

**An Analysis of the Calibration Stability and Measurement Accuracy of an Underwater Stereo-
Video System Used for Shellfish Surveys**

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ABSTRACT

Assessment of changes in the population structure of fauna and flora is often used to detect and analyse the affect of changing environmental factors or other impacts upon the marine environment. A primary tool in the characterisation of population structure is the assessment of the distribution and size frequency of a large sample of individual specimens of highly indicative species such as fishes, corals and sponges. One species that is under increasing pressure from commercial and recreational harvesting in New Zealand is the Tuatua (*Paphies donacina*), a shellfish inhabiting shallow, near-shore waters.

In shallow water, the collection of data on the frequency and size of species within delimited areas (transects) is typically carried out using visual estimation by SCUBA divers. Beyond the depths accessible to divers this data is often collected by trawl or dredge samples with specimens being physically brought to the surface for classification, enumeration and measurement. Both of these survey techniques have clear disadvantages, such as inter-diver variability and habitat disturbance respectively. As an alternative, an underwater stereo-video system has been developed to make accurate measurements of marine flora and fauna. In common with any system used for accurate measurement, the design, calibration and use of the underwater stereo-video system is of paramount importance to realise the maximum possible accuracy and precision from the system. Further, the determination of the relative orientation of the two cameras is vital to the correct estimation of size. Also at issue is the stability of the calibrations and relative orientation of the cameras during and within deployments, as any variations will inevitably lead to systematic errors, and therefore inaccuracies in the measurements. This paper describes a series of experiments concerning the determination and testing of camera calibration, relative orientation and stability of the underwater stereo video system used for the morphometric measurements of Tuatua.

INTRODUCTION

Many marine scientists and biologists have experimented with conventional photography and video imagery as a non-destructive tool for sampling organisms. For example, stereo-photography has been used to measure the growth of coral (Done, 1981) and to estimate the size of free-swimming sharks (Klimley and Brown, 1983). These systems were viable underwater, convenient to use for measurement and could be developed or purchased at a reasonable cost. As a consequence, stereo-video cameras were quickly adopted for a wide range of applications in the marine environment (Boland and Lewbel, 1986; Hamner *et al.*, 1987; Vrana and Schwartz, 1989) and virtually unchanged systems continue to be used for novel applications (Brager and Chong, 1999). In recent times there have been rapid technological improvements in video cameras which has improved the utility and accuracy of such systems (Harvey and Shortis, 1996), adding to the other, often stated advantages of non contact measurement, predictable precision, motion sequence capture, digital image enhancement and archival storage. This technique can be potentially adapted for use by divers (Harvey *et al.*, 2000 a,b) or in conjunction with remotely operated vehicles and manned submersibles (Baldwin and Newton, 1982; Li *et al.*, 1996) to capture images at depths beyond those accessible by SCUBA divers.

The system described and tested in this paper was developed as an experimental sampling tool for determining the distribution, abundance and size frequency of a shellfish commonly called Tuatua (*Paphies donacina*), (Figure 1). The Tuatua is a bivalve primarily found in the shallow waters of beaches on the east coast of the South Island and west coast of the North Island of New Zealand. It is one of eight species of surf clam currently harvested commercially in New Zealand, although at restricted levels. Surf clams are expected to become part of the Quota Management System (Clark *et al.*, 1988) administered by the New Zealand Ministry of Fisheries in the near future. Once this occurs, increasing commercial pressure will be placed on these resources. Consequently, managers will require high precision estimates of the biomass and size frequency of the population to ensure the sustainable harvest and long term management of these shellfish stocks.

The widely used technique of dredge surveys is typically employed to provide this data. Dredge surveys have disadvantages in that they have variable sampling efficiencies and often result in high mortality rates for those shellfish sampled or remaining in the track of the dredge. Mortality rates as high as 62% have been reported for clams not collected by a bottom-sorting dredge (Haskin and Wagner, 1986), with increased numbers of predators being attracted to the sampled area to consume dead and dying shellfish (Meyer *et al.*, 1981).

Shellfish mortality usually occurs when viscera or other soft body parts are exposed due to shell damage resulting from contact with the dredge (Meyer 1981). Some contacts result in the foot of the clam being partially or totally severed (Michael *et al.*, 1990).

Therefore, any alternative, non-destructive technique resulting in minimal damage to the species and the habitat would be valuable (Ault *et al.*, 1997). Underwater stereo-video photogrammetry does offer an alternative solution that is both accurate and impersonal (Harvey and Shortis, 1996) and, to the authors' knowledge, has not been applied to similar species to ascertain size or mass. The Tuatua is a bivalve spending much of its time buried in the sand and, being a suspension feeder, it sucks in water providing food and oxygen via an inhalant siphon. Often both the inhalant and exhalant siphons are visible on the surface of the sand (see inset in Figure 1). It is possible that a strong relationship may exist between the diameter or the surface area of the inhalant siphon and the wet weight of an individual, facilitating the determination of biomass. With visible siphons ranging from approximately 5mm to 18mm in diameter, any photogrammetric system applied to this measurement problem needs to be extremely accurate and precise to ascertain a very fine level of detail.

The use of a stereo-video system introduces the issue of the stability of the calibrations and relative orientation of the cameras. Handling of the system could be expected to cause variations in the calibrations and relative orientation of the cameras. Small variations might be expected to result from routine use, whilst disassembly would result in larger changes. In an operational scenario, small changes in the camera calibration and relative orientation of the stereo-video system might be expected for a single dive where the cameras are being manipulated in the underwater environment. Larger changes would be likely to occur between dives, as the cameras are handled more and the waterproof housings must be opened to retrieve video tapes. Dramatic changes may occur if the cameras are refocused or the camera base bar or waterproof housings are disassembled for inspection or routine maintenance.

Harvey and Shortis (1998) investigated the calibration stability of an underwater stereo-video system with a 1.5 metre camera separation, used to survey the size frequency of populations of reef fish. It was found that within one deployment the calibration parameters remained stable but that the calibration parameters varied between deployments. This was probably due to the individual housings being opened, cameras being removed from the housing to facilitate the replacement of tapes and batteries. Additionally, it was found that the removal of the housings from the base bar probably also affects the stability of the relative orientation of the cameras and calibration parameters. As the stereo-video system used in this research is

in use for making small scale biological measurements, it uses a lesser camera separation of 25 cm. It is equally important here to estimate the variability in the accuracy and precision of any measurements caused by the routine disassembly, maintenance and transportation of the system. Therefore, it is also desirable to confirm the variability in the calibration parameters during one deployment, over a series of deployments where housings are being opened and cameras removed, or when the housings are removed from the base bar. Accordingly, this paper has four principal aims:

1. To determine the stability of the calibration parameters during single deployments when the stereo-video system remains intact.
2. To determine the stability of calibration parameters over a series of deployments where the housings are being opened and the cameras are taken out to change tapes or batteries between deployments.
3. To determine the stability of calibration parameters over a series of deployments in the case where the housings are being removed from the base bar, simulating the dismantling of the stereo-video system between deployments.
4. To determine the accuracy and precision of measurements made with this stereo-video system and the affects that the disassembly of components of the stereo-video system has on the accuracy and precision of measurements.

System description

The stereo-video system used in this research comprises two Sony Hi8 video camcorders mounted in water proof housings and attached to a base bar which separates the cameras by 25 cm (Figure 2). The CCD arrays used in the video cameras are 1/3" format, colour sensors with an actual resolution of 795 by 596 pixels and a sensor element spacing of 6.3 microns. The minimum focal length of the camcorders in air is approximately 3.75 mm, corresponding to 5.5 mm in water. As the image format is approximately 5mm by 3.8mm, the maximum diagonal field of view is of the order of 60° which results in a rectangular field of view of 12 cm by 8 cm at the working distance of 40-50 cm.

Each camera is inwardly converged at 8.5° to gain a field of view that has virtually 100% overlap at 50 cm distance (Figure 3). Like the base separation, these design issues are adopted as a compromise between competing considerations (Harvey and Shortis, 1996). For example, shorter focal lengths increase the field of view, but decrease the measurement precision. Similarly, a more acute convergence would improve the measurement precision, but will decrease the useable field of view and increase the apparent perspective distortion. Assuming an image measurement precision of one half of a pixel, the predicted object space

precision of the system in the working range is approximately 0.6 mm and 1.5 mm in position (the plane parallel to the mean image plane) and depth (the direction perpendicular to the camera base) respectively at a 95% confidence level.

The system also has a calibration check plate located 30 cm in front of the stereo-video cameras. The check plate is a flat, rectangular aluminium plate 50 by 10 mm in size in the horizontal and vertical dimensions respectively (Figure 4). The plate is black with 11 evenly distributed white dots 2 mm in diameter, so designed to enable automatic calibration checking in the future. This calibration check plate can be seen in the bottom right hand corner of the upper left image and the bottom left hand corner of the upper right image shown in Figure 4.

The left and right cameras of the stereo-video system are synchronised visibly using a small light emitting diode (LED) on the check plate. As the camcorders are operated in a “free run” mode based on their own internal clocks, drift in the synchronisation can be expected. The LED is illuminated periodically by a button press from the operator to synchronise the cameras to within one frame, as well as indicate image sequences that are of interest for later analysis.

Calibration Strategy

Calibration of the system is necessary for two reasons. First, the interior orientation of the cameras must be defined to determine the internal geometric characteristics of the cameras, using physical parameters for principal distance, principal point location, radial and decentring lens distortions, plus affinity and orthogonality terms to compensate for bias in the spacing of the pixels on the CCD sensor and effects of the analog tape recording (Shortis *et al.*, 1993). Second, the relative orientation of the two cameras with respect to one another must be determined. The relative orientation effectively defines the separation of the perspective centres of the two lenses, the pointing angles of the two optical axes of the cameras and the roll rotations of the two CCD sensors.

The camera and relative orientation calibration is accomplished using a total of 40 images of a purpose built frame (Figures 4 and 5) and self-calibration. The frame is a 15 cm open cube constructed from light weight aluminium. It is black in colour and has 72 white, 1.3mm diameter circular targets attached to the surface. The targets provide high contrast, unambiguous points that allow a simultaneous, self-calibration of both cameras. The colour patches on the upper surface of the frame are present to allow the orientation of the frame to be easily recognised during the measurement phase in order to unambiguously identify the targets on the frame.

Video footage is captured during four rotations of the frame whilst held by a diver at various angles with respect to the mean camera axis direction. The first rotation set is made with the camera base in the “normal” horizontal position, and the following rotation sets with the camera base vertical and in other orientations to complete a 0°, 90°, 180° and 270° roll set. The frame is rotated in four positions with the orientation perpendicular to the mean camera axis direction (Figure 4), and then an additional four sets of four rotations with the frame held obliquely to the mean camera axis direction. The rotation of the frame is more efficient than the diver manoeuvring the cameras around the frame, and emulates a set convergent of camera stations surrounding the frame.

This procedure effectively captures a multi-station, convergent network of exposures suitable for a simultaneous self-calibration of the two cameras. The rotation of the camera base is necessary to de-couple external and internal parameters of the self-calibration, such as the principal point position and camera station locations. Note that accurate information for the positions of the targets on the frame is not required, as co-ordinates of the targets are derived as part of the self-calibration procedure. Hence it is immaterial if the frame distorts or is disassembled between calibrations, however the frame must retain its structural integrity during a calibration sequence.

From the video footage, the 20 synchronised pairs of frames are gathered and the locations of the target images measured. The self-calibrating bundle solution provides estimates and precisions of the camera calibration parameters and the locations and orientations of the cameras at each synchronised pair of exposures. The camera calibration model does not contain explicit terms for the refractive effects of the glass camera ports and the refractive interfaces, as analysis of the effects of the refractive surfaces in the optical path in an ideal camera housing shows that images are displaced radially from the principal point (Li *et al.*, 1996). Whilst the assumptions that the optical components of the housing are symmetric around the optical axis of the camera and refractive surfaces are in general perpendicular to the optical axis are unlikely to be perfectly fulfilled in practice, it is clear that the primary component of the refractive effect is radial. As a consequence, the approach that has been widely adopted has been to allow the refractive effects of the optical components and refractive interfaces to be absorbed by the conventional, physical camera calibration parameters. The principal component is implicitly taken up by the standard, odd-ordered polynomial model for radial distortion, whilst any residual effects from asymmetric components of the housing are partly, or wholly absorbed into other parameters of the camera calibration, such as decentring lens distortion or the affinity term. No assumptions need to be

made concerning the refractive indices of the air, glass or water media, and modelling of the optical components of the underwater housing is unnecessary. This approach has been used successfully by previous systems (Turner, 1992; Schewe *et al.*, 1996), whereas a rigorous approach to optical ray tracing requires a two phase calibration approach and assumed values for the refractive indices of the media (Li *et al.*, 1997). The refractive index of water is known to change with depth, temperature and salinity (Newton, 1989) and the shape of the camera housings and port may change with depth due to the changing pressure. A procedure that incorporates implicit calibration of the complete system under prevailing conditions and at a particular working range is likely to be more accurate and reliable.

Whilst the camera calibration data are used directly in the subsequent calculations, the location and orientation data must first be transformed. The data for the 20 pairs of synchronised exposures are initially in the frame of reference of the calibration frame. Each pair is transformed into a local frame of reference for the camera base. The local frame of reference is adopted as the centre of the base between the camera perspective centres, with the axes aligned with the base direction and the mean optical axis pointing direction. The final parameters for the relative orientation are computed as the average of the values for the 20 pairs. Whilst the computation of the relative orientation is currently a post-process after the bundle solution, a future development of the system will be the incorporation of a stereo-pair constraint solution such as that developed by King (1995).

EXPERIMENTAL DATA COLLECTION

Calibration Stability Testing

Three sets of calibrations of the stereo-video system were performed, each with a different protocol (Table 1).

1. *Continuous Calibrations* : Eleven calibrations were recorded in the Dunedin Harbour at the Portobello Marine Laboratory wharf on October 16, 1998 at a depth of 2 metres. All of the calibrations were made one after the other during a period of 24 minutes, with no changes being made to the stereo-video system. Each calibration required on average 2 minutes 6 seconds with visibility being estimated at approximately 4 metres.
2. *Camera Removal Calibrations* : Eleven calibrations were recorded in a saltwater aquarium at the Portobello Marine Laboratory on July 16, 1998 at a depth of 2 metres. Between each calibration the stereo-video system was removed from the water, each camera was turned off, the housing opened and the camera removed from the housing

before being reassembled. Each calibration required on average 1 minute 20 seconds with visibility being estimated at approximately 5 metres.

3. *Housing Removal Calibrations* : During July 30-31, 1998 ten calibrations were recorded in the saltwater aquarium at a depth of 2 metres. Between each calibration the stereo-video system was removed from the water, each camera was turned off and the housing removed from the base bar before being reassembled. Each calibration required on average 1 minute 30 seconds with visibility being estimated at approximately 4 metres.

All calibrations followed the procedure described in the previous section, and the working distance between the cameras and the calibration frame were consistent. In general, there were no substantial variations to the prevailing conditions for each of the calibration tests. The conclusion can therefore be reached is that comparisons of results will not be significantly influenced by external or environmental conditions.

The Effect of Calibration Stability on the Accuracy and Precision of Measurements

From each of the three sets of calibrations, a series of measurements were made from the first pair of images from any individual calibration. Measurements were made between points of a known location. Ten repeat measurements between three different pairs of points were made for each length from each calibration. The lengths derived from the video system were subsequently compared to the known lengths determined by direct measurement with a steel ruler. The measured lengths were recorded between identified targets on the control frame, corresponding approximately to the X, Y and Z co-ordinate axis directions (Figure 4) to verify the scale of measurements in orthogonal directions. The measurement in the X direction had the additional aim of replicating, as nearly as possible, a measurement across the diameter of a Tuatua funnel. Identical pairs of targets were recorded for all tests from stereopair images with the frame in the orientation shown in Figure 4.

Variability in the accuracy and precision of field measurements

In addition, measurements were made to the calibration check plate during open water dives for field testing of the system. Periodic measurement of the points on the check plate are made to detect any variation in measurement accuracy due to any potential calibration instability. Measurements were made horizontally across the top edge of the plate. Theoretically, if the calibrations are stable there should be little, if any, variation between lengths derived from image measurements from one stereo-pair taken from any particular deployment.

ANALYSIS OF DATA AND RESULTS

Analysis of the Stability of Calibration Parameters

For each of the sets of calibrations between 18 and 20 stereo-pairs were used in each of the photogrammetric network solutions. A very small percentage of images are regularly rejected from the solutions, based on an assessment of the residuals of the image measurements, probably due to video tape recording or media defects manifest by uncharacteristically large image residuals.

The post-processing to compute the relative orientation is based on all stereo-pairs in each network. Average values of the relative orientation parameters and estimates of their precision, in the form of standard deviations, can be computed from the 18 to 20 samples. On average 5-10% of the image pairs are rejected, an artefact which is most probably due to minor synchronisation errors between paired images. As previously noted, synchronisation errors of less than one frame, or 1/30 seconds, are possible. Both the frame and the camera system can be moving at the instant of exposure, so errors in the synchronisation result in relative orientations for the pair which are inconsistent with the other pairs making up the set.

Analysis of the results of the camera calibrations and relative orientation calibrations showed consistent results. In general, the camera calibrations produced an estimate of the image measurement precision of 1.1 to 1.4 micrometres for the target image centroids, which is approximately one fifth of the dimension of a pixel in the video images. Precisions from target measurements are typically less than 0.1 pixels for in-air calibrations recorded to video tape (Shortis *et al.*, 1993), and the poorer result in this work can be readily attributed to the influence of the dispersion effects of water and incompleteness of the refractive model. The results of the relative orientation computations were also reasonably consistent, after rejection of one or two stations of the twenty, in most cases.

An initial impression of the variation of all the calibration parameters can be obtained from the standard deviations of the average parameters from the individual continuous, camera removal and housing removal calibrations. Table 2 summarise these values, which can be used to determine a comparative variability between the continuous and camera, and continuous and housing calibrations. Selected parameters only are shown in the table. As radial and decentring distortion are modelled by multiple parameters, comparisons for these employ the magnitude of the distortions at a radius of 2 mm from the principal point, corresponding to the edge of the typical region used within the video image format.

The table demonstrates that there is greater overall variability of calibration parameters when

the cameras are removed from the underwater housings (“camera” calibration sets). Although the variability of the left rotations is less for the housing calibrations than for the continuous calibrations, in general the trend of more variability for the camera and housing calibrations is clear. The mean ratio of the standard deviations is 1.66 for the camera calibrations and 1.30 for the housing calibrations, which indicates that on average the camera and housing removal calibrations are more variable than the continuous calibrations. This shows that in general, as could be expected, handling and disassembling the stereo-video system leads to changes in calibration parameters.

A finer level of detail for the variability can be derived by comparisons of consecutive calibrations. No differences would be recorded for a perfectly stable system, whilst in a realistic system, the larger the magnitude of the difference, the greater the variability. However, raw differences are not sufficient for the comparison, as the variability of each of the average parameters from each network solution or relative orientation solution must also be considered. For example, due to the geometry of the relative orientation, omega rotations are derived more confidently than phi rotations. As a consequence, the same magnitude of variation for an omega and a phi rotation is much more significant for the omega rotation. Hence, significance values are computed using ratios of parameters differences to combined precisions of the parameters :

$$\text{Significance} = \frac{|\text{parameter}_n - \text{parameter}_{n-1}|}{\sqrt{\text{variance}_n + \text{variance}_{n-1}}}$$

where the variance is the square of the standard deviation. The value effectively gives a weighted, dimensionless estimator of the significance of the change in the parameter. These values can be statistically tested against a distribution such as the Student T. For a 95% confidence level and 15 degrees of freedom the critical value is 2.1, however comparative values are generally sufficient for the purpose of this investigation.

Significance values for the right camera calibration parameters and the relative orientation parameters for the continuous, camera and housing calibration sets are shown in Figures 6a and 6b. The calibration significance values for the left camera are similar to, or slightly less in magnitude and are therefore not shown. In general, the significance values are at or below the critical value of 2.1, indicating that the changes are barely significant. The exception to this is camera removal calibration sets, which do show some significant changes. Relative orientations are similar for all these calibration conditions and the change significance is typically well below the critical value. With the exception of some marginally significant values for the housing removal calibration sets, all relative orientation values indicate that the

base bar and housings are maintaining their rigidity.

A potential cause of variation in the camera calibration parameters may be the insertion of the camcorders into the waterproof housings. The mechanical attachment of the cameras inside the housings is the least reliable component in the mounting process, and changes in the relative positions of the cameras and the glass ports of the housings would lead to different refraction regimes. In turn this will lead to changes in calibration parameters and is the most likely explanation of the greater variability of the camera removal calibrations, as compared to the housing removal calibrations.

Analysis of the Accuracy and Precision of Stereo-video Measurement Data

The error of stereo-video measurements in the X, Y and Z dimensions of the control frame and check plate length measurements were calculated by subtracting the stereo-video estimate from the known distances between targets on the control frame and known length of the check plate. The mean error, standard error (SE) and coefficient of variation (CV) were then calculated. Standard error is defined here as the standard deviation (SD) of the mean, and coefficient of variation is defined as the ratio of the standard deviation of the estimate and the value of the estimate, expressed as a percentage.

Stereo-video estimates were derived from the stereopair comparator (see Figure 4) which computes locations using the camera calibration and relative orientation data provided from the system calibration, and a simple 3D spatial intersection based on image measurements (Harvey and Shortis, 1996). The comparator also provides a quality measure in the form of the root mean square (RMS) image error, which indicates the exactness of the intersection.

Analysis of variance (ANOVA) was used to determine whether differences existed between measurement errors recorded between dimensions and also between calibrations. Least significant differences were used to determine differences between individual dimensions and calibrations when ANOVA tests detected differences.

Effects of Calibration Variation on Measurement Accuracy and Precision

All measurements made from the three sets of calibrations (continuous, camera and housing) using the associated calibration data sets show good accuracy and precision (Table 3). The accuracy for the measurements made from images under continuous calibration conditions is close to 0.4mm (mean of measurement error taken in all dimensions). Figure 7 shows that higher than expected mean error is caused primarily through deviations of measurements in the Y dimension.

At a 95% confidence level and again assuming an image space precision of one half of one pixel for manual measurement of the images, the expected precisions of distances measured in the working range are approximately 0.9 mm and 2.1 mm in position and depth respectively. However, the levels of precision will be affected by the range at which they are measured. Measurements in the X, Y and Z dimensions were made at distances ranging between 32 and 52 cm from the cameras. Measurements in the Z dimension are always furthest away from the cameras followed by the Y and X dimensions. Therefore it would be expected that the X dimension would exhibit the best accuracy and precision, followed by measurements in the Y and Z dimensions, as the precision of measurements taken with the stereo-video system deteriorates with increasing distance.

This anticipated pattern is partly reflected in the mean error results. However the large anticipated error is not seen in the Z dimension, although the poorer precision is clearly evident. The coefficient of variation (Figure 8) does not follow the same pattern as the mean error, which is apparent in Figure 7. The shortest length measured was the X dimension and consequently any measurement error for this dimension will be relatively large in comparison to measurement errors in the other dimensions. This accounts for the coefficient of variation (Figure 8) being higher for this measurement.

A one-way analysis of variance (ANOVA) was used to test for differences in the measurement error recorded between the three dimensions for each of the three calibration trials (continuous, camera and housing; see Table 4). Significant differences and low correlations are shown between the dimension types for the measurement errors recorded during trials where the cameras were removed from the housings and where the housings were removed from the base bar. However, the measurement errors for the continuous calibrations were not significantly different between the three dimensions.

Differences between dimension types were determined for the three calibration trials (continuous, camera and housing) by calculating least significant differences. Table 5 shows that there were no differences in measurement error between the X and Y and X and Z dimensions, but that differences existed between Y and Z measurements for all calibration conditions (continuous, camera and housing).

One-way ANOVA tests for differences between the measurement errors recorded between calibrations for all dimensions were also carried out. Significant differences are apparent for the different calibration conditions for the X and Y dimensions while no significant difference was observed for the Z dimension (Table 6).

Differences between calibration conditions were determined for the X, Y and Z dimensions by calculating least significant differences (Table 7). There are significant differences at the 95% confidence level for the calibration treatments in the X and Y dimensions, but not in the Z dimension.

Variability in the accuracy and precision of field measurements

To provide a more rigorous understanding of the variation in the accuracy and precision of field measurements, 120 measurements of the horizontal dimension of the calibration check plate were made during four field deployments. The dates of deployment, duration and number of measurements made are listed in Table 8.

The accuracy and precision of the measurements (Table 8) made of the check plate during each of the dives was less than 0.5 mm on average. This level of error is less than the X and Y dimension measurements made during the calibrations, however the check plate is closer to the cameras and measurements should exhibit a slightly improved precision. However there were significant differences in the measurements between each dive (Tables 10 and 11). The mean measurement error for the length measurements during the four separate open water dives is shown in Table 9 and the individual measurements are shown in Figure 9. Mean measurement error for dives 1 and 2 is generally negative while for dives 3 and 4, mean measurement error is positive. The consistency of the results for the two groups of two dives is not surprising, as the two groups were on separate days and the housings were opened and the cameras removed between the two days.

DISCUSSION

The calibration strategy used for this research resulted in small variations within calibration and orientation parameters and small variations in measurement accuracy and precision within the duration of one deployment. The dismantling of the housings from the base bar, and removal of the cameras from the housings caused barely significant variations to some rotation parameters of the relative orientation, some significant variations to the camera calibration parameters and decreases in the accuracy and precision of measurements.

The system is designed to eliminate any minor variations in re-assembly. The cameras slide into a groove in the underwater housings and are locked in place within the housings, which are then bolted into position on the base bar. However, the results of the experiments where the cameras have been removed from the housings show a greater variation in camera calibration parameters than either of the calibration sets where all the calibrations were

undertaken in one deployment or where housings were removed between deployments. This pattern is also reflected in the accuracy and precision of measurements. Consequently there must still be some movement in the placing of the housings and, more importantly, of the cameras within the housings. Variations in the camera calibration parameters are most likely due to the insertion of the camcorders into the housings, as changes in the relative positions of the cameras and the glass ports of the housings would lead to different refraction regimes. This is a technical problem that can be resolved in the future as part of the development of an improved and technologically more sophisticated system. However, for a biologist wishing to use a stereo-video system for field work, it is important that the system can be quickly dismantled and reassembled during transportation to and from field sites with minimal variations in accuracy and precision.

Therefore, to ensure that sufficient information is recorded to account for variations in camera calibration parameters over any particular deployment, a calibration should be recorded before the housings are opened to facilitate access to tape or batteries and before the housings are removed from the base bar. Nevertheless, it is clear that small variations in calibration parameters between calibrations made during the same deployment have a very small affect on the accuracy and precision of measurements, given that any single measurement from the stereo-video system has an RMS error of less than 1 mm in all the testing that has been carried out.

Small variations were verified by the errors recorded for the calibration check plate length measurements from the four dives made in the field. Dives 1 and 2 underestimated the length of the check plate, while dives 3 and 4 overestimated its length. The difference between dives 2 and 3 is certainly due to the cameras being removed from their housings between these dives in order for batteries and tapes to be changed. Dives 1 and 2 were carried out the day before dives 3 and 4. Only one calibration was carried out and was not done until after dive 4. As an additional safety measure, routine measurements should be made of a check plate or other objects of a known size during the analysis of recorded images for deployments in which the system is not calibrated. Measurements of the calibration check plate which exhibit an RMS error higher than 1 mm would indicate the presence of unacceptable error levels from variation in the system calibration, or other sources such as poor synchronisation of images.

Further investigation of the large variation in measured dimensions in the X and Y directions (see Figure 4) needs to be undertaken. The data indicate a correlation between the attitude of the cameras and under-estimation and over-estimation of distances. The required roll strategy of 0°, 90°, 180° and 270° changes the influence of gravity on the base bar and housings, which

may induce local movement of the cameras within the housings and changes in the orientations of the housing with respect to the base bar. It is apparent from the results shown in Table 6 that these effects have the largest influence on the Y dimension for the measurement data. The Z direction should be affected most strongly, as this is the dimension for which precision deteriorates most quickly with distance, degrading in proportion to the square of the range from the cameras, as opposed to degrading in proportion to the range for the X and Y dimensions. Hence the degradation in the accuracy of the measurements in X and Y direction is, to some extent, unexpected and unexplained. It is important to note that the precisions of measurement in the X and Y directions are comparable to the theoretical values. If the influence of gravity on the base bar and housings during the roll strategy were a major factor, a greater variation in the measurements could be expected.

The implication of these results is that a significant scale bias remains in the measurement system, and this conclusion is supported by previous research (Harvey and Shortis, 1998). Potential sources of the scale bias are the calibration procedure, the interaction of camera calibration and camera orientation parameters, the incomplete refraction model or other, unknown factors. A further, confounding factor is the manual measurement of the points, necessitated here to emulate the real use of the system. Previous research (Harvey *et al.*, 2000a) has also shown that the operator consistently selects point just outside of the true region of interest. Further analysis of the scale bias errors must eliminate this influence from the measurements and subsequent analysis.

Variations in calibration parameters and correlations with camera attitude may also be attributable to flex in the control frame whilst it is being rotated as part of the calibration procedure. Flex has been noted by Harvey and Shortis (1996) during pool and open water testing, particularly when the frame is being manipulated and rotated by more vigorous field assistants. However the frame used for this previous work was much larger (2 m by 2 m by 1 m) than the frame used for the present experiments (15 cm on each side). The frame used in this work is therefore far less prone to flex than a much larger control frame. Harvey and Shortis (1996) concluded that the design of a more rigid frame may assist in the reduction of these small variations.

To date most of the measurements made with the system have been from images recorded at depths between 2 and 4 metres. It is possible that increasing water pressure due to increasing depth may deform components of the underwater housings and frames, causing deterioration in measurement accuracy and precision, but this is unlikely at these shallow depths. This is an issue which needs to be investigated and resolved if stereo-video systems are to be

mounted onto remotely operated vehicles or submersibles to assist in deep sea marine research.

Whilst future development of the system aims to minimise such errors, the influence on real measurements of the length and height of mobile and sessile marine species is generally much less significant for two reasons. The first is that, in general, the lengths and heights of individuals to be measured with this particular stereo-video system are less than 20 mm and the potential error will be reduced in proportion to the distance. The second reason is related to the preferred orientation of individual fish or other species to be measured. Previous research (Harvey and Shortis, 1996) has shown that measurement errors are minimised when the length or size to be measured is approximately parallel to the plane of the images. Acute angles reduce the visibility of edges or key points (such as the edge of a siphon) used for measurement. Hence the vast majority of measurements are made in the X direction (see Figure 4), avoiding the Y dimension which is most influenced by the variability.

Notwithstanding the scale bias, the error level is likely to be of the order of 1mm at worst, or approximately 5% of the dimension of the object. Whilst this is not an exemplary outcome as far as photogrammetric measurement is concerned, a coefficient of variation of 5% is certainly acceptable in the marine science community and is still preferable to the high mortality rates of direct sampling methods such as dredge surveys.

CONCLUSIONS

This paper has presented a study of the calibration stability of an underwater stereo-video system designed for non-contact sampling of populations of marine species. The results show that there were few significant changes to the calibration parameters, indicating that the system is very stable if the cameras and housings are not disturbed. The significant changes to some of the parameters for the system calibration is attributed to the disassembly of the system required for transport between sites and access to video tapes and batteries. However, calibrations of the camera system appear to be generally stable both within and between deployments of the system. The small variations in camera parameters appear to have minimal affect on the accuracy and precision of measurements made with the system. Therefore, marine biologists wishing to utilise this technology can be assured that there will be minimal variability in the accuracy and precision of measurements made at different times on any one deployment and over repeated deployments.

Future development of the system will include both hardware and algorithmic improvements. Improved housings will reduce the potential for relative movement of the cameras within the housings and the housings with respect to the base bar. The next revision of the system will

incorporate digital video cameras, with a time code capability, in order to enable the automatic, accurate matching of image pairs from the two cameras. Research is currently underway to automate the measurement of images required for the calibration using coded patterns on the control frame. Further, an advanced network solution is under development and will incorporate scale constraints to reduce the impact of correlations between calibration parameters, as well as minimise the apparent correlation between the attitude of the cameras and the derived distances.

The improvements in automation and accuracy will allow the underwater stereo-video system to be a precise, reliable tool that can gather information on marine fauna quickly and conveniently. The ability to gather large samples of length and size data for populations of marine species, with little temporal or spatial variation in the integrity of the data, will allow much more powerful statistical testing. More powerful tests will in turn dramatically improve the ability of marine biologists to detect and predict the influence of environmental impacts on populations of marine species.

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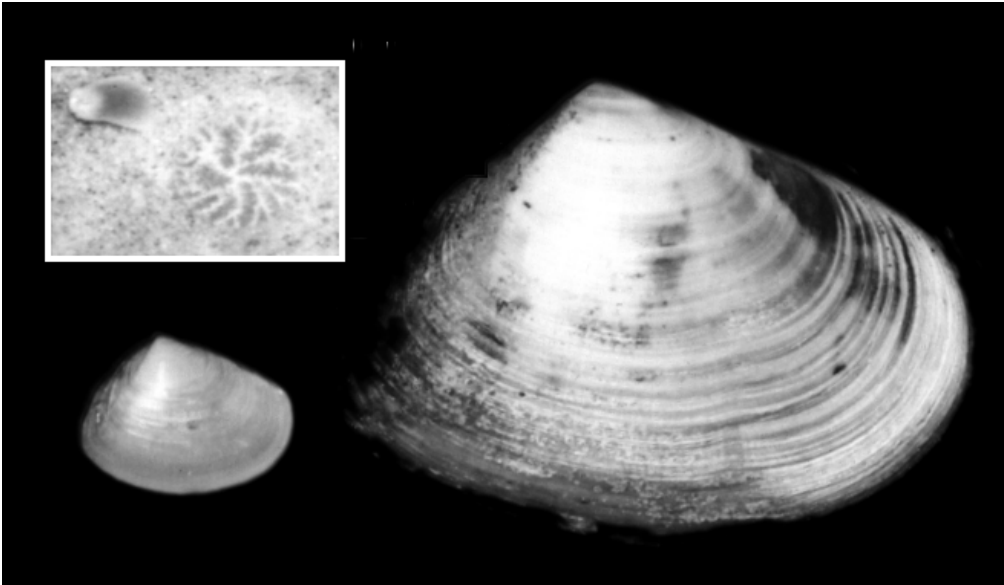


Figure 1. Tuatua (*Paphies donacina*). Inset shows exhalant (upper left) and inhalant (centre right) siphons protruding through the sand.



Figure 2. Stereo-video camera set-up. Note the aluminium frame on which the cameras are mounted.

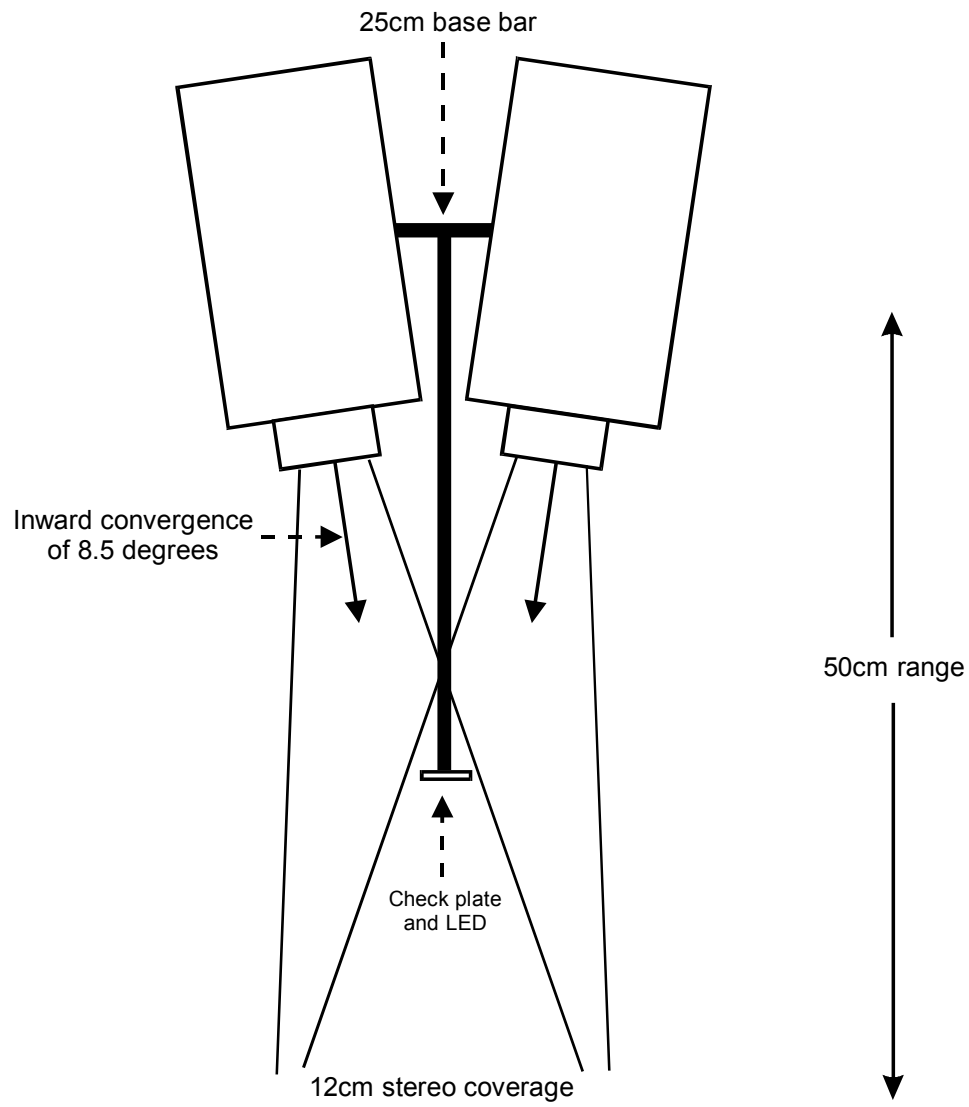


Figure 3. Diagram showing stereo-video system to scale.

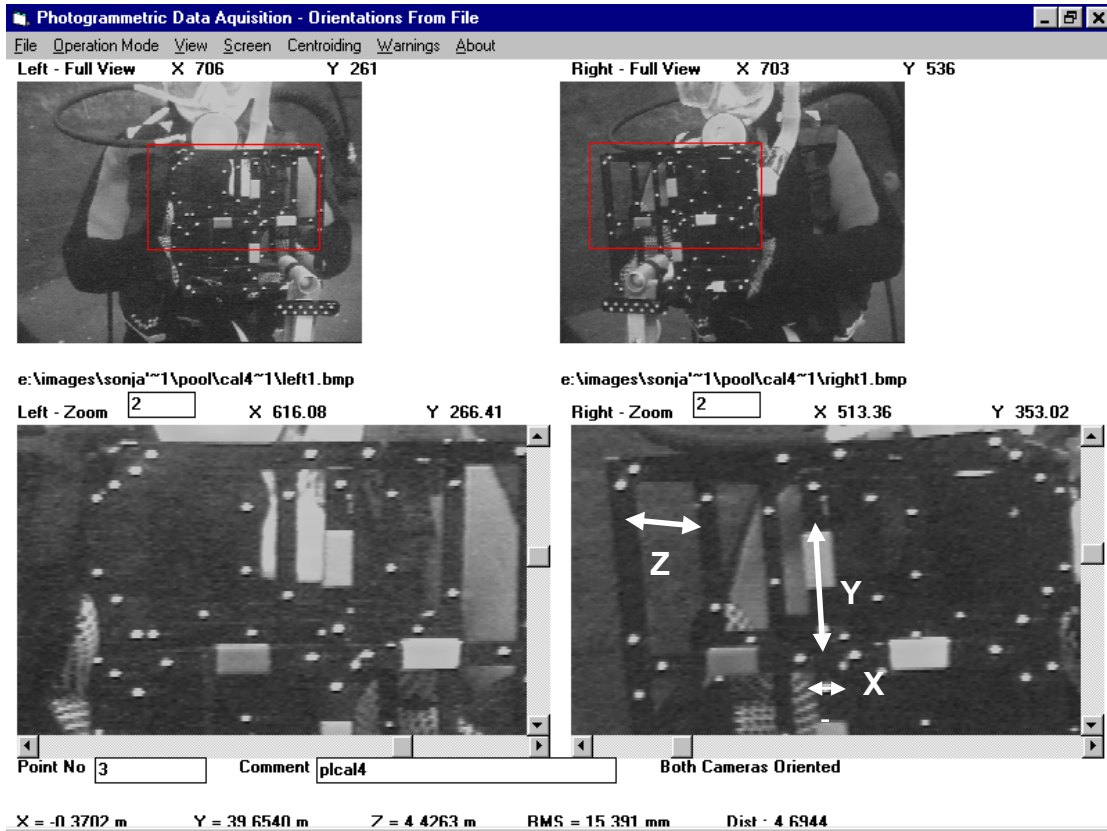


Figure 4. Stereopair comparator showing location of measured lengths on the control frame in lower right image. The check plate is visible in bottom right corner of upper left image and bottom left corner of upper right image.

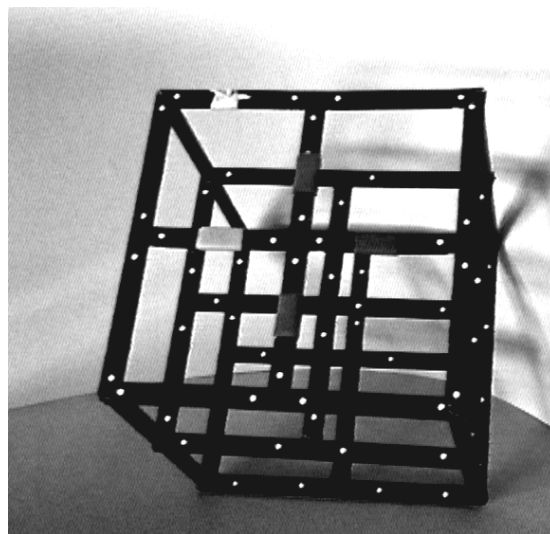


Figure 5. Calibration cube.

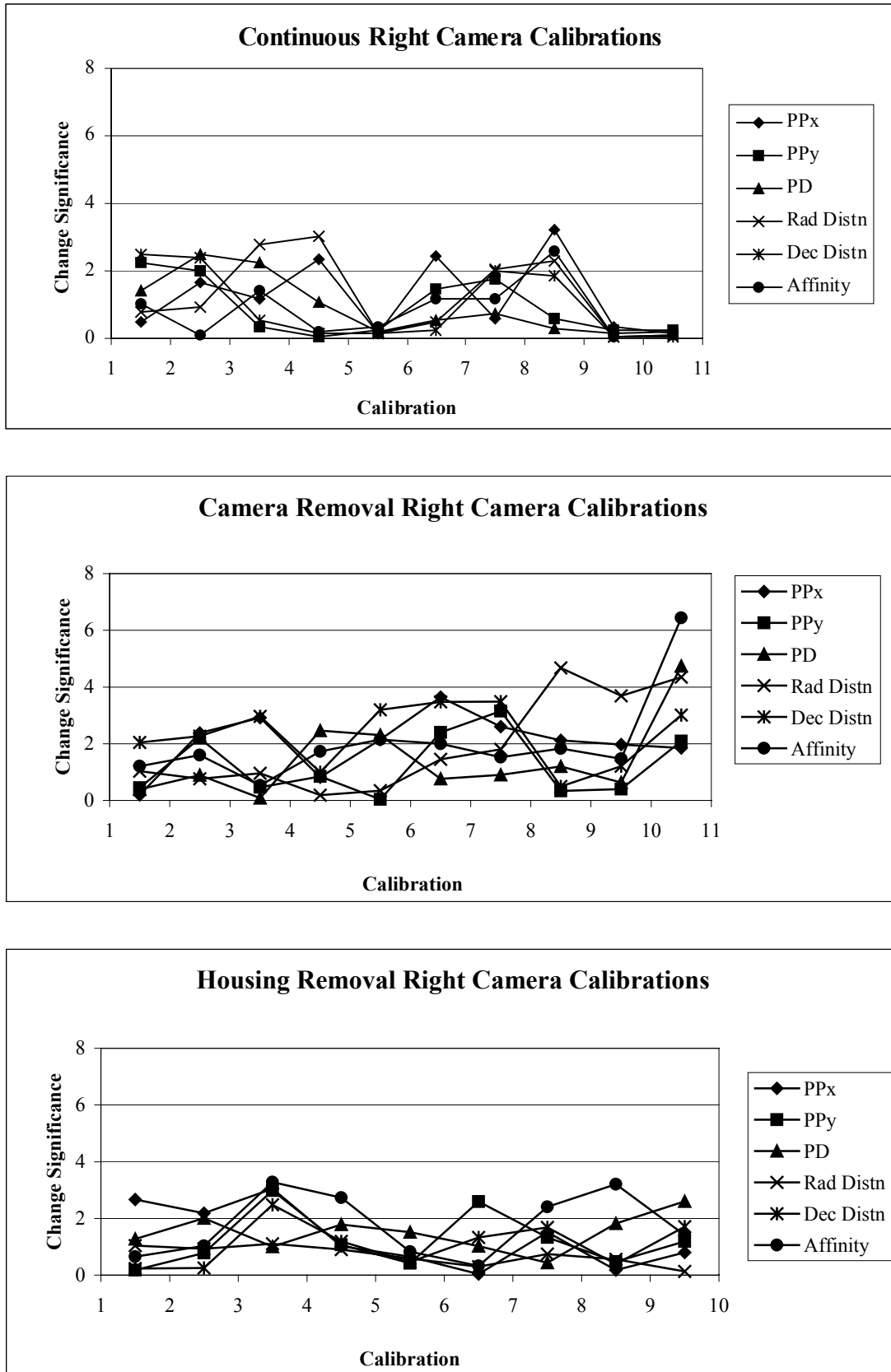


Figure 6a. Significance values for right camera calibration parameters for continuous, camera and housing calibrations.

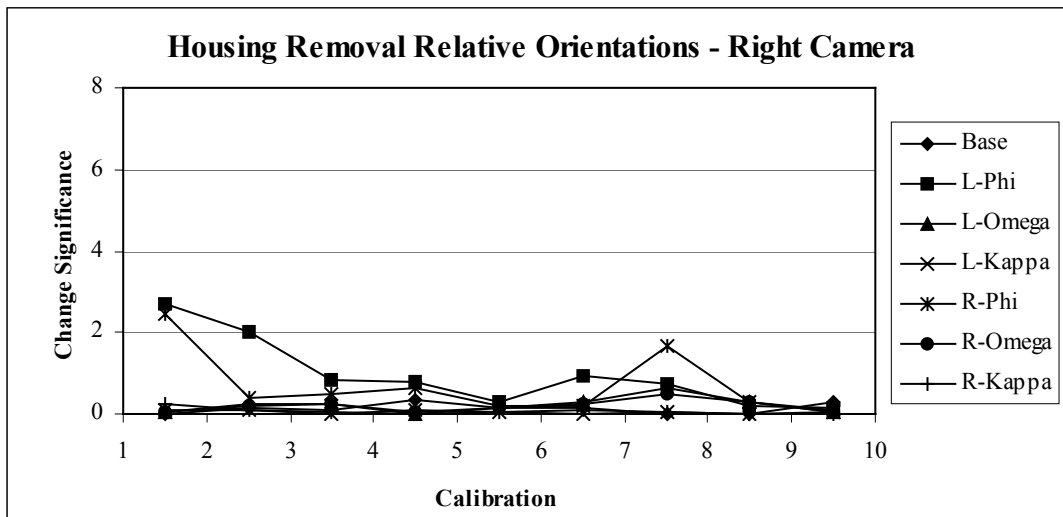
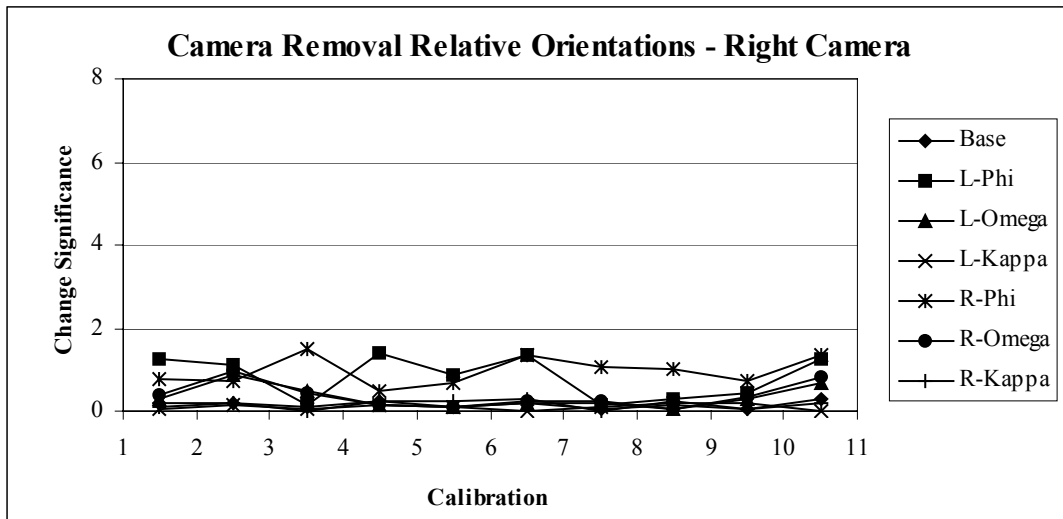
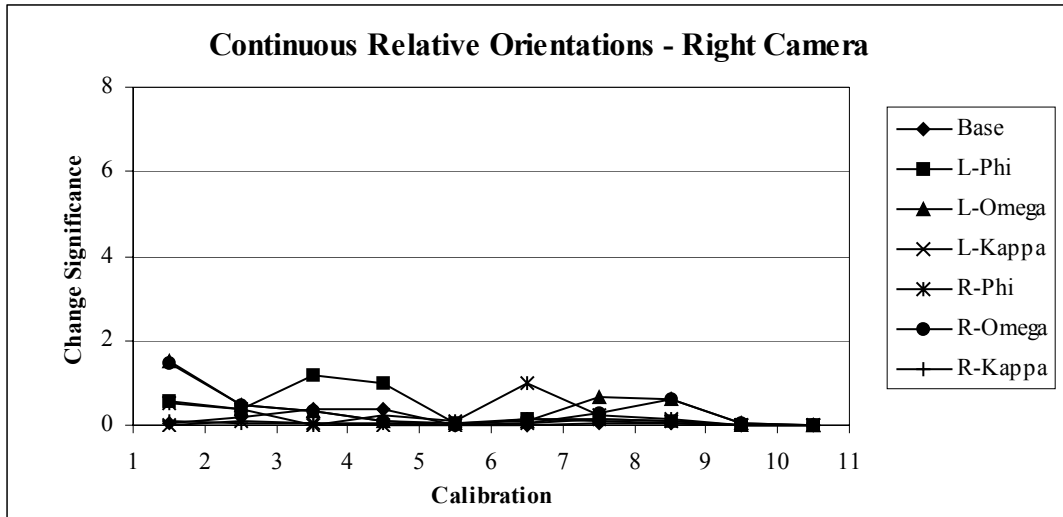


Figure 6b. Significance values for right camera relative orientation parameters for continuous, camera and housing calibrations.

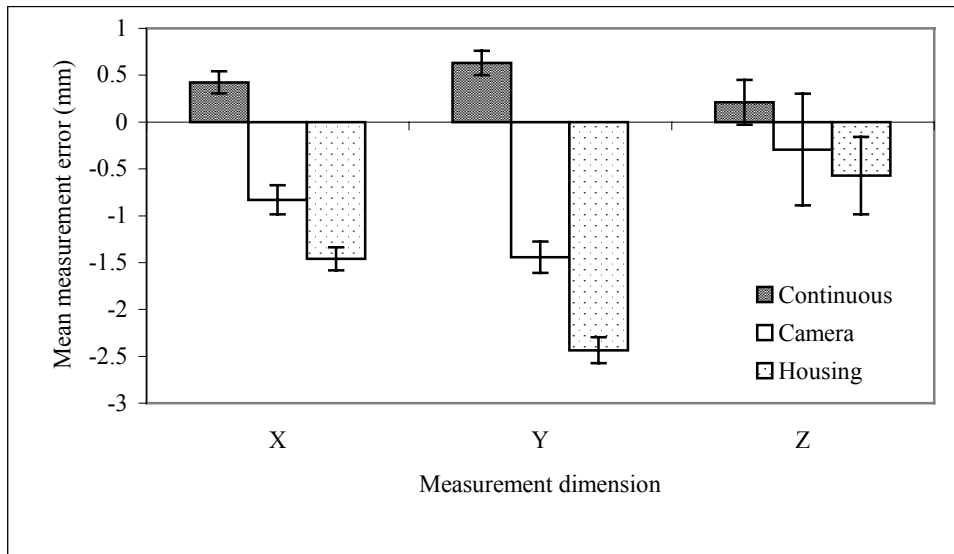


Figure 7. Mean measurement error for the continuous, camera and housing calibrations in the X, Y and Z and dimensions (+/- 2SE).

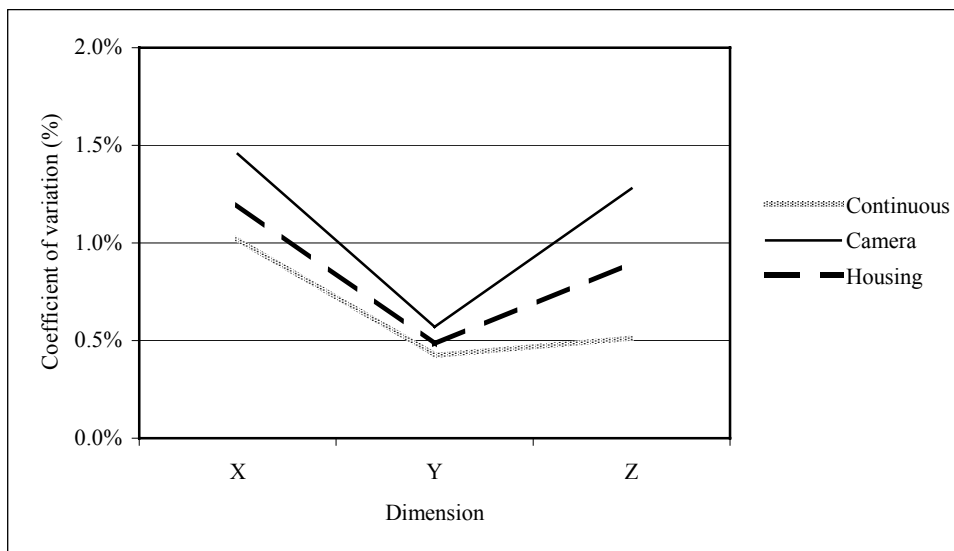
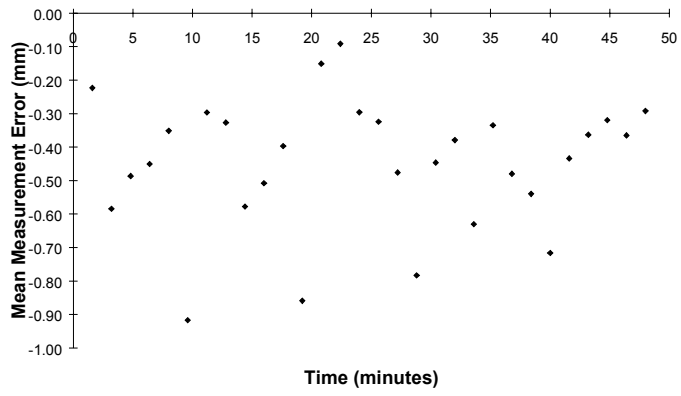
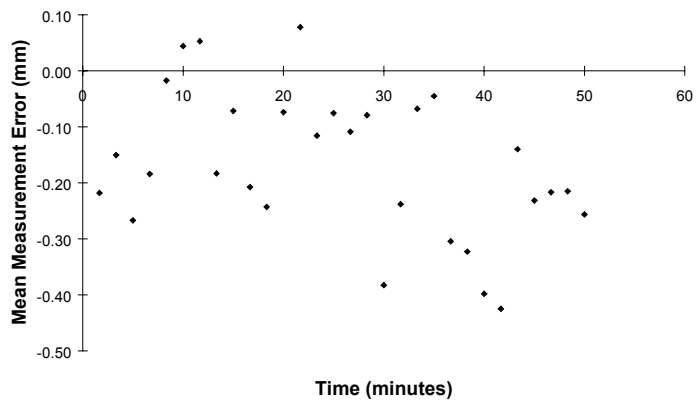


Figure 8. Coefficient of variation for measurements taken in the X, Y and Z dimensions during continuous, camera and housing calibrations.

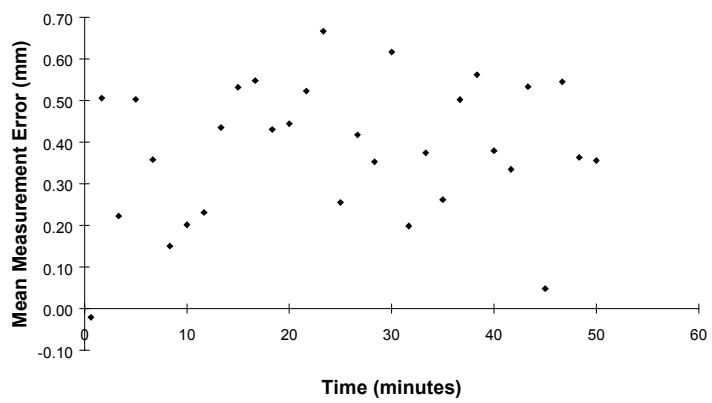
Dive 1



Dive 2



Dive 3



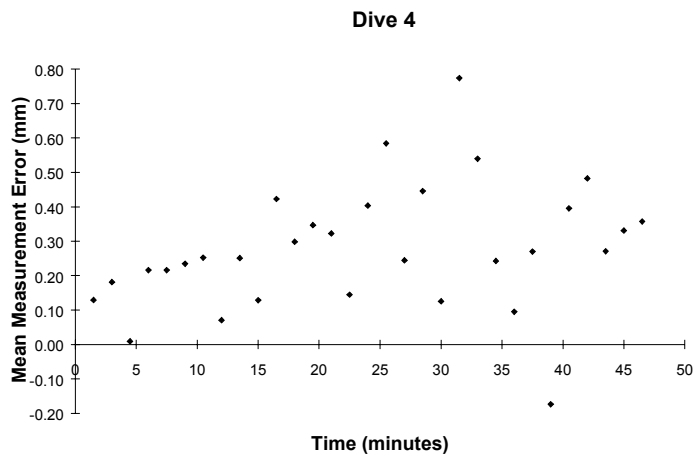


Figure 9. Mean measurement error for the calibration check plate length measurements over time during four separate open water dives.

Calibration Type	Date recorded	Visibility (metres)	Mean duration of calibration underwater (minutes)	Duration of laboratory processing per calibration (hours:minutes)		
				Mean	Min	Max
Continuous	16/10/98	4	2:06	1:24	1:18	1:28
Camera	16/07/98	5	1:20	1:26	1:12	1:29
Housing	30/07/98	4	1:30	1:17	1:04	1:23

Table 1. Details of calibrations of the underwater stereo-video system for continuous, camera and housing deployments.

Calibration Type	Base (cm)	Left Rotations (degrees)			Right camera calibration parameters				
		Phi	Omega	Kappa	PPx	PPy	PD	Rad.dist	Dec.Dist
Continuous	0.023	0.211	0.090	0.057	0.014	0.007	0.005	0.979	0.367
Camera	0.026	0.272	0.099	0.081	0.019	0.014	0.011	1.438	1.116
Housing	0.023	0.160	0.062	0.047	0.018	0.013	0.008	0.836	1.056
Ratio Cameras / Continuous	1.150	1.293	1.101	1.407	1.369	2.028	2.086	1.469	3.038
Ratio Housing / Continuous	0.987	0.761	0.688	0.823	1.317	1.946	1.421	0.854	2.874

Table 2. Comparison of the standard deviations of selected calibration parameters for continuous, camera and housing calibration sets.

X Dimension Length	Error (mm)	SE	Std. Dev.	Sample Size
Calibration Type				
Continuous	0.42	0.06	0.19	10
Camera	-0.83	0.08	0.25	10
Housing	-1.46	0.06	0.19	10

Y Dimension Length	Error (mm)	SE	Std. Dev.	Sample Size
Calibration Type				
Continuous	0.63	0.06	0.20	10
Camera	-1.44	0.08	0.26	10
Housing	-2.44	0.07	0.22	10

Z Dimension Length	Error (mm)	SE	Std. Dev.	Sample Size
Calibration Type				
Continuous	0.21	0.12	0.38	10
Camera	-0.29	0.30	0.94	10
Housing	-0.57	0.21	0.65	10

Table 3. Accuracy values and precision measures in the X, Y and Z dimensions for the continuous, camera and housing calibrations.

Calibration Type	Degrees of Freedom			Fisher Statistic	Correlation Factor
	Dimension	Error	Total		
Continuous	2	27	29	2.25	0.124
Camera	2	27	29	3.25	0.055
Housing	2	27	29	7.26	0.003

Table 4. Results of ANOVA tests of the 3 measurement dimensions for the continuous, camera and housing calibration tests.

Comparison of measurement dimension		Continuous	Camera	Housing
(a)	vs (b)			
X	Y	No	No	No
X	Z	No	No	No
Y	Z	Yes	Yes	Yes

Table 5. Results of LSD tests of the three measurement dimensions for the continuous, camera and housing calibration tests (Yes and No refer to significant differences at a 95% confidence level).

Dimension	Degrees of Freedom			Fisher Statistic	Correlation Factor
	Dimension	Error	Total		
X	2	27	29	22.39	0.000
Y	2	27	29	47.85	0.000
Z	2	27	29	1.05	0.363

Table 6. Results of ANOVA tests of the 3 calibration conditions in the X, Y and Z dimensions.

Comparison of Treatments		X	Y	Z
(a)	vs			
	(b)			
continuous	camera	Yes	Yes	No
continuous	housing	Yes	Yes	No
continuous	housing	Yes	Yes	No

Table 7. Results of LSD tests of errors between continuous, camera and housing calibrations in the X, Y and Z dimensions (Yes and No refer to significant differences at a 95% confidence level).

Dive Number	Date	Dive Time (minutes)	Visibility (m)	Number of check plate measurements per dive
1	5/8/98	48	3	30
2	5/8/98	50	3	30
3	6/8/98	50	3	30
4	6/8/98	45	3	30

Table 8. Details of open water dives and calibration check plate measurements.

Dive Number	Error (mm)	SE (mm)	Std. Dev. (mm)
1 (5/8/98)	-0.4465	0.0545	0.1541
2 (5/8/98)	-0.1690	0.0599	0.1694
3 (6/8/98)	0.3817	0.0537	0.1520
4 (6/8/98)	0.2778	0.0610	0.1726

Table 9. Accuracy values and precision measures of horizontal measurements of the control plate over four open water dives.