small trailer pulled by a 4-wheel vehicle. The topographic surveys performed with DGPS have theoretically a centimetric precision (say 0.03 m) both in planimetry and in elevation. Observations of the scattering of the coordinates of the control points obtained during the different surveys can also give an idea of the precision which may be achieved in practice. During the main experiment at the Teignmouth site in 1999, for example, the maximum deviation was usually less than 0.05 m for all the available control points. The difference between the obtained coordinates and the values provided by HR Wallingford is also less than 0.05 m. An important condition to achieve precise measurements is that the control points are distributed all around the surveyed zone.

Some additional errors may also occur during the beach survey. The actual difference in elevation between the beach and the reference level of the DGPS is measured before every survey but may vary during the experiment. The trailer indeed penetrates more or less (say 0.02 m) in the soil depending on its resistance characteristics, which influences this parameter. Overall, the vertical accuracy is about 0.05 m on relatively flat and smooth areas and about 0.10 m on steep sloping faces of bars (no tilt correction).

5.4   Conclusions

The following conclusions are given:
- bed level soundings performed by means of a ship-mounted echo sounder have a vertical inaccuracy of about 0.1 m to 0.15 m in depths larger than about 6 m due to tide level corrections, ship-induced motions and wave-induced motions; the inaccuray may be as large as 0.25 m in shallow depths (smaller than 6 m) due to relatively large ship-induced motions;
- bed level soundings performed by means of a DGPS system mounted on the WESP vehicle have a vertical inaccuracy of about 0.1 m to 0.15 m in depths smaller than 6 m;
- beach level soundings performed by use of a DGPS receiver mounted on a small vehicle moving over the beach have a horizontal inaccuracy of about 0.05 m and a vertical inaccuracy of about 0.05 m on relatively flat and smooth areas and about 0.1 m on steep sloping faces of bars (without tilt correction).

6.   Conclusions and recommendations

Based on intercomparison results of various instruments for measurement of velocity, wave height, sand concentration and bed levels in field conditions, the following conclusions are given:

Velocity
- peak orbital velocities of Electromagnetic velocity meters may have an uncertainty of maximum 15%; Acoustic Doppler velocity meters yield peak orbital velocities which are somewhat smaller (about 15%) than those of Electromagnetic velocity meters;
- time-averaged velocities smaller than 0.05 m/s may have an inaccuracy of maximum 100%;
- time-averaged velocities in the range of 0.15 to 0.3 m/s may have an inaccuracy of maximum 30%;
- time-averaged velocities larger than 0.5 m/s are assumed to have an inaccuracy of maximum 15%;

Wave height
- rms and significant wave height in non-breaking conditions derived from direct measurement of surface elvation by use of capacity wires or derived from pressure sensors using linear wave theory may have an uncertainty of maximum 10%;
- rms and significant wave height in breaking conditions (surf zone) derived from direct measurement of surface elvation by use of capacity wires or derived from pressure sensors using linear wave theory may have an uncertainty of maximum 15%;
- significant wave heights derived from pressure sensor measurements (using linear wave theory) are systematically somewhat smaller (maximum about 15%) than those derived from direct wave elevation (capacity/resistance wires) measurements;
- wave heights derived from direct water surface elevation measurements and from pressure data using linear wave theory are in reasonably good agreement (within 15%) suggesting that local nonlinearity effects are not extremely strong;
- the energy density spectra of a pressure transducer system do not show frequencies higher than about 0.4 Hz, which is the cut-off frequency in the filter method used in the transformation of the data from pressure to water elevation levels; thus the pressure transducer system is not accurate for relatively small waves with periods smaller than about 2.5 s; large errors may occur when relatively small waves (<0.5 m) are of importance within the wave spectrum;
- the inaccuracy of the water depth derived from Pressure sensors is strongly dependent on the inaccuracy of the vertical position of the sensor above the bed; this latter parameter should be measured continuously (acoustic depth sounder) in conditions with rather large bed level changes; the inaccuracy of the wave height is much less affected by inaccuracies of the position of the pressure sensor (except in shallow water);

Sand concentration
- the OBS sensors are highly sensitive to particle size;
- the OBS concentrations should be corrected for the smaller size of the suspended sand relative to that of the sand bed material used during calibration; this requires samples of suspended sand during field measurements;
- the effective concentration range for OBS sensors is 1 to 100 kg/m^3; concentrations measured within this range have an inaccuracy of about 50%;
- OBS concentrations below 1 kg/m^3 are not accurate (inaccuracy larger than factor 2) and should not be used;
- the OBS sensors often show a reasonably steady offset concentration, which is related to the background concentration of relatively fine sediments (silt and mud), which should be subtracted from the original time series data; if the background concentration to be subtracted from the record is of the same order of magnitude as the sand concentration, the OBS concentrations will be rather inaccurate;
- Acoustic concentration sensors (ASTM) for point measurements are not very sensitive to particle size; the effective measurement range is 0.1 to 10 kg/m^3; concentrations measured by sensors mounted in a tripod have an inaccuracy of about 50%;
- Acoustic concentration sensors (ABS) for profile measurements are sensitive to particle size; the effective measurement range is 0.1 to 20 kg/m^3; three different acoustic frequencies are used to simultaneously determine the size and the concentration of the suspended sediment involved; the sand concentration

profiles can be determined with an inaccuracy of about 30% if the suspended sand size is known and some pump concentrations are available for calibration; the optimum conditions for the ABS system are: rather uniform fine sand (0.1 to 0.3 mm) in non-breaking wave conditions;

- the mass concentration at range r from the ABS transducer is estimated from a complex function, depending on the voltage V measured at range r, the sediment density, the speed of sound in water and the attenuation of sound by water and sediment of radius a; this function is not yet properly defined resulting in relatively large inaccuracies (factor 2 to 3) of the measured concentration, if calibration samples of concentration and sediment size are not available;
- the ABS system is rather sensitive for the presence of air bubbles in the water column (surf zone conditions with breaking waves) resulting in an increase of the concentration;

Bed levels
- bed level soundings performed by means of a ship mounted echo sounder have a vertical inaccuracy of about 0.1 m to 0.15 m in depths larger than about 6 m due to tide level corrections, ship-induced motions and wave-induced motions; the inaccuray may be as large as 0.25 m in shallow depths smaller than 6 m due to relatively large ship-induced motions;
- bed level soundings performed by means of a DGPS system mounted on the WESP vehicle have a vertical inaccuracy of about 0.1 m to 0.15 m in depths smaller than 6 m;
- beach level soundings performed by use of a DGPS receiver mounted on a small vehicle moving over the beach have a horizontal inaccuracy of about 0.05 m and a vertical inaccuracy of about 0.05 m on relatively flat and smooth areas and about 0.1 m on steep sloping faces of bars (without tilt correction).

Recommendations
Tripods should be equipped with at least 5 electromagnetic current meters to be able to determine the local bed-shear stresses and effective bed form roughnesses under various wave-current conditions, which is essential for a better understanding of sand transport processes. An acoustic bed level recording instrument is required for accurate determination of the bed surface level.

Accurate determination of the wave heights from the pressure sensor signals require continuous information of the distance between the pressure sensor and the (varying) bed surface. Continuous bed level recordings should be carried out using an acoustic instrument on each tripod.

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