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Wave buoy and translator motions - on-site measurements and simulations

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Abstract—For a complete understanding of a wave energy conversion device, it is important to know how the proposed device moves in the water, how this motion can be measured, and to what extent the motion can be predicted or simulated. The magnitude and character of the motion has impacts on engineering issues and optimization of control parameters, as well as the theoretical understanding of the system. This paper presents real sea measurements of buoy motion and translator motion for a wave energy system using a linear generator. Buoy motion has been measured using two different systems: a land-based optical system and a buoy based accelerometer system. The data has been compared to simulations from a Simulink model for the entire system. The two real sea measurements of buoy motion have been found to correlate well in the vertical direction, where the measured range of motion and the standard deviation of the position distributions differed with 3 and 4 cm respectively. The difference in the horizontal direction is more substantial. The main reason for this is that the buoy rotation about its axis of symmetry was not measured. However, used together the two systems give a good understanding of buoy motion. In a first comparison, the simulations show good agreement with the measured motion for both translator and buoy.

I. INTRODUCTION

For the past decade, the Division for Electricity at Uppsala University has been working on a wave energy system, consisting of a linear generator at the sea bed and a point absorbing buoy at the surface. The Uppsala project is one of many past and present wave energy projects around the world, with very differing technical approaches. A few of these other projects and technologies are described in [1]–[6].

A common interest in all projects is to gain knowledge about how the proposed device behaves in the water. In this paper distributions of experimental data from the Lysekil Research Site are compared to results from simulations using a Simulink model of the system. Measurements have been made of surface elevation, buoy motion and translator motion. Simulations have been made of buoy motion and translator motion.

The purpose of the work is to i) make comparisons of different systems for measuring buoy motion, ii) compare the measured motions of buoy and translator, and qualitatively describe their relation, iii) make a primary evaluation of the accuracy of the model.

In the following section, the background of the Lysekil project is presented. The research site is also described. Section III deals with the theoretical model used, and the assumptions made. The experimental setup and the details of the measurements are then presented in section IV. Finally, in sections V and VI the measured data and achieved results are put forward and discussed.

II. BACKGROUND

The experimental work presented in this paper was performed at the Lysekil Research Site (LRS), off the Swedish west coast. LRS is located about 10 km south-southwest of the town of Lysekil and was established in 2004. The site has a water depth of about 25 meters and a flat sandy bottom. It is connected electrically to the small island of Gullholmen through a 3 km long sea cable. More details on LRS can be found in [7].

Four different complete wave energy converters, named *L1*, *L2*, *L3*, and *L9*, and around 30 “biology buoys” for environmental studies [8]–[10] have been in use for different periods at the site since 2006. The data in this paper comes from measurements on *L3* during the spring of 2009. Fig. 1 shows a photo of *L3* before deployment, and a sketch of the principal layout of the generator. As a wave passes, the buoy is lifted, and this motion is transferred to the translator in the generator. Several rows of magnets are mounted on the translator, and the relative motion between these and the stator induces a voltage in the stator windings. There are springs in the bottom of *L3*, to pull down the translator when the buoy is in a wave trough. There are also end stop springs at the top and bottom to prevent the translator from slamming into the ceiling and floor of the generator. The free stroke for the translator is ± 89.5 cm. It can then move an additional 23 cm at the top or 19 cm at the bottom while compressing the end stop springs, making the full possible stroke length 221 cm. The casing is kept water-tight using a top-mounted mechanical lead-through device. In Table I, details on weights and sizes for parts of *L3* are found. In the appendix, a detailed to-scale drawing is presented, with the relevant positions and sizes indicated.

Table I
FEATURES OF *L3*

Buoy diameter	4.00 m
Buoy height	0.69 m
Buoy mass	2500 kg
Translator mass	1200 kg
Free stroke length	± 0.895 m
Max stroke length	2.21 m
Nominal power	10 kW

Several papers have been published on the Lysekil project, e.g. regarding energy potential [11], force measurements [12], power absorption [13]–[15], farm layout [16], and electrical control [17], [18].

Several experiments with measurements of buoy motions in tank environments have been made by other teams around

Figure 1. L3 before deployment (left), and a principal sketch of the generator layout (right).

the world, see for example [19]–[22]. Descriptions of measurements on buoy systems made during ocean trials are more rare. A few examples of wave power experiments where buoy motion or acceleration was measured can be found in [23]–[25]. Acceleration of a wave-driven pump was measured in [23]. In [24] buoy motion along a spar was measured using a potentiometer coupling, and acceleration was measured using an inductive type transducer. In [25] six degree of freedom measurements of buoy motion were performed using a triaxial magnetometer, accelerometer, and gyroscope. Two magnetostrictive linear position sensors were also used to measure relative motion between the buoy and a spar. In all of the systems above, the power-take off was located at the surface.

III. SIMULATIONS

The model is developed in Simulink based on the basic equations of the force balance. The model is built in a modular fashion with five main subsystems:

- Buoy subsystem
- Generator Subsystem
- Electric subsystem
- Measurement subsystem
- Reaction force subsystem

The Buoy subsystem is designed based on potential linear wave theory. The impulse response of the buoy is obtained using the program ‘WAMIT’. The Buoy subsystem takes the wave amplitude from the Waverider wave measurement buoy at LRS as the input and computes the excitation and hydrodynamic reaction force components [14]. These are used to simulate the buoy dynamics of the coupled system. The factor of ‘added mass’ is taken into account. Only heave motion is considered.

The Generator subsystem uses a model with the mass, spring and the damping parameters of the generator [26]. The line between the buoy and the generator is simulated as a very stiff spring. The generator electrical parameters obtained

from the finite element analysis [27] are used to simulate the electrical behavior of the generator. The effect of the translator moving partially out of the stator is also included, in the form of a look up table. The magnetic losses are neglected based on the assumption that the operating frequencies in the generator are low [28]. The copper loss is included. The frictional losses in the moving elements of the translator are modeled as a constant parameter. More measurements need to be done in this area to quantify these frictional losses as functions of velocity.

The electric subsystem models the winding impedances, the transmission cable, the diode rectifier and the load. The relevant values from the actual site installation are incorporated into the model. The windings and the cable are modeled in lumped parameters. The power electronic devices are modeled using the generic device models available in Simulink with limited parametric changes made to suit the actual installation.

The measurement subsystem provides the measurement of the required parameters like the displacements, velocities, electrical parameters like the voltage, currents and calculated parameters like the real and reactive power.

The reaction force subsystem calculates the reaction force applied on the translator movement by the currents flowing in the generator coils. This force is fed back to the translator subsystem. This factor allows a more realistic simulation possible under different sea states and loading conditions.

IV. EXPERIMENTAL SETUP

All measurements were made at LRS on May 27, 2009. Translator motion and buoy motion (through accelerometers and images) was measured on L3 from 15:38:07 to 15:40:16 Central European Summer Time. The surface elevation was measured from 15:38:00 to 15:40:30. At the time of measurements, there were three complete WECs at the site: L1, L2, and L3. An offshore underwater substation was also deployed, connecting L2 and L3 to land [29]. The measurements of translator motion, buoy motion and wave motion are described below. Apart from this the following measurements were made on L3: temperature on the stator and inside the generator [30], pressure and humidity inside the generator, and the magnetic flux on eight of the stator teeth. There were also sensors to indicate water leakage, and subsequent possible water levels inside the casing. The measurement signals were amplified inside the generator and transmitted to the substation where they were sampled at 256 Hz and digitally transmitted to the measurement station onshore. Output voltages and currents from L3 were measured in the substation and transmitted to shore.

During the experiment, L3 was connected via the substation to a 2.5Ω DC load on shore. The setup was the same as is described in [17], and means that the damping is very high.

The three different measurement systems on L3 (inside generator, in the buoy, and camera system) are not synchronized, and may have a temporal difference of a few seconds. Time series data can therefore only be approximately compared. The choice in this paper was instead to compare distributions.

A. Translator motion

The position of the translator was measured with a standard draw-wire sensor from Micro Epsilon (WDS-3000-P115-SA-P-E). The analog output from the sensor was signal-conditioned inside the generator and sent through a 70 m twisted pair cable to the substation where it was measured with a CompactRIO system from National Instruments [31]. The digitized data was then transferred 3 km with a point to point copper link from the substation to the measuring station, where it was stored on a hard disk drive. Calibration of the wire sensor was made in the lab by measuring the position of the translator and the corresponding output voltage in two different positions. The overall accuracy of the draw-wire sensor system is ± 17.7 mm plus an additional 5.18 % of the measured deviation from -0.55 m.

B. Buoy measurements

The buoy is equipped with a detached measurement system. Since the buoy is moving relative to the ocean floor, it is difficult to make a cable connection to the substation or any other structure placed on the ocean floor. Instead the buoy is equipped with a 16 Hz 16 bit data logging system that sends the data through the GSM network. There are three types of measurements done on the buoy: force, acceleration and pitch/roll velocity. Directly beneath the buoy the line force is measured with a force transducer from HBM (U2B 200 kN) placed between the buoy and the line. The acceleration of the buoy is measured in three directions using accelerometers (Analog Devices ADXL202). The pitch and roll velocity is measured with a yaw rate gyro (Analog Devices ADXRS614). The accelerometers and gyros are placed in the center of the buoy. Calibration of each of the accelerometers was made by measuring the impact of earth gravity when pointing the accelerometer straight up and straight down. The specifications from the manufacturer were used to calculate the yaw rate from the yaw rate sensor voltage output. In Fig. 2, the buoy coordinate system is illustrated.

Figure 2. Buoy coordinate system

The output from the accelerometers does not purely reflect the movement of the buoy in surge, sway and heave. The measurements are also affected by pitch and roll of the buoy. The effect is a sine function of the angle towards the vertical and is large when the sensor is parallel to the earth surface, but almost negligible when the sensor is oriented vertically. Because of the accelerometer characteristics, the output for motions in the horizontal plane is more affected than the output

for vertical motion. Therefore the buoy pitch and roll angles must be measured to calculate the surge and sway of the buoy. This is the reason for installing the yaw rate sensor. When the buoy angle is known the impact of the gravity on the accelerometers can be balanced out. 99.6 % of the measured angles were within $\pm 10^\circ$.

The yaw rate as well as the accelerometer data must be integrated to get the angle and the position. Because of the integration drifting errors are introduced. The errors means that the data will have an offset. The offset was removed using a sliding mean filter and then subtracting the mean. The window for the sliding mean was set to 21 seconds, corresponding to three wave periods.

C. Optical measurements

The optical measurement system is located on Klamerskär, an islet south of LRS. The station consists of a controllable network camera, mounted in a lattice tower at 14 m height. The distance between the tower and L3 is approximately 250 m, and the bearing from the camera to the buoy is approximately 22° . The camera system is powered through two solar cell panels and a set of batteries. Images from the camera were downloaded through the 3G-network. The temporal resolution is one image per second. Additional details on the system can be found in [32].

To obtain buoy motion from image data, a cylindrical model was fitted to images of the buoy. The resulting position of the cylinder virtual center of mass (x_0, y_0) was taken as the position of the center of mass for the buoy, and the buoy angle relative to the x -axis δ was extracted. δ is in the range $[-7.7^\circ, 10.0^\circ]$ for the measurement period. Fig. 3 shows an illustration of the coordinate extraction. Using this method means that motions to/from the camera are neglected. These motions are assumed to be small in relation to the motions in the x and y directions. The motivation for this is that the principal wave direction is from the west, which is approximately 22° from the x -axis. An estimation of the introduced error due to this simplification is found below, and is further discussed in section VI. In Fig. 4, the relation between the image coordinate system (xyz) and the buoy coordinate system ($x'y'z'$) is illustrated. The angle α , which describes the difference between the two systems, depends on the horizontal distance d between the camera (point A) and the buoy (point B), as well as the height h of the camera. In this case, $d \approx 250$ m and $h \approx 14$ m, which means that $\alpha \approx 3.2^\circ$. Because of this angular difference, motions in the y' -direction will be projected as smaller than they actually are in the y -direction. For instance, a line at $y' = a, z' = 0$ will be projected at $y = \cos \alpha \cdot a$ in the image plane. This error will be small since α is small and $\cos \alpha = 0.998 \approx 1$.

A larger measurement error will occur if the buoy position changes in the z' -direction, in the range of a few meters. For a theoretical situation where the buoy has moved one meter in the z' -direction, but is still centered in the x' - and y' -directions, the resulting projected vertical position in the image plane is $y = -1 \cdot \sin \alpha \approx 6$ cm (see the appendix for an illustration). From studying camera sequences, the buoy

motion in the z' -direction has been estimated to be less than ± 2 m at all times. This introduces an uncertainty in the vertical coordinate of less than ± 12 cm. The effect of this uncertainty is discussed in section VI.

At high sea states, it is also common with high winds at the site. At the time of measurements, the wind speed measured in the area was approximately 12 m/s. The camera will then experience vibrations, and this will add an error in the images. To quantify this error, the camera was pointed at a stationary object at the horizon, and the image vibrations were measured over one minute. The difference between the maximum and the minimum value in the x -direction was six pixels, and in the y -direction thirteen pixels. When centering the distribution around the average value the standard deviation in the x -direction was 1.2 pixels and in the y -direction 2.9 pixels. This corresponds to 2.9 cm and 6.9 cm. These values have been added as error bars in Fig. 5.

Figure 3. Extraction of buoy coordinates from images.

Figure 4. Coordinate relations. The dashed rectangle represents the image plane and the solid rectangle represents a vertical cross section. The camera is at point A and the buoy at point B.

D. Wave measurements

The waves at LRS are measured by a non-directional Datawell Waverider buoy. The buoy measures the vertical surface displacement and sends the information through radio link to the Sven Lovén Centre for Marine Studies in Fiskebäckskil. The measurement frequency is 2.56 Hz. Spectral analysis is carried out on shore. The overall accuracy of the buoy is 3.5% of the measured value [33]. Between 15:30 and 16:00 the significant wave height was measured to 2.5 m.

V. RESULTS

Since the measurements systems are not synchronized, comparisons of time series have not been made. Instead, distributions of measured values over the period are presented, along with statistical parameters for the distributions.

In Fig. 5, the position of the buoy over the measurement period as gathered from the images is plotted. There are two sorts of data points. For positions where the buoy has been clearly visible in the images, there are small error bars. The error bars represent one standard deviation due to vibration errors in the camera. There are also data points with larger error bars. These points are from images where the buoy was partly concealed by waves. This leads to an increased uncertainty in the buoy's position. The error was estimated to a maximum of ± 6 pixels (corresponding to approximately 14 cm) in both directions. The uncertainty due to motions to/from the camera has not been added as an error bar, but is discussed in section VI.

Figure 5. Buoy position measurements from images, centered around the mean. The short error bars correspond to vibrations in the camera. The longer error bars correspond to uncertainties in buoy position due to wave shielding.

In Fig. 6, the sideways motion of the buoy in the buoy's reference system as gathered from the accelerometers is plotted. The path of the buoy from point a to point e takes 9 seconds. Using the associated accelerometer data for vertical motion (not plotted), it can be seen that the buoy goes from a wave trough at a to a wave top at b . From b to c it then descends 0.5 m and remains in the same vertical position between c and d . From d it moves again to a wave top at e .

If Figs. 7 and 8, histograms of vertical buoy and translator position are plotted. In Fig. 7, histograms of measured buoy position are given for the two different measurement methods, as well as for simulations. Finally, the values for the Waverider buoy is given, as a comparison. The zero level represents the mean position for the four histograms. This is not necessarily the same as the equilibrium position in calm weather. In Fig. 8, measured and simulated distributions for translator position are given. For translator positions, zero corresponds to the translator being centered in the stator. The histograms are based on different amount of data points, due to the different measurement frequencies. The histograms for vertical buoy

Figure 6. Horizontal buoy motion in the buoy coordinate system, as measured by the accelerometers.

position are based on 2080/130 data points for accelerometers/images, the Waverider histogram is based on 385 data points, and the translator histogram is based on 33280 data points.

In Fig. 9, the calculated distance from the top of the generator to the buoy due to both horizontal and vertical motion is displayed. The data in Fig. 5 has been used to find this distribution, which is based on a vertical distance of 15.7 m between the generator top and the buoy in its centered position.

Table II displays some statistical parameters for the distributions in Figs. 7 to 9.

VI. DISCUSSION

The range of measured sideways motion of the buoy in Figs. 5 and 6 differ by almost a factor two. The accelerometer data seem to overestimate this motion, and does not show a concentration along a line that could be interpreted as the dominating wave direction. Three major matters contribute to these errors. One: the buoy rotates about its axis of symmetry, and so does the sensors fixed inside the buoy. Two: gravity has impact on the accelerometer measurements. Three: the size of the window for calculating the sliding mean after the integration affects the result.

The buoy rotation about its axis of symmetry is not measured inside the buoy. The reason for this is that the rotation was anticipated to be too slow to detect with a yaw rate gyro at the time of designing the measurement system. Studying the images, it can be seen that the magnitude of the rotation about the axis of symmetry is some $\pm 30^\circ$, and that the maximum rotational speed is approximately $3^\circ/\text{s}$. Since the accelerometers are fixed in the buoy, the accelerometer output will of course also display a motion where the direction changes. But this is not the only way rotation about the axis of symmetry affects the measurements. The rotation also influences the calculated speed of the buoy from accelerometer data, and the calculated pitch/roll angle from the measured yaw rate sensors. This effect can be illustrated with a simplified example: suppose that two accelerometers are mounted at a

right angle in the horizontal plane, and that accelerometer 1 is aligned with the east direction. If the buoy moves east, this motion will be picked up by accelerometer 1. But if the buoy turns 90 degrees as it comes to a stop and returns to the west, this motion will instead be picked up by accelerometer 2. Since the velocity in each direction is integrated from the acceleration, both accelerometer 1 and 2 will show faulty speeds after integration. This might be the case between point *c* and *d* in Fig. 6, where data shows that the buoy moves sideways but not in the vertical. It is likely that the measured acceleration in one direction is not compensated when the buoy changes direction, because of buoy rotation.

The yaw rate sensors were installed to compensate for the impact of gravity on the accelerometers due to the buoy tilt. However, when analyzing the results from the sensors inside the buoy, the compensated accelerometer data did not show a better correlation with the optical measurements than the uncompensated data. One reason for this is that the absolute pitch/roll angle is not known precisely due to the drifting errors. The compensation signal for the horizontal accelerometers is highly affected by this angle. Another reason is the buoy rotation disturbs the yaw rate sensors in the same way as the accelerometers described above.

The size of the window for the sliding mean is very important when analyzing the accelerometer data. If the measured acceleration has been disturbed, either by a distorted signal from the sensor or from noise picked up from the GSM transmitter, the integrated error will remain throughout the width of the sliding window. If the sliding window is too short real measurements are filtered away, and the measurement will only display small movements around zero.

Turning to Fig. 7, the histograms of vertical buoy motion exhibit a lot of similarities. The range of motion is approximately 2.2 m for measured buoy motion and about 5 % higher (2.3 m) for the simulated motion. The accelerometer and the image histogram are similar in their shape. Both histograms have a sharper left side increase, a less pronounced right side decrease, and a maximum that is below the mean. Both have also positive skewness values (see table II). The accelerometer histogram is somewhat smoother, which is an effect of the higher sampling frequency.

The standard deviations for the measured positions matches well with the simulated distribution - the three σ values are within 5 cm, although the shape of the histograms is somewhat different. The simulated histogram is more similar in shape to the Waverider histogram, which is expected since it takes the Waverider data as input. The changes in standard deviation (a decrease of 0.06 m) and histogram shape between the Waverider motion and simulated buoy motion are effects of adding damping and constraints to a free buoy motion.

In Fig. 8 it can be seen that the simulated and measured translator histogram are similar in shape, but that the measured data is somewhat more centered, and has a lower standard deviation. An exact match would not be expected, since the simulated and the actual translator has experienced different, but similar, waves. The lower end shows an example of this: in the simulations the translator does hit the bottom, but in the measurements it does not. Possibly a few of the incoming

Figure 7. Distributions of buoy position, centered around the mean value.

Table II
STATISTICAL PARAMETERS FOR THE DISTRIBUTIONS

	Max (m)	Min (m)	Range (m)	Mean (m)	Median (m)	Std. dev. (m)	Skewness
Buoy vertical motion (accelerometer)	1.01	-1.21	2.22	0	-0.02	0.43	0.19
Buoy vertical motion (image data)	1.20	-0.99	2.19	0	-0.08	0.47	0.35
Buoy vertical motion (simulated)	1.10	-1.20	2.30	0	0.03	0.48	-0.28
Waverider motion	1.39	-1.49	2.88	0	0.06	0.54	-0.26
Translator motion (measured)	1.02	-0.82	1.84	0.08	0.05	0.40	0.21
Translator motion (simulated)	1.13	-1.08	2.21	0.05	0.08	0.47	-0.20
Buoy - generator distance (measured)	1.24	-0.96	2.20	0	-0.09	0.47	0.43

waves for the Waverider, which the simulations are based on, had a lower trough than the waves reaching L3.

Comparing the measured translator position in Fig. 8 to the measured buoy positions in Fig. 7, it can be seen that the range of motion for the translator (1.84 m) is approximately 17 % smaller than the range of motion for the buoy (accelerometers: 2.22 m, images: 2.19 m). This difference would be smaller if the allowed stroke length of the translator was larger. It can be seen in the sharp decrease on the right side of the measured translator histogram that the motion is constrained by the end stop.

In Fig. 9 the distance from the top of the generator to the position of the buoy, as calculated from the image data in Fig. 5, is displayed. It can be seen that this distribution is similar to the pure vertical distribution. The reason for this is that the distance from the surface to the generator

(approximately 16 m) is much larger than the magnitude of the sideways motion. This implies that the sideways motion, although it is twice as large as the vertical motion, does not contribute much to the motion of the translator.

The x -axis of the images and the dominating wave direction are not quite aligned. The approximate angular difference between the two is 22° , and means that some of the surge motion of the buoy will be projected as motion to/from the camera. This in turn means that the projected position will be lower/higher than otherwise. The effect of this can be seen in Fig. 5, where left-hand values tend to be grouped somewhat lower, and right-hand values tend to be grouped somewhat higher. The effect was estimated to ± 0.12 m in section IV-C, and so does not account for the entire difference between the left-hand side and the right-hand side. The buoy motion is not symmetrical.

Figure 8. Distributions of translator position.

Figure 9. Distribution of the variation of the buoy-generator distance based on image data. The standard deviation σ is 0.47 m.

In comparing the two buoy measurement systems, a few remarks can be made from an engineering perspective. Both systems have flaws and strengths. The major limitations for the accelerometer system are the drifting errors, combined with the difficulties of determining the horizontal motion properly. The latter can be attended to by measuring rotation about the buoy axis of symmetry. It is recommended that the rotation is measured in relation to an external reference point (e.g. using a digital compass or by detecting a signal sent from a local fixed position). Drifting errors on the other hand is an inherent limitation in using accelerometers. However, using accelerometers can give a high temporal resolution, and accelerometers are cheap to install. The accelerometer measurements have been very valuable earlier in the project, since they have been used to verify measurements from other sensors (e.g. buoy force). The optical system gives an output which is easy to interpret, and it is not associated with drifting errors. The use of such a system means that there is a need for a fixed reference point for camera installation however, and the installation is costly and difficult in offshore environments. A monocamera system is much easier to install

than a dual camera system, which also demands that there are two suitable places with enough distance between them, but brings limitations in estimating motion to/from the camera. In the present work, the camera and accelerometer systems complement each other. For example, it would have been difficult to know whether a sliding mean window of 21 seconds gave reasonable results without the use of the complementing image data. Conversely, the data from the accelerometers is easier to gather for long time periods. If possible and economically feasible, a combination of different measurement systems is recommended.

VII. CONCLUSIONS AND FUTURE WORK

The two different systems for measuring buoy motion have been found to correlate well in finding the range of vertical motion. The range data from the camera system (2.22 m) differs by less than 2 % from the accelerometer data (2.19 m). For standard deviation, the images give a value that is 9 % higher than the one from the accelerometers. The absolute difference is only 4 cm, however. Used together, the two systems can give a very good description of the vertical buoy motion, where the accelerometer data has a high temporal resolution, and the image data can be visually interpreted. The correlation of vertical data from the two systems strengthens the conclusions that they are accurate, and leads to the conclusion that the accelerometer data in the present setup overestimates the sideways motion. The work has also given a lot of practical experience on the advantages and disadvantages of the measurement systems used. The handling of accelerometer data has proven to be more complex than anticipated, and there is future work to be done on correctly estimating sideways motion from buoy-based measurements.

The translator motion is smaller than the buoy motion, which is to be expected since the translator is bound by the end stops. The range of measured motion for the translator is slightly above 80 % of what was measured for the buoy (83 % for images, 84 % for accelerometers). The standard deviation of the translator is 85 %/93 % (image/accelerometer) of the standard deviation for the buoy motion. Though the sideways motion of the buoy is a factor two larger than the

vertical motion, the vertical component is clearly dominating in producing motion for the translator.

It is not possible to compare simulations and measurements of the same real wave, but for similar waves the simulations make good predictions of both buoy motion and translator motion. The standard deviation of the simulated buoy motion (48 cm) agree with the one measured by the camera (47 cm), and is 4 cm higher than measured by the accelerometers (43 cm). More work and future studies of synchronized time series are needed in order to evaluate the capacity of the model to predict temporal differences between motions of buoy and translator. Synchronization of the measurement systems could also mean that the optical system could be used to continuously remove drifting errors in the accelerometer signal, reducing the need for filtering afterwards.

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APPENDIX

Image error estimation

When the buoy is in position one, it is centered in the image plane. At position 2, the buoy has moved a distance c on the surface. It will now be projected at a point a' below the center in the image plane. Since the angle α is small, and since the displacement c is much smaller than the buoy-camera distance, the two lines b and b' are approximately parallel and the distances a and a' are approximately equal. From Fig. 10, it can be seen that $a = c \cdot \sin \alpha$. For $c = 1$ m and $\alpha = 3.2^\circ$, a' is then approximately $1 \cdot \sin 3.2^\circ = 5.6$ cm.

Camera position

Figure 10. Estimation of the error from neglecting motion to/from the camera.

Figure 11. Generator geometry for L3, to scale.