SVAŠEK HYDRAULICS

COASTAL, HARBOUR AND RIVER CONSULTANTS

Wave measurement instruments

Desk study and advice for wave measurement instruments at the Dutch lakes IJsselmeer and Slotermeer

Final Report

MVDB/04453/1309

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SAMENVATTING

Het Nederlandse Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (Rijkswaterstaat/RIZA) en Rijkswaterstaat Directie IJsselmeergebied (Rijkswaterstaat/RDIJ) maken gebruik van een meetnet waar wind-, waterstands- en golfmetingen bijna continu worden uitgevoerd. De meetlocaties liggen in het IJsselmeer en Slotermeer.

Een belangrijke toepassing van de metingen is de afregeling en de validatie van verschillende numerieke golfmodellen (zoals SWAN). Deze golfmodellen worden onder andere gebruikt om de ontwerpcondities voor de dijken te berekenen. Hiervoor is het van essentieel belang dat de storm condities van de komende vijf jaar nauwkeurig worden gemeten. Echter het afregelen van golfmodellen vereist ook een grote spreiding aan fysische omstandigheden zodat een breed bereik van strijklengten, windsnelheden en waterdiepten moet worden beschouwd. De strijklengtes en de waterdiepten op de meetlocaties variëren tussen 0.8 and 25 kilometer respectievelijk 1.5 and 6 meter. Qua wind ligt het interessebereik tussen de 10 en 32 m/s (bij alle richtingen), ofwel 5-12 Beaufort. Deze specifieke kenmerken van het IJsselmeer en Slotermeer resulteren in golfhoogte tot 3 meter, piek periodes variërend tussen 1 en 5 seconden en stilwaterstandsvariatie van ongeveer 1 meter. Dit vereist golfmeetinstrumenten die kleine hoog frequente golven en grotere golven gedurende storm condities goed en nauwkeurig kunnen meten. Er is weinig ervaring in golfmetingen op ondiep water onder deze condities.

Op dit moment wordt gemeten met capaciteitsdraden ('Multicap DC11"). Deze golfmeetinstrumenten vragen veel onderhoud (veel algen aangroei) en her-calibratie (als gevolg van het verloop van het instrument). RIZA en RDIJ overwegen nieuwe golfmeetinstrumenten voor deze metingen aan te schaffen. Het RIZA heeft Svašek Hydraulics gevraagd een bureaustudie naar de geschiktheid van verschillende typen golfmeetinstrumenten voor de metingen op de huidige IJsselmeer- en Slotermeerlocaties uit te voeren.

Het doel van dit onderzoek is het analyseren van de geschiktheid van verschillende golfmeettechnieken en de daarbij horende golfmeetinstrumenten voor de metingen op het IJsselmeer en Slotermeer. Het resultaat is een advies over het meest geschikte golfmeetinstrument(en) voor deze metingen.

De aanpak van deze studie is als volgt:
Allereerst is een literatuurstudie uitgevoerd om een overzicht te krijgen van de verschillende bestaande golfmeettechnieken en de daarbij horende golfmeetinstrumenten. Tevens is een enquête uitgevoerd bij verschillende leveranciers van de golfmeetinstrumenten. Naar aanleiding van de literatuurstudie, de ervaringen van Svašek en RIZA en de uitgevoerde enquêtes is een voorlopige selectie gemaakt van mogelijk geschikte golfmeetinstrumenten. Om meer praktische informatie te krijgen van de golfmeetinstrumenten zijn ook interviews uitgevoerd met verschillende specialisten en golfinstrument gebruikers. Uiteindelijk is een multi-criteria analyse uitgevoerd om tot een advies te komen over de geschiktheid van de geselecteerde golfmeetinstrumenten.

Naar aanleiding van deze studie kan het volgende geconcludeerd worden:

- Het resultaat van de multi-criteria analyse is dat de Nortek AWAC ADCP het meest geschikte golfmeetinstrument voor de metingen op het IJsselmeer en Slotermeer is. Dit type instrument bestaat uit een Acoustic Doppler Current Profiler die in staat is golfhoogten, richtingsspectra en stromingsprofielen te meten. De geschiktheid van de AWAC is gerelateerd aan zijn "Acoustic Surface Track" (AST). De AST (in de AWAC) is een omhoog kijkend echolood waarmee nauwkeurig de afstand tussen het instrument en het wateroppervlak gemeten kan worden. De AST kan goed samplen met hoge frequenties (tot 4 Hz) en de afdruk op het oppervlak blijft klein als gevolg van de kleine bundelhoek (1.8°). Wel moet worden opgemerkt dat dit een golfmeetinstrument is dat pas kort op de markt is.

- De naar beneden kijkende radar, radio en akoestische instrumenten (plaats 3 t/m 5) zijn allemaal serieuze opties als golfmeetinstrument voor de metingen op het IJsselmeer en Slotermeer. Hetzelfde geldt voor de stappenbaak. De negatieve ervaring die RIZA en RDIJ hebben gehad met de stappenbaak heeft waarschijnlijk te maken met het achterhaalde ontwerp van dit instrument. Etrometa heeft een nieuw ontwerp stappenbaak waarmee betrouwbaar golfmetingen op ondiepwater kunnen worden uitgevoerd.

- De druksensoren zijn geen serieuze optie als golfmeetinstrument voor de metingen op het IJsselmeer en Slotermeer omdat de sensoren ongeveer een kwart golflengte onder het wateroppervlak geplaatst moeten worden. Bij hoog frequente golven moet de druksensor erg dicht bij het wateroppervlak geplaatst worden. Dit geeft problemen bij fluctuaties van de waterstand of bij hoge golven (de sensor komt dan droog te staan). Om dit probleem op te lossen zouden meerdere druksensoren gebruikt moeten worden wat de meting erg complex maakt.

- Waveriders (Datawell) zijn de meest gebruikte en bekende golfmeetinstrumenten. Zij hebben een zeer goede "track record" en worden wereldwijd gebruikt. De golven op het IJsselmeer en Slotermeer zijn echter erg kort en hoog frequent en met de golfmeetboeien is het niet mogelijk deze golven goed te meten. Ook de kleine "Datawell" boei kan de hoog frequente golven niet nauwkeurig meten.

- De onnauwkeurigheid van de golfhoogtemetingen met de Wave Radar, WAVEX en WAMOS maakt deze golfmeetinstrumenten (Remote Sensing Measuring) ongeschikt voor de metingen op het IJsselmeer en Slotermeer.

- De op dit moment gebruikte capaciteitsdraden zijn deels op maat gemaakt. RIZA en RDIJ willen in de toekomst alleen nog maar gebruik maken van commercieel beschikbare instrumenten. Dit is de reden dat de naar beneden kijkende laser en de Zwats Pole niet worden geadviseerd, ondanks dat ze misschien erg geschikt kunnen zijn voor de metingen (de naar beneden kijkende laser wordt niet meer geleverd en de Zwarts Pole is geheel op maat gemaakt (zie Verhagen, 1999)).

SUMMARY

The Dutch Institute for Integral Water Management and Waste Water Treatment (Rijkswaterstaat/RIZA) and the Regional Directorate IJsselmeergebied (Rijkswaterstaat/RDIJ) make use of a monitoring network where wind, water levels and waves are measured almost continuously. The measurement points are located in the Dutch lakes IJsselmeer and Slotermeer.

The key application of these wave measurements is tuning and validation of numerical wave models that are being used to evaluate design conditions for dikes. Hence, first criterion for monitoring is that storm conditions will be measured accurately. However, wave model tuning also requires a great diversity of physical conditions. This implies a wide range of fetches, wind speeds and bottom depths that has to be considered. The fetches and water depths at the measurement locations are between 0.8 and 25 kilometres and between 1.5 and 6 meter respectively the range of the wind speed is between 10 en 32 m/s (all directions), or 5-12 Beaufort. These site specific features of the Dutch lakes IJsselmeer and Slotermeer result in wave heights conditions up to 3 m, wave peak periods between 1 and 5 seconds and still water level fluctuations of 1m. This requires measuring instruments that can measure both relatively small high frequency waves and larger waves during storms. Shallow water wave measurements related to these conditions are not common practise.

Currently capacitance probes are used. These probes require a lot of maintenance and re-calibration. In that respect, RIZA and RDIJ are considering to include new wave measurement instruments within their measurement program. Therefore RIZA asked Svašek Hydraulics to carry out a desk study to evaluate different, available, wave measurement instruments to be used at the IJsselmeer and Slotermeer measurement locations.

The objective of this study is to investigate the suitability of different techniques and instruments for wave monitoring in the Dutch Lakes IJsselmeer and Slotermeer. The output of this study is a recommendation about the wave measurement instrument that is most suitable for these measurements.

The approach of this study is as follows:
First a literature study is carried out in order to make an inventory of existing wave measurement techniques and wave measurement instruments. Besides, questionnaires for suppliers are performed. By means of the literature study and the questionnaires a preliminary selection of potential suitable wave instruments is made. Interviews are carried out in order to get more specific (practical) information, with people that have practical experience with wave measurements at shallow water and/or with the specific wave measurement instruments. Based on the information from the suppliers, the questionnaires and the information of experts and instrument users a multi-criteria analysis has been performed. This multi-criteria analysis resulted in a ranking of the selected wave measurement instruments. The instrument with the highest score is the most suitable instrument for the measurements at the Lakes IJsselmeer and Slotermeer.

As a result of this study the following conclusions can be drawn:

- The result of the multi-criteria analysis shows that the bottom mounted Nortek AWAC ADCP is the best suitable equipment to be used in the lakes IJsselmeer and Slotermeer. This type of equipment consists of an Acoustic Doppler Current Profiler that is suited for measuring wave height and direction spectra. It measures current profiles as well. The feasibility of the AWAC is related to its accurate Acoustic Surface Track (AST) feature, using a central upward looking beam. This AST feature can be sampled at high frequency rates (up to 4 Hz) and the footprint at the surface remains small due to its narrow beam angle (1.8°). It should be noted that this equipment is new on the market.

- The downward looking radar, radio and acoustic instruments are all serious options as wave instrument for wave monitoring in the IJsselmeer and Slotermeer. The same applies for the step gauge. The negative experiences of RIZA and RDIJ with the step gauge ("Marine 300-II") seem to be related to the outdated design of this gauge. Etrometa has made a new modular design that overcomes most of the former step gauge related problems.

- Pressure gauges are not a serious option since for high frequency waves the sensor has to be located within a quarter of the wave length below the water surface. This could give problems by fluctuations of the still water level on a time scale of hours, days or weeks (the sensor could dry if for example a trough of a high wave passes the sensor). To resolve this problem more pressure sensors could be used (at different heights below the water surface), but this makes the monitoring technique very complex.

- Wave buoys are the most widely used wave measuring gauges, but they are less favourable for the shallow water conditions at the Dutch Lakes IJsselmeer and Slotermeer. The reason is that they cannot follow high frequency waves. Finally the low accuracy of wave height measurements with Wave Radar and WAVEX/ WAMOS makes this measuring equipment based on Remote Sensing not suitable for the measurements in the IJsselmeer and Slotermeer.

- The currently used capacitance probes are more or less "tailor" made. In future RIZA and RDIJ want to apply commercially available equipment only. For this reason the downward looking laser and the "Zwarts Pole" are not recommended although their performance might be good (the downward looking laser is no longer supported and the "Zwarts Pole" is completely "tailor" made (see Verhagen 1999)).

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1 INTRODUCTION

1.1 General

The Dutch Institute for Integral Water Management and Waste Water Treatment (Rijkswaterstaat/RIZA, henceforth, RIZA) and the Regional Directorate IJsselmeer area (Rijkswaterstaat/RDIJ) make use of a monitoring network where wind, water levels and waves are measured almost continuously. The measurement points are located in the Dutch lakes IJsselmeer and Slotermeer. They are by order of the Regional Directorate IJsselmeer area (RDIJ) of Rijkswaterstaat in the Netherlands and are performed by the RDIJ, division PAM. These wave measurements are analysed and validated by M. Bottema working for RIZA, division WSH. The key application of these wave measurements is tuning and validation of numerical wave models that are being used to evaluate design conditions for dikes. Hence, it must be made certain that the storm conditions of the next five years will be accurately measured. However, wave model tuning also requires a great diversity of tuning cases. This implies a wide range of fetches, wind speeds and bottom depths that has to be considered.

Currently capacitance probes are used. These probes require a lot of maintenance and re-calibration. In that respect, RIZA and RDIJ are considering to include new wave measurement instruments within their measurement program.

Therefore RIZA asked Svašek Hydraulics to carry out a desk study to evaluate different wave measurement instruments to be used at the IJsselmeer and Slotermeer measurement locations. At a later stage (not part of this survey) selected equipment will be tested during a try out period.

1.2 Scope of work

The objective of this study is:

To investigate the suitability of different wave monitoring techniques for measurements in the Dutch lakes IJsselmeer and Slotermeer. The output of this study is a recommendation about the wave measurement instrument that is most suitable for these measurements.

1.3 Methodology

This product survey is divided in different phases:

- *Phase 1: A literature study*
  This literature study is carried out in order to make an inventory of existing wave monitoring techniques and wave measurement instruments.
- *Phase 2: Preliminary instrument selection*
  By means of the literature study and the questionnaires among suppliers (see phase 3) a preliminary selection of potentially suitable wave instruments is made.

- *Phase 3: Conduct questionnaires about the selected wave measurement instruments among the suppliers of these wave measurement instruments*
  In order to get more specific information about the wave measurement instruments postal questionnaires are administered to the suppliers of the instruments.

- *Phase 4: Final selection of the instruments*
  Using the questionnaires mentioned above, a selection of the most useable wave measurement instruments can be made. These instruments are investigated further in order to come to an advice about the most suitable wave measurement for the specific wave measurements at the IJsselmeer and Slotermeer.

- *Phase 5: Carry out interviews, about the selected wave measurement instruments, to experts and instrument users.*
  In order to get more specific (practical) information with people that have practical experience with wave measurements at shallow water and/or with the specific wave measurement instruments, interviews are carried out.

- *Phase 6: Sort the selected wave measurement instruments and generate an advice about the wave measurement instruments for the measurements at the IJsselmeer and Slotermeer.*
  The selection of the most suitable wave measurement instrument is performed by a multi-criteria analysis and by means of the results of phase one to five.

The phases one to five will not be performed separately but almost simultaneously.

The set up of this report is as follows:
The present situation of the wave measurements at the IJsselmeer and Slotermeer, including the objective of these measurements, a description of the measurement locations and the used measurement technique with its advantages and disadvantages are presented in chapter two. Subsequently a brief description of several possible wave monitoring techniques (possible for these specific measurements) is given in chapter three. Chapter four presents both the preliminarily and the final selection of the wave instruments that have been considered to be suitable for these measurements. This chapter contains brief descriptions of the final selected instruments as well. In chapter five a summary of user's interviews and used published instruments comparisons is given. To come to an advice about the most suitable wave measurement instrument a multi-criteria analysis is carried out and this analysis is presented in chapter six. Chapter seven contains the conclusions and the recommendations.

2 PRESENT SITUATION

2.1 General

Wave measurements at the Dutch lakes IJsselmeer and Slotermeer are performed almost continuously, except during cold spells when the lakes freeze over. They started in 1997 at 5 locations in the IJsselmeer and from 1999 at one location in the other Dutch Lake Slotermeer. It is intended to continue these wave measurements till 2009. They are by order of the Regional Directorate IJsselmeer area (RDIJ) of Rijkswaterstaat in the Netherlands and are performed by the RDIJ, division PAM. These wave measurements are analysed and validated by M. Bottema working for Rijkswaterstaat/RIZA, division WSH.

The applications of these wave measurements are for instance:

a) Evaluate dike safety
b) Tuning and validation of numerical wave models (like SWAN) which are to be used to evaluate the design conditions for dikes around such lakes.
c) Visualisation the wave growth at the IJsselmeer and Slotermeer (including the establishment of the wave growth limit at shallow water).
d) Visualisation the wave development at shallow foreshore.
e) For navigational aspects.
f) Composition of the hydraulic boundary conditions.
g) Descriptions of the ambient conditions during storms.
h) Gaining an understanding of the physical behaviour of the water system.
i) Description of wave climate at the locations IJsselmeer and Slotermeer.

The wave measurement instruments have to be available on daily basis. This has two reasons:

1. The daily availability of the data output (for quality control and to have a quick response to external questions about the wave conditions).
2. To see if the instrument still works properly, otherwise action can be taken in order to minimise the unreliable or missing records (because sufficient continuity is a big asset to evaluate the wave climatology and some events to be measured are too rare to accept a substantial risk of not being able to measure them because of measurement interruptions).

2.2 Objective

The main objective of the wave measurements at the IJsselmeer and Slotermeer is:

To collect and compute qualitative correct and well-documented wave measurements under different circumstances (especially storms, but also calm weather) at different measurement locations in the Dutch Lakes IJsselmeer and Slotermeer.

2.3 The locations and measurements

Currently the wave measurements in the Dutch Lakes IJsselmeer and Slotermeer are carried out at six locations. These measurement locations are selected by the Regional Directorate IJsselmeer area (RDIJ) of Rijkswaterstaat in the Netherlands in such a way that the different phenomenon's of the waves are taken in consideration. At three measurement locations wind conditions are measured as well. The site co-ordinates and water depths (with respect to the Dutch NAP datum) are presented in table 2.1 (situation March 2003).

Lake	Station	Measure	RD X-coord [m]	RD Y-coord [m]	Water depth [m NAP]	Objective (in respect to the waves)
IJsselmeer	FL2	Wave + wind	167850	530021	-4.43	To measure the waves, especially at long fetches and to measure the wave run up.
IJsselmeer	FL9	Wave	161766	535919	-4.18	To measure the development of the waves from deep to shallow water and to measure waves with long fetches.
IJsselmeer	FL5	Wave	163391	538780	-1.45	To measure the development of the waves from deep to shallow water and measure waves with long fetches
IJsselmeer	FL25	Wave	148997	525997	-2.91	To measure the wave growth with short fetches
IJsselmeer	FL26	Wave + wind	152990	526011	-5.49	To measure the wave growth with short fetches
Slotermeer	SL29	Wave + wind	172496	548506	-2.12	To measure the wave growth in shallow water (" wave growth limit", maximum attainable wave height)

Table 2.1: Measurement locations at the IJsselmeer and Slotermeer (March 2003)

An overview of the IJsselmeer and Slotermeer and its measurement locations are shown in appendix A.

The site specific features key items of the lakes IJsselmeer and Slotermeer are:

Range of fetches:	1 – 40 km
Range of wind speeds:	0 – 32 m/s
Range bottom depths:	1.5 – 10 m
Range H_{m0}:	0.05 – 2 m
Range peak period:	1 – 8 s
Range T_{m01}:	0.7 – 6 s
H_{max}:	up to 4 m

The primary interest of the wave measurements at the IJsselmeer and Slotermeer is measuring the wave heights and the wave height spectra. By contrast, measuring wave directions is considered to be of secondary interest. These measurements must gain an insight of the wave growth (small high frequency waves at shallow water) and storm situations as well. This means that the wave measurement instrument has to be capable to measure a wide range of wave conditions accurately.

2.4 Wave measurement instrument

2.4.1 General

First, at almost every measurement location at the IJsselmeer and Slotermeer, step gauges were used (Marine 300-II) as the wave measurement instrument. These step gauges were 5 cm resolution step gauges (for a more specific description of the technique of the step gauge is referred to paragraph three section 3.2.1). These step gauges had several disadvantages:

- The step gauge is very sensitive to marine growth. Consequently it often happened that one sensor was covered with a marine string resulting in a registration of the sensor as a wet sensor in spite of the lower (actual) water level ("stick to the sensor").
- The step gauge has sensors at an equal distance of each other (discrete) therefore the instrument could not measure between the sensors.
- It was very sensitive to failure because of many conversion strokes. Actually, this was the biggest problem with this instrument.

These disadvantages resulted in the decision to use another instrument for these measurements. Since 1997 a capacitance probe ("Multicap DC11") is introduced and used first at one location FL25. Since March 2001 the capacitance probe ("Multicap DC11") is used at all the measurement locations in the IJsselmeer and Slotermeer.

Section 2.4.2 presents a short description of the currently used wave measurement instrument the "Multicap DC11".

2.4.2 Multicap DC11

The Multicap DC 11 probe is primarily designed for continuous level measurements and limit detection in liquids. The capacitance probe consists of a teflon coated probe and a mass tube of metal, which are corrosion-resistant materials and are able to withstand extremely aggressive products, with fully insulated screening and plastic coated flange.

The capacitive measuring principle works on the basis of a capacitor. An alternating current produces an electrical field between two electrodes. The characteristic value of a capacitor is its capacitance C (pF), which again is determined by the following diverse factors:

- distance of the electrodes (s)
- area of the electrode surface (A)
- dielectricum, of the material between the electrodes

For these measurements the water acts as the dielectricum between the electrodes. The measured capacitance depends on the instantaneous water level. The output of the capacitance probe is a voltage. A calibration in advance has established the relationship between the measured voltage and the length of the wire which is under water. Consequently by knowing the voltage the actual water level is easy to calculate. Appendix B shows a figure of a capacitance probe used for these measurements. At all the wave measurement locations except FL25 (see paragraph 2.3) the sample frequency is 4 Hz. The fetch at FL25 is smaller than 1 kilometre resulting in very short waves and therefore the sample frequency at this location is 8 Hz.

2.5 Control and maintenance of the present wave measurement instruments

The same as the first used step gauge ("Marine 300-II"), the capacitance probe is fixed at a measuring pole (see figure 2.1). This measurement pole is equipped with a wind set as well in order to provide wind data which are needed for the interpretation of the wave data. A data logger is situated at the measurement pole as well. This logger is used to collect the data from the capacitance probe and the wind sensor. This data can be transferred to a shore station by telemetry (like GSM), which takes place every day where it can be stored and be worked up (for quality control and to have a quick response to external questions about wave conditions). Telemetry is used as well to verify if the instruments perform properly.

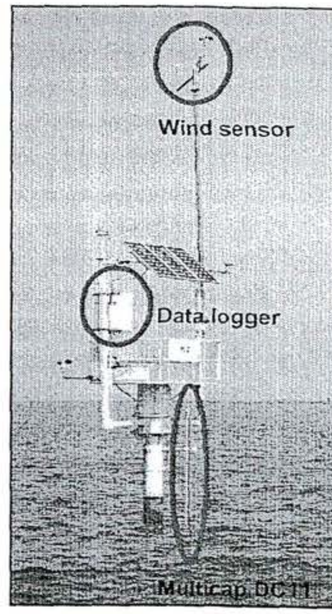


Fig 2.1 Measurement pole with the Multicap DC11 and wind sensor (FL2)

Problems with the present wave measurements in regard to the used wave measurement instrument ("Multicap DC11", see section 2.4.2) can be separated in two parts:

1. Failure of the wave measurement data which had several reasons:
a. Frosty periods.
b. Modem problems.
c. PC failure.
d. To small wave heights (resulting in rejecting by the processing scripts).
e. Not enough memory of the data logger.
f. Memory failure data logger.
g. Failure of the electronics.
h. Failure by damage of ice, vandalism or driftwood.

2. Unreliability of the wave measurement data. This was caused namely by:
a. Soiling of the capacitance probes (like marine growth, see Appendix B).
b. Ice accretion at the capacitance probes.
c. Non-linearity's at the calibrations of the capacitance probes.
d. The sensitivity of the capacitance probes for drift.

The biggest problem of capacitance probes is soiling of the probes. Therefore this problem will be more specified here.

The capacitance probes are very sensitive to soiling and therefore require a lot of maintenance and re-calibration. This maintenance is crucial because RIZA and RDIJ want year-round measurements including rare events like heavy storms. Currently the probes are cleaned at least ten times a year and each time a calibration test is taken. Appendix B shows a capacitance probe before and after cleaning. To get an impression of the necessity of cleaning the capacitance probe, appendix C presents the capacitance probe test before and after cleaning. This test is performed Monday 30 August 2004 at the location FL25 (see Appendix A). The effect of the cleaning is clearly visible. The signal of the water level is after cleaning lowered with approximately 0.05m. Before cleaning, a real displacement of 0.5m corresponds with 0.43m in the measured value – an underestimation of 14%. After cleaning, a displacement of 0.5m corresponds with 0.53m in the measured value – an overestimation of 6%. The results indicate some drift (6%) of the capacitance probe.

For a more specific description of the present wave measurements at the Dutch IJsselmeer and Slotermeer lakes can be found in the following reports:

- Beyer, D., E.R.F. van der Goes, *"Golfmetingen IJsselmeergebied – verslag meetseizoen 1997-1998"*, RIZA, 2000, werkdocument (Internal Report RIZA) 2000.158X
- Jacobs en Van Vledder, *"Rapportage golfmetingen IJsselmeergebied 1999-2000"*, report A972, Alkyon (also available as work document 2002.190X, RWS/RIZA)
- Bottema, M., *"Rapportage golfmetingen IJsselmeergebied 1998-1999"*, RIZA, 1 Oct 2003, werkdocument (Internal Report RIZA) 2003.143X.
- Bottema, M., *"Rapportage golfmetingen IJsselmeergebied 2000-2001"*, RIZA, 8 March 2002, werkdocument (Internal Report RIZA) 2002.191X.
- Bottema, M., *"Rapportage golfmetingen IJsselmeergebied 2001-2002"*, RIZA, 12 Dec 2002, werkdocument (Internal Report RIZA) 2002.063X.
- Bottema, M., *"Rapportage golfmetingen IJsselmeergebied 2002-2003"*, RIZA, 12 Dec 2003, werkdocument (Internal Report RIZA) 2003.144X.
- Bottema,M., de Waal,J.P., Regeling,H.J., *"Some applications of the Lake IJssel/Lake Sloten wave data set"*, Proc 4th Int. Conf. Coastal Engineering, 2003
- Goes, vd, E.. *"Onderhoudsronde 1eweek September 2004"*, (Internal Report RDIJ)
- Kleine, R.S.E., *"Onderhoudsplan golfmeetopstellingen"*, Rijkswaterstaat Directie IJsselmeergebied, afdeling ANM, IB-nr: 090.5.09.001

3 WAVE MONITORING TECHNIQUES

3.1 General

The objective of this study is to give a recommendation about the most suitable wave measurement instrument for the measurements performed in the Dutch Lakes IJsselmeer and Slotermeer.

This chapter briefly describes the possible wave monitoring techniques. A distinction is made between measurement techniques that produce directly the desired wave data and indirect methods for which assumption(s) has to be made (like an assumption of a linear wave, wave shape, array assumption). The following measurement techniques are considered:

1. <u>Direct measurement techniques:</u>

- Step gauge measurements
- Capacitance probe measurements
- Zwarts pole measurements
- Buoy measurements
- ADCP (when using acoustic surface tracking as wave height sensor)
- Radar measurement technique
- Laser technique

2. <u>Indirect measurement techniques:</u>

- Pressure measurement technique
- Point current and pressure measurement technique
- ADCP (when using orbital velocity sensor and pressure sensor)
- Remote sensing (wave mapping techniques)

A short description of these techniques are described in section 3.2 (the direct measurement techniques, section 3.21 up to 3.2.7) and in section 3.3 (the indirect measurement techniques, section 3.3.1 up to 3.3.3).

3.2 Direct measurement techniques

3.2.1 Step gauge measurements

The step gauge is an instrument for measurements of instantaneous water levels. This instrument has to be mounted at a fixed structure (like a measuring pole or platform etc.). The step gauge consists of a pole with a number of electrodes which are situated at an equal distance from each other. Using electronic scanning technique the highest wet electrode is detected. This is, by definition, the actual water level. The accuracy of such an instrument is mainly determined by the distance between the electrodes. This is a discrete measurement technique.

The advantages:
- This instrument has no drift.
- The step gauge is not dependent of temperature.

- Accuracy is range independent only dependent on the distance between the sensors.
- Low power consumption (internal batteries work for 10 years).
- Good track record.
- Can be used to measure high frequency waves.

The disadvantages:
- Because the instrument is discrete, it only measures in steps. These steps can be too big in comparison to the wave height.
- The step gauge is sensitive to soiling (marine growth).
- The accuracy is dependent on the distance between the electrodes.
- There is a possibility of interference of the gauge or the fixed structure with the waves.
- Some step gauge types suffer from frequent disturbance and/or overall failure due to electronics problems (like the one used by RWS, "Marine 300-II").

3.2.2 Capacitance probe measurements

The capacitance probe is an instrument for continuous level measurement and limit detection in liquids. This instrument must be mounted at a fixed structure (like a measuring pole or platform etc.) similar as the step gauge. A capacitance probe consists of a probe and a capacitor. An alternating current produces an electrical field between two electrodes. The water will act as the dielectricum between the electrodes and the measured capacitance depends on the instantaneous water level. The output of the capacitance probe is a voltage and by knowing the relationship between the measured voltage and the length of the wire which is under water, the actual water level is easy to calculate.

The advantages:
- This instrument is easy to use.
- Can be used to measure high frequency waves.

The disadvantages:
- The capacitance probe is sensitive to soiling.
- The capacitance probe is sensitive for drift.
- There is a possibility of interference of the gauge or the fixed structure with the waves.
- The connecting parts between the mass tube and wire tend to cause "hiccups" in the calibration curve which may lead to significant errors, especially when such a connecting part is close to the still water level.

3.2.3 Zwart pole measurements

The Zwarts pole acts as the equivalent of a coax cable. The pole is constructed of two concentric tubes. Holes in the outer tube allowed the water to flow freely into the gab between the tubes thus maintaining the same water elevation within the pole as outside. The air-water interface provides a discontinuity in the dielectric properties of the "cable" and cases a "reflection" of an electric wave. Zwarts (1974) showed hat an electromagnetic standing wave can be established along the pole. The period of this wave is directly proportional to the length of the air gab between the head or top of the pole and the air-water interface (dielectric discontinuity). The final output from the electronics was a square wave. This square wave output is connected to a counter circuit which contained two Programmable Array Logic (PAL) chips programmed to convert the frequency signal to a two byte number. Representing the instantaneous water elevation at the Zwarts pole.

Advantages:

- The calibration is independent of the physical properties of the water.
- The salinity or conductivity has no influence on the calibration of the instrument.
- High accuracy.
- High sample frequency.
- Very low costs.

Disadvantages:

- The pole calibration is temperature sensitive.
- Not ideal for measurements of very low frequencies (tides, infra gravity waves or seiches).
- Fouling of the holes in the pole with algae resulting in blocking the water from entering the pole.
- There is a possibility of interference of the pole or the fixed structure with the waves.

3.2.4 Buoy measurement systems

These measurements are based on the movement of the buoy. The buoy movements are measured using accelerometers and tilt sensors. There are different buoy systems. Buoy systems that give no information about the directional wave (normal waverider) only measure the vertical displacement of the buoy using a gimballed accelerometer. A gimballed accelerometer is an accelerometer that is placed in a gimbal ring which keeps the accelerometer vertical under all conditions.
Directional waveriders work on the heave-displacement principle, measuring time series of wave elevation and displacement in two orthogonal directions and relies on the buoy moving closely with the orbital motion of a free-floating particle predicted by the linear theory. Finally there are buoy systems with a GPS receiver equipped at the buoy, which measures the velocity of the buoy in different directions resulting in directional wave parameters also. A buoy's heave is not sensitive to wavelengths less than the buoy's diameter. Buoys using an accelerometer are insensitive for small accelerations (long wave periods).

Advantages:

- Wave following, not affected by spray (non GPS buoy), follows the effective water level even under extreme conditions and white capping .
- Accurate, most instrument manufacturers use the wave buoy as a "calibration" verification instrument.
- Used at many locations.
- No special measuring poles or platforms required (simple installation).

Disadvantages:

- Measuring both high frequency and extreme wave heights is very difficult to design (being small enough to measure small waves and at the same time able to measure continuously during years and being rugged enough to survive and measure these extreme conditions).
- The GPS buoys lose contact with the GPS satellites when spray is washed over their GPS-antenna, they will measure again when the antenna is clear again.
- High frequency waves can not be measured.
- The orbital movement of the buoy is less accurate with nonlinear waves with a significant Stokes drift.
- Has to be removed during periods with ice.
- The buoy does not provide any wind data or still water level data which are needed for the interpretation of the wave data. Hence a separate instrumented pole is needed.

3.2.5 ADCP

The ADCP has to be mounted on the bottom. It has 3 or 4 slanted beams to measure current profiles. An ADCP that can be used to measure waves has various internal methods to measure wave height and direction:

- Pressure gauge (only suitable for wave height)
- Acoustic surface track: With each of the transducers, currents and at the same time the distance to the surface can be measured. This distance can be converted into wave height.
- Near surface velocity measurement. The near surface velocity measurement can be analysed and filtered for orbital wave motion. This orbital wave motion can be used to address wave height and wave directions.
- AST: A special form of acoustic surface track, an "AST beam" is oriented vertically. It uses a short acoustic pulse to detect the surface more accurately than the "current beams". Moreover, its "footprint" on the surface is smaller.

Advantages

- AST is capable of measuring high frequency waves.
- Internal verification of wave measurement quality (independent methods of wave height measurement).
- Additional current measurement.
- Not sensitive for marine growth.
- Weather independent, bottom mounted no ice or storm related problems are to be expected.
- Measurement is not influenced by pole or construction.

Disadvantages

- Cable connection between pole and instrument.
- More complex installation.
- More complex data processing and interface with existing data logger.
- A separate instrumented pole is needed to provide wind data which are essential for the interpretation of (fully wind generated) waves on lakes.

3.2.6 Range measurement techniques (Radar, radio or acoustic)

This measuring technique measures instantaneous water levels by making use of a to the water surface the time difference between transmitting and receiving signal will be measured. This interval is proportional to distance to the surface. This technique avoids direct contact with the water surface and therefore avoids structural interference. When mounted in an array, also wave directions can be measured.

The speed of sound is a few orders higher than the maximum vertical velocity of the water surface (or wave). Therefore the interference of the vertical "wave" velocity on the measured distance between the instrument and the water surface is smaller than the instrument resolution. The same applies for the radar and radio based measurement systems.

Advantages
- Simple installation and maintenance.
- Accurate, no re-calibration required.
- Not influenced by rain, or fog.
- *High frequency sampling.*
- Instrument is well known within the RWS organisation.

Disadvantages
- Radar, radio and acoustic beam has a relative large opening angle (5°).
- When measuring short waves radar beam tends to be biased towards the concavely shaped part of the wave (through).
- Reflected Acoustics signal can be influenced by storm conditions.

3.2.7 Laser technique

The laser technique operates by emitting a narrow laser beam that is reflected from the water surface and collected by a sensor. It measures the delayed signal returning from the water surface. This technique has been used at the Noordwijk platform and is used at the Ekofisk platform

Advantages
- This system does not interfere with the waves.
- Small footprint at the water surface.
- Accurate.
- High frequency sampling is possible.

Disadvantages
- No support from potential suppliers.
- Sensitive for water vapour (fog).
- Sensitive for spray.
- Beam can be obstructed by spider webs.

3.3 Indirect measurement techniques

3.3.1 Pressure measurement technique

The measured pressure will be converted into the water surface elevation (by using the linear wave theory). A pressure gauge must be located within a quarter of a wavelength of the surface because wave-induced pressure fluctuations decrease exponentially with depth (so when the pressure sensor is placed too far away from the water surface the pressure sensor would not be sensitive for the waves anymore). When placed close to the water surface it will be frequently above water.

Advantages
- Relatively cheap.
- Easy to install.
- Insensitive for marine growth.
- Well known measurement technique.

Disadvantages
- Assumptions have to be made (like the assumption of linear wave theory for the pressure to wave height conversion).
- For high frequency waves the sensor has to be located near by the water surface which could give problems by fluctuations of the still water level on a time scale of hours, days or weeks (the sensor could stand clear from water if for example a trough of a high wave passes the sensor).

3.3.2 Point current and pressure measurement technique

These systems consist of two measuring principles. Pressure for measuring wave heights and point current measurements for deriving orbital velocities and thus wave directions. The point current measurement could be based on either an electro magnetic sensor (like the Seapack 2000) or an ADCP measurement technique with one single cell/cell area.

Advantages:
- Relatively cheap.
- Easy to install.

Disadvantages
- Assumptions have to be made (like the assumption of linear wave theory for the pressure to wave height conversion).
- For high frequency waves the sensor has to be located nearby the water surface which could give problems in rough weather (the sensor could stand clear from water if for example a trough of a high wave passes the sensor).

3.3.3 Remote sensing (wave mapping techniques)

Wave related parameters can be deduced from the "clutter" which is the reflected signal from the sea surface received by an ordinary navigation radar. Wave length, wave direction and wave period can be deduced applying spatial Fourier techniques.

Wave heights can be measured indirectly by assuming a relation between received signal strength and wave height. This relation is location specific. Tests have been carried out at Petten using the WAMOS software package.

Advantages

- Onshore based equipment.
- Spatial information.
- Additional current information.

Disadvantages

- Inaccurate wave heights (20%).
- Will not work during "light" weather conditions (no bragg waves).

4 INSTRUMENT SELECTION

4.1 General

This chapter presents the instruments that are considered to be suitable for the Lake IJsselmeer and Slotermeer measurements. The first selection is based on a literature study, a product survey on the internet and experiences of Svašek Hydraulics, Rijkswaterstaat and other consulted specialists.

The final selection is based on the preliminary selection and the knowledge of the literature study, product survey on the internet, experiences of Svašek Hydraulics, Rijkswaterstaat, questionnaires and interviews with experts and instrument users. A number of instruments have not been further investigated (see paragraph 4.3) after the final selection. The remaining instruments are further investigated and are used within a multi-criteria analysis by using the questionnaires to the suppliers (see appendix D), the interviews with experts and instrument users (see appendix E) and the specifications of the instruments (see appendix F). The purpose of this multi-criteria analysis is to facilitate the instrument selection. The multi-criteria analysis is discussed in chapter 6.

4.2 Preliminarily selection

By means of the literature study and questionnaires a preliminary selection of wave instruments, which seems to serve the purpose for the wave measurements in the IJsselmeer and Slotermeer, is made and this selection is presented in Table 4.1 below.

Index	Type of instrument	Name of instrument	Supplier	Remark
1	**Step gauge**	**Etrometa step gauge (5cm resolution)**	Etrometa	Telephone conference indicated that high sampling rates are possible standard rate is 2.56 Hz, new rate can be 5.12 Hz.
		Vlissingen step gauge		Used in the WACSIS experiment can be sampled at 10 Hz, not longer in use, replaced by the marine 300 step gauge, this last instrument is not longer supported.
2	**Capacitance probe**	**Multicap DC11**	Endress & Hauser	This instrument is currently used for the measurements at the IJsselmeer and Slotermeer.
		Baylor wave staff		Used in the WACSIS experiment can be sampled at 4 Hz, no supplier found.
		Zwarts wave pole		Used successfully in the lake George experiments (see interview with Dr. Louis Verhagen). Relative insensitive for marine growth and can be sampled at high frequencies. This instrument has been "tailor made" and is not available on the market.
3	**Wave buoy**	**Waverider SG** **Dir Waverider MKII** **Dir waverider GPS** **Mini Waverider GPS**	Datawell	The supplier "Datawell" indicates that small size buoys (40 cm) could be used and that sampling interval could be up to 3.84 Hz for the directional wave rider and 10 Hz for their GPS based wave rider. GPS based measurement technique is sensitive for spray over the antenna surface.
		Endeco/YSI wave buoy	Endeco/YSI	Directional wave buoy, used by Svašek in Malta and Ghana, Specification comparable with waverider, not further investigated (instrument is not longer supported by supplier).
4	**Pressure gauge**	**Paroscientific pressure sensor**	Bakker & Co	The paroscientific pressure gauge is highly accurate (0.01% of FS) and suitably priced (as from Euro 3500). This system could be easily interfaced within the existing system. The "WL, Neelke Doorn" report contains the most significant information regarding pressure sensors (see literature).

Index	Type of instrument	Name of instrument	Supplier	Remark
	Pressure gauge	Midas WTR	Valeport	Can be sampled at high frequencies (8 Hz), low power consumption and internal data logger for over 3-4 month's of data.
5	Wave ADCP	RDI wave ADCP	Aqua vision BV	Bottom mounted, directional wave measurement based on ADCP data, and surface track using the oblique "ADCP beams", system lacks capability in measuring waves at high frequencies (beam separation and depth related cut off frequency (pressure)). The IMAU desk study report contains valuable background information (see literature).
	Wave ADCP	Nortek AWAC	Qmetrix	Bottom mounted ADCP contains narrow beam (1.8°) upward looking "echosounder". This system is relatively insensitive for the mounting depth, marine fouling, marine growth and weather impact. Accuracy's when sampling at high frequencies is yet not known. Internal storage capacity and power supply could make this a mobile and fast installable piece of equipment. It measures also wave direction, current velocities and water temperature. Recent validation data at 8m water depth in Tampa bay Florida shows reliable high frequency data. Sample interval can be 4 Hz.
6	Downward looking Radar	Directional WaveGuide	Radac	Sampling frequency can be a potential problem. Wave directions can be measured using an array of sensors. A lot of experience available at RIKZ, TNO/TPD. Potential problem with the measurements of short wave length due to a bias to the wave trough (radar signal are converged).
		Wave Radar (SM-050)	Miros Norway	Microwave and radar level sensors, beam width is also 5°, more information is expected from Miros. Used in the WACSIS experiment can be sampled at 4 Hz. Beam width 5° or bigger.
		Saab Radar		Used in the WACSIS experiment can be sampled at 10 Hz.
7	Remote sensing	MIROS Wavex	Miros Norway	Required power can be a problem for the installation on a pole, indirect wave mapping measurement technique, inaccurate wave heights.
8	Downward looking Laser		Laseroptronix Sweden	
			Optech Canada	Advised by Miros in Hydro article (see literature).
		Thorn/EMI wave height sensor		Used in the WACSIS experiment, can be sampled at 4 Hz.
9	Downward looking Acoustic	LOG_alevel	General Acoustics GmbH	This seems to be a very promising technique, accuracy and sampling interval seems not to be a problem. Nearly maintenance free, no fouling freezing or weather related problems are foreseen and this system could be interfaced more or less within the existing infrastructure. Open questions are the capability of measuring steep waves.
		SRD	SRD UK	System is not yet operational.
10	Downward looking radio	Rangefinder (SM-094)	Miros Norway	Microwave (FM radio) based range measurement system, insensitive for rain, fog and water spay.
11	PUV (p, pressure, u velocity , v velocity)	Nortek Aquadopp	Qmetrix	Point (single bin) velocity measurement based on ADCP measurement technique, used to measure orbital velocity and through that wave directions. Uses pressure sensor for wave height measurement, can be sampled at 1 Hz.
		Seapack 2100	Whisl	Point current measurement with Marsh Mc Birney, electro magnetic sensor. Uses pressure sensor for wave height measurement, can be sampled at 2Hz.

Table 4.1 Preliminary selection of the wave measurement instruments

4.3 Final selection

4.3.1 General

In view of the questionnaires conducted to suppliers of the instruments and interviews with experts and instrument users a final selection of the most useable wave measurement instruments for the measurements at the IJsselmeer and Slotermeer has been made and some instruments were dropped out for further investigation. The instruments (and reasons why) that were dropped out of the selection are:

- Endeco/YSI wave buoy — This wave buoy is no longer supported by supplier.
- SRD — System is not yet operational.
- Aquadopp — This instrument can not measure at required sampling rate.
- Seapack 2100 — This instrument is outdated. Leakage has been a problem.
- Thorn wave height sensor — THORN/EMI has been taken over and probably now part of Thales, there seems to be no support for this system anymore.
- Baylor wave staff — Supplier, and nowadays users are not found and probably not existing anymore.
- Vlissingen step gauge — Is not supported anymore by supplier.
- Saab Radar — This system is supposed to be supported by WS ocean systems, this company has been taken over. No support for this instrument has been founded by supplier.
- Zwarts pole — Although this has proven to be a reliable and accurate technique, no supplier is available.

The rest of the instruments of the preliminary selection (see table 4.1) are investigated further in order to come to an advice about the most suitable wave measurement for the specific wave measurements at the IJsselmeer and Slotermeer lakes.

The following paragraphs shortly describe the selected wave measurement instruments and for a complete description is referred to Appendix F.

A multi-criteria analysis will be performed in order to come to a ranking of suitability of the selected instruments for the measurements at the IJsselmeer- and Slotermeerlocations. The different criteria used in the multi-criteria analysis are summarised below and they will be briefly discussed in the next subparagraphs for each selected instrument. The specification of criteria and the satisfactory of the instruments to the criteria will be elaborated in chapter 6. Here only a global description will be given. The following criteria are used in this study:

Criteria (short description):

1) Wave frequency range (low)
   What is the capability of the instrument to measure low frequency waves?
2) Wave frequency range (high)
   What is the capability of the instrument to measure high frequency waves with low amplitude?

3) Resolution small waves
What is the resolution of the instrument in respect to small waves (H_{m0}=0.05m)?
4) Resolution high waves
What is the resolution of the instrument in respect to high waves (H_{max} 2.5m)?
5) Range high waves
What is the range of the instrument with respect to high waves (H_{max} 2.5m +1m water level variation resulting in a minimum range of 3.5m)?
6) Accuracy
What is the accuracy of the instrument?
7) Wave Direction
Can the instrument measure wave direction?
8) Direct/Indirect
Are there assumptions needed (like linear theory)?
9) Sample frequency
What is the sample frequency of the instrument?
10) Power consumption
The present poles do have approximately 5 W of power available for an instrument. How much power does the instrument need to function?
11) Daily data production
How much data will be produced by the instrument in one day?
12) Data output
Does the instrument give extra output (like wave direction, vertical current profiles, water level or water quality parameters or current information)?
13) Autonomy
How long can the instrument measure continuously without human interference?
14) Internal Memory
What is the internal memory of the instrument?
15) Calibration/drift
How many times a year is re-calibration of the instrument needed?
What is the risk on significant drift (>5 –10 %)?
16) Costs
What are the costs of the instrument?
17) Interface present equipment
Does the instrument fit in the present situation or are adaptations needed?
18) Combination with other instruments
Can the instruments be combined with other instruments?
19) Soiling, marine growth, maintenance requirements
How sensitive is the instrument for soiling and marine growth. How many times a year is maintenance required in order to function properly?
20) Reliability/robustness
How reliable and robust is the produced data (resistance of vandalism)?
21) Storm, ice and fog
How sensitive is the instrument for storm, ice and fog?
22) Feasibility of checking the instruments in the field
Is it possible to check (like check the instrument on measurement errors) the instrument in the field without removing it?
23) Nonlinear calibration
What is the effect of nonlinearities in the calibrations?
24) Necessity of repairing the output signal of the instruments
Does the output signal need to be repaired if so how often and in what cases?
25) Errors by breaking waves (bubbles, spray)

How does the instrument work with spray and bubbles in the water column?

26) Errors by wave asymmetry
What are the measuring errors by asymmetric waves?
27) Human errors
What is the change on human errors (like no perfect placing of the instrument or using a wrong calibration factor)?
28) Influence temperature salinity
What is the influence of the temperature or salinity on the measurements?
29) Logger capacity
What is the data logger capacity?
30) Transfer data by telemetry
Is it possible to transfer data by telemetry from the instrument (data logger) without interruption of the measurements?

4.3.2 Capacitance probe

Multicap DC11

Function:
The "Multicap DC 11" measures continuously the water level and detects limit in liquids. The capacitive measuring principle works on the basis of a capacitor. An alternating current produces an electrical field between two electrodes. For these measurements the water acts as the dielectricum between the electrodes. The measured capacitance depends on the instantaneous water level. The output of the capacitance probe is a voltage.

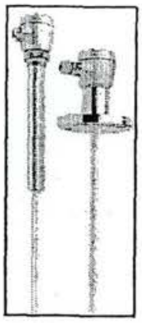


Fig 4.1 Multicap DC11

Wave frequency range (low):	No limit.
Wave frequency range (high):	Up to 2 Hz. The time of response of the capacitance probe is very short (ca 1 mS). The frequency range will not be determined by the limits of the capacitance probe but by the limits of the data logger.
Resolution small waves:	≈ 0.002 m.
Resolution high waves:	≈ 0.002m.
Range high waves:	0m – 3 m /section.
Accuracy:	< 5cm.
Wave Direction:	No.
Direct/Indirect:	Direct.
Sample frequency:	Up to 8 Hz.
Power consumption:	No information of supplier, part of the present system, so smaller than 5 W.
Daily data production:	1 parameter 8 Hz results in 2.5 MB per day.
Data output:	Water level.
Autonomy:	No internal memory and batteries.
Internal Memory:	None.
Calibration/drift:	Drift expected due to marine growth re-calibration is required with each cleaning operation.
Costs	Round 1000 Euro.
Interface present equipment	Is part of the present set up.
Combination with other instruments	None.

Soiling, marine growth, maintenance requirements	Frequent cleaning required.
Reliability/robustness	Relatively simple instrument not very attractive for vandalism. Partly placed above the water level (easy accessibility for vandals). Reliability see cleaning maintenance and drift.
Storm, ice and fog	System is not able to measure during icing and ice. System is not sensitive for fog and storm.
Feasibility of checking the instruments in the field	The output data can be easily checked.
Non-linearity's	The capacitance probe biases towards the support beams.
Necessity of repairing the output signal of the instruments	Is required if the capacitance probe is too short.
Errors by breaking waves (bubbles, spray)	Not expected
Errors by wave asymmetry	Not expected
Human errors	Wrong installation suspension, subsidence with regard to the bearing construction
Influence temperature salinity	No
Logger capacity	2MB
Transfer data by telemetry	Yes

Table 4.2 Criteria Multicap DC11

Remarks:

- This instrument is currently used at all the measurement locations at the IJsselmeer and Slotermeer as from March 2001. The capacitance probe can be fixed to a pole or another supporting structure.
- The Multicap DC11 is the only capacitance probe which is investigated because only precursors could be found and these were not produced any more (like the Baylor Wave Staff) other suppliers of capacitance probes could not be found.
- Currently these capacitance probes are cleaned 10 times a year.

4.3.3 Step gauge

<u>Step gauge E5000</u>

Function:

The step gauge itself is built up by individual sections of 3 m length, which are vertically mounted on each other and form one functional entity. Each section contains 60 electrodes in a vertical line which are separated at distances of 0.05m. At the lower end of a section there are two so called "earth electrodes". During submerging these electrodes make first contact with the seawater and are used as a reference for the wet/dry detection of the measuring electrodes. All electrodes (top-down) are checked on the condition wet/dry until the first wet electrode has been detected. This is, by definition, the water level. The application of internal Li batteries (life expectancy of at least 10 years) and inductive data transmission between the sections results in a completely self-supporting section without swivels, cables, connectors etc. A range of 3 m is possible with a single

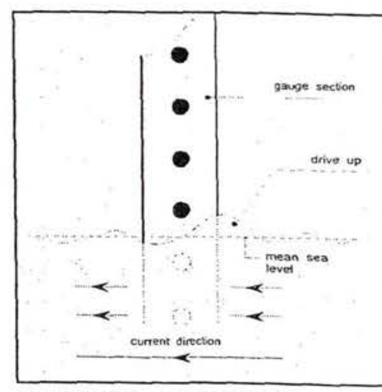


Fig 4.2 Step gauge E5000

section. By simply mounting a section on the top of the previous one it is possible to assemble a step gauge with a range of 21 m.

Wave frequency range (low):	No limit
Wave frequency range (high):	Up to 2 Hz
Resolution small waves:	+/- 2.5cm and +/- 1cm for a 2 cm resolution step gauge
Resolution high waves:	+/- 2.5cm and +/- 1cm for a 2 cm resolution step gauge
Range high waves:	0m – 3m /section more section can be easily coupled (maximum of 21m)
Accuracy:	+/- 2.5cm and +/- 1cm for a 2 cm resolution step gauge
Wave Direction:	No
Direct/Indirect:	Direct
Sample frequency:	up to 10 Hz (Standard 4 Hz)
Power consumption:	65mW (SGE +gauge head)
Daily data production:	2.8MB/day for sampling rate 4 Hz
Data output:	Instantaneous water level
Autonomy:	Optional
Internal Memory:	Optional
Calibration/drift:	Not expected
Costs	13830 Euro (including software)
Interface present equipment	No problems expected
Combination with other instruments	None
Soiling, marine growth, maintenance requirements	Brushing and spraying once a year and repainting (anti fouling) every three to four years.
Reliability/robustness	Relative simple instrument not attractive for vandalism. Part of the instrument is placed partly above the water (easy accessibility for vandals). Reliability very high.
Storm, ice and fog	The instrument is sensitive for icing
Feasibility of checking the instruments in the field	Can be checked, the actual water level can be read on the display of the instrument
Non-linearity's	Not expected
Necessity of repairing the output signal of the instruments	Not expected
Errors by breaking waves (bubbles, spray)	Wet cells are measured
Errors by wave asymmetry	No errors expected
Human errors	Wrong suspension, subsidence with regard to the bearing construction
Influence temperature salinity	Will work to salinity up to 6g/l (standard).
Logger capacity	No logger
Transfer data by telemetry	Yes

Table 4.3 Step gauge E5000

Remarks:

- For guarding purposes the next 7 electrodes under the water are also checked whether they are wet. If this is not the case they are marked as false dry electrodes in the output signal. This can be the case with breaking waves.
- After the decision wet/dry electrode, the input signal is digital, with corresponding advantages such as no-zero drift, no temperature dependence etc.
- The salinity should be known roughly for the adjustment of the wet/dry detector in the sections.

4.3.4 Buoy

Waverider SG

Function:

This buoy is a non-directional flexible moored buoy with internal stabilised platform and accelerometer.

Directional Waverider MKIII

Function:

This buoy is a directional flexible moored buoy with internal stabilised platform and accelerometer in combination with horizontal accelerometers and compass. By measuring the orbital motion of the water particles the wave height and wave direction are measured.

Directional Waverider GPS

Function:

This buoy is a directional flexible moored buoy with measures the wave height and wave direction by following the orbital motion of the water particles and detecting this motion via the GPS-system.

Mini Waverider GPS

Function:

This buoy acts the same as the Directional Waverider GPS it only has a smaller diameter namely 0.4m. Therefore higher frequency waves can be measured in comparison with the directional waverider GPS .

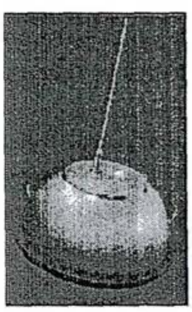


Fig 4.3 Dir. Waverider MKIII

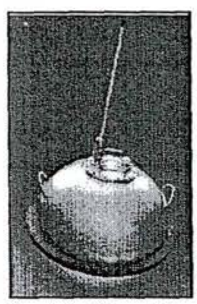


Fig 4.4 Waverider SG 0.7m

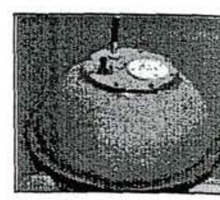


Fig 4.5 Mini Dir. Waverider

Wave frequency range (low):	Waverider SG:	higher than 0.033 Hz
	Dir. Waverider MKIII:	higher than 0.033 Hz
	Dir. Waverider GPS:	higher than 0.01 Hz
	Mini Dir. Waverider:	higher than 0.025 Hz
Wave frequency range (high):	Waverider SG:	up to 1 Hz
	Dir. Waverider MKIII:	up to 1 Hz
	Dir. Waverider GPS:	up to 0.6 Hz
	Mini Dir. Waverider:	up to 0.6 Hz
Resolution small waves:	Waverider SG:	0.01m
	Dir. Waverider MKIII:	0.01m
	Dir. Waverider GPS:	0.01m
	Mini Dir. Waverider:	0.01m
Resolution high waves:	Waverider SG:	0.01m
	Dir. Waverider MKIII:	0.01m
	Dir. Waverider GPS:	0.01m
	Mini Dir. Waverider:	0.01m

Range high waves:	Waverider SG: -20m – +20m Dir. Waverider MKIII: -20m – +20m Dir. Waverider GPS: -50m – +50m Mini Dir. Waverider: -50m - +50m
Accuracy:	Waverider SG: 0.5% of the measured value Dir. Waverider MKIII: 0.5% of the measured value Dir. Waverider GPS: 1-2cm Mini Dir. Waverider: 1-2cm
Wave Direction:	Waverider SG: No Dir. Waverider MKIII: Yes Dir. Waverider GPS: Yes Mini Dir. Waverider: Yes
Direct/Indirect:	Waverider SG: direct Dir. Waverider MKIII: direct Dir. Waverider GPS: direct Mini Dir. Waverider: direct
Sample frequency:	Waverider SG: 10.24Hz Dir. Waverider MKIII: 3.84Hz Dir. Waverider GPS: 10Hz Mini Dir. Waverider: 10Hz Frequency can be adjusted to these ranges
Power consumption:	Waverider SG: 0.27W Dir. Waverider MKIII: 0.38W Dir. Waverider GPS: 0.9W Mini Dir. Waverider: 0.9W
Daily data production:	Waverider SG: 1.4MB Dir. Waverider MKIII: 1.4MB Dir. Waverider GPS: 1.4MB Mini Dir. Waverider: 1.4MB At unknown sampling interval and sampling duration
Data output:	Waverider SG: Wave height Dir. Waverider MKIII: Wave height + Wave direction Dir. Waverider GPS: Wave height + Wave direction Mini Dir. Waverider: Wave height + Wave direction Optional : Water temperature
Autonomy:	Waverider SG: up to 1.5 year Dir. Waverider MKIII: up to 1 year Dir. Waverider GPS: up to 0.7 year Mini Dir. Waverider: up to 0.7 year
Internal Memory:	Waverider SG: up to 1GB Dir. Waverider MKIII: up to 1GB Dir. Waverider GPS: up to 1GB Mini Dir. Waverider: up to 1GB
Calibration/drift:	Waverider SG: drift 0.5 % - 2% Dir. Waverider MKIII: drift 0.5 % - 2% Dir. Waverider GPS: drift 0.5 % - 2% Mini Dir. Waverider: drift 0.5 % - 2% Calibration required every three to six years
Costs	Waverider SG: 11700 Euro Dir. Waverider MKIII: 22500 Euro Dir. Waverider GPS: 17200 Euro Mini Dir. Waverider: -
Interface present equipment	Problems expected
Combination with other instruments	None
Soiling, marine growth, maintenance requirements	Minimal maintenance requirement no effect of soiling or marine growth
Reliability/robustness	Thousands of these buoys have been sold they have been used successfully in the hardest environments
Storm, ice and fog	Buoys have to be removed from the water during ice periods.
Feasibility of checking the instruments in the field	Can be checked using the radio link
Non-linearity's	Not expected
Necessity of repairing the output signal of the instruments	Will be handled by wave processing software

Errors by breaking waves (bubbles, spray)	Waverider SG/Dir. Waverider MKIII: The wave following buoys can not handle spilling waves. By definition buoys follow the effective water level Dir. Waverider GPS/ Mini Dir. Waverider: water on the GPS antenna stops the measurement for the time the antenna is submerged
Errors by wave asymmetry	No errors expected
Human errors	None
Influence temperature salinity	None
Logger capacity	Up to 2GB
Transfer data by telemetry	Yes

Table 4.4 Criteria Buoys

Remarks:

- GPS based measurement technique are sensitive for spray over the antenna surface
- High frequency waves can not be measured by buoys with a diameter of 0.9m
- No errors occur with the spilling and collapsing and surging waves. In case of plunging waves the buoy can not follow the water surface correctly

4.3.5 Acoustic

Log_alevel

Function:

This instrument is a remote sensing, stand-alone wave and water level gauge on the basis of ultrasonic sensors with solar power supply (optional with solar power supply and wind generator) and wireless data transmission. This system measures from above and it works automatically and is independent of any external connections.

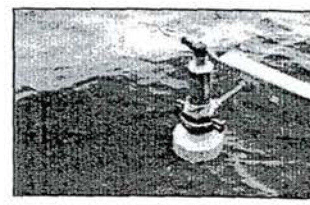


Fig 4.6 : Log_alevel

Wave frequency range (low):	No limits
Wave frequency range (high):	Up to 2 Hz
Resolution small waves:	1mm
Resolution high waves:	1mm
Range high waves:	0m – 6m
Accuracy:	1cm
Wave Direction:	No
Direct/Indirect:	Direct
Sample frequency:	Up to 8 Hz
Power consumption:	Starting from 3W (depending on specification)
Daily data production:	24MB/day for sampling rate 5 Hz
Data output:	Water level
Autonomy:	No
Internal Memory:	64MB up to 2 GB
Calibration/drift:	Calibration not required and drift not expected
Costs	4820 Euro
Interface present equipment	No problems expected
Combination with other instruments	None

Soiling, marine growth, maintenance requirements	Minimal
Reliability/robustness	Robust and weather proof system successfully used in the harbour of Hamburg. Placed above the water level (easy accessibility for vandals)
Storm, ice and fog	Possible problems are expected with the received signal during extreme wind conditions.
Feasibility of checking the instruments in the field	Possible with radio link.
Non-linearity's	None.
Necessity of repairing the output signal of the instruments	*Software related outliers should be eliminated prior to data processing.*
Errors by breaking waves (bubbles, spray)	Potential problems are expected.
Errors by wave asymmetry	Very steep slopes are potential problem.
Human errors	None.
Influence temperature salinity	None.
Logger capacity	Up to 2 GB.
Transfer data by telemetry	Yes (GPRS possible also).

Table 4.5 Criteria Log_alevel

Remarks:

- Single potential mavericks - being labelled as such outlier - should be eliminated before calculation.
- Steep waves can be measured with up to a slope of 1:7 in laboratory conditions, with very smooth water surface, a surface slope of 1:11 can be reached.

Range finder SM-094

Function:

This instrument emits a microwave FM chirp signal and receives the echo from the water surface. The signal propagation given by the distance from the antenna to the water surfaces causes a beat signal in the receiver. By means of advanced signal processing the beat frequency is converted to an accurate distance. The SM-094 is available in different range versions with different antenna beam width.

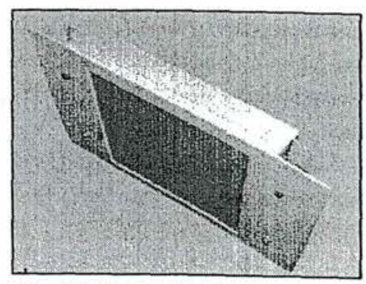


Fig 4.7: Range finder SM-094

Wave frequency range (low):	No limits.
Wave frequency range (high):	Up to 2 Hz.
Resolution small waves:	1mm.
Resolution high waves:	1mm.
Range high waves:	0m – 10m (up to 85m possible).
Accuracy:	1cm.
Wave Direction:	No.
Direct/Indirect:	Direct.
Sample frequency:	Up to 8 Hz.
Power consumption:	4.8W.

Daily data production:	2.8 –5.6 MB/day for sampling rate 4 Hz.
Data output:	Water level.
Autonomy:	No.
Internal Memory:	None.
Calibration/drift:	Calibration not required and drift not expected.
Costs	12000 Euro.
Interface present equipment	No problems expected.
Combination with other instruments	None.
Soiling, marine growth, maintenance requirements	Minimal.
Reliability/robustness	Robust and weather proof system successfully used by, among others, NOAA.
Storm, ice and fog	No problems expected.
Feasibility of checking the instruments in the field	Possible with radio link to data logger.
Non-linearity's	None.
Necessity of repairing the output signal of the instruments	Software related outliers should be eliminated prior to data processing.
Errors by breaking waves (bubbles, spray)	Potential problems are expected.
Errors by wave asymmetry	Very steep slopes are potential problem.
Human errors	None.
Influence temperature salinity	None.
Logger capacity	No internal logger.
Transfer data by telemetry	Yes, through external data logger.

Table 4.6 Criteria Range Finder SM094

Remarks:

- It is important that there is no shadowing of incoming seas or reflections from structure on which the sensor is mounted
- There could be a lack of return signals to the sensor if waves are steep with no ripple. This has been encountered when tests have been performed in model tanks. Such problems are not experienced elsewhere
- The SM-094 sensors have been subjected to heavy weather and are providing data even under adverse conditions

4.3.6 Radar

<u>WaveGuide</u>

Function:

This instrument measures the distance from downward looking radar to the water surface. The WaveGuide is a frequency modulated continuous wave radar, operating in the X-band (10Ghz). The difference in frequency between transmitted signal and reflected is the measure of the distance.

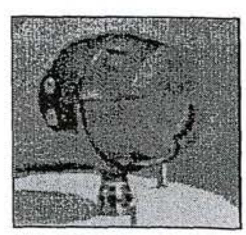


Fig 4.8: WaveGuide

Wave frequency range (low):	No limits.
Wave frequency range (high):	Up to 2 Hz.
Resolution small waves:	10mm.

Resolution high waves:	10mm.
Range high waves:	0m – 75m.
Accuracy:	≈ 2cm.
Wave Direction:	Yes when mounted in array.
Direct/Indirect:	Direct.
Sample frequency:	Up to 10 Hz.
Power consumption:	6W.
Daily data production:	1 MB/day for sampling rate 4 Hz.
Data output:	Water level.
Autonomy:	No.
Internal Memory:	None.
Calibration/drift:	Calibration not required and drift not expected.
Costs	18965 Euro.
Interface present equipment	No problems expected.
Combination with other instruments	None.
Soiling, marine growth, maintenance requirements	Due to spray the antenna need to be cleaned once a year.
Reliability/robustness	There is no risk for mechanical damage. It is protected against lightning damage. Placed above the water (easy accessibility for vandals).
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	Possible with radio or GSM
Non-linearity's	None
Necessity of repairing the output signal of the instruments	Not expected
Errors by breaking waves (bubbles, spray)	Potential problems are expected
Errors by wave asymmetry	Very steep slopes are potential problem
Human errors	None
Influence temperature salinity	None
Logger capacity	No internal logger
Transfer data by telemetry	Yes, through external data logger

Table 4.7 Criteria WaveGuide

Remarks:

- Short waves (compared to the footprint of the radar) generally >1Hz the position of the reflecting parts in the footprint of the radar beam become of influence and therefore the shape of the waves.
- Not a lot of experience in shallow water
- On short notice a report will become available in which the RADAC has been tested in laboratory conditions with short waves

SM-050 MkIII

Function:

A Microwave Doppler Radar for directional wave and surface current measurements. This radar measures from above and observes the water surface in a semi-circle at a distance of 180 – 450 m depending on the installation height.

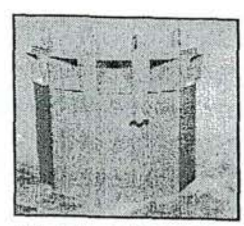


Fig 4.9 : SM-050 MKIII

Wave frequency range (low):	No limits
Wave frequency range (high):	Up to 0.3 Hz
Resolution small waves:	10cm
Resolution high waves:	10cm
Range high waves:	0m – 30m
Accuracy:	+/-5%
Wave Direction:	Yes
Direct/Indirect:	Indirect
Sample frequency:	Wave mapping equipment
Power consumption:	< 300W
Daily data production:	Not specified large storage required
Data output:	Spectral information
Autonomy:	No battery power possible
Internal Memory:	None
Calibration/drift:	Radar signal strength is to be calibrated for wave height
Costs	150000 Euro
Interface present equipment	Not possible
Combination with other instruments	None
Soiling, marine growth, maintenance requirements	No
Reliability/robustness	System seems to be very robust and survived ten meter submerged water. It is placed above the water (easy accessibility for vandals).
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	No
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Measurement system is not accurate
Errors by wave asymmetry	Measurement system is not accurate
Human errors	None
Influence temperature salinity	None
Logger capacity	No internal logger
Transfer data by telemetry	Raw data amount is too large to transfer

Table 4.8 Criteria SM-05 MKIII

Remarks:

- Indirect measurement technique successfully employed at platforms and ships
- Not suitable for small waves
- A slight wind creating ripple on the surface is required in order that return signals of sufficient quality are received.
- See report of Jur Vogelzang (2001) in which radar measurements have been used in Petten.

4.3.7 ADCP

RDI wave ADCP

Function:

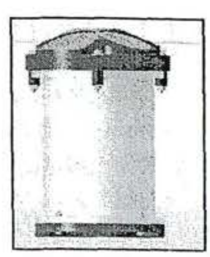


Fig 4.10: RDI wave ADCP

ADCP array measurement resolves waves incident from multiple directions while accounting for distortion due to the near surface current field. ADCP wave current gauge is bottom mounted. The wave measurement based on pressure gauge and ADCP data, and surface track, system lacks capability in measuring waves at high frequencies (beam separation and depth related cut off frequency (pressure)).

Wave frequency range (low):	No limits
Wave frequency range (high):	Up to 0.5Hz
Resolution small waves:	1mm
Resolution high waves:	1mm
Range high waves:	1mm – 30m
Accuracy:	8-16 cm (bin size / √12)
Wave Direction:	Yes
Direct/Indirect:	Direct (acoustic surface track one beam) Indirect (pressure sensor)
Sample frequency:	Up to 4 Hz
Power consumption:	0.6W
Daily data production:	9MB/day
Data output:	Various options are possible internal processing of data is optional
Autonomy:	Internal storage and battery power available
Internal Memory:	Yes maximum 2GB
Calibration/drift:	Calibration not required drift not expected
Costs	On quotation only
Interface present equipment	Possible, adaptations required
Combination with other instruments	None
Soiling, marine growth, maintenance requirements	No influence
Reliability/robustness	Very reliable instrument
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	Through cable connection and external data logger/radio
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Breaking waves; problems are expected
Errors by wave asymmetry	No errors expected
Human errors	Good placing on the bottom is required.
Influence temperature salinity	None
Logger capacity	Up to 2GB
Transfer data by telemetry	Possible

Table 4.9 Criteria RDI wave ADCP

Remarks:

- See IMAU report: directional wave measurements using ADCP
- Recent article of A J.F. Hoitink and M. Schoevers (2004) presents experiment in which the RDI equipment has been compared with directional wave rider.
- Any acoustic surface tracking measurement may be effected by the presents of bubbles in the water column.
- The conversion from the near surface velocity measurement to wave direction (and wave height) relies on a linear wave theory conversion

AWAC

Function:

This instrument (integrated Acoustic Waves and Current sensor) provides three independent methods for measuring wave height and wave period. The three methods utilise the pressure, orbital velocity and acoustic surface tracking. With the Acoustic Surface Tracking (AST) firmware you can measure the long waves (swell), storm waves and the short waves generated from local winds. Moreover, the AST also gives you the ability to derive wave parameters based on times series analyses, which is a major advantage relative to the classical bottom mounted systems that derive the wave parameters from spectral estimates of pressure or velocity. This means that AWAC can directly measure wave parameters such as Hmax, H1/10, Tmean, etc. which other bottom mounted systems simply cannot. The AWAC is usually mounted in a frame on the bottom.

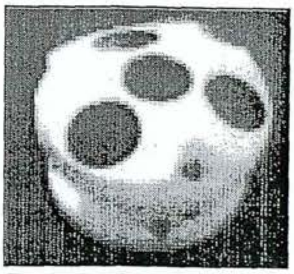


Fig 4.11 AWAC

Wave frequency range (low):	No limits
Wave frequency range (high):	Up to 2Hz
Resolution small waves:	1mm
Resolution high waves:	1mm
Range high waves:	0m – 30m
Accuracy:	2-3mm
Wave Direction:	Yes
Direct/Indirect:	Direct (acoustic surface track upward looking beam) Indirect (pressure sensor)
Sample frequency:	Up to 4 Hz
Power consumption:	1W
Daily data production:	Up to 3MB/day (depends on settings)
Data output:	Various options are possible internal processing of data is optional
Autonomy:	Internal storage and battery power available
Internal Memory:	Yes maximum 154MB
Calibration/drift:	Calibration not required drift not expected
Costs	21000 Euro
Interface present equipment	Possible adaptations required
Combination with other instruments	Yes, water quality sensors can be connected and logged on the AWAC
Soiling, marine growth, maintenance requirements	No influence
Reliability/robustness	Very reliable instrument
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	Through cable connection and external data logger/radio
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Upward looking beam has a small footprint and will be able to measure steep waves Bubbles may cause problems.

Errors by wave asymmetry	No errors expected
Human errors	Good placing on the bottom is required.
Influence temperature salinity	None
Logger capacity	Up to 154MB
Transfer data by telemetry	Possible

Table 4.10 Criteria AWAC

Remarks:

- Successfully deployed in Guyana.
- Tampa Bay experiment showed measurement capability of high frequency waves.
- It is hard to measure close to structures.
- The instrument should be mounted nicely flat and stable.
- Breaking waves are a potential problem as bubbles are entrained in the water column.

4.3.8 Pressure

Paroscientific pressure sensor

Function:

This general pressure sensor is to be mounted on a pole and should be connected to a data logger. It measures the water pressure. Water pressure has to be converted into wave heights using linear wave theory. Pressure sensors are widely used. Atmospheric compensation is not available in this sensor and should be externally measured, if required data should be compensated for the air pressure. The Paroscientific pressure sensors are very accurate

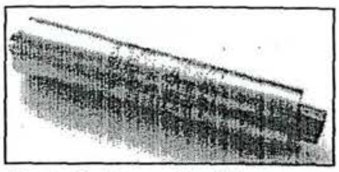


Fig 4.12: Paroscientific pressure

Wave frequency range (low):	No limit
Wave frequency range (high):	Up to 0.43 Hz. No limit within instrument, but instrument should be mounted within ¼ of the wave length that needs to be measured, below the water surface. In practice waves as from wave length of 8m can be measured. This results in minimum wave periods of 2.3 seconds
Resolution small waves:	0.01mm
Resolution high waves:	0.01mm
Range high waves:	Limited by the pressure range of the sensor
Accuracy:	Wave frequency related (as from 1mm)
Wave Direction:	No
Direct/Indirect:	Indirect
Sample frequency:	Can be as high as requested
Power consumption:	0.03 Watts
Daily data production:	Approximate 1 MB/day for sampling rate 4 Hz.
Data output:	Pressure
Autonomy:	No
Internal Memory:	None

Calibration/drift:	No
Costs	As from 3500 Euro
Interface present equipment	Relatively easy
Combination with other instruments	Not possible
Soiling, marine growth, maintenance requirements	No influence on accuracy as long as pressure sensor is not obstructed
Reliability/robustness	Very robust. This instrument is successfully used in a Tsunami detecting system.
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	Through the datalogger
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Linear wave theory is to be applied, breaking waves can not be detected directly
Errors by wave asymmetry	Linear wave theory is to be applied
Human errors	None
Influence temperature salinity	Sensor is compensated for temperature fluctuations
Logger capacity	None
Transfer data by telemetry	No problem through attached data logger

Table 4.11 Criteria Pressure sensor

Remarks:

- It is difficult to measure high frequency waves and extreme waves with the same pressure sensor.
- Indirect measurement technique linear wave theory has to be applied to calculate wave heights. See WL Report from Neelke Doorn (2004).
- To minimize current related effects on the measured pressure, sensor and sensor housing should disturb the orbital flow as least as possible

Midas WTR

Function:

This instrument is a sophisticated pressure based wave recorder and it operates autonomously. It has onboard data processing and uses linear wave theory to give a real time output of wave height and period, together with full spectral analysis.

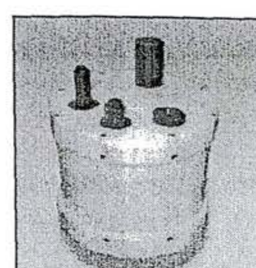


Fig 4.13: Midas WTR

Wave frequency range (low):	No limits
Wave frequency range (high):	Up to 0.43 Hz. No limit within instrument, but instrument should be mounted within ¼ of the wave length that needs to be measured, below the water surface. In practice waves as from wave length of 8m can be measured. This results in minimum wave periods of 2.3 seconds
Resolution small waves:	0.01 mm

Resolution high waves:	0.01 mm
Range high waves:	No limit
Accuracy:	Wave frequency related (as from 1mm)
Wave Direction:	No
Direct/Indirect:	Indirect
Sample frequency:	Up to 8 Hz
Power consumption:	0.7W
Daily data production:	Depends on settings,(4 Hz 2.4 Mb/day)
Data output:	Raw sensor data
Autonomy:	Internal storage and battery power available
Internal Memory:	Yes maximum 64MB
Calibration/drift:	Calibration not required drift not expected
Costs	9840 Euro
Interface present equipment	Possible, adaptations required
Combination with other instruments	Optional turbidity and or conductivity sensor
Soiling, marine growth, maintenance requirements	No influence
Reliability/robustness	Very reliable instrument
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	Through cable connection and external data logger/radio
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Linear wave theory is to be applied, breaking waves can not be detected directly
Errors by wave asymmetry	Linear wave theory is to be applied
Human errors	None
Influence temperature salinity	Sensor is compensated for temperature fluctuations
Logger capacity	64MB
Transfer data by telemetry	Possible

Table 4.12 Criteria Midas WTR

Remarks:

- It is difficult to measure high frequency waves and extreme waves with the same pressure sensor.
- Indirect measurement technique linear wave theory has to be applied to calculate wave heights. See WL Report from Neelke Doorn (2004).
- To minimize current related effects on the measured pressure, sensor and sensor housing should disturb the orbital flow as least as possible

4.3.9 Remote sensing

Wavex

Function:

This system applies imaging techniques and using Marine X-band Radar as sensor for data acquisition and presentation of directional wave and current data. The systems are used on commercial and military vessels, on platforms and foreshore installations. The radar water-echo amplitude depends on the "roughness" of the water surface.

Gravity waves form images. A full three dimensional wave spectrum may be derived from the digitised radar back scatter images.

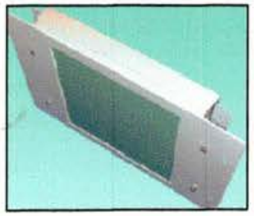
Wave frequency range (low):	as from 0.055 Hz (18 sec)
Wave frequency range (high):	up to 0.3 Hz (3 sec)
Resolution small waves:	10 cm
Resolution high waves:	10 cm
Range high waves:	0m-30m
Accuracy:	0.25-0.50 m
Wave Direction:	Yes
Direct/Indirect:	Indirect technique for wave height
Sample frequency:	Wave mapping technique
Power consumption:	Depends on Radar used as from 100 W
Daily data production:	20.4MB/day
Data output:	Directional information + wave height + wave period (surface current information if required)
Autonomy:	No
Internal Memory:	No
Calibration/drift·	Not expected
Costs	84000 Euro
Interface present equipment	Not possible
Combination with other instruments	Not possiible
Soiling, marine growth, maintenance requirements	Not expected
Reliability/robustness	Systems seems to be very robust
Storm, ice and fog	No problems expected
Feasibility of checking the instruments in the field	No
Non-linearity's	None
Necessity of repairing the output signal of the instruments	No
Errors by breaking waves (bubbles, spray)	Indirect technique, Measurement system is not accurate
Errors by wave asymmetry	Indirect technique, Measurement system is not accurate
Human errors	None
Influence temperature salinity	None
Logger capacity	None
Transfer data by telemetry	Raw data amount is to large

Table 4.13 Criteria WAVEX

Remarks:

- This system sends and receives return signals at a small angle of inclination to the sea surface. A slight wind creating ripple on the surface is required in order that return signals of sufficient quality are received. If not so, there will be no sensible data.
- See report of Jur Vogelzang (2001) in which radar measurements have been used in Petten.
- Is vulnerable to excessive signal noise for example when there is very heavy precipitation (squalls).

4.4 Summary of the selected instruments

Name of Product	Step gauge	Wavex	Wave & current radar SM-050 Mk II	Range finder SM-094
Company Name	Etrometa	Miros	Miros	Miros
Brand	Etrometa stepgauge	Miros Wavex	Miros Wave & current radar SM-050 Mk II	Miros Range finder SM-094
Method of measurement	Resistance (between electrodes)	Remote sensing	Microwave Doppler Radar	Acoustic
Instrument consist of	Stepgauge; SGE; mechanical installation packet ; Stepgauge head ; cable Modular stepgauge sections; Software	PC with data acquisition card installed/VDU/KB + IF box + optional Marine Radar to suit	Sensor and software on CD + optional Mounting Bracket ; cable	Sensor, PC with software installed/VDU, JB & IF-unit + optional pedestal, Cooling unit Sun shield & pedestal
Material	Water tight PVC-inner tube covered with Fiberglas reinforced polyester. SGE: Polyester box IP65. Electrodes are of manganese bronze		Aluminium (AL57S)	Aluminium (AL57S) housing
Sample Range	4Hz (standard) up to 10Hz	Wave mapping technique	Wave mapping technique	Up to 8Hz
Frequency Range	Up to 2 Hz	Up to 0.3Hz	Up to 0.3Hz	Up to 2Hz
Range	0.05m - 3 m/section (maximum 21m)	0m – 30m	0m – 30m	1m – 10m (up to 85m possible)
Resolution	± 2.5 cm / ± 1cm for 2cm resolution step gauge	0.1m	0.1m	0.001m
Accuracy	± 2.5 cm / ± 1cm for 2cm resolution step gauge	0.25m – 0.5m	± 5%	0.01m
Energy use	65 mW (SGE _+ gauge head)	As from 100W	< 300W	4.8W
Dimensions (HxWxD)	86 x 85 mm length:3m minus 5 mm for spacing between the sections (distance between electrodes is 0.05m)		870 x 900 x 700 mm	70 x 510 x 420 mm
Beam width	-		10 degrees	5 degrees
Internal memory	Optional	Capacity is included in the PC	None	Non (in about a half a year storage of 24 days is internally possible)
Output data	The instantaneous water level.	Directional information + wave height + wave period (if required surface current data can be provided)	Spectral information	Distance to the water surface (subsidence, tide, and wave heights/periods)
Mooring type	Pole or solid structure	Pole or solid structure	Pole or solid structure	Pole or solid structure
Drift expected	No	No	No	No
Specifications	See pages 133-139	See pages 201-204	See pages 195-200	See pages 205-207
Price	From 9200 Euro (13830 Euro incl. software) for a 3m length stepgauge)	84000 Euro	150000 Euro	12000 Euro
Remarks	-For guarding purposes the next 7 electrodes under the water are also checked whether they are wet. If this is not the case they are marked as false dry electrodes in the output signal. This can be the case with breaking waves. -After the decision wet/dry electrode, the input signal is digital, with corresponding advantages such as no-zero drift, no temperature dependence etc. -The salinity should be known roughly for the adjustment of the wet/dry detector in the sections.	- Is vulnerable to excessive noise when there is very heavy precipitation (squalls). - A slight wind creating ripple on the surface is required in order that return signals of sufficient quality are received -See report written by J. Vogelzang (2001)	-Indirect measurement technique successfully employed at platforms and ships -Not suitable for small waves -A slight wind creating ripple on the surface is required in order that return signals of sufficient quality are received - See report written by J. Vogelzang (2001)	- It is important that there is no shadowing of incoming seas or reflections from structure on which the sensor is mounted - The SM-094 sensors are subjected to heavy weather and are providing data even under adverse conditions - There could be a lack of return signals to the sensor if waves are steep with no ripple (wind effect).
				

SVASEK HYDRAULICS

Name of Product	Directional WaveGuide	RDI wave ADCP	AWAC
Company Name	Radac	Aqua Vision	Qmetrix
Brand	Radac WaveGuides	RDI	Nortek
Method of measurement	ENARF SmartRadar	Acoustic	Acoustic Doppler systems and acoustic Doppler horizontal velocity and pressure
Instrument consist of	Radar unit ; antenna WaveGuide server;	4 beams for velocity measurements ; cable 4 transducers	AWAC ; Delrin housing ; Underwater cables ; battery container
Material	The radar unit, a aluminium sphere (radius ca 12 cm) plus a stainless steel antenna. The WaveGuide server is a steel box housing a PC104 computer system	Plastic – polyurethane transducer faces, titanium bolts	Delrin and polyurethane plastics with titanium screws
Sample Range	Up to 10Hz	Up to 4 Hz	Up to 4Hz (vert beam) up to2Hz (other beams)
Frequency Range	Up to 2Hz	Up to 0.5 Hz	Up to 2Hz
Range	0m - 75m	0.001m – 30m	0m – 30m
Resolution	0.01m	0.001m	0.001m
Accuracy	Round 0.02m	0.08m -0.16m	0.002m – 0.003m
Energy use	6W (radar unit) + 6W (WaveGuide server)	0.6W	1 W
Dimensions (hxWxD)	23 x 20 x 9 cm (box), Diameter 250mm, 400mm high	Height 0.4m width 0.2m	Width: 0.21m Height: 0.18m
Beam width	5 degrees	20 degrees	25 degrees
Internal memory	None	Up to 2GB	Up to 154 MB
Output data	Water level	Various options are possible internal processing of data is optional	Various options are possible internal processing of data is optional
Mooring type	Solid structure	Bottom mounted	Bottom mounted
Drift expected	No	No	No
Specifications	See pages 187-194	See pages 171-179	See pages 179- 183
Price	Round 18965 Euro	Quotation only	21000 Euro
Remarks	- Short waves (compared to the footprint of the radar) generally > 1Hz the position of the reflecting parts in the footprint of the radar beam become of influence and therefore the shape of the waves. - Not a lot of experience in shallow water. - On short notice a report will become available in which RADAC has been tested in laboratory conditions with short waves.	- See IMAU report (see literature) - Any acoustic surface tracking measurements may be effected by the presence of bubbles in the water column. - The near surface velocity measurement relies on a linear wave theory conversion but this measurement is un-effected by very near surface bubbles.	-The instrument should be mounted nicely flat and stable. -it is hard to measure waves close to structures. - Wave direction measurements have limits in measuring short waves - Breaking waves are in principle a problem as bubbles may be entrained in the water column. -Successfully deployed in Guyana.
			

Name of Product	Log_aLevel	Capacitance probe	Pressure sensor	Waverider SG
Company Name	General Acoustics GMbH	Endress Hausser	Bakker & Co	Datawell bv.
Brand	Log_alevel	Multicap DC 11	Pressure sensor	Datawell
Method of measurement	Acoustic	Capacitance probe	Parascientifics	Based on accelerometer
Instruments consists of	Ultrasound level sensor Controller Sound velocity probe	A probe and a mass tube products, with screening and flange	Pressure sensor	Stainless steel hull, batteries, vert reference unit, vert accelerometer, horz accelerometer, analogue electronics, digital electronics data logger receiver HF transmitter LED-flashlight
Material	Housings: stainless steel Mounting: seawater resistant pole (anodised aluminium or stainless steel) with base plate	Teflon coated probe; mass tube of metal (corrosion-resistant); screening is fully insulated; flange is plastic coated	Stainless steel	Stainless steel (AISI316)
Sample Range	Up to 8Hz	Up to 8 Hz	Can be as high as requested	10.24Hz
Frequency Range	Up to 2Hz	Up to 2Hz	Up to 0.43 Hz	0.033Hz – 1Hz
Range	0m - 6 m	0m - 3m/section	Limited by pressure range of the sensor	-20m - 20m
Resolution	0.001m	0.002m	0.00001m	0.01m
Accuracy	0.01m	< 0.05m	As from 0.001m (wave frequency related)	0.5% of the measured value
Energy use	Minimal 3W	< 5W	0.03W	0.27W
Dimensions (H x W x D)	Housing (500 x 500 x 200 mm) Sensor (100 x 50mm) Sound velocity gauging (0.2m)	Diameter: 0.38m Length: 3m/section	Diameter: 0.089m, length round 0.227m	Diameter 0.7m (also available in 0.9m)
Beam width	5 degrees	-	-	-
Internal memory	up to 2 GB	None	None	Up to 1GB
Output data	Water level	Water level	Pressure	Wave height
Mooring type	Pole or solid construction	Pole or solid construction	Pole or solid construction	floated
Drift expected	No	yes	Very small	yes
Specifications	See pages 207-210	See pages 139-151	See pages 163-170	See pages 152-153
Price	4820 Euro (basis price)	1000 Euro	From 3500 Euro	11700 Euro
Remarks	- Steep waves can be measured with up to a slope of 1:7 in laboratory conditions, with very smooth water surface, a surface slope of 1:11 can be reached. -Single potential mavericks – being labelled as such outlier- should be eliminated before calculation	- Currently used at all the measurement locations at the IJsselmeer and Slotermeer (from March 2001) - Currently these probes are cleaned 10 times a year	-Difficult to measure high frequency and extreme waves with the same pressure sensor. -To minimize current related effects on the measured pressure, sensor and sensor housing should disturb the orbital flow as least as possible. - See report written by Neelke Doorn (see literature)	- No errors occur with the spilling and collapsing and surging waves. In case of plunging waves the buoy can not follow the water surface correctly. -The raw data is transmitted and stored on logger ready for the customer. - The high frequency waves can not be followed by buoys with this diameter
				

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Name of Product	Directional Waverider MKIII	Directional waverider GPS	Mini Directional waverider GPS	Midas WTR
Company Name	Datawell	Datawell	Datawell	Valeport
Brand	Datawell	Datawell	Datawell	Valeport
Method of measurement	accelerometer and or GPS	accelerometer and or GPS	accelerometer and or GPS	Pressure
Instruments consists of	reference unit, vert accelerometer horz. Accelerometer compass, analogue electronics data-logger GPSA receiver HF transmitter LED-flashlight, sea water	Stainless steel hull batteries GPS receiver digital electronics data-logger HF transmitter LED flashlight, sea water temperature sensor.	Stainless steel hull batteries GPS receiver digital electronics data-logger HF transmitter LED flashlight, sea water temperature sensor.	Pressure sensor and a fast response PRT temperature sensor , the housing, and software, cable
Material	Stainless steel (AISI316)	Stainless steel (AISI316)	Stainless steel (AISI316)	Acetal housing, optional stainless steel (316) cage
Sample Range	3.84Hz	10Hz	10Hz	Up to 8 Hz
Frequency Range	0.033Hz - 1Hz	0.01Hz - 0.6Hz	0.025Hz - 0.6 Hz	Up to 0.43 Hz
Range	-20m – 20m	-50m – 50m	-50m – 50 m	No limit
Resolution	0.01m	0.01m	0.01m	0.01mm
Accuracy	0.5% of the measured value	0.01 –0.02m	0.01m – 0.02m	As from 0.001m
Energy use	0.38W	0.9W	0.9W	0.7W
Dimensions (H x W x D)	Diameter 0.7m (also available with diameter 0.9m)	Diameter 0.7m (also available with diameter 0.9m)	Diameter 0.4m	Diameter: 0.3m ; Height 0.29m
Beam width	-	-	-	-
Internal memory	Up to 1GB	Up to 1 GB	Up to 1GB	64 MB
Output data	Wave height and wave direction, temperature	Wave height and wave direction, temperature	Wave height and wave direction, temperature	Wave height wave period and wave direction
Mooring type	Floated	Floated	Floated	Bottom mounted
Drift expected	yes	yes	yes	No
Specifications	See pages 156-157	See pages 158-159	See pages 160-163	See pages 211-212
Price	22500 Euro	17200 Euro	Not known	9840 Euro
Remarks	- No errors occur with the spilling and collapsing and surging waves. In case of plunging waves the buoy can not follow the water surface correctly. -The raw data is transmitted and stored on logger ready for the customer - The high frequency waves can not be followed by buoys with this diameter	- Loses contact when spray is washed over the GPS antenna and start again when the GPS antenna is clear. -The raw data is transmitted and stored on logger ready for the customer - The high frequency waves can not be followed by buoys with this diameter	- Loses contact when spray is washed over the GPS antenna and start again when the GPS antenna is clear. -The raw data is transmitted and stored on logger ready for the customer. - The high frequency waves can be followed by buoys with this diameter	- It is difficult to measure high frequency waves and extreme waves with the same pressure sensor. - See WL report written by Neelke Doorn (see literature). -To minimize current related effects on the measured pressure, sensor and sensor housing should disturb the orbital flow as least as possible .
				

5 USER EXPERIENCES AND INSTRUMENT COMPARISON

5.1 General

Part of the instrument selection procedure consists of the interviews with specialists. The objective of these interviews was either to verify if selected equipment would be a good option to consider. Secondly we were looking for their measurement experiences of waves on shallow water. The interviews were carried out by phone, email and face to face. In appendix the record of the interviews can be found. In next paragraph the main findings are presented.
Published instrument comparisons have been used to facilitate the instrument selection procedure. Conclusions from the most relevant articles are presented.

5.2 User experiences

A short summary of the execute interviews are presented here:

Bas Blok (WL, Delft) is at present head of the hydro graphic survey department of WL. He has been involved in the software used for wave buoy data analysis. His suggestions to measure high frequency waves at shallow water were step gauges and capacity wires. He suggested to use the 2 cm step gauge of Etrometa. Laser based instruments could function well but he expected problems with fog, spray and rain.

Mr van Doorn (RWS/RIKZ) was involved in the WACSIS project. This project executed on the Noordwijk platform was focussed on measuring crest height of waves. Measurements were executed with various types of equipment. Mr van Doorn explained to us the history of step gauge. The Vlissingen and Marine 300 step gauges have been replaced with the superior step gauge produced by Etrometa. He suggested to contact Jos Kokke related to radar measurements and Rinus Schoevers related to ADCP wave measurements

Evert Bouws (KNMI) has performed wave measurements at the Dutch lake Markermeer near by Lelystad (1983-1984) (see memorandum 1986, provisional results of a wind wave experiment in a shallow lake). During the wave measurements at the Dutch lake Markermeer throughout the winter, a capacitance probe was used for the wave measurements. These measurements were calibrated with a Datawell waverider. He noticed that a laser can be a wave measurement instrument which can function very well for wave height measurements and especially for measurement of very short waves (because of the small footprint). He thinks that several disadvantages can be found also by using a laser and he advised to contact dr. Harald Krogstad (Trondheim).

Harald Krogstad (Trondheim). We have asked him after his experiences with laser based wave measurements. He uses the Optec Range finder Laser which is currently also in use at the Ekofisk field in the North Sea (http://www.optech.on.ca/). High frequency wave information is not a problem with the Optec laser. At Ekofisk the sampling is 5Hz and the distance to the surface is about 20m. The footprint of laser is of the order of cm-s. They do have frequent occasional (weather related) data drops, and I have no experience how much better this will be for shorter ranges, probably not a major problem. The measuring principle is, that 80 pulses are sampled at 2000Hz and the final data value is an average of those (the good ones). He suggests that the Optec laser would work fine for the IJsselmeer location.

Jos Kokke (RWS). As a result of the conversation with Mr. Van Doorn we have contacted Jos Kokke in order to get more information about experience with Radar level and Radar "mapping" equipment. Measurements at the North Sea are carried with *the Saab Radar* (at least ten years). A report RADAC wave measurement will be published by Jos Kokke. This report describes laboratory tests with the RADAC wave gauge. On *Radar wave mapping;* FEL/TNO is working on a field experiment of measurements by means of a ship radar measuring the wave height and direction. At the end of 2004 a report of this experiment will be published.
Herman Peters (RWS Noordzee) Herman Peters has a lot of experience with Radar level measurements. He refers to the report on RADAC measurements written by J Kokke. He advised to take the Radar level measurement instrument of Endress Hausser into consideration. His knowledge and experience of the wave measurements with a laser: Laser is a very accurate instrument to be used during perfect weather conditions or in a laboratory. For long term deployments in the field he considers laser as not suitable

Mr. Jur Vogelzang (AGI RWS) has been involved in the Radar wave mapping (WAMOS) measurements at Petten. The measurements have been compared with DIWAR buoy data. His conclusion was that the equipment worked well under extreme conditions. A brief experiment has been executed at lake IJsselmeer. Small waves and short wave length's can not be recognized. Only in storm conditions RADAR will produce reliable data at Lake IJsselmeer

Remco Kleine (RDIJ) is a staff member of the instrumentation of the wave measurements at the IJsselmeer and Slotermeer. He has experience with the capacitance probe and the step gauges (marine 300 II version). The disadvantages of the step gauge in his opinion were the following:

- Soiling / marine growth:
  Because of marine growth at the step gauge it often happened that one sensor was covered with a marine string resulting in a registration of the sensor as a wet sensor in spite of the actual (lower) water level.
- Discrete instrument
  This instrument has sensors at an equal distance of each other (could not measure in between.
- Electronics
  The step gauge was very sensitive to failure due to the many conversion strokes.

Mr. Ruessink (IMAU) wrote a report for RIKZ. The title of this report was Directional wave spectra from ADCP's. IMAU is using pressure sensors for wave measurements in the coastal waters. To the opinion of Mr. Ruessink, these pressure gauges are not a good option for the short waves at the IJsselmeer. The position should be to close to the water surface which is probably not feasible. The RDI wave gauges are probably also not capable of measuring short waves. He suggested laser measurements or staff gauges. The contact person to approach in respect of laser measurements was Mr. Ap van Dongeren from WL- Delft

Mr A. van Dongeren (WL-Delft) is asked about his experience with laser based wave measurements. Mr. van Dongeren explained that his experiences were related to laboratory scale wave measurements in which laser was combined with video to record wave heights. He did not have experience on shallow water measurements and considers the Video-Laser option as not usable outside the laboratory situation.

Mr Cornelissen (RWS, Meetdienst Zeeland) He had some remarks about three instruments he worked with:

- The pressure sensor: They do not use this measurement instrument because results depend on the water column above the pressure sensor.
- The buoy: The buoy has proven itself over the years.
- Step gauge (Etrometa): is reliable

Dr Louis Verhagen (LogicaCMG) was approached related to his extensive measurement knowledge on shallow water waves. His main findings in regards to the instrument selection and measurement program in Lake IJsselmeer and Slotermeer are:

- The Zwarts Wave Pole has been a very reliable, relatively cheap instrument, which has proven to function nearly continuously during the 3 year measurement program.
- The capacitance staff gauge is a good "laboratory" tool, due to sensitivity for marine growth, their limited robustness and re-calibration requirements it is not suitable for unattended field operations.

- The RIZA/RDIJ wave measurement program requires in respect of the measurement for differential wave growth studies a modified set-up.
- If validation of wave models in general is one of the measurement purposes, then it would be recommendable to have scientific participation (Delft University) in the project.
- It would be well worthwhile (time and budget permitting) to consider a trial with two or three instruments in one site. There is no substitute for field testing of the instruments.

Dr. H.D. Niemeyer (Forschungsstelle Küste) had some remarks with regard to our study. He advised not to use the pressure sensors because of the probable presence of sharp waves. He had nice experiences with the radar gauge. He mentioned that Joska Andorka Gál working for Rijkswaterstaat /RIKZ had experience with the radar gauge. Dr. Niemeyer has also good experience with the wire gauges (they were very reliable), fouling was one of the problems.

5.3 Instrument comparison

5.3.1 WACSIS

At meetpost Noordwijk several instruments were compared in respect of the Wave crest Sensor Intercomparison Study (see literature). Abstract and conclusion form this experiment is given below:

" Wave crest sensor intercomparison study: An overview of WACSIS" (Forristall, G.Z., Barstow, S.F., Krogstad, H.E., Prevosto, M., Taylor, P.H., Tromans, P.S., 2004)

The abstract of this report is:
"The Wave Crest Sensor Intercomparison Study (WACSIS) was designed as a thorough investigation of the statistical distribution of crest heights. Measurements were made in the southern North Sea during the winter of 1997–1998 from the Meetpost Noordwijk in 18 m water depth. The platform was outfitted with several popular wave sensors, including Saab and Marex radars, an EMI laser, a Baylor wave staff and a Vlissingen step gauge. Buoys were moored nearby to obtain directional spectra. Two video cameras viewed the ocean under the wave sensors and their signals were recorded digitally. The data analysis focused on comparisons of the crest height measurements from the various sensors and comparisons of the crest height distributions derived from the sensors and from theories. Some of the sensors had greater than expected energy at high frequencies. Once the measurements were filtered at 0.64 Hz, the Baylor, EMI and Vlissingen crest height distributions matched quite closely, while those from the other sensors were a few percent higher. The Baylor and EMI crest distributions agreed very well with the statistics from second order simulations, while previous parameterizations of the crest height distribution were generally too high. We conclude that crest height distributions derived from second order simulations can be used with confidence in engineering calculations. The data were also used in investigations of crest and trough shapes and the joint height/ period distribution."

The conclusions from this report are:
"The WACSIS project collected a very interesting data set which has enabled us to give reasonably definite answers to the questions which were posed at the start of the experiment. The most important questions concerned the accuracy of the various sensors which can be used to measure wave crest elevations and the verification of one or more theoretical models for the crest height distribution. We cannot really determine the accuracy of the sensors since there is no absolute standard against which they can be judged. The most we can hope for in a comparison experiment is that a consensus will develop from which a reasonable judgment of the physical truth can be made. In that sense, we were successful since the EMI laser, Baylor wave staff and Vlissingen step gauge gave very similar results after the data were filtered at 0.64 Hz. The filtering is reasonable since the raw data have unexpectedly high spectral densities above this frequency. The Saab radar gave higher crests than those three instruments even after the filtering, and the Marex radar had too many noise spikes for a good comparison with the other instruments. It should be emphasized that these results might differ for other examples of these instrument types because of changes in calibration or internal signal processing. Second-order simulations of the sea surface based on measured directional spectra gave crest height statistics which matched the filtered measurements from the EMI, Baylor and Vlissingen gauges very well."

5.3.2 Recent Nortek/AWAC shallow water experiences

The Nortek AWAC has recently been deployed in shallow water. In the following abstract a situation has been described in which high and low frequency waves were measured using the Accoustic Surface Track.

Tampa Bay AWAC Data (Pedersen,T, Siegel, E, 2004)

The abstract of this report is:

"The Nortek AWAC was deployed in 4 meters of water inside Tampa Bay. Tampa Bay is a shallow estuary mostly protected from the Gulf of Mexico swell. This meant that the wave environment was limited to waves that were short and small. The deployment location was at 27° 39.708' N and 82° 35.669' W. The data collection exercise with the AWAC lasted two weeks; beginning July14th 2004 and lasting until July 28th 2004. A set up of one burst every half hour led to 673 wave burst measurements while the AWAC was in the water. Bursts while the AWAC was out of the water were disregarded. Velocity profiles were measured every 10 minutes. The performance and overall quality of the data was quite encouraging. Only 2 bursts were flagged for dubious quality (too many poor detects with the Acoustic Surface Tracking [AST]) and subsequently defaulted to the pressure signal for wave estimates. Since we had a shallow depth in this test, defaulting to the pressure sensor meant that we really on missed the wave energy above 0.3-0.4 Hz, and therefore does not amount to a substantial loss. It is encouraging to see that much less than 1% of the wave bursts were flagged for having AST estimates as questionable. Out of curiosity, we decided to look at the two flagged bursts and found that both were a result of ship wake. Wave estimates based on AST that have peak periods greater than 30 seconds are flagged with warnings since they generally fall outside what we commonly refer to as wind generated waves. Therefore the AST worked perfectly throughout the test; it was the post processing which conservatively flagged these two burst. A first glance of the wave results can cause a little alarm as one notes that there are well defined waves up until July 21st, and then suddenly it appears something may have happened to the instrument (i.e. flipped over). However a little closer inspection of the data shows that everything is fine with the AWAC and the very calm sea state (that lasted for a week!) is a real event."

5.3.3 Recent comparison of ADCP with Directional Wave Rider

Recently bottom mounted RDI directional wave ADCP's were compared with collocated directional wave rider. The following reference is an article which is not yet published:

"Validation of ADCP surface wave measurements in a shelf sea" (Schoevers,R. (RIKZ) Hoitink, A.J.F. (IMAU), 2004).

The abstract of this report is:

"The performance of two wave ADCPs was analyzed, which were deployed at the North Sea nearby the Dutch coast. A 1200 kHz ADCP was deployed in 13 m water depth, which was set-up with two different protocols: (1) at 2 Hz in mode 1, with depth cells of 0.5m and (2) at 1.25 Hz in mode 12, with 1 m cells. A 600kHz ADCP was deployed in 18 m water depth, sampling at 2 Hz in profiling mode 1, with depth cells of 1 m. At both locations, a wave directional buoy was co-located for reference data. Spectral estimates of wave height and wave period from surface tracking agreed well with corresponding wave buoy estimates, showing only a small bias. Regarding

surface tracking, especially the configuration with the 600 kHz ADCP with 1 m depth cells performed well. Scatter plots of ADCP velocity versus wave rider buoy estimates of spectral wave period feature a substantial bias for all configurations: spectral wave periods are increasingly underestimated for longer waves. This is caused by a relative excess of high-frequency energy density in the surface elevation spectra derived from ADCP velocity spectra via linear wave theory. The agreement between wave buoy and ADCP velocity-derived estimates of the principal wave direction increases if the sea state becomes more energetic."

5.3.4 Analysis of wave measurement equipment

<u>*"Measurement errors of instruments for velocity, wave height, sand concentrations and bed levels in field conditions" (Van Rijn, L.C., Grasmeijer, B.T and Ruessink, B.G. 2000)*</u>

<u>*Abstract*</u>
"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. Information of the measurement errors involved can be obtained by comparing instruments based on different measurement principles under controlled conditions. In this note some results of instrument intercomparisons are presented."

<u>*Conclusions*</u>
The following conclusions are given:
"• Rms and significant wave height in non-breaking conditions derived from direct measurement of surface elevation 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 elevation 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). "

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6 MULTI-CRITERIA ANALYSIS

6.1 General

Wave measurement instruments and their suitability for the measurements at the IJsselmeer and Slotermeer were analysed by applying a multi-criteria analysis. A matrix was set up that contains columns of the different criteria and rows of the different selected instruments. This matrix was populated with assessment scores that quantify the suitability of the different instruments with respect to the chosen set of criteria.

In section 4.3.1 thirty criteria are mentioned. Some of the criteria are included in other criteria (see section 6.2). Hardly any information about the influence of the temperature or salinity on the measurements could be found. Therefore all the information found about this criterion is written down in paragraph 4.3 and is not used in the multi-criteria analysis.

6.2 Scoring

All selected instruments are assessed on various criteria. The assessment is determined using score factors. The better the instrument satisfies the criterion the higher the score. The score factors range from 0 to 10, where zero represents no positive connection with these criteria and 10 is associated with a very positive connection with these criteria. Below the scoring is specified for each criterion.

1. Wave frequency range (high)
   One objective of the measurements is to measure the wave growth. Therefore, the instrument has to be able to measure high frequency waves. The score factors on this criterion are higher if the instrument can measure higher frequency waves.
   Score: Specification:
   10: <= 2Hz (including beam width related limitations of measuring short wave lengths)
   7: <= 1.5Hz (including beam width related limitations of measuring short wave lengths)
   4: <= 1Hz (including beam width related limitations of measuring short wave lengths)
   1: <= 0.25Hz (including beam width large beam width results in lower grade)

2. Wave frequency range(low)
   One objective of the measurements is to measure waves from long fetches and seiches related wave effects. This requires that the instrument has to be able to measure low frequency waves. The score factors on this criterion are higher if the instrument can measure lower frequency waves.
   Score: Specification:
   10: >= 0Hz (no drift absolute measurement)
   5: >= 0.033Hz
   1: >= 0.1Hz

3. Resolution

The resolution in wave height is important especially in respect to measuring small waves (on the order of 10cm, which could be a result of a fetch of 1 km and a wind force 5). The score factors with respect to this criterion are higher if the resolution is higher.

Score:	Specification:
10:	< 1mm
7:	< 1cm
5:	< 5cm
0:	> 10cm

4. Accuracy (waves < 20cm)

Some equipment has a low resolution resulting in inaccurate measurements of small waves. Period related errors are expected when instruments are not able to measure the high or low frequency part of the spectrum. The nonlinear calibration related inaccuracies (if relevant) are included in the criteria for H_{m0} errors.

Score:	Specification:
10:	$H_{m0\ errors}$ <= 1cm and no anticipated period related errors
5:	$H_{m0\ errors}$ <= 5cm and/or period related errors in order of maximum 1s
0:	$H_{m0\ errors}$ >= 10cm and/or period related errors > 1s

5. Accuracy (waves > 1m)

Period related errors are expected when instruments are not able to measure the high or low frequency part of the spectrum. The nonlinear calibration related inaccuracies (if relevant) are included in the criteria for $H_{m0\ errors}$. The vertical range of the instrument has to be such that both wave related water level changes and slow water level changes can be suitably measured. For the former, a maximum wave height of 3 meters has to be taken into account, for the latter an additional still-water level range of 1 meter. This yields a total required range of 4 meters. Expected measurement errors related to vertical measurement range of the instrument are included in the H_{m0} errors.

Score:	Specification:
10:	$H_{m0\ errors}$ < 5cm and no anticipated period related errors
5:	$H_{m0\ errors}$ <= 10cm and/or period related errors in order of maximum 1s
0:	$H_{m0\ errors}$ >= 15cm and/or period related errors > 1s

6. Errors due to breaking waves and wave asymmetry

Wave asymmetry has mainly influence on the conversion from the pressure signal or orbital signal to the wave signal and has no influence on the more direct measurements. However, because of footprint and view angle effects, wave asymmetry may also influence the data produced by ADCP radar and log-a-level. The measurement of a breaking wave is related to the wave asymmetry. It has been very difficult to obtain reliable information on this subject. Buoys are able to follow the water surface even under breaking waves (no plunging waves). The upward or downward looking systems do not clearly define how they respond to a foam layer resulting from breaking waves.

Score:	Specification:
10:	no effect of wave asymmetry on the measurement, accurately measuring the water surface even under breaking wave conditions

5: no effect of asymmetry, influence expected of a foam layer, resulting from breaking waves. Measurement gives a clear indication if breaking waves occurred

0: Indirect measurement. Errors to be expected during wave breaking, but no identification of exclusion of suspect data possible because the onset of wave breaking can not be detected by the instrument.

7. <u>Wave direction</u>

Of secondary interest is wind information but this information contributes to a better interpretation of the wave data. Some instruments can distinguish waves coming from different directions at the same frequency. These instruments score a ten for this criterion. The score factors with respect to this criterion can not have any number between 0 and 10 only a 10, 6 or 0.

Score:	Specification:
10:	Capability of multi-directions at the same frequencies
6:	Single direction at a frequency
0:	Non directional

8. <u>Direct/Indirect</u>

Indirect measurements may cause extra errors due to assumption (like linear wave theory) which has to be made. The score factor 10 is given to instruments that do not need any conversion. The lower the score factor the more conversions have to be made.

Score:	Specification:
10:	Direct measurement (no conversion required)
5:	Direct measurement but measured indirectly (like resistance cap)
0:	Indirect measurements (with assumptions)

9. <u>Sample frequency</u>

High sample frequencies are required to measure high frequency waves. On the other hand the capability of measuring at high sample rates does not necessarily mean that high frequency waves can be measured, other limitations like beam angle or pressure attenuation may influence this.

Score:	Specification:
10:	>= 8Hz
9:	= 4Hz
5:	<= 2Hz
2:	<= 1Hz
0:	< 0.5Hz

10. <u>Power consumption</u>

Currently measurement poles are located at the IJsselmeer and Slotermeer measurement locations (see figure 2.1). These poles have 12 Volt average and maximal 0.4 Ampere (4.8 Watt) available for other instruments. The score factors in respect to this criterion:

Score:	Specification:
10:	< = 1W
5:	<= 6W
0:	> 100W

11. Daily data production/transfer data

If the instrument produces only one output parameter, the transfer of data will be fast and the memory requirements will be limited. Such instrument will receive 10 points as score for this criterion.

Score:	Specification:
10:	1 parameter logging, no problem with data transfer
5:	5 parameters logging, higher (than present) data transfer rates are required
0:	mapping, data transfer not easily possible

12. Internal memory/logger capacity

Internal memory or logger capacity could enhance the reliability of the instrument. In all cases instruments having an internal memory do have internal batteries as well. The criterion autonomy is included in this criterion, because all the instruments having an internal memory and batteries can function autonomously.

Score:	Specification:
10:	Stand alone operation possible for longer then one month
0:	No internal storage

13. Calibration/drift/feasibility of checking the instrument in the field

Calibration requirement involves high cost both in maintenance and data validation. Drift of the instruments should be avoided. It is a requirement that the instrument could be checked in the field. A separate temporary reference sensor may be required.

Score:	Specification:
10:	No calibration required, can easily be validated in the field
8:	No calibration required, verification requires reference sensor
5:	Calibration required (max 2 times per year), can be easily validated in the field
0:	Calibration required, 10 times or more a year

14. Cost

Obviously the instrument with the lowest purchasing costs is the best with respect to this criterion and therefore receives a ten. All the purchasing costs of the selected instruments are viewed and afterwards they are divided in classes resulting in the following score factors:

Score:	Specification:
10:	<= 5000 Euro
9:	<= 10000 Euro
8:	<= 20000 Euro
7:	<= 30000 Euro
0:	>=100000 Euro

15. Maintenance cost

At present the wave poles are visited 10 times per year for cleaning, battery replacement and recalibration of the sensors. Required maintenance results in large (returning) costs.

Score:	Specification:
10:	no maintenance

9: one trip a year
5: *5 times a year simple cleaning and or removal during ice periods*
0: >10 times including cleaning and calibration

16. <u>Interface present equipment, combination with other instruments</u>
For the interpretation of wind waves on shallow lakes, wind and still-water level data are of crucial importance. In the present configuration both can be easily measured. Of all the instruments considered, most can be easily connected to the measurement pole. Exceptions are the buoys and especially the shore based radar. It is preferable to include new equipment without extensive adaptations to the present pole configuration. The score factor ten is given to instruments which are easy to adapt in the present equipment infrastructure and the score factor zero is given to the instruments which are not possible to fit in.
Score: Specification:
10: No special problems expected
5: Adaptations required
0: Not possible

17. <u>Soiling, marine growth</u>
The score factors with respect to this criterion are based on the effect of soiling (like marine growth) on the measurements of instrument. The score factor ten is given to the instruments on which soiling has no effect on the measurements.
Score: Specification:
10: No effect on the measurements expected
5: Soiling or marine growth may have affect on the measurements
0: A strong influence on the measurement quality

18. <u>Reliability/robustness/vandalism</u>
Score: Specification:
10: Reliable proven technology and not vulnerable for vandalism
9: Reliable proven technology and placed at the bottom
5: Above the water and reliable
0: Unreliable above the water

19. <u>Storm, ice, fog, spray</u>
Storm, ice and spray can influence the measurements. Therefore the score factors are related to the sensitivity of the instrument for these conditions.
Score: Specification:
10: Not sensitive to spray fog and ice
1: Very sensitive to spray fog and ice

Remark:
The criterion related to human errors when using, installing or maintaining the instruments will be mentioned in table 6.2 (section 6.4) under the header "Remarks". No scoring factor will be applied for this criterion since hardly any objective information is available. The same applies for the criterion "Necessity of repairing the measured data".

6.3 Weighting

Numerical weights to the criteria are assigned to reflect the relative importance of each criterion in this analysis. The weighting factors for each criterion are briefly explained in table 6.1.

Criteria	Weight factors	Remark
1. Wave frequency (high)	10	In respect of the short fetches at lake IJsselmeer and Slotermeer this is a highly important aspect.
2. Wave frequency (low)	3	Not vital for the (wind) wave measurement but very useful to address seiches related motions and water level fluctuations.
3. Resolution	4	Becomes important to address low wave heights during the wave growth process.
4. Accuracy (small waves)	4	When accuracy is range independent, small waves should be considered separately.
5. Accuracy (high waves)	7	This criterion is very important in order to measure accurately during storm conditions, which is one of the objectives of these measurements.
6. Errors due to breaking waves/Wave asymmetry	4	Important criterion. Criterion 19 (spray) is related.
7. Wave direction	3	Second order interest, could be useful however.
8. Direct/indirect	4	Important aspect, direct measurements are suitable to measure nonlinear wave effects.
9. Sample frequency	3	High sample frequencies are required to measure the high frequency waves. Criterion 1 is related. Since the capability of measuring high frequency waves is not only related to the sample rate, buoy dimensions or beam angle are important as well it is presented as a separate criteria.
10. Power consumption	8	Very important criterion, limited power is available on the poles.
11. Daily data production/transfer data	5	The data should be sent to the base station, preferably this should be possible with the present infrastructure.
12. Internal memory	2	Internal memory could enhance the reliability of the instrument.
13. Calibration/drift/feasibility of checking the instrument in the field	3	Calibration requirement involves high cost both in maintenance and data validation. Drift of the instruments should be avoided. It is a requirement that the instrument could be checked in the field. A separate temporary reference sensor may be required.
14. Cost	5	This is an important criterion.
15. Maintenance cost	10	Maintenance is a returning cost and should be minimized
16. Interface with present equipment /combination with present equipment	6	Important criterion. There are extra costs if adaptations are needed to adapt the instrument in the present equipment. It is important to measure wind as well The wind data is needed to interpretation of the wave data.
17. Soiling, marine growth	7	This is a very important aspect. The weighting factor is not very high because this criterion has some overlap with the criterion 15.
18. Reliability/ robustness/vandalism	6	Important criterion. There are extra costs if the instrument has to be repaired. It is important to measure during storms. This weighting is not very high because it has some overlap with the criteria 19 and 15.
19. Storm ice fog spray	6	Important criterion. One objective of the measurements is to generate reliable and accurate data during storms. Failure of the instrument during storms is not permitted. Fog and spray can influence the measurements. There are extra costs if the instrument has to be removed during ice periods. This weighting is not very high because it has some overlap with the criteria 18 and 6.

Table 6.1 Weighting factors

6.4 Results

6.4.1 Results

The results of the multi-criteria analysis are presented in table 6.2.

Table 6.2 Results multi-criteria analysis

Type of instrument	Name of instrument	Score	Wave frequency range (high)	Wave frequency range (low)	Resolution	Accuracy (small waves)	Accuracy (high waves)	Breaking waves, wave asymmetry	Wave direction	Direct/indirect	Sample frequency	Power consumption	Daily data production/Transfer data	Internal memory, logger capacity	Calibration/drift, feasibility of field checking	Cost	Maintenance cost	Interface present equipment	Soiling, marine growth	Reliability/robustness/vandalism	Storm, ice, fog, spray	Remarks
	Weighting factors	100	10	3	4	4	7	4	3	4	3	8	5	2	3	5	10	6	7	6	6	
Golf ADCP	AWAC	86,8	10	10	10	10	10	5	10	10	9	10	3	10	8	7	9	5	9	9	10	Produced by Nortek.This instrument can produce current profiles and water quality parameters as well. Instrument should properly installed at the seabed, diver assistance recommended. Notes: A2, A3.
Downward looking laser	Laseroptronics	81,4	10	10	10	10	10	7	0	10	10	9	10	0	10	8	6	8	10	5	6	No product support by manufacturer. Notes: A1, B2.
Downward looking radio	SM-094 Range Finder	80,8	7	10	10	10	10	7	0	10	10	6	10	0	10	8	9	8	10	5	9	Produced by Miros. False signal reflections of the pole are to be avoided. Notes: A1, B3
Downward looking Acoustic	LOG_alevel	80	7	10	10	10	10	7	0	10	10	6	10	10	10	10	7	8	10	5	6	Produced by General acoustics. Used at a number of locations in Germany. False signal reflections of the pole are to be avoided. Notes: A1, B3.
Downward looking Radar	Waveguide	78,4	7	10	7	9	10	7	0	10	10	5	10	0	10	8	9	8	10	5	9	Produced by radac. Used by RWS. False signal reflections of the pole are to be avoided. Notes: A1, B3.
Step gauge	Etrometa step gauge 2 cm*1	76,7	10	10	7	9	10	7	0	7	10	10	10	0	10	8	5	10	5	5	7	Special order at Etrometa.
Step gauge	Etrometa step gauge 5 cm	75,5	10	10	6	7	10	7	0	7	10	10	10	0	10	8	5	10	5	5	7	Produced by Etrometa. RWS used the marine 300-II step gauge at a number of locations, at *new locations Etrometa step gauge is used*.
Golf ADCP	RDI wave ADCP	74,3	4	10	10	4	7	5	10	5	9	10	4	10	8	6	9	5	9	9	10	Produced by RDI. Used by RWS. This instrument can produce current profiles as well. Instrument should properly installed at the seabed, diver assistance recommended. Notes: A2, A3.
Pressure gauge	MIDAS WTR	70,2	4	10	10	4*3	10	0	0	0	10	10	10	10	8	10	7	8	6	8	10	Produced by Valeport. This instrument can produce water quality parameters as well. Note: B4.
Pressure gauge	Paroscientific pressure sensor	69,4	4	10	10	4*3	10	0	0	0	10	10	10	0	8	10	7	10	6	8	10	Produced by paroscientific. Accurate pressure sensor. In practice the high frequency waves are difficult to measure. Note: B4.
Staff gauge/ capacitance wire	Multicap-DC11	66,7	10	10	9	4	10	7	0	7	10	8	10	0	3	10	1	10	2	5	7	Produced by Endress and Hausser. Endress and Hausser did not supply us with updated information. Used at the currently measurements at the IJsselmeer and Slotermeer. Notes: A4, B5.
Wave buoy	*Waverider SG*	61,5	4	5	7	8	10	10	0	10	10	6*2	8	10	8	8	5	3	8	5	7	Produced by Datawell. Widely used wave gauge. System is extensively used and tested. Software contains routines to validate the measured signal. Note: B1.
Wave buoy	Dir Waverider MKII	61,2	4	5	7	8	10	10	6	10	8	6*2	6	10	8	7	5	3	8	5	7	Produced by Datawell. Used by RWS. System is extensively used and tested. Software contains routines to validate the measured signal. Note: B1.
Wave buoy	*Dir waverider GPS*	61,1	3	9	7	8	10	8	6	10	10	6*2	6	10	8	8	5	3	8	5	6	Produced by Datawell. Used by RWS. System is extensively used and tested. Software contains routines to validate the measured signal. Note: B1.
Wave buoy	Mini Waverider GPS	60,8	3	8	7	8	10	8	6	10	10	6*2	6	10	8	8	5	3	8	5	6	Produced by Datawell. Used by RWS. System is extensively used and tested. Software contains routines to validate the measured signal. Note: B1.
Remote sensing	*SM-050 MKIII Wave Radar*	37,1	2	5	1	0	5	0	6	0	3	0	0	0	8	0	8	0	10	8	8	Produced by Miros. Directional wave information normally located on a platform, doppler radar principle. Note: A1.
Remote sensing	WAVEX/WAMOS	33,2	2	2	1	0	0	0	6	0	3	0	0	0	8	1	8	0	10	8	8	WAVEX/WAMOS comparable systems from different suppliers, delivers software with which navigational radar can be used for wave measurements. System has been tested at Petten by RWS (comparable with the SHIRA system from TNO). Note: A1.
Staff gauge/ capacitance wire	Baylor wave staff																					Supplier not found or not existing any more, not further used in comparison.
Downward looking Radar	Saab Radar																					Has been used often by RWS, current supplier did not respond, WS ocean system the supplier of these systems has been taken over.
Downward looking Radar	MAREX SO5 wave radar																					Not further used in comparison.
Laser	Thorn wave height sensor																					THORN/EMI has been taken over and probably now part of Thales optronics, they do not support this system.
Acoustic	SRD																					Wave version not yet on the market only used as tide gauge in the UK.
PUV	Aquadopp																					Not further used in the comparison, due to sample rate of 1 Hz.
PUV	Seapack 2100																					Not further used in comparison, outdated and very vulnerable for leakage.

The notes *1, *2, *3, A1 to A4 and B1 to B5 can be found on the next page.

*1: Special order.
*2: Radio link between buoy and pole necessary.
*3: Small long waves can be measured accurately.
Small short waves cannot be measured due to practical implication (placement too close to the water surface).

Human errors;
Human errors in relation to the quality of the wave measurement are addressed subjectively.

A1: Installation errors could result in measurement errors. For example if the beam of the downward looking instrument is not pointed vertically downward signal reflections from the pole could influence the measurement.

A2: Care should be taken in programming the instrument. For example measurement schedules for different sensors are to be programmed within the instrument prior to installation. For example within the ADCP's, current measurement intervals and water level recordings are scheduled on a different interval than the wave height measurement.

A3: Diver inspection required to verify if the (bottom mounted) instrument is placed on a flat and horizontal sea bed.

A4: Calibration coefficients are to be verified in the field and used in the (post) processing of the data. Inaccurate or wrong calibration data may result in measurement errors

Signal repair;

B1: The raw measurement signal has to be verified on false readings, using the post processing software. For example wave buoys use the criteria that the succeeding samples may not differ more than 2-3 times the standard deviation of the signal from each other. A false reading is replaced by interpolated values prior to the data processing.

B2: Each sample is an average of number of sub samples. Error checks on both the sub samples and the sample itself is required.

B3: Wave slope related signal reflection errors can be expected on steeper wave slopes (1:7)

B4: Measurement range related errors are possible (for example pressure sensors are to be mounted as close as possible to the water surface in order to measure high frequency waves, which results in the possibility that the sensor becomes above water

B5: In the capacitance probe calibration, non-linearities (hiccups) near the probe support beams cause preferential values, which may in turn affect the measurement results. Correction would be desirable but becomes ineffective as soon as instrumental drift is non-zero (which is often the case).

6.4.2 Score specifications

The score of an instrument on each criterion is based on the instrument specifications (see appendix F), questionnaires (see appendix D), literature, user experiences (see appendix E), engineering judgement and the boundaries as attributed in section 6.2.

The maximum score an instrument can obtain in this multi-criteria analysis is 100, by scoring a ten on each criterion. Logically, the minimum score is 0, by scoring a zero on each criterion. In other words you could interpret the total score of an instrument as a grade between 0 and 100. Table 6.2 shows that not one of the selected instruments obtains a total score of 100. This means that every instrument used in this analysis has its own limitation for these measurements (see specifications in chapter 4, 5 and 6).

Below are the scores are briefly described.

The scores on the criterion *"wave frequency (high)"* range from 2 to 10. For the WAVEX/WAMOS and the SM-050 MKII wave radar, the score is 2 as only waves longer than 3 seconds can be sampled. For the AWAC, the laser and the step gauges, the score is 10 as wave spectra can be suitably represented up to 2 Hz. The other scores range from 4 to 9 because of the instrument size (buoys), the sample frequency and footprint size (radar), the short wave attenuation with depth (pressure sensor).

The scores on the criterion *"wave frequency (low)"* range from 2 to 10. The WAVEX/WAMOS scores a 2 as it can sample waves with a wave frequency higher than 0.055Hz (periods smaller than 18 sec). For the waverider SG and the directional waverider MKII, the score is 5 as they can sample wave frequencies higher than 0.033Hz (periods smaller than 30 sec). The mini waverider GPS can sample waves with a wave length up to 40 seconds resulting in a score of 8. The directional waverider GPS scores a 9 as it can sample wave frequencies higher then 0.01Hz. The remaining instruments score a 10 as they have no limitations on the low frequencies.

The scores on the criterion *"resolution"* range from 1 to 10. For the AWAC, laser, SM-094 range finder, log_alevel, the score is 10 as the resolution in wave height is 1mm. For the RDI wave ADCP and the Pressure sensor, the score is 10 as the resolution in wave height is 1mm. For the Multicap DC11, the waveguide and the buoys, the sore is 7 as the resolution in wave height is in the order of 1cm. For the remote sensing equipment, the score is 1 as the resolution in wave height is 10cm.

The scores on the criterion *"Accuracy (small waves < 20cm)"* range from 0 to 10. For the remote sensing equipment, the score is 0 as the accuracy is 10cm. The MIDAS WTR and the pressure sensor can measure long period waves very accurately (accuracy as from 1mm) but short waves with reasonable amplitudes cannot be measured accurately due to practical implication (instrument sensor has to be close to the water surface). For this reason they score a 4 on this criterion. For the Multicap DC11 and the RDI wave ADCP, the score is 4 as the accuracy on small waves is round 5cm. The accuracy of the step gauge (resolution 5cm) is 2,5cm resulting in a score 7. The buoys have an accuracy of 1cm but they cannot measure high frequency waves accurately because of the instrument size (see criterion wave frequency (high)). For this reason the buoys score an 8 on this criterion. For the Waveguide and the Step gauge (2cm resolution), the score is 9 as their accuracy is 2cm. The remaining instruments score a 10 as the accuracy is smaller than 1cm and no anticipated period related errors exist.

The scores on the criterion *"Accuracy (high waves > 1m)"* range from 0 to 10. The WAVEX/WAMOS score a 0 on this criterion because the accuracy lies between the 0.25 and 0.5 m. For the SM-050 MKII, the score is 5, since the inaccuracy of the measurement is up to 5% of the measured value. For a wave of 3m this means an inaccuracy of 15 cm. For this reason the score is relatively low. The RDI wave ADCP scores a 7 as the accuracy is between 8 and 16 cm (related to the instrument setting for bin size). For the remaining instruments, the score is 10 as the accuracy is smaller than 5cm and no anticipated period related errors exist. Downward revision of the assessment scores may be required in extreme conditions, especially if:
- for step gauges and capacitance probes the instrument top is less than 0.5 times H_{m0} above the still water level (see Bottema, 2002, p 66)
- for pressure sensors if the sensor is too close to the still water level and falls dry for at least 10 – 25% of the waves (see van Doorn, 2004)

The scores on the criterion *"Breaking waves/wave asymmetry"* range from 0 to 10. It has been difficult to obtain reliable information on criterion. Wave buoys (inertia based) score a 10 on this criterion since they follow the water surface and the water air interface on a clear and consistent way. The downward looking instruments do not have a clearly defined water air transition, they score a 7. The same applies for the step and staff gauges. Entrained air bubbles in the near surface layer may cause that the surface tracking feature of the bottom mounted do not work accurately, they score a 5. Pressure gauges rely on the linear wave theory in the conversion from pressure to wave height they cannot directly measure wave asymmetry or breaking waves, they score a 0. Measured wave heights in breaking wave conditions may have an uncertainty of maximum 15 % between direct measurement techniques and pressure gauges. (see van Rijn, 2000). This is the only reference found related to the measurement inaccuracies related to breaking waves. Due to the lack of information on this part of the criterion the measurement inaccuracy due to breaking waves has not been taken into account in table 6.2.

The scores on the criterion *"wave direction"* range from 0 to 10. For the directional buoys, the remote sensing equipment, the score is 6 as a single wave direction can be measured at one wave frequency. The ADCP's score a 10 on this criterion because they are capable of measuring multi-directions at the same frequency. The other instruments score 0 as they do not measure wave direction.

The scores on the criterion *"Direct/indirect"* range from 0 to 10. For the AWAC, Laser, SM-094 Range Finder, Log_alevel, Waveguide and all the buoys, the score is 10 as they measure the actual water level more or less directly. The step gauges and the MulticapDC11 score a 7 on this criterion as they are direct measurements but a few conversions have to be carried out. The RDI wave ADCP scores a 5 as it measures with slanted beams, conversions and correlation analysis between the beams are to be carried out. For the remote sensing equipment, pressure sensor and the MIDAS WTR, the score is 0, as assumptions have to be made.

The scores on the criterion *"Sample frequency"* range from 3 to 10. The remote sensing equipment are based on wave mapping technique, sample frequency is not very relevant in this respect. The directional waverider MKII can sample with a frequency of 3.84 Hz, therefore the score on this criterion for this instrument is 8. For the ADCP's, the score is 9 as they can sample with a frequency of 4 Hz. The other instruments score a 10 on this criterion as they can sample with frequency of 8Hz or higher.

The scores on the criterion *"Power consumption"* range from 0 to 10. The remote sensing equipment needs more than 100W of power. Since installation without external power supply is hardly possible on remote the score on this criterion is 0. The power consumption of the buoys is smaller than 1 W, but the radio link between the pole and the buoy requires more power this results in a score value of 6. In the present situation 4.5 -5 W is available at the measuring pole for the instruments. The instruments that need a power consumption of 1W or smaller score a 10, because there is still enough power available for other instruments. The other scores range from 5 to 9 depending on the power consumption of the instrument (see section 6.2).

The scores on the criterion *"Daily data production/Transfer data"* range from 0 to 10. The score is related to the amount of data to be transferred between the pole and the base station. The downward looking instruments, capacitance probe, step gauges and pressure gauges measure one parameter; they score a 10 on this criterion. The data produced by the wave mapping type of equipment can hardly be transferred by radio link.

The scores on the criterion *"Internal memory/logger capacity"* are 0 or 10. All the instruments with internal memory score a 10. The others score a 0. It should be noted that for some instruments (like Multicap DC11 etc.) a connection with an external logger can be applied. For this reason this criterion has a low weight factor.

The scores on the criterion *"Calibration/Drift/feasibility of checking in the field"* range from 3 to 10. Drift of the instrument performance is relevant for the Multicap. This instrument requires frequent recalibration and scores a 3. The downward looking instruments and step gauges can be easily checked in the field and do not require recalibration they score a 10. The instruments mounted below the water surface and the buoys require a separate reference sensor to check the accuracy of the measurement, they score an 8.

The scores on the criterion *"costs"* range from 0 to 10. For the log_alevel, MIDAS WTR, Pressure sensor and the Multicap DC11, the score is 10 as the purchasing costs are lower than 5000 Euro. For the laser, SM-094 Range Finder, Waveguide, the buoys (except the directional waverider MKII) and the step gauges, the score is 8 as the purchasing costs is between 10000 and 20000 Euro. The directional waverider MKII and the AWAC scored a 7 on this criterion as the purchasing costs is between 20000 and 30000 Euro. For the WAVEX/WAMOS, the score is 1 as the purchasing cost is 84000 Euro. The SM-050 MKII wave radar did not score on this criterion as the purchasing cost is 150000 Euro.

The scores on the criterion *"Maintenance cost"* range from 1 to 10. The operational cost of the wave measurements are mostly related to maintenance. The maintenance cost is related to the cleaning and recalibration requirements and the fact that some instruments are to be removed during ice periods. See section 6.2 for the specification of the score.

The scores on the criterion *"Interface present equipment"* range from 0 to 10. The remote sensing equipment cannot be placed at the pole. For these reasons the score is 0. For the buoys, the score is 3. The buoy can be placed in the neighbourhood of the pole in order to use the data of the wind sensor at the pole and for data communication. The Multicap DC11 (currently used instrument), pressure sensor and the step gauges, the score is 10, as they are or can be integrated in the present equipment. The ADCP's are bottom mounted instruments and cannot be placed at the pole therefore some adaptations are required. These instruments are easier to connect with the pole in comparison with the buoys so they score a little bit higher (5). The other instruments score an 8 as some small adaptations are required in order to place the instruments in the present equipment.

The scores on the criterion *"soiling, marine growth"* range from 2 to 10. All instruments which are measuring from above the water level score a 10. Bottom mounted ADCP's are not sensitive for marine growth, large local sedimentation on top of the instrument may cause some influence on the measurement (experiments has showed that a silt layer of 0.5m on top of a ADCP did not effect the measurements), the ADCP's score a 9. Large marine growth may influence the characteristics of the buoys. Barnacle growth on pressure sensors may obstruct the pressure recording, they score a 6. The step gauge is seems to be less sensitive for marine growth than the staff gauge, the score a 5 and a 2 respectively.

The scores on the criterion *"Reliability/Robustness/Vandalism"* range from 5 to 10. The ADCP's are reliable instruments placed at the bottom and they are the least sensitive for vandalism. For this reason they score a 9. For the remote sensing equipment and the pressure sensors, the score is 8 as they are reliable instruments but they are a little bit more sensitive for vandalism. The other instruments are reliable instruments. They all have at least a part of the instrument placed above the water surface resulting in easy accessibility for vandals. For this reason the score on this criterion is a 5.

The scores on the criterion *"Storm/Ice/Fog/Spray"* range from 6 to 10. The instruments that are bottom mounted are not sensitive for storm ice fog and spray and they can be deployed 365 days/year, these instruments score a 10. Buoys, capacitance probe and step gauges are sensitive for ice, measurements during severe winter storms can be lost, they score a 7. The GPS based buoys are sensitive for water on top of the antenna (GPS reception is lost) they therefore score a 6. The laser may have problems with spray and fog and the acoustic log_alevel may have problems during severe winds (loss of signal), they both score a 6. The remote sensing equipment requires surface roughness in order to measure waves. During foggy conditions the water surface is expected to be too smooth for wave measurements. The wave guide and range finder may have some spray related problems in detecting the water surface.

The applied set of weighting factors has been determined especially for the area of interest being IJsselmeer and Slotermeer. Obviously, these subjective weight factors have a significant influence on the total scoring. The scores on the contrary are objective and are mainly based on technical specifications.
Changes in weight may lead to a different listing. For example, a choice to consider well developed waves only (and to use a different instrument for small and short waves) may decrease the weighting factor for the criterion "wave frequency range

(high)" from 10 to 0. In such a case, the difference in total score between the ADCP's of AWAC and RDI will decrease by 6 points. This would imply that a difference in total score which is (well) above 6 points can be considered as significant or robust. This is because the ranking will not be affected by minor changes in the weighting of the criteria. Conversely, this example shows that a total score difference of less than 6 points appears to be insignificant as with such a small difference, the instrument ranking is likely to be sensitive to the choice of the weighting factors.

6.4.3 Conclusions

The bottom mounted Nortek ADCP is selected by the multi-criteria analysis as the most suitable equipment to be used in the lakes IJsselmeer and Slotermeer (total score of 86.6). However, it should be noted that this equipment is relatively new on the market.

The second most suitable wave measurement instrument is the downward looking laser (total score of 81.4). Despite this high score it is not advised to be used. The main reason is that this instrument is no longer supported and in future RIZA and RDIJ want to apply commercially available equipment only.

The step gauge and the specifically the 2 cm version (total score of 78.7) seems to be very suitable for the wave measurements. The Etrometra step gauge seems to be more reliable then the Marine 300 gauge which has been used in the past. The negative experiences of RIZA/RDIJ with the marine 300 step gauge are related to the outdated design of this step gauge.
The RDI ADCP scores 12 points lower than the Nortek AWAC. Both instruments use Acoustic Doppler measurement techniques. The RDI instrument uses a less accurate surface tracking technique which results in a low accuracy of the measured wave heights. Further the sample frequency of the instrument (without scarifying the accuracy further) is 2 Hz.

The pressure gauge is ranked relatively high (total score of 69.4). Despite the fact that this instrument can measure low high frequency waves and high waves in storm conditions very accurately this instrument is not a serious option. The reason for this is that the pressure sensor has to be located within a quarter of the wave length below the water surface to measure the low high frequency waves accurately. This could give problems by fluctuations of the still water level on a time scale of hours, days or weeks (the sensor could dry if for example a trough of a high wave passes the sensor). To resolve this problem more pressure sensors could be used (at different heights below the water surface), but this makes the monitoring technique very complex.

The capacitance probe ("Multicap DC11") scores relatively low (total score of 66.1) in comparison with the step gauges and the downward looking instruments. This is mainly related to the high maintenance cost, the influence of soiling and marine growth on the measurements, and the calibration requirements.

Wave buoys (total score round 64) are the most widely used wave measuring gauge They are less favourable for the shallow water conditions at the IJsselmeer and Slotermeer, because they can not follow the high frequency waves.

The low score of Wave Radar (total score of 39.4) and the WAVEX/ WAMOS (total score of 35.5) is mainly devoted to the low accuracy of the measurements with these instruments.

It should be noted that there is a difference in the amount of information about the instruments. This gives an uncertainty to the multi-criteria analysis. For example, a lot of specific information is known about the currently used capacitance probe which could result in a lower or higher ranking. By asking additional questions to the suppliers, experts and instrument users we tried to limit this uncertainty as much as possible.

A recommendation is to carry out a field test in which the present capacitance probe is tested against Nortek AWAC, the Etrometa step gauge (preferably the 2 cm version), the Radac wave guide and either the General Acoustic log a level or the Miros downward looking radio. This field test could give answers to the uncertainties of this multi-criteria analysis.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The objective of this study was:

To investigate the suitability of different techniques and instruments for wave monitoring in the Dutch lakes IJsselmeer and Slotermeer. The output of this study is a recommendation about the wave measurement instrument which is most suitable for these measurements.

The site specific features, shallow water and short fetches, of the Dutch lakes IJsselmeer and Slotermeer result in wave heights conditions up to 3 m, wave peak periods between 1 to 5 seconds and still water level fluctuations of 1m. This requires measuring instruments that can measure both relatively small high frequency waves and larger waves during storm periods. Shallow water wave measurements related to these conditions are not common practice. Hardly any commercial wave measuring equipment is available for these measurements. The present measurement system consists of "tailor" made capacitance wires.

By means of a literature study, questionnaires for suppliers, interviews with experts and wave instrument users a selection of potential suitable wave instruments is made. Next, a multi-criteria analysis is performed with these instruments. This multi-criteria analysis resulted in a ranking of the selected wave measurement instruments.

In the next two paragraphs present the conclusions and recommendations of this study.

7.2 Conclusions

The conclusions from this study are as follows:

- The result of the multi-criteria analysis shows that the bottom mounted Nortek AWAC ADCP is the best suitable equipment to be used in the lakes IJsselmeer and Slotermeer. This type of equipment consists of an Acoustic Doppler Current Profiler that is suited for measuring wave height and direction spectra. It measures current profiles as well. The feasibility of the AWAC is related to its accurate Acoustic Surface Track (AST) feature, using a central upward looking beam. This AST feature can be sampled at high frequency rates (up to 4 Hz) and the footprint at the surface remains small due to its narrow beam angle (1.8°). It should be noted that this equipment is new on the market.

- The downward looking radar, radio and acoustic instruments are of the downward looking type. They are all serious options as wave instrument for wave monitoring in the IJsselmeer and Slotermeer. The same applies for the step gauge. The negative experiences of RIZA/RDIJ with the step gauge ("Marine 300-II") seem to be related to the outdated design of this gauge. Etrometa has made a new modular design that overcomes most of the former step gauge related problems.

- Pressure gauges are not a serious option since for high frequency waves the sensor has to be located within a quarter of the wave length below the water surface. This could give problems by fluctuations of the still water level on a time scale of hours, days or weeks (the sensor could dry if for example a trough of a high wave passes the sensor). To resolve this problem more pressure sensors could be used (at different heights below the water surface), but this makes the monitoring technique very complex.

- Wave buoys are the most widely used wave measuring gauges, but they are less favourable for the shallow water conditions at the Dutch Lakes IJsselmeer and Slotermeer. The reason is that they cannot follow high frequency waves. Finally the low accuracy of wave height measurements with Wave Radar and WAVEX/ WAMOS makes this measuring equipment based on Remote Sensing not suitable for the measurements in the IJsselmeer and Slotermeer.

- The currently used capacitance probes are more or less "tailor" made. In the future RIZA and RDIJ want to apply commercially available equipment only. For this reason the downward looking laser and the "Zwarts Pole" are not recommended although their performance might be good (the downward looking laser is no longer supported and the "Zwarts Pole" is completely "tailor" made (see Verhagen 1999)).

7.3 Recommendations

- Carry out a field test in which the present capacitance probe is tested against the Nortek AWAC, the Etrometa step gauge (preferably the 2 cm version), the Radac wave guide and either the General Acoustic log_alevel or the Miros downward looking radio.

- Consider "tailor" made equipment; the presently used capacitance probes are more or less tailor made. Results from the Lake George experiments showed that the "Zwarts poles" have functioned very well. The "Zwarts poles" are not commercially available, but they could be a good option for the IJsselmeer and Slotermeer. The downward looking, laser based systems are also not commercially (anymore) available as wave measurement equipment, but they also could be a good option to be considered.

- Since validation of wave models in general is one of the measurement purposes, it would be recommendable to have scientific participation (Delft University) in the project.

- If wave growth measurements are important as well, it would be useful to explicitly follow the wave growth process. For that reason, RIZA and RDIJ are advised to consider the feasibility of a modified set-up of their measurement programme, with one or more (temporary) extra measurement locations.

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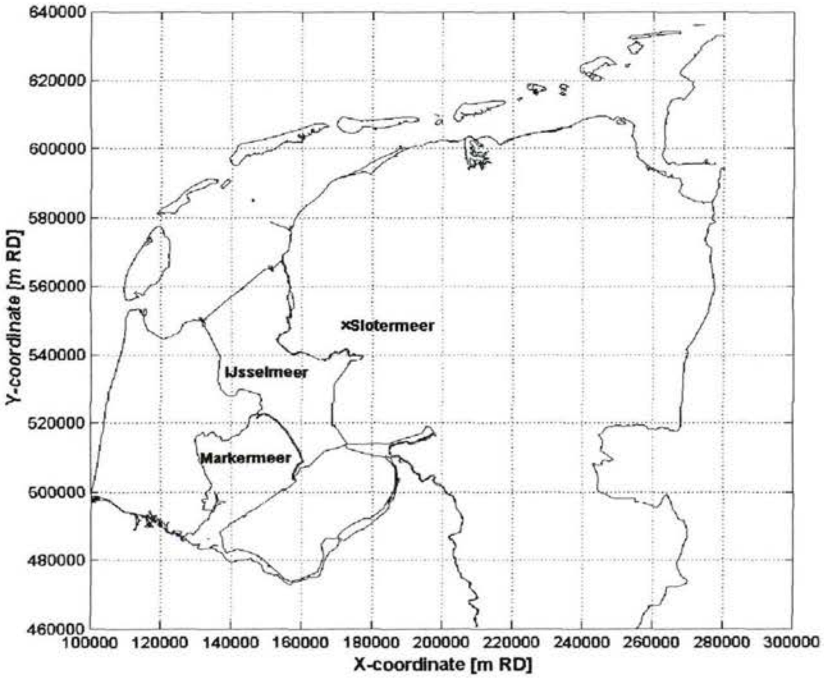
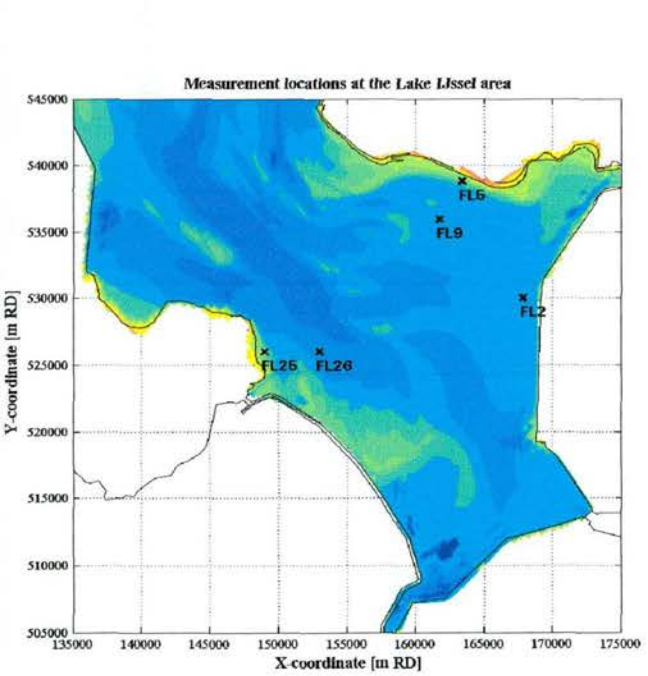
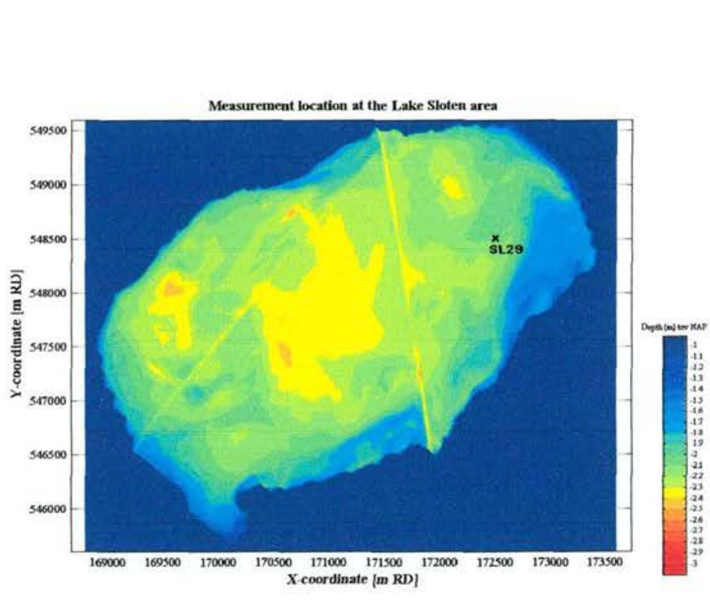
APPENDICES

APPENDIX A OVERVIEW OF THE WAVE MEASUREMENT LOCATIONS







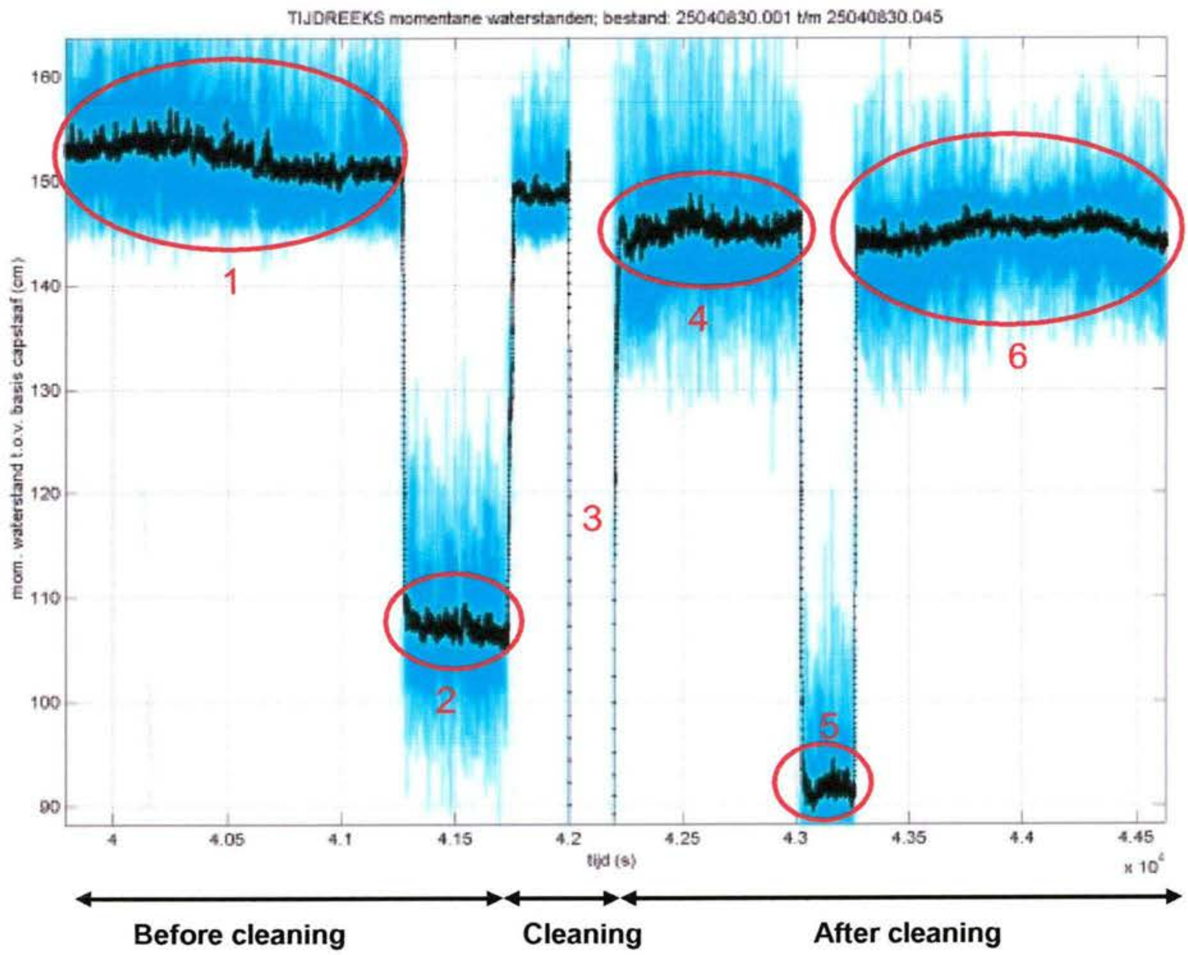
APPENDIX B CAPACITANCE PROBE (MULTICAP DC11)

Before cleaning

After cleaning

APPENDIX C CAPACITANCE PROBE TEST

This test is performed at the location FL25 (see Appendix A) in the first week of September 2004 (Monday 30 August 2004).



Phases:

1: Current water level measurement (before cleaning).

2: Water level measurement after lowering the probe with 0.5 m with respect to the height in phase 1 (before cleaning)

3: Cleaning

4: Water level measurement after cleaning and the probe placed at the same height as in phase 1.

5: Water level measurement after cleaning and after lowering the probe with 0.5 m with respect to the height in phase 3 or phase1 (this is the same height as in phase 2).

6: Water level measurement after cleaning and the probe back in its origin position (raising 0.5m in respect to phase 5). This is the position where all the actual wave height measurements take place.

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APPENDIX D QUESTIONNAIRES TO THE SUPPLIERS

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QUESTIONNAIRE WITH REGARD TO WAVE MEASUREMENT INSTRUMENTS

All the questions listed below refer to the wave measurement instruments which are suitable for measurements at the IJsselmeer and Slotermeer (see accompanying letter). So if your company sells more then one wave measurement instrument suitable for these measurements please answer all the questions for each wave measurement instrument.

1. Company specifications:

Company name:	Miros A/S
Address:	PO Box 364 NO 1372 Asker Norway
Phone:	+ 47 66 98 75 00 direct to undersigned: + 47 66 98 76 17
E-mail:	Office@miros.no Direct to undersigned: rj@miros.no
Filled in by:	Rolf A.Jørgensen, Marketing Executive

2. Which wave measurement instrument(s) does your company sell?

The Miros Wave & Current Radar, SM-050 Mk III. – A Microwave Doppler Radar for directional wave and current measurement. Data collection and Presentation System for installation on floating or stationary platforms or shore sites.

Miros Wavex – A System applying imaging techniques and using Marine X-band Radar as sensor for data acquisition and presentation of directional wave and current data. Used on commercial and military vessels, on platforms and for shore installations.

Miros Range Finders – Microwave downward viewing sensors providing distance information to the sea, with software available for distance presentation including tide monitoring and wave height and period (not direction). Miros has two basic models SM-094 Range Finder and SM-048/2 Microwave Altimeter. The electronics of these two sensors are identical and include substantial improvements from the former models SM-055 and SM-048 (which were tested by Rijkswaterstaat in 1997 Ref Theo Sijben)

3. Give a short description of the functions of the(se) wave measurement instrument(s)?

SM-050 and Wavex include the same functionality, viz. To provide directional spectra and all parameters related to Wave & Current Data. The systems are both used, SM-050 being more accurate wrt. Wave Height (less than 5% error) and not being subject to noise disturbance when heavy precipitation occurs.

The SM-050 Mk III version has been subject to substantial hardware and software improvements as of this year.

Wavex is now delivered with SW 4.0 and has also been subject to very recent major upgrade. Further SW option modules available are 1) Currents – multipoint direction and speed vectors within the polar image, and 2) Oil Spill Detection. These option modules will be subject to verification tests in the Autumn of this year.

The Range Finders are extremely accurate and lower in cost. We understand that the project, when operational, would comprise a number of sensors, 10 say. It is our impression that the SM-050 units should be best suited for the purpose in this case. You may consider also to include one Wavex system for the purpose of acquiring directional data is so required.

4. What is the brand(s) of the(se) wave measurement instrument(s) (if your company sells more than three different brands of one instrument, then please list only the three most suitable for wave measurements on the IJsselmeer or Slotermeer (see accompanying letter)):

Range Finder SM-094
Wavex
Wave & Current Radar SM-050 Mk III

5. The wave measurement instrument(s) consists of:

Normal Miros Supply:
Range Finder SM-094 – Sensor and SW on CD + optional Mounting Bracket
Wavex – PC with Data acquisition card installed /VDU/KB + IF box + optional Marine Radar to suit.
SM-050 – Sensor, PC with software installed/VDU/KB, JB & IF-unit + optional Pedestal, Cooling Unit, Sun shield & Pedestal.

6. Which materials the wave measurement instrument(s) consist of?

See Specifications

7. What are the physical specifications of the wave measurement instrument(s)?

See Specifications

8. What is the energy use of the wave measurement instrument(s)?

See Specifications

9. How many days can the wave measurement instrument(s) measure non-stop with internal batteries and memory (so if autonomously)?

SM-050 and Wavex do not lend themselves to battery operation, but may be shore based looking into the sea from a distance.

Range Finders have low power consumption and may be battery operated. Nominal 22-32 VDC, 0.2 A

10. How sensitive is the wave measurement instrument(s) for damage of storm, ice, driftwood or vandalism?

Range Finder SM-094 Sensor would be installed out of the sea and looking towards the sea surface from above. Provided well installed and the foundation also being well designed, there should then be little vulnerability for damage by storm ice and driftwood.

One of the SM-094 Sensors supplied to NOAA, USA and installed at the US Army test site Duck was subjected to complete submergence by a 10m freak wave resulting in severe damage to other sensors at the station. The SM-094 suffered a bent mounting bracket and limited water intrusion – no major damage to the sensor. No assurance against vandalism, except that there should be little excitement in damaging the sensors.

11. What is (are) the price(s) of the wave measurement instrument(s) (include the technical specifications)?

Ex Works Approximate 2004Prices in accordance with 5 above unless otherwise stated.

Range Finder SM-094/10 or SM-094/20W	About NOK 100,000
Wavex incl. Marine Radar	About NOK 700,000
Wave & Current Radar SM-050 Mk III	About NOK 1,250,000

12. Is the wave measurement instrument(s) available for trails/purchase in the short term?

We batch produce all sensors which may therefore be on stock. Normal delivery times could be:

Range Finder: 2-9 weeks from order
Wavex incl. Marine Radar: 6-9 weeks from order
SM-050 2-4 months from order

13. What does the output data consist of (e.g date, wave height, wave direction, etc)?

SM-094 provides: distance to sea (subsidence, tide and wave heights/periods) Footprint would be directly under the sensor. It is important that there is no shadowing of incoming seas or reflections from structure on which the sensor is mounted.

Wavex provides: directional information + wave height and period. May also provide surface current information if so required. The Wavex computer and Miros associated SW may also be used to acquire other Met Data.
Footprint would be at a distance from the Radar Antenna, typically 1-2 km away

SM-050 provides: directional information + wave height and period. Also provides surface current information. The SM-050 computer and Miros associated SW may also be used to acquire other Met Data. Footprint would be at a distance from the Sensor, typically 150- 250m away on a shore installation, but highly dependant on the installation height of the sensor.

14. Is it possible to transfer the output data (for example with GSM/Satel transmitters (9600 Bps)) without interruption of the measurements?

Miros is well acquainted with GSM/Satel transmitters. We have for instance successfully applied Satel VHF Modems (9600Bps) with our SM-050 radar, without interruption providing nearby traffic with wave radar data from an installation on a semi-submersible on the Foinaven Field.

GSM could be installed in the SM-094 sensor. Satel unit would be in separate box.

We may, in the event that you are looking for single source responsibility, provide complete package. We do however require information to assess models to be used for the purpose of the project.

15. Does the wave measurement instrument(s) measure continuously (3600sec/h and 24h/day)?

Range Finders would provide as stated. Wavex and SM-050 would collect data continuously, but not present data at the suggested rates.

Wavex may present new data every 2 minutes, but would normally be configured to present averaged data over12-18 minutes rolling averages with intermittent updates

SM-050 will also acquire data continuously and present rolling averaged data about each 15 minutes.

16. How much output data does the wave measurement instrument(s) produce in one day (MB)?

Please advise if your reference is raw data or processed data – and which type of data? In simplest form with service pack MirLog 06 and Range Finder sending 2 samples per second, say, disk usage is 432 Kbytes/h (Raw data 24 hour files 10368 Bytes) and statistical 24 hour file data 15 kBytes with 10 minute averaging.

17. How much output data can be stored by the wave measurement instrument(s) (MB)?

None in the SM-094 at present.

With logging to PC storage capacity will depend on disc size. 260 Gbyte discs are available and could store 25077 days of raw data (68 years) at 4 Hz half that amount at 2 Hz.

We have developed a Digital Signal Processor which is in use on the SM-050 Mk III and which shortly will be included in modified SM-094 to be supplied to NOAA this Autumn.

Storage of data in the Range Finder has not yet been implemented, but may easily be included for in the DSP version which has available memory of 2 Mbytes, which is insufficient for storage of raw data, but well suited for storage of 10 min statistical data. It is, with 15 kBytes pr. 24 hours, possible to store 10 min statistics for 260 days. It is, by increasing capacity of the memory chip possible to arrange for storage of one year of data in the Range Finder. Data acquisition must then be stopped during data transfer.

It is our intension in the next generation DSP for Range Finder to use a 512 Mbyte Flash-disk. This will facilitate storage of 25 days of raw data at 4 Hz (or 50 days at 2z) and 34000 days (94 years) of 10 min. statistics internally. We expect such version to be available in about one to one and a half year's time.

Next step in our further development of the SM-094 will be to include GSM (clock) and as advise above to utilise the capacity of the DSP to process and store data.

For Wavex and SM-050 storage capacity is included in the PC.

18. Please specify any critical assumptions and conversions to evaluate the waves from raw signal which may effect the accuracy of the end results?

SM-094: There could be a lack of return signals to the sensor if waves are steep with no ripple (wind effect). This has been encountered when tests have been performed in model tanks. We have not experienced such problems elsewhere.

Wavex and SM-050: These systems send and receive return signals at a small angle of inclination to the sea surface. A slight wind creating ripple on the surface is required in order that return signals of sufficient quality are received. If not so, there will be no sensible data.

Marine Radar, therefore also Wavex, is vulnerable to excessive noise when there is very heavy precipitation (squalls). SM-050 penetrates precipitation and provides quality data even in such condition.

19. What is the accuracy of the wave measurement instrument(s) (wave periods (e.g Tp,Tm01) and wave heights),please specify ?

See specifications.
Wave height provided by SM-094 are accurate as the distance monitored is accurate.

No particular assumptions are made on conversion from time series to spectra.

Time series are weighted with a Hamming Window and standard method for averaging of periodograms is thereafter applied .

Distance (Height) is measured with an accuracy of 1 cm or better (instrument accuracy). Sampling is driven by a crystal clock with a data emitted accuracy better than 6*E-6 (6 ppm) which implies that periods are measurable at equal accuracy (instrument accuracy). The statistical properties of the sea, the form of the specter and averaging time will, for all practical purposes, decide the accuracy of the integrated wave parameters derived from the spectrum. If min 20 minutes averaging time is used, then corresponding or better accuracy is expected than for a wave buoy with corresponding averaging time applied.

Wave heights provided by SM-050 and Wavex will have slightly reduced accuracy in shallow water.

20. Can the wave measurement instrument(s) accurately measure at a sample frequency of 4 Hz? If not is it possible to adjust the instrument(s) to such a frequency?

SM-094 will provide 4 Hz data. Present sampling without DSP is 2 Hz. SM-050 and Wavex operate on different principle. SM-050 collects 2kHz data applying 2Hz sampling rate which was chosen as this is most conventional. Could probably by converted to 4 Hz at a cost. Wavex processes sea clutter of the marine radar's raw video data, presenting estimated parameter data about every 2 minutes. This is not possible to adjust.

21. What are the resolution and range (cm) of the wave measurement instrument(s) and do they fit into the requirements of a resolution (raw signal) which does not exceed 5 cm and a range (Hm0) of 5-200 cm?

Range Finder Resolution may be 0.001 m. Wavex and SM-050 0.01 m. Range Finder Range will be from min 1 m or 3 m depending on model and max, 10, 20, 50 or 85 m depending on model. Note it is assumed that the sensor is installed sufficiently high above water, not to be damaged in cases of freak waves occurring. Distance readings may be configures to relate to a standard prenomianted level and thus satisfy range 5-200 cm. Hm0 range for Wavex and SM-050 is 0-30 m.

22. What is the wave frequency range of the wave measurement instrument(s)?

For SM-094 today typically 0-0.5 Hz

23. How robust is/are the wave measurement instrument(s) (like how large is the risk that the instrument(s) or its electronics fails or becomes unreliable during a storm)?

We have had excellent experience with our sensors. Very high speed vessels fitted with our SM-048 sensors have been operating on daily routes between Hong Kong and Macau since 1994/95. The sensors are vital instruments within the ride control system directing angle of inclination of the foils. Nothing else than one minor repair on each of two of 5 sensors has been required during about 9 years of operations. The owners have now ordered 32 new sensors to replace sensors on other vessels with Miros sensors. Miros SM-094 sensors are subjected to heavy weather on our offshore installations. The sensors are providing data even under adverse conditions.

24. Can any measuring or processing errors be expected during asymmetric or breaking waves? If so, how large are those errors, and what type?

Yes, with Wavex and SM-050. Direction information, however, should not be influenced.
I am not sure. Will revert

25. Is it possible to check the performance and accuracy of the wave measurement instrument(s) in the field without removing it, and if so how?

Firstly, let us start by saying that none of our sensors require periodic calibration. In the event of failures, we would expect not slight inaccuracies to occur but something more substantial which easily become obvious.

Checking on accuracy in situ would normally be carried out against reference sensor.

26. How large is the expected drift in the calibration after a given period of time, and after how much time would a re-calibration be needed?

No drift expected and no re-calibration required.

27. What approach would you suggest to obtain mean water level data and wind data in order to interpret the wave data obtained with your instrument(s)?

SM-094 provides tide and mean water level data by software provided by Miros.

Wind data is not discussed herein, but may be included within our Met-Ocean System Software. We agree that wind data is good to collect

Attach a comparison of wind and wave data from an offshore field with Miros Met-Ocean System and Miros SM-050.

28. After how many days should the wave measurement instrument(s) be cleaned in order to function properly and keep measuring accurately?

No cleaning required. (The Miros SM-094 does not, as ultrasonic sensors, require regular cleaning).

29. Are there any reference customers we could approach for an user interview?

There are, depending on which type of sensors you require, many customers that could be contacted. You will note from our reference lists that there are many repeat customers, indicating that they must be satisfied. I shall be happy to arrange for contacts as you may wish.

30. Is there any other relevant information about the wave measurement instrument(s)we need to know for finding the best wave measurement instrument(s) for measurements at the IJsselmeer and Slotermeer?

The SM-050 is operating at 5.8 GHz. Check on permission for use of this frequency in the specific site area is recommended This is my response.

Best regards,
Miros A/S, 01.09.2004

Rolf A.Jørgensen
Marketing Executive

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Questionnaire with regard to wave measurement instruments

All the questions listed below refer to the wave measurement instruments which are suitable for measurements at the IJsselmeer and Slotermeer (see accompanying letter). So if your company sells more then one wave measurement instrument suitable for these measurements please answer all the questions for each wave measurement instrument.

1. *Company specifications:*

Company name:	Radac B.V.
Address:	Zomerluststraat 4 2012 LM Haarlem Nederland
Phone:	+31(0)23.5518853
E-mail:	Info@radac.nl
Filled in by:	Tom van der Vlugt

2. *Which wave measurement instrument(s) does your company sell?*

WaveGuides: Radar based water level and wave height sensors.

3. *Give a short description of the functions of the(se) wave measurement instrument(s)?*

By measuring the distance from the downward looking radar to the water surface the water level is sampled at rates from 2 to 10Hz. These samples are processed to water level, tide and wave parameters in the WaveGuide Server

4. *What is the brand(s) of the(se) wave measurement instrument(s) (if your company sells more than three different brands of one instrument, then please list only the three most suitable for wave measurements on the IJsselmeer or Slotermeer (see accompanying letter)):*

WaveGuide level and
WaveGuide Waveheight/level.
The WaveGuide Server

5. *The wave measurement instrument(s) consists of:*

A radar unit for sampling the instantaneous water level and if required a processing unit (WaveGuide Server) to calculate parameters. The WaveGuide Server has also facilities for data logging, remote service and data distribution.

6. Which materials the wave measurement instrument(s) consist of?

The radar unit, a aluminium sphere (radius ca 12 cm) plus a stainless steel antenna. The WaveGuide Server is a steel box (23x20x9cm) housing a PC104 computersystem.

6. What are the physical specifications of the wave measurement instrument(s)?

see brochure.

7. What is the energy use of the wave measurement instrument(s)?

The radar uses 6 Watt and the WaveGuide Server uses also 6 Watt. The next generation will consume 4 Watt (the combination of radar + WaveGuide Server)

8. How many days can the wave measurement instrument(s) measure non-stop with internal batteries and memory (so if autonomously)?

There are no batteries inside the system.

9. How sensitive is the wave measurement instrument(s) for damage of storm, ice, driftwood or vandalism?

As the instrument is mounted high above the water there is no risk for damage.

10. What is (are) the price(s) of the wave measurement instrument(s) (include the technical specifications)?

WaveGuide Waterlevel/ Tide with F08antenna	6.200,--
WaveGuide Waves and Tide with F08antenna	14.265,--
WaveGuide Server	2.200,--
WaveGuide Server option "tide processing/ datalogging"	1.200,--
WaveGuide Server option "wave and tide processing/ datalogging "	2.500,--

11. Is the wave measurement instrument(s) available for trails/purchase in the short term?

Yes.

12. What does the output data consist of (e.g date, wave height, wave direction, etc)?

Several output messages can be selected (also simultaneous via different output channels)
Raw samples (2 – 6 Hz) next generation 2-10Hz
strings with selected wave parameters.

13. *Is it possible to transfer the output data (for example with GSM/Satel transmitters (9600 Bps)) without interruption of the measurements?*

Yes

14. *Does the wave measurement instrument(s) measure continuously (3600sec/h and 24h/day)?*

Yes

15. *How much output data does the wave measurement instrument(s) produce in one day (MB)?*

Depends the requested output.
Raw data (4 Hz) 345600 samples =ca 1MB
Parameters (10 parameters each 10 minutes)=1440 parameters= ca 10kB

16. *How much output data can be stored by the wave measurement instrument(s) (MB)?*

Up to 1GB

17. *Please specify any critical assumptions and conversions to evaluate the waves from raw signal which may effect the accuracy of the end results?*

When it comes to very short waves (compared to the footprint of the radar). Generally >1Hz. The position of the reflecting parts in the footprint of the radarbeam become of influence and therefore the shape of the waves.

18. *What is the accuracy of the wave measurement instrument(s) (wave periods (e.g Tp,Tm01) and wave heights),please specify ?*

These numbers are very difficult to give. But comparison studies show that the differences with the waveriders remains within the statistical variability of the parameter compared.

19. *Can the wave measurement instrument(s) accurately measure at a sample frequency of 4 Hz? If not is it possible to adjust the instrument(s) to such a frequency?*

yes

20. *What are the resolution and range (cm) of the wave measurement instrument(s) and do they fit into the requirements of a resolution (raw signal) which does not exceed 5 cm and a range (Hm0) of 5-200 cm?*

The resolution is 1cm and the range 1-75meters

21. <u>What is the wave frequency range of the wave measurement instrument(s)?</u>

From DC to ca. 1Hz. Around 1Hz the mounting height of the radar and hence the size of the footprint causes a low pass filter effect. At a mounting height of 5m the footprint size is less than 1 meter.

22. How robust is/are the wave measurement instrument(s) (like how large is the risk that the instrument(s) or its electronics fails or becomes unreliable during a storm)?

There is no risk for mechanical damage. The instrument is protected against lightning damage.

23. Can any measuring or processing errors be expected during asymmetric or breaking waves? If so, how large are those errors, and what type?

This is very difficult to say. From comparison studies at open sea we can say that the agreement with the Datawell buoys is very good. We don't have yet enough experience in shallow water .

24. Is it possible to check the performance and accuracy of the wave measurement instrument(s) in the field without removing it, and if so how?

It is possible to service the radar remotely by radio or GSM. So by that way the instrument performance can be checked eg signal strength, shape of the reflection etc.

25. How large is the expected drift in the calibration after a given period of time, and after how much time would a re-calibration be needed?

The instrument has a very good zero point stability and has a custody approval so recalibration is never needed.

26. What approach would you suggest to obtain mean water level data and wind data in order to interpret the wave data obtained with your instrument(s)?

Waterlevel is measured by the WaveGuides as well. For wind information we are no experts.

27. After how many days should the wave measurement instrument(s) be cleaned in order to function properly and keep measuring accurately?

No maintenance is needed. Maybe due to spray the antenna surface need to be cleaned once a year. But that can be checked by remote service.

29. Are there any reference customers we could approach for an user interview?

RIKZ
Franzius Institut fur wasserbau und Kusteningenieurwesen in Hannover
Other organizations are using the WaveGuides in deep water for large waves.

30. *Is there any other relevant information about the wave measurement instrument(s) we need to know for finding the best wave measurement instrument(s) for measurements at the IJsselmeer and Slotermeer?*

We are able to collect all the very raw data (10 times per second all the 1024 samples of the 25ms during measurement). We have had some measuring campaigns where we stored all these data.

- December 2003 we evaluated the WaveGuide together with RIKZ in the wave basin of Delft Hydraulics in Delft. Comparison to a resistance wire.
- November 2003-Januari 2004 Three systems at Meetpost Noordwijk. Comparison with two directional waveriders.
- winter 2004 we will measure in the large wavetank of Delft Hydraulics in the Noordoost Polder.
- At the pier van Scheveningen a test site is being set up for long term tests.

All these data give excellent opportunities to evaluate and tune the systems to the high frequency needs for the Ijselmeer and Slotermeer.

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Questionnaire with regard to wave measurement instruments

All the questions listed below refer to the wave measurement instruments which are suitable for measurements at the IJsselmeer and Slotermeer (see accompanying letter). So if your company sells more then one wave measurement instrument suitable for these measurements please answer all the questions for each wave measurement instrument.

1. *Company specifications:*

Company name:	Aqua Vision BV
Address:	Servaasbolwerk 11 3512 NK Utrecht
Phone:	030 2459872
E-mail:	info@aquavision.nl
Filled in by:	J. Aardoom

2. *Which wave measurement instrument(s) does your company sell?*

Workhorse Waves Array - Directional Wave Gauging and Current Profiling ADCP

3. *Give a short description of the functions of the(se) wave measurement instrument(s)?*

Directional wave spectra and statistics,
Non-Directional Wave spectra and statistics from three independent methods for added quality assurance.
Current profiles,
Water level,
Additional: temperature, heading pitch&roll.

4. *What is the brand(s) of the(se) wave measurement instrument(s) (if your company sells more than three different brands of one instrument, then please list only the three most suitable for wave measurements on the IJsselmeer or Slotermeer (see accompanying letter)):*

RD Instruments

5. *The wave measurement instrument(s) consists of:*

THREE INDEPENDENT MEASUREMENTS OF HS with acoustic surface tracking, near surface velocity as well as pressure based measurements.
The Wave ADCP, possible external battery case or sentinal housing (housing with battery included) or cable for online communications. And (offcourse) PC for data handling.

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6. Which materials the wave measurement instrument(s) consist of?

Plastic – polyurethane tranducer faces, titanium bolts.

6. What are the physical specifications of the wave measurement instrument(s)?

See spec sheet.

7. What is the energy use of the wave measurement instrument(s)?

One Internal alkaline battery pack (450Wh) will be sufficient for 1 month duration where a 20 minute wave burst was collected every hour. Screen dumps of the RDI planning software that calculate battery consumption are included in the document "WHY RD INSTRUMENTS WAVES ARRAY.doc"

8. How many days can the wave measurement instrument(s) measure non-stop with internal batteries and memory (so if autonomously)?

Depending on settings. SEE ANSWER TO QUESTION 8.

9. How sensitive is the wave measurement instrument(s) for damage of storm, ice, driftwood or vandalism?

The instrument is placed at the bottom. The mounting frame (bottom frame) en possible cables will be the key factor, not the instrument itself.

10. What is (are) the price(s) of the wave measurement instrument(s) (include the technical specifications)?

Prices are provided for quotations only.

11. Is the wave measurement instrument(s) available for trails/purchase in the short term?

Yes, RWS already has several.

12. What does the output data consist of (e.g date, wave height, wave direction, etc)?

Output data:
System Config settings (fixed Leader)
Date, HH:MM:SS:HH, Pressure, Compass, Temperature etc (variable leader)
Water velocity profile
Echo Intensity profile
Surface Track range

<u>Calculated data:</u>
Wave Height: Hs, Hmax, Hmean
Period: Tp, Tmean
Direction: Dp
Custom: Hsea, Hswell, Tsea, Tswell, Dsea, Dswell

13. <u>Is it possible to transfer the output data (for example with GSM/Satel transmitters (9600 Bps)) without interruption of the measurements?</u>

Yes. RAW ADCP Waves Array data can be transferred by a variety of telemetry options without interrupting the functionality of the ADCP. The ascii text and graphical output format data from RD Instruments PC based WavesMon software can be sent to a communications port or sent to a file on the PC hardrive.

14. <u>Does the wave measurement instrument(s) measure continuously (3600sec/h and 24h/day)?</u>

Intervals can be set by the user, so yes but not necessarily.

15. <u>How much output data does the wave measurement instrument(s) produce in one day (MB)?</u>

Depending on settings. A 1 month deployment of an ADCP waves array will produce ~96 MB of data if one 20 minute wave burst is sampled every hour.

16. <u>How much output data can be stored by the wave measurement instrument(s) (MB)?</u>

2 Gb.

17. <u>Please specify any critical assumptions and conversions to evaluate the waves from raw signal which may effect the accuracy of the end results?</u>

RDI's surface tracking capability for Non-Directional wave measurements is a direct measurement of surface displacement. Any acoustic surface tracking measurements may be effected by the presence of bubbles in the water column.
RDI's near surface velocity measurement for Non-Direction and Directional array measurements relies on a linear wave theory "conversion" or transformation. This measurement is un-effected by the presence of very near surface bubbles.

18. <u>What is the accuracy of the wave measurement instrument(s) (wave periods (e.g Tp,Tm01) and wave heights),please specify ?</u>

The resolution of the wave period measurement is defined by the frequency bandwidth. For default settings, this value is 1/128 hz. The accuracy of the wave height measurement is ~8 cm for a 1200kHz ADCP and ~16 cm for a 600kHz ADCP. With a custom setting that sacrifices the directional spectral measurement capability of the waves array (which I believe your application is allowed), an range to surface measurement accuracy of 2 cm with a 1200kHz and 4 cm with a 600khz is possible.

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19. Can the wave measurement instrument(s) accurately measure at a sample frequency of 4 Hz? If not is it possible to adjust the instrument(s) to such a frequency?

If the user optimizes the measurement for surface tracking only, sacrificing the redundant velocity spectra measurement and directional spectra capability, a sample rate of 4 hz are possible.

20. What are the resolution and range (cm) of the wave measurement instrument(s) and do they fit into the requirements of a resolution (raw signal) which does not exceed 5 cm and a range (Hm0) of 5-200 cm?

I do not understand this question..... The resolution of the HS measurement is in milimeters. The range is from 1 mm to ~30 meters (note measurement of 30 meter wave height requires that the ADCP be deployed in water depth that is >30 meters).

21. What is the wave frequency range of the wave measurement instrument(s)?

Wave periods may be resolved from 1.5 to 30 seconds with a 2048 ping burst at a 2 Hz rate. Longer periods may be resolved with longer duration sampling.

22. How robust is/are the wave measurement instrument(s) (like how large is the risk that the instrument(s) or its electronics fails or becomes unreliable during a storm)?

Very.

23. Can any measuring or processing errors be expected during asymmetric or breaking waves? If so, how large are those errors, and what type?

RDI surface tracking capability directly measures non-linear asymmetric waves. Breaking waves may compromise the capability of the surface tracking. During breaking wave conditions, the ADCP velocity array may not be compromised.

24. Is it possible to check the performance and accuracy of the wave measurement instrument(s) in the field without removing it, and if so how?

Yes. By performing reference measurements, as long as the acoustic beams are uninterfered/unblocked.

25. How large is the expected drift in the calibration after a given period of time, and after how much time would a re-calibration be needed?

None. ADCP velocity measurements never require calibration.

26. What approach would you suggest to obtain mean water level data and wind data in order to interpret the wave data obtained with your instrument(s)?

The water level is measured by the instrument itself.

27. <u>After how many days should the wave measurement instrument(s) be cleaned in order to function properly and keep measuring accurately?</u>

For example: at the measurement poles in NorthSea we service once a year but the ADCP performance is not affected by biofouling. Eventually, barnacle growth will bore into the transducer face and compromise the water tight integrity of the ADCP. What kind of biofouling is there to be expected?

29. <u>Are there any reference customers we could approach for an user interview?</u>

M. Bottema already has contacted HI.

30. <u>Is there any other relevant information about the wave measurement instrument(s) we need to know for finding the best wave measurement instrument(s) for measurements at the IJsselmeer and Slotermeer?</u>

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