Auto-levelling geophone development and testing

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ABSTRACT

An auto-levelling, motion sensor (multi-component geophone) is developed and tested. The geophone elements are mounted in a sphere free to rotate inside a spherical cavity in the sensor case. Both one-component (vertical element) and three-component (one vertical and two horizontal elements) devices have been built and tested. A testing apparatus has also been developed. It consists of a large speaker coupled to a platform upon which the geophone device is attached. Reference elements as well as a laser interferometer provide calibration signals for the device under test. Conventional geophones have sinusoidally decreasing output when they are tilted from the vertical (about 70% of maximum when tilted 40 degrees from vertical). The auto-levelling device has a vertical geophone output that decreases less than 3% under similar tilt for frequencies from 10Hz to 100Hz. Horizontal motion, as measured by the auto-levelled elements, is within 3% of the calibrating horizontal element for frequencies from 10Hz to 120Hz. Penduluming of the inner sphere does not appear to be a problem above 2Hz. The auto-levelling sensor shows considerable promise to improve conventional seismic recording and fully capture multicomponent seismic motion.

INTRODUCTION

Multicomponent measurements have been showing increasing usefulness and interest in this technique, especially in the marine case, has been growing rapidly. However, there are numerous unresolved issues in the deployment, logistics and recording response of the sensors. The work on the auto-orienting geophone is directed at improving the facility of planting multicomponent sensors as well as increasing the recording fidelity.

Two geophones have been built incorporating elements inside a sphere, free to rotate in a spherical cavity in a casing. The sphere is supported by a fluid providing neutral buoyancy and levels by rotation to give an upright orientation. Tests indicate that this provides significantly better response than poorly planted conventional geophones. One of these prototypes is a single element sensor for vertical motion measurement; the second is a multicomponent geophone with three orthogonal elements.

The auto-orienting method described above has been patented by the authors and issued with the US Patent number 5,866,827. Testing of the auto-orienting motion detector has been ongoing for some time with some results available. This report covers a “proof of concept” analysis of the prototypes.

The term auto-orienting refers to both auto-levelling and rotation to a particular pre-selected azimuth. The work carried out here is in effect a subset of this, dealing with the auto-levelling of the internal elements and the coupling between the outer case and the inner sphere. Since this is a particular application for the patented idea, the term auto-levelling geophone has been used throughout this report.

The rotation to an azimuth is not an essential aspect of the device when being used as a geophone on a seismic survey, as the inner sphere can be constrained to a particular orientation within the case and the top marked with an arrow as is used currently on commercial 3 component geophones for orientation during planting.

If the geophones are being used in a 3-D seismic survey, then because of the changes in azimuth of the different shots the axes need to be rotated algorithmically in the pre-processing stage. The algorithms for auto-rotation of multi-azimuth data are still being developed, and are not a part of this report.

CONSTRUCTION OF THE PROTOTYPES

The main feature of this sensor is a spherical inner carrier with the geophone elements mounted inside it suspended at neutral buoyancy inside a spherical chamber containing a fluid. With the centre of gravity of the inner sphere below the geometric centre of the sphere, the inner sphere rotates to a position such that the internal geophone elements are in the desired vertical orientation. There are some constraints on how far the inner sphere can rotate in the initial design, as connections to the elements are made by flexible wires entering the sphere through a stalk on the top. A schematic of the design is shown in Figure 1.

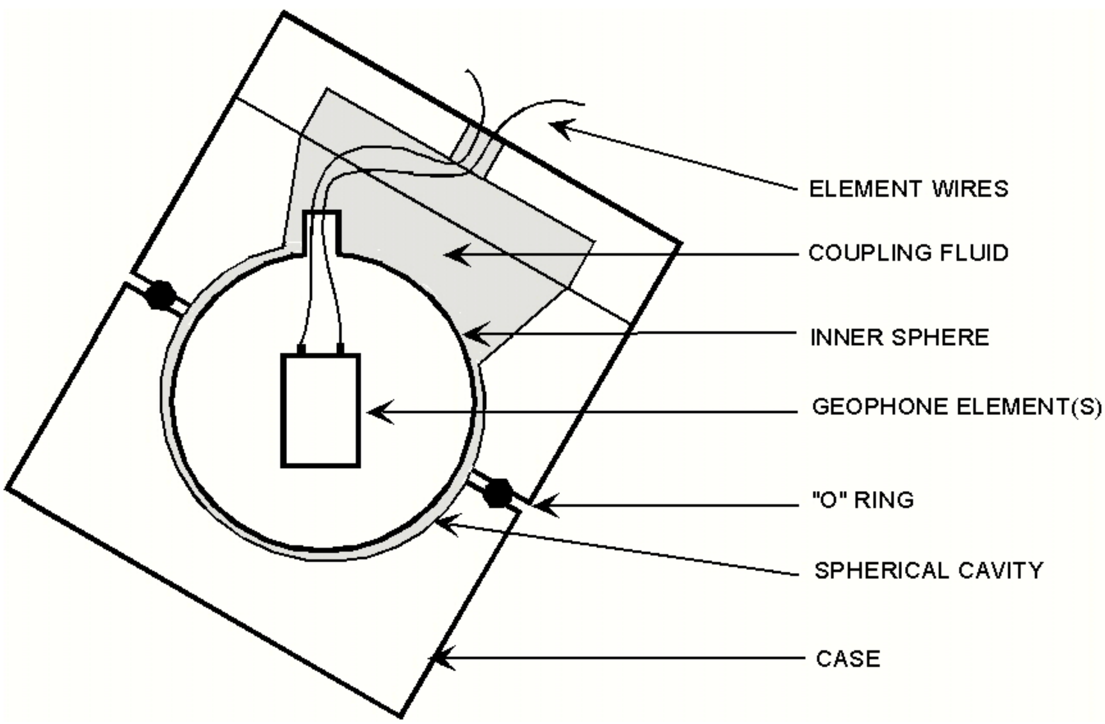

Figure 1. Schematic of the auto-levelling geophone with the case tilted.

The prototype geophones being used for testing have a range of motion of about +/-30 degrees. The chamber containing the inner sphere is totally fluid filled, providing hydraulic coupling between the outer case and the inner sphere as well as the support medium for the inner sphere. In the test geophones, the fluid used is water for ease of adjustment and transparency. The design calls for testing of more viscous fluids of different types for two reasons:

- Water is unsuitable due to the extreme operational temperature range required of the device.
- As a method of damping pendulum oscillations of the inner sphere with sideways motion of the outer case (i.e. damping of the inner sphere).

Commercially produced auto-levelling 3 component geophones use a gimbal system for rotation with a variety of internal fluids, ranging from a light oil to a heavy silicon fluid with a viscosity of 8000 cps. In some cases the chamber may be left dry.

Building the prototypes

The two prototype geophones being used for testing are shown in Figure 2. The smaller unit contains a single vertical geophone element, the larger is a 3 component sensor with one vertical and 2 horizontal elements.

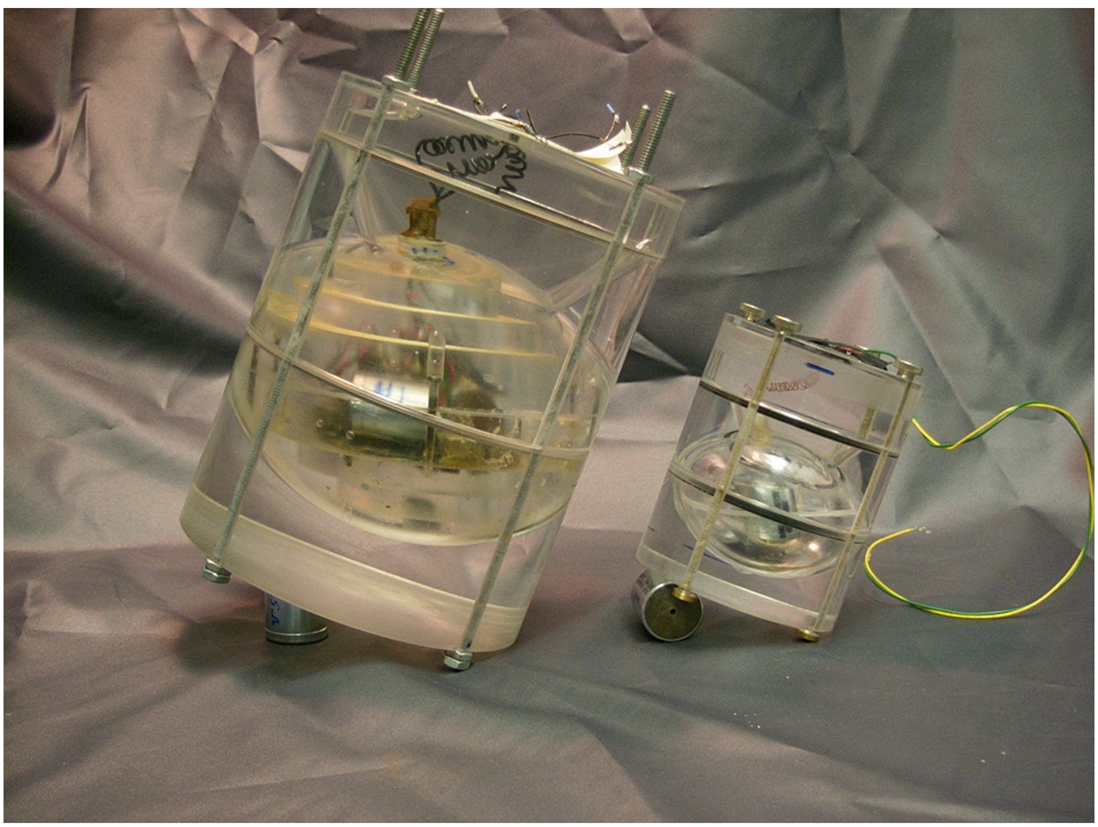

Figure 2. Prototypes used for testing.

The prototypes are constructed from clear acrylic material to allow visual inspection of the auto-levelling operation, as well as to check the pendulum motion, and the presence of any air bubbles.

Three on-campus workshops were involved in the manufacture of these prototype geophones:

- Faculty of Environmental Design (EVDS) Workshop
- Engineering Faculty Services (Faculty of Engineering)
- Faculty of Science Workshop

Construction of special jigs and use of a CNC Lathe to cut the spherical surfaces to high accuracy was necessary, as the original design called for a clearance of only a fraction of a millimeter between the inner sphere and the outer housing. The rationale for this was to provide minimum "slop" of the supporting fluid i.e. the fluid would not be able to travel around the gap at a rate that would respond to movement at seismic frequencies. The inner sphere would therefore be held in position and forced hydraulically to respond in sympathy with the outer case. If the gap between the inner and outer spherical surfaces was too large, then the fluid would be able to move more easily and the inner sphere might lag the outer case motion or bump against the cavity wall generating noise. An increase in fluid viscosity would help eliminate this problem, and hence provide some more leeway in the clearance specification. The small clearance also keeps the radius of the inner sphere very close to that of the cavity, which enlarges the contact area between the two and reduces frictional binding from point contact.

The test geophones went through many iterations as the clearance gap was widened to overcome problems with lack of sphericity of the two surfaces, caused mainly by distortion of both the inner sphere and the outer case when assembled from the 2 halves (see Figure 3), and distortion caused by heat generated during machining of the acrylic rod to manufacture the various "ball and socket" components. These distortions were causing the surfaces to bind, so free rotation was restricted or impossible. The prototypes now have much larger clearance gaps than the original design called for, so one of the main tests was to determine if there was indeed any "slop" of the fluid (in this case water) causing coupling loss to the inner sphere.

The prototype geophones currently have 10Hz GS-20DM elements manufactured by Oyo-Geospace installed. These are a commonly used element in seismic surveys and have been supplied for testing purposes by Oyo-Geospace Canada. These elements are available in both horizontal and vertical orientations.

TEST EQUIPMENT

The equipment used to test these geophones was assembled from some components already available in the department and some items specifically purchased for the task.

Excitation for the geophone motion is provided by a 15 inch speaker mounted in a box with a diaphragm covering the side in front of the speaker. The space between the speaker and the diaphragm is sealed, so that motion of the speaker cone is transmitted pneumatically to the diaphragm. A programmable signal generator drives the speaker via a power amplifier.

Figure 3. Disassembled parts of the geophone prototypes

This system has a good response across the seismic frequency range, and can simulate ground motion of the same magnitude a geophone would experience in the field. There are two of these speaker systems – one is currently being used for vertical motion measurements, the other for horizontal.

The first system did have some mechanical resonances caused by the square shape and size of the diaphragm and the mass of the geophone under test, but most of this could be compensated for by the signal generator. To try to minimize the resonance problem, a second speaker box was constructed with a heavier diaphragm. This shifted the resonance to a lower frequency and broadened the peak, but did not eliminate it. The main problem to date has been a lack of true horizontal motion transferred to the geophone in the horizontal jig caused by distortion of the diaphragm by the loading of the geophone mounted on the outer side. The system has been modified to suspend the geophone independent of the diaphragm on a platform driven by the diaphragm via a coupling rod. The horizontal test jig is shown in Figure 4.

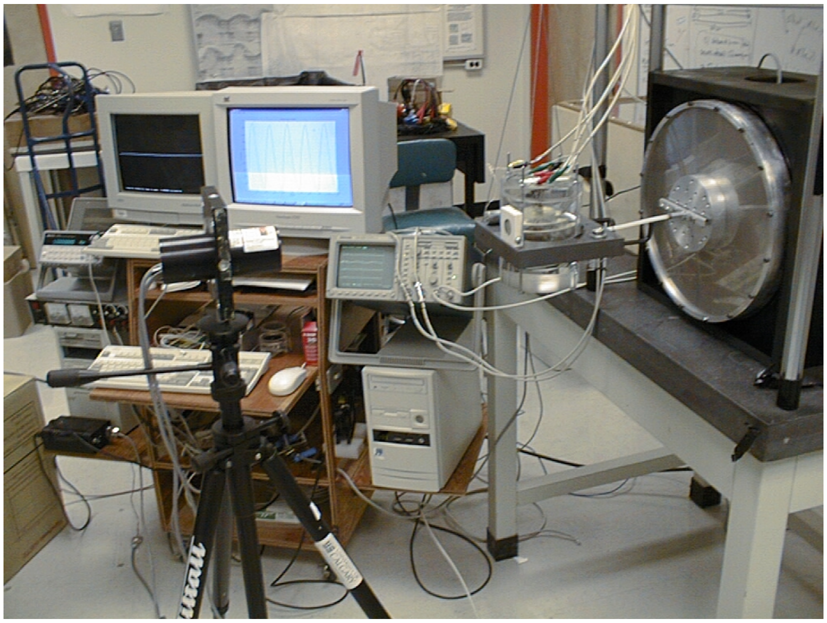

Figure 4. The horizontal test jig with the test equipment visible.

The output of the geophone elements under test is displayed on a digital oscilloscope. This is used as a “first look” and to help set up acquisition parameters. The output is then captured by a 12 bit GageScope Model 8012 PC oscilloscope card that saves the data to file for analysis by the Matlab software package. A schematic of the test equipment setup is shown in Figure 5.

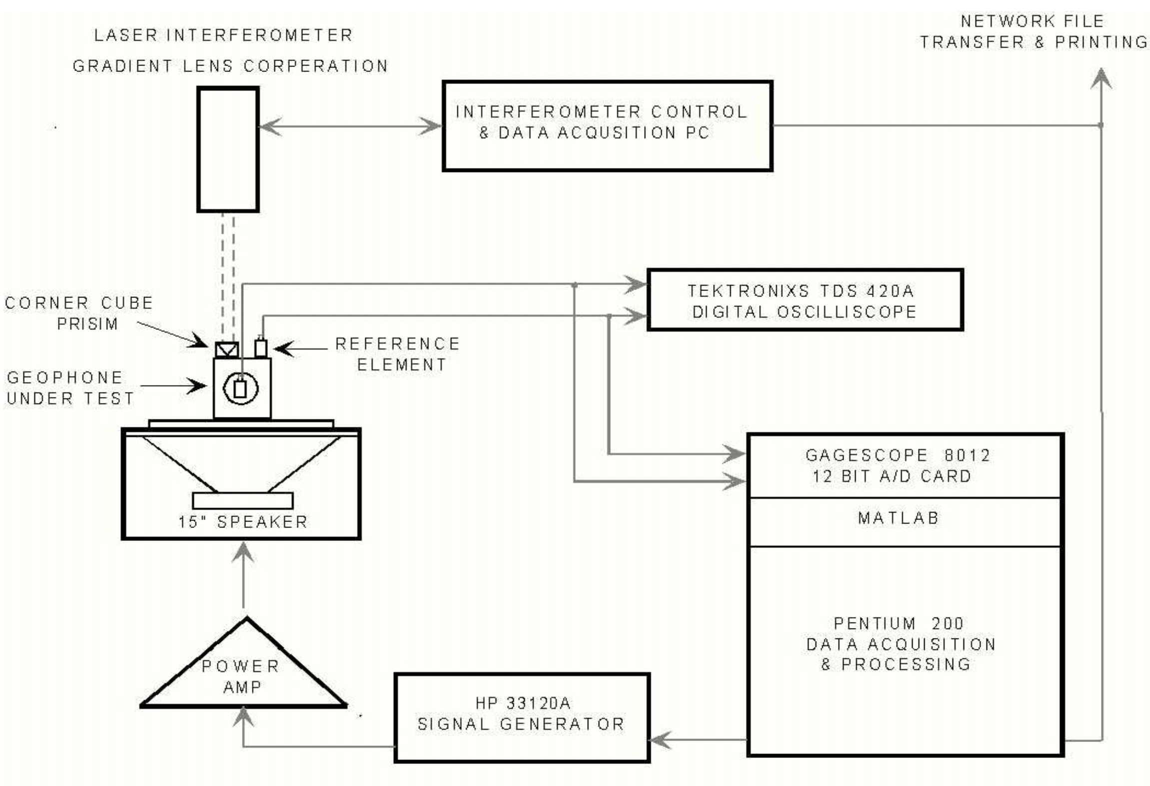

Figure 5. Schematic of the test equipment setup.

The original specifications for this test equipment called for a 24 bit analog-to-digital (A/D) converter to be constructed for data acquisition. However, previous analysis of field data from seismic surveys using standard geophones, and some lab testing, showed that the 12 bit A/D converter in the PC oscilloscope card is adequate for the first series of tests. The need for 24 bits in the field is to supply sufficient dynamic range to handle direct arrival energy as well as reflection returns from depth. When the field testing of the prototypes is carried out they will be attached to a standard seismic recording system to ensure that true comparisons can be made with commercially available standard geophones.

The case motion amplitude applied to the geophones is kept to approximately the same level as a geophone experiences on a standard seismic survey, typically a few micrometers. Because of the high ambient noise level in the building, some of the testing was carried out with actual displacements up to 100 micrometers. The displacement is measured using a laser interferometer that detects absolute position to an accuracy of 80 nanometers. The laser beam is reflected from a corner cube mounted on the outer case of the geophone under test to ensure that the actual case motion is being detected. The output from the interferometer is captured and used to analyse the distortion of the geophone signal relative to the case motion. This system is being used in a ongoing analysis of geophone elements in the Department, and is used on this test jig mostly for ensuring the displacement is within expected limits. As with all geophone testing, it is necessary to limit displacement so that acceleration is always less than that due to gravity.

To ensure that all data is comparable to field acquisition measurements all data is recorded at 1 or 0.5 millisecond sample rate to a record length of either 1024 or 2048 samples. The entire trace is used for data analysis, but only the first two cycles of signal are plotted for visual checking. Some of these plots are presented later in this report.

Data analysis is performed using Matlab software, which, provides an excellent range of mathematical functions as well as the ability to plot the results.

TESTING INDIVIDUAL GEOPHONE ELEMENTS

After the initial tests had been made, comparison of the response of the internal element with an external reference element over a range of frequencies, produced several discrepancies that could not be easily explained. To try to establish the cause of the problem, some tests were carried out on element pairs which showed that there were marked differences in response of two similar elements. This effect was most noticeable at frequencies above 60Hz. Below this, the elements tracked very closely. A plot of a test data set showing this response variation is shown in Figure 6. The actual output voltage is plotted with no normalisation for displacement.

To make these measurements, two elements were strapped together and placed in the centre of the diaphragm. The two outputs were then captured and compared. The test setup is shown in Figure 7.

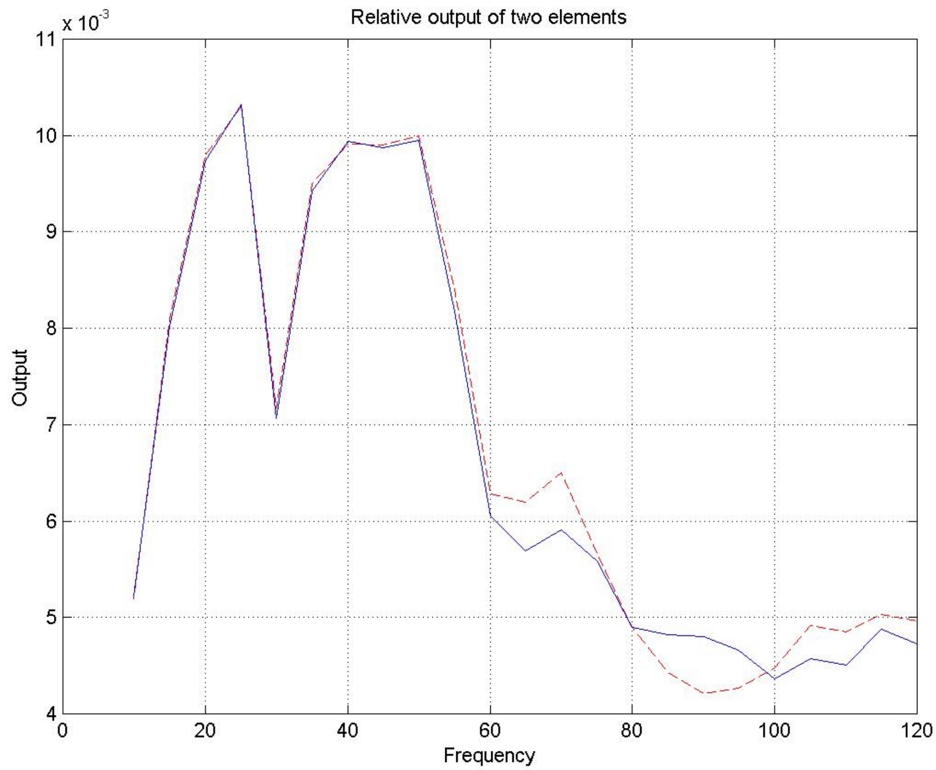

Figure 6. The outputs from two elements plotted against frequency.

Note the difference in output between 60Hz and 80Hz, where one element has a higher output, then the area between 80Hz and 100Hz where this same element is now lower in output. Another crossover point occurs at 100Hz.

These results suggested that by working at lower frequencies, conclusions regarding coupling of the inner sphere and response at different angles would be valid. Less confidence might be placed on data acquired above 50Hz.

A number of tests of different pairs of elements yielded the pair with least variation, which was used in the vertical response tests covered later.

Response at an angle

Another test performed on individual elements was to measure the response of the element as the angle was increased away from vertical. This was then compared with the theoretical output derived from the cosine of the angle. These measurements were made to ensure that the elements being used behaved as expected before starting on the auto-levelling tests using the prototype geophones.

The jig used to make these measurements is shown in Figure 8, with the protractor on one side for setting the angle visible. A trace was captured every 2 degrees from –70 to +70 degrees and the output plotted for comparison.

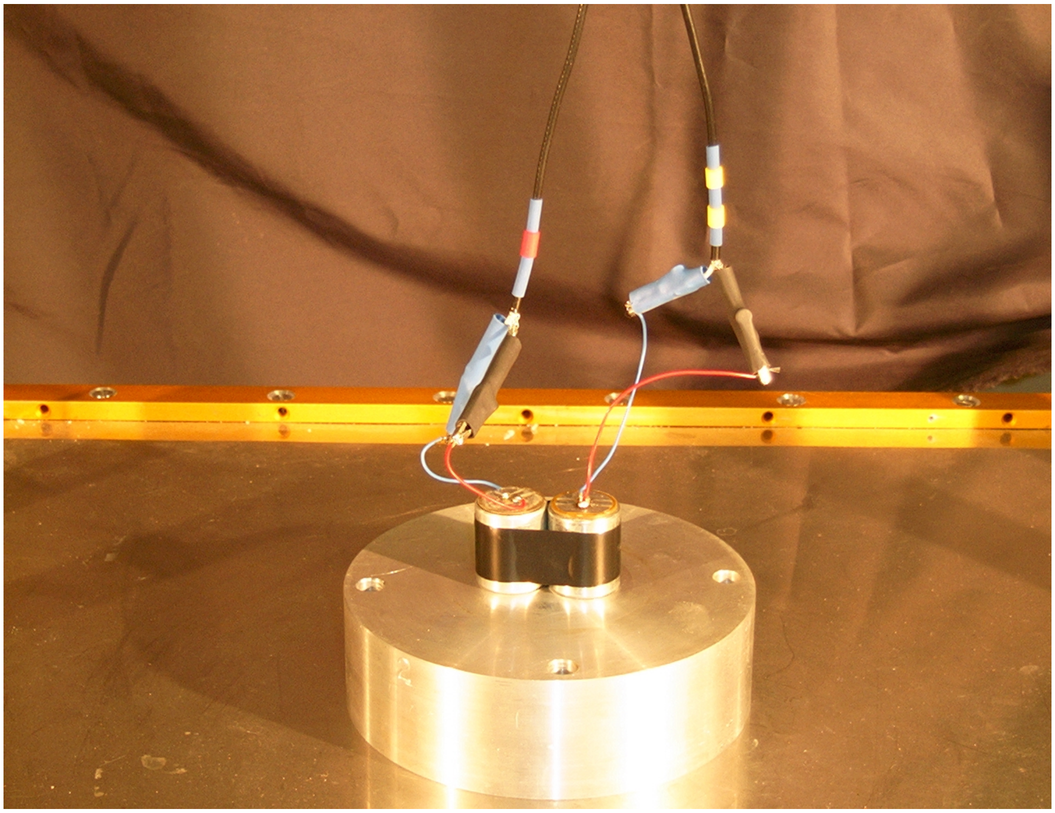

Figure 7. The test setup for comparing two similar elements.

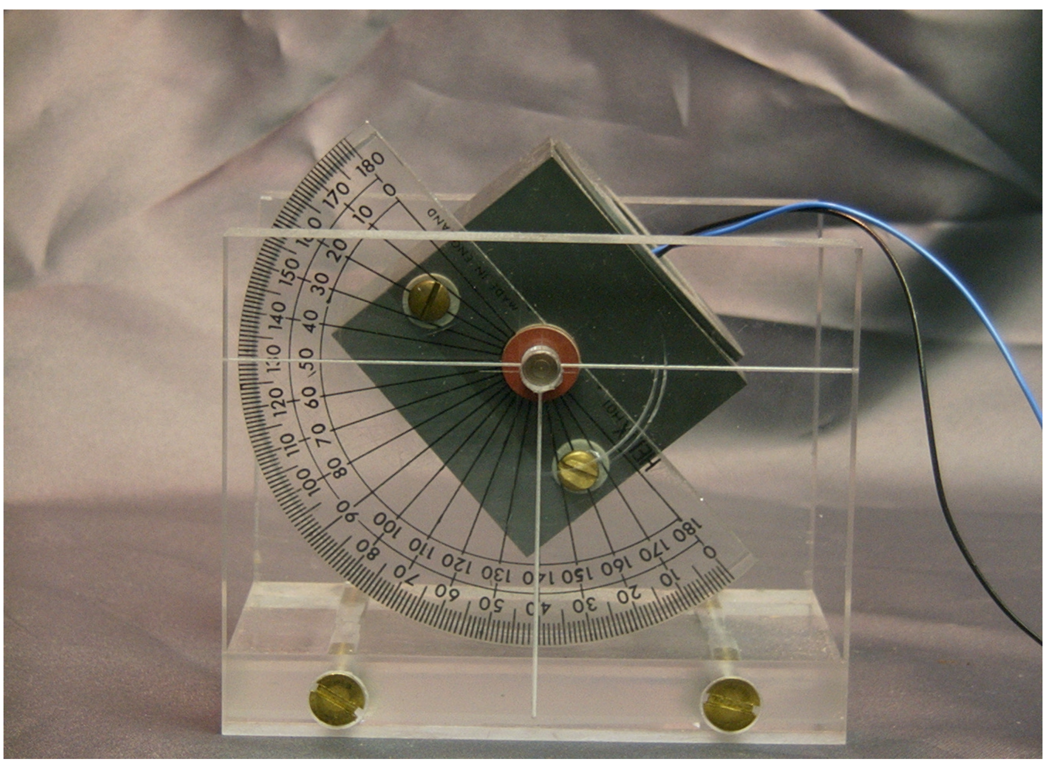

Figure 8. The jig used to measure the output from a single element at different angles.

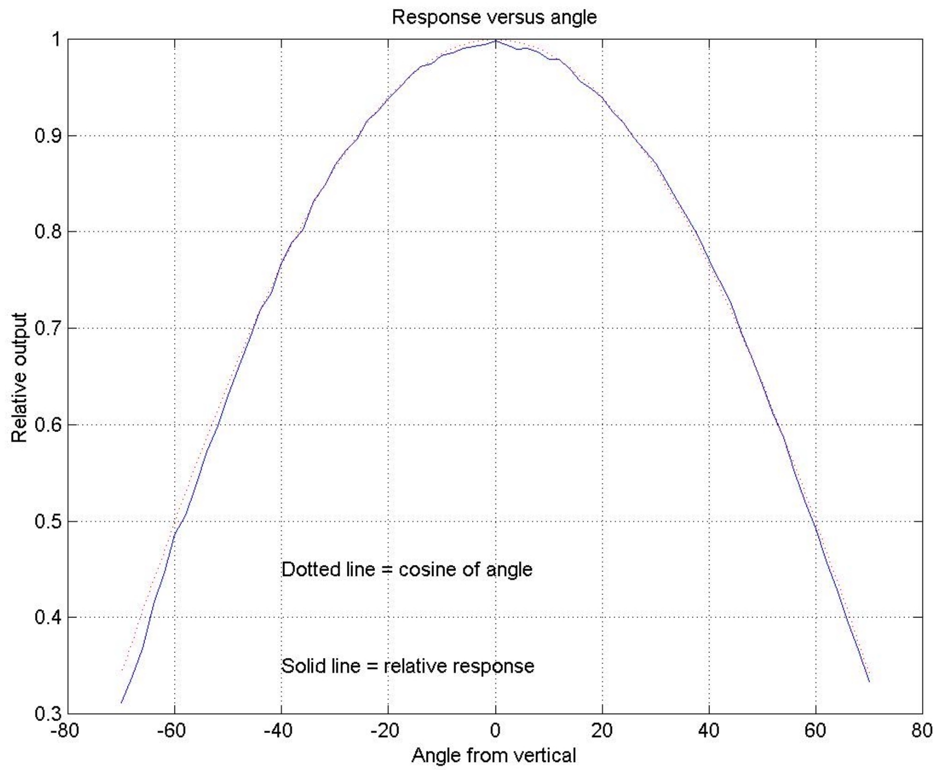

Figure 9. Element output plotted against angle from vertical.

Figure 9 shows that the output of a geophone element as it is tilted away from vertical follows almost exactly along the predicted line. As expected the output falls to 50% at an angle of 60 degrees. At this point the element coil is no longer suspended in the centre of travel and consequently there is more distortion in the signal, and the range of measurable case motion is reduced

Figure 10 shows a second plot of response at varying angles. In this case the three lines are 10, 15 and 20Hz responses. Again it is clear that the output follows the expected response, although there are diaphragm distortion effects causing the curves to be offset.

TESTS ON AUTO-LEVELLING AND GEOPHONE RESPONSE AT AN ANGLE

To test the prototype geophones for auto-levelling ability, the jig shown in Figure 11 was used. This holds the single vertical element geophone in a supporting frame, which can then be rotated to 90 degrees each side of vertical.

The output of the internal element is compared with the output of the external reference element for both amplitude and phase.

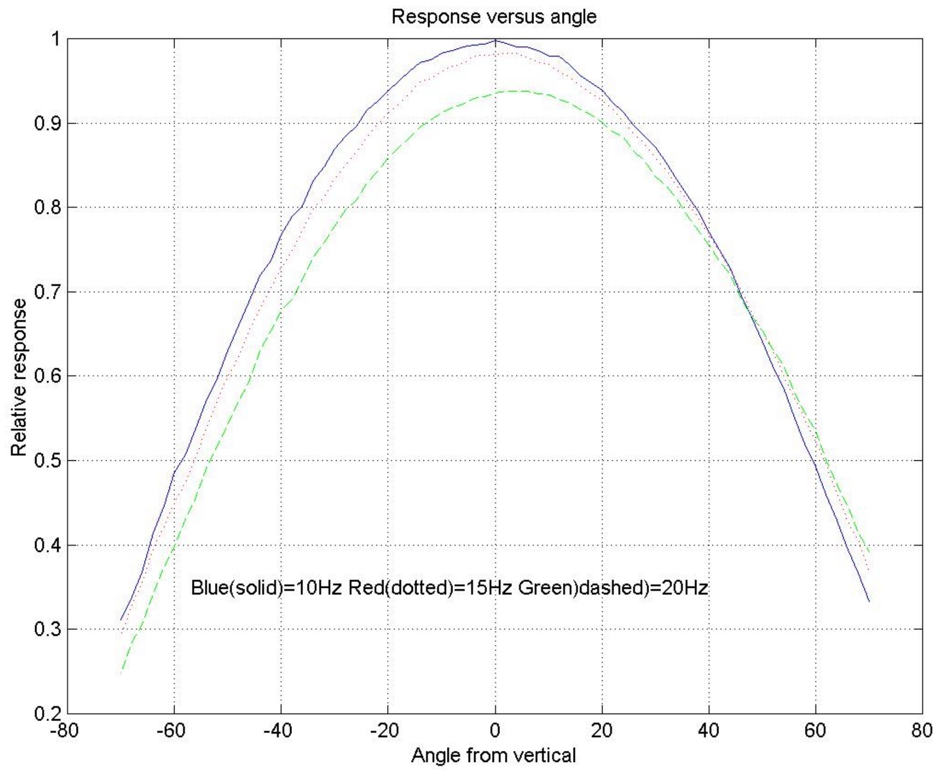

Figure 10. A second plot of output response at varying angle from the vertical.

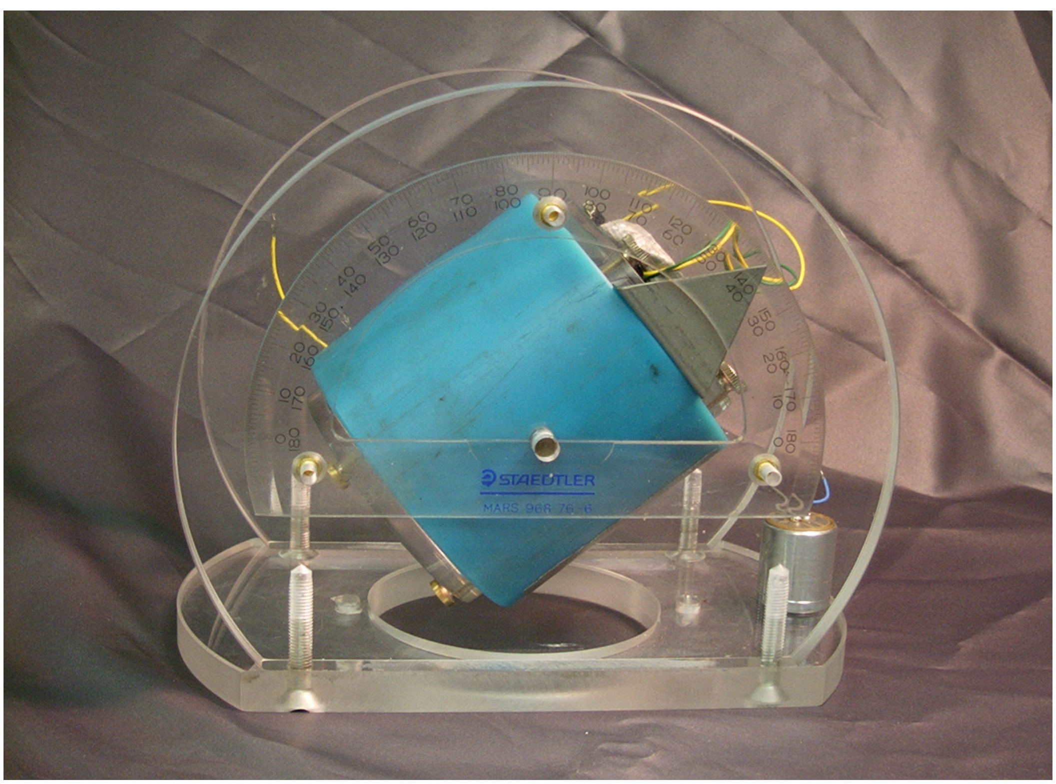

Figure 11. The jig for testing auto-levelling of the prototype geophone. The reference element is visible on the base.

Shown in Figure 12 is the plot of the relative output of the auto-levelling geophone at a frequency of 20Hz as the test jig is rotated from –80 degrees through vertical to +80degrees in 2 degree increments.

This shows clearly that the auto-orienting geophone does an excellent job of keeping the internal element vertical over the expected range of case angles (at least 30 degrees each side of vertical). The slight variation of the output ratio across the flat portion at the top of the plot is caused by the connecting wires having a stiffness sufficient to push the inner sphere slightly out of alignment. The variation is only about +/- 1.5% and is less than the variation of geophone output in the field caused by planting differences. The problem of stiff connecting wires is one area that needs to be addressed further with more experiments made on different types of coupling wire.

In the case of the 3 component geophone, the greater mass of the inner sphere reduces the problem significantly.

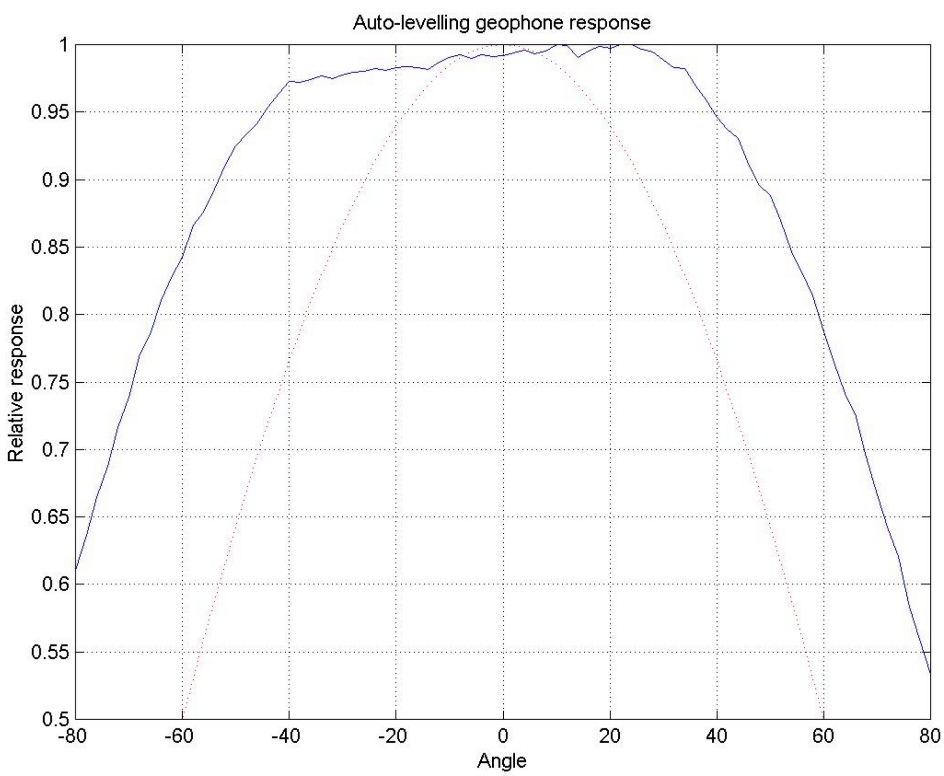

Figure 12. The output from the auto-levelling geophone over the range of angles 80 degrees each side of vertical. The theoretical element response curve (cosine) is also plotted for comparison.

Most seismic crews operating single component acquisition systems (vertical only) use strings of geophones (typically 6 or 9 at a time) spread over a distance along the surface of the ground and connected together electrically to output a single signal. With this approach, differences in the planting of each individual geophone (e.g. effects of angle or coupling) are averaged out over the string. In the case of a crew using a single geophone for each trace, the difference in geophone planting can be a significant factor in signal levels, causing problems in trace amplitude analysis in processing and interpretation. This is becoming a more important consideration as more and more detail is being demanded from the data in the early processing stages. As can be seen in the plot from the auto-levelling geophone above, the response over a range of +/- 30 degrees from vertical is within the 2% specification given in the data sheets.

Two more plots of auto-levelling tests are shown below (Figure 13 and 14). In these cases the test was run over the angles from –75 to +75 degrees, then the geophone was rotated 90 degrees in the holder and the test run again. This ensures that angular rotation in both vertical planes has been checked.

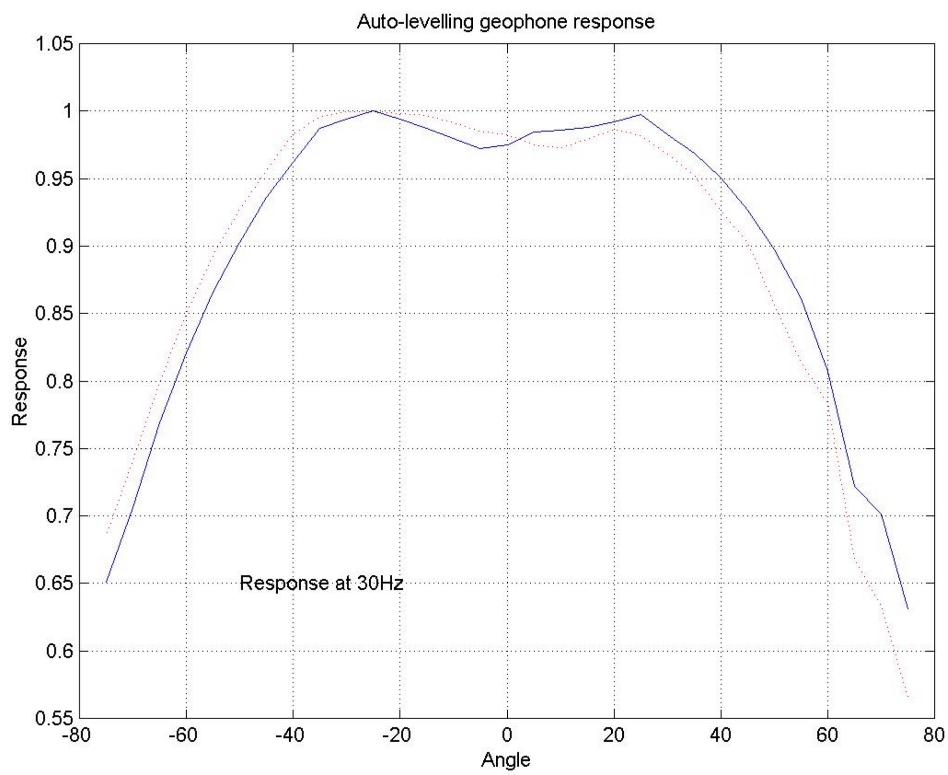

Figure 13. Response of the auto-levelling geophone at 30Hz.

The wire stiffness effect is again visible as the dip in the top portion of the plot. The blue line is the first test, and the red dotted line is the second test after rotating the geophone 90 degrees in the holder. Response linearity across the range of +/- 30 degrees is better than 1.5%.

Figure 14 shows the same measurements made at 100Hz. At this higher frequency, there is apparently some diaphragm distortion shown by the slope of the top of the plot. From –30 to +20 degrees, however, the response stays within +/-2 percent, with degradation of the signal between +20 and +30 degrees caused by the diaphragm distortion.

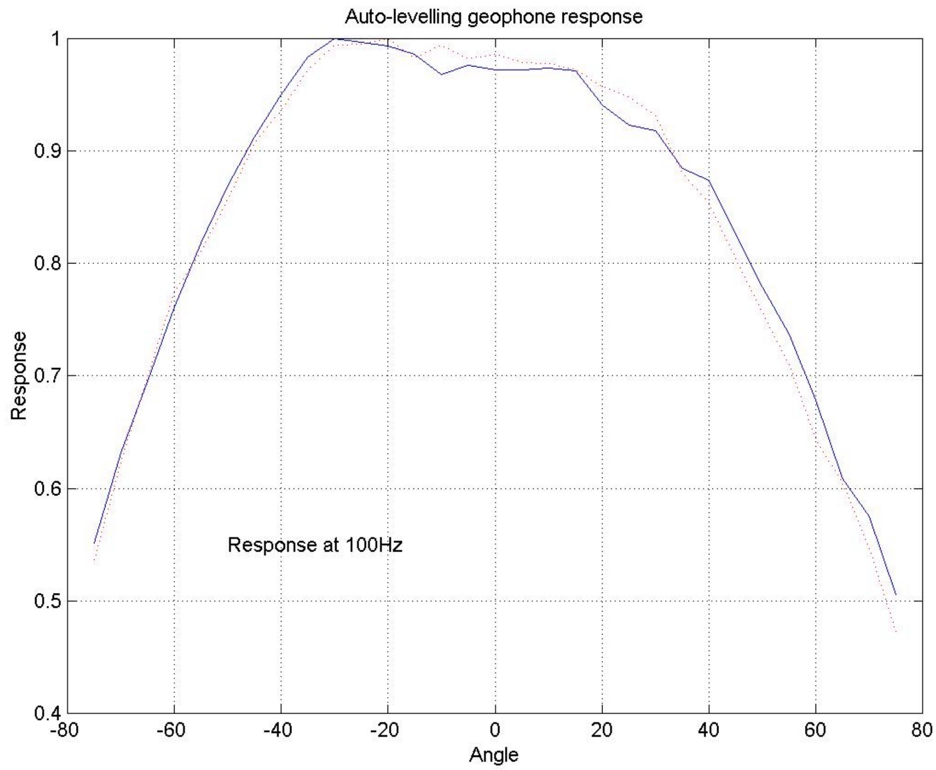

Figure 14. The response of the auto-levelling geophone at 100Hz.

COUPLING TESTS

One important factor to determine was the coupling between the outer case and the inner sphere. It is essential that the inner sphere follow the motion of the outer case as closely as possible.

Tests showed that if there is any air pocket in the chamber, then the free surface of the water would ripple causing extra noise internally, and the inner sphere had more freedom to move causing noise when it contacted the sides of the chamber. This was also a visible effect as the ripples on the water surface could be clearly seen through the top of the geophone. Expelling the air by adding more water fixed this problem and showed that the hydraulic coupling method worked very well. This air pocket effect was not as noticeable on the single component geophone as the chamber is much smaller.

Tests on all axes showed very good fidelity of signal from the internal geophone element when compared to the reference element attached to the outside of the case. The ratio of internal to reference signals was used as a measure of coupling over both frequency and amplitude and showed consistent results within the limits previously established by the comparison of element pairs.

The second test jig was used for testing the horizontal element response with the geophone suspended from a cable and coupled to the diaphragm by two flexible plastic rods as shown in Figure 15.

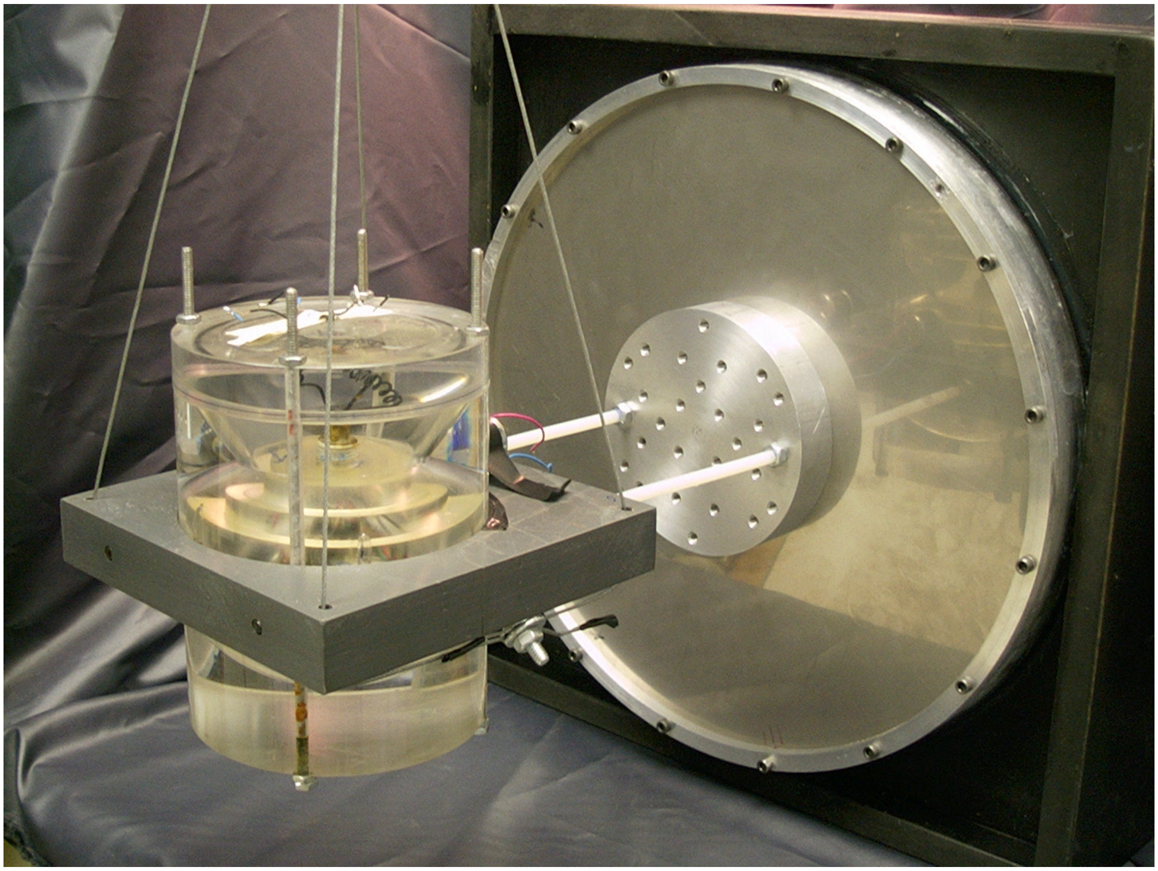

Figure 15. The test jig setup for measuring the horizontal element response over frequency and amplitude.

Figure 16 shows the test results of measuring response over the seismic frequency range for the horizontal axis of the 3 component geophone. In this case, the response stays within +/- 3% from 10Hz to 120Hz. The variations between 40Hz and 80Hz are a result of the test setup still having some torsional distortion effects from mechanical resonances. This affected the ratio of output from the internal and external elements as they were positioned in different locations on the jig. For this test, the external reference element was located directly in line with the internal element, but on the outside edge of the platform. The signal generator was adjusted to give the same amplitude at each frequency by using the laser interferometer to measure peak to peak displacement of the reference element. For this plot the amplitude was set to 30 micrometers.

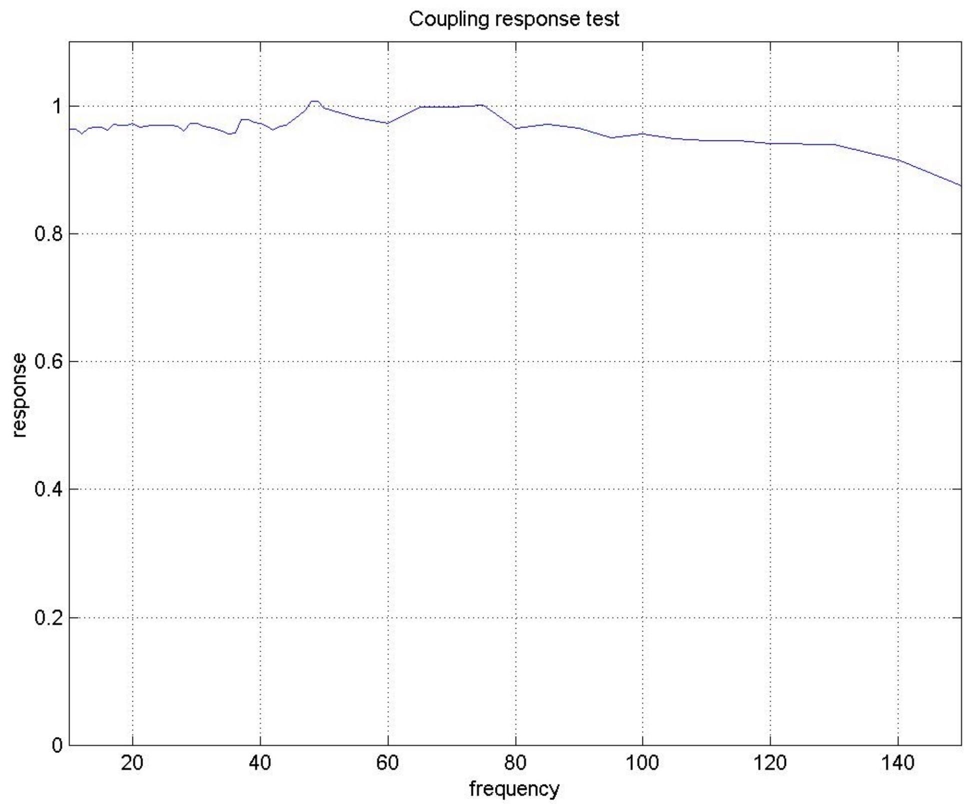

Figure 16. Horizontal element response in the 3 component geophone over frequency.

Figure 17 shows the amplitude linearity test at a fixed frequency of 10Hz. The low frequency was used so that the amplitude could be increased to a high level without exceeding an acceleration limit of g. The x axis shows the signal generator output in volts peak to peak. In this case the linearity is excellent, with a variation of only about 1% over the whole range. Other frequencies gave equally good linearity, but the amplitude range was limited because of the acceleration exceeding safe levels.

Figure 18 shows a test run of the vertical element over the frequency range 20 to 90Hz. In this run no attempt was made to normalize the test jig amplitude as was done for the horizontal element plot of Figure 16. Tests of amplitude linearity produced similar results to the plot for the horizontal elements.

These tests show that the coupling between the outer case and the inner sphere is good over the seismic frequency range, and over a range of displacement.

If the inner sphere did not follow the motion of the outer case, then some phase lag would be expected from the inner element. There was no significant variation measurable in the tests over all frequencies. As an example of the data acquired during these tests, Figure 19 is a plot of the first portion of two traces (internal element and external reference element) captured at the frequency of 15Hz.

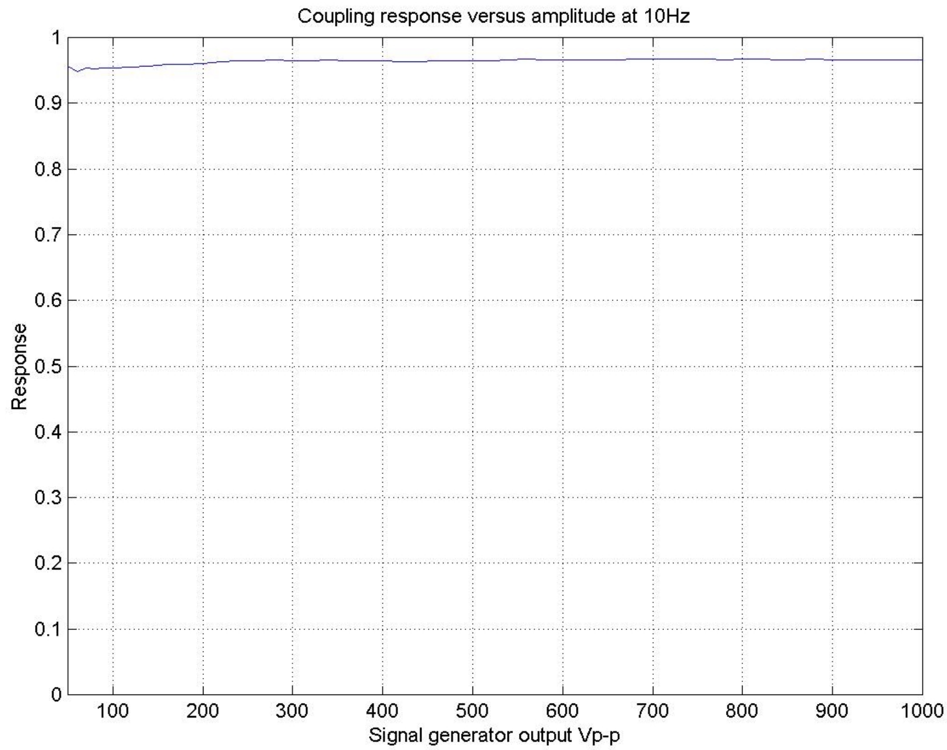

Figure 17. Horizontal element response in the 3 component geophone over amplitude at a frequency of 10Hz

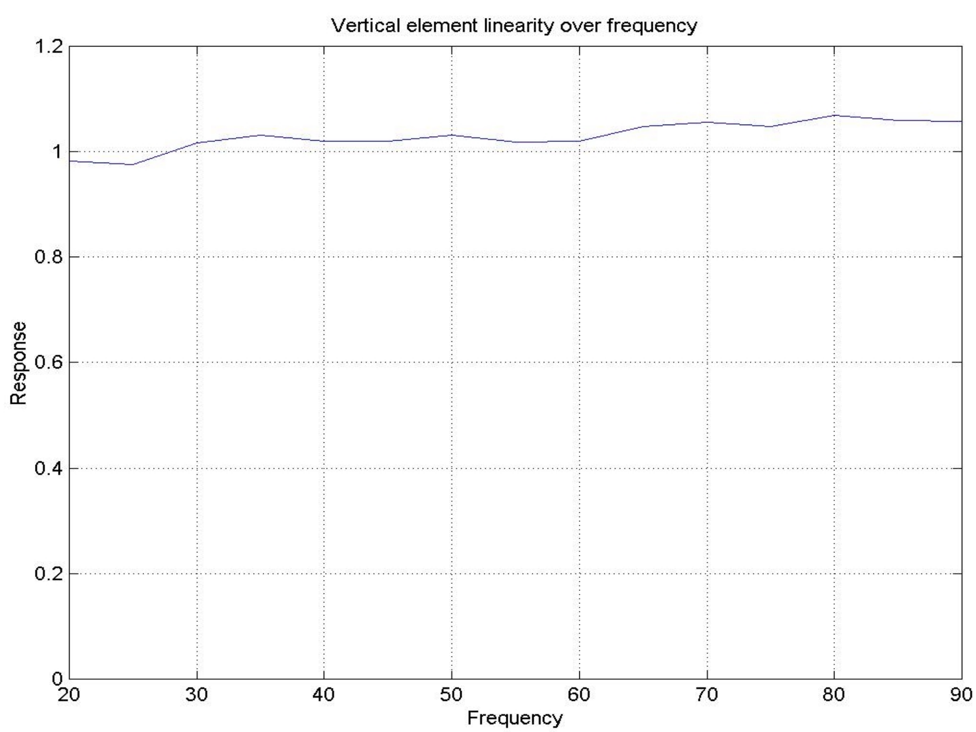

Figure 18. Vertical element response over frequency.

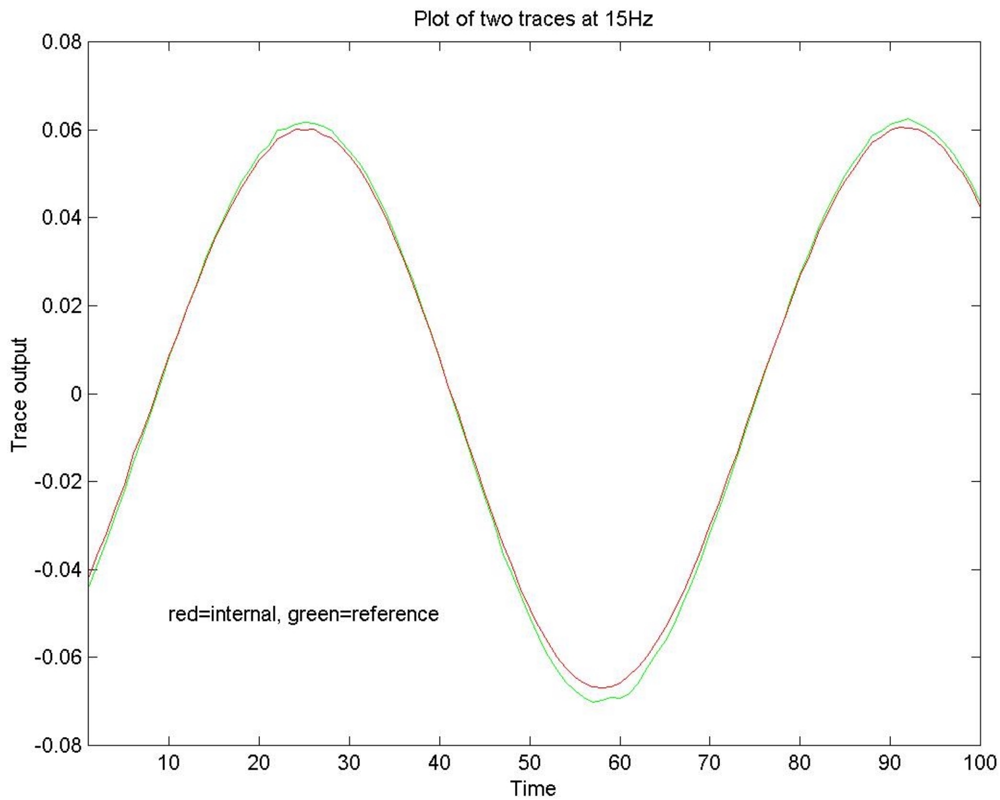

Figure 19. Plot of the first portion of the traces captured at 15Hz for phase analysis. The curve with slightly greater amplitude is the reference element.

OTHER TESTING OF THE HORIZONTAL ELEMENTS

Much of the testing of the horizontal elements was to make sure that there was no cross coupling or spurious effect within the inner sphere. The outputs of the inline and crossline elements were measured and the geophone rotated to minimize the crossline output. The axes were then compared over a range of frequency and displacement to determine whether there was any outer case motion being converted to rotational motion of the inner sphere. There was no measurable effect discernible in the test data acquired.

PENDULUMING

As with any gravity driven auto-levelling system, it is necessary to have the centre of mass of the inner sphere below the geometric centre so that the inner sphere will rotate to the upright position. This means that with a sideways motion of the case, the inner sphere can be expected to pendulum to some extent. The amplitude of pendulum motion and its frequency will vary with the distance between the centre of mass and the geometric centre, and with the total mass of the inner sphere.

The test geophones do indeed show a pendulum motion when shaken side to side, but the frequency at which the pendulum motion becomes resonant is at about 1Hz. This is when using water as the supporting fluid. With a more viscous fluid, the frequency and amplitude will drop or be eliminated. At frequencies above 2Hz, there is no visible pendulum motion.

All attempts to measure the effect of the pendulum motion failed, as the test geophones use 10Hz elements and the output is too low and noisy to make useful measurements when the jig is driven at any frequency below 4 Hz. An attempt will be made at some point to use the laser interferometer to measure pendulum motion, but this will involve modifying the test geophones physically, and this will not be attempted until all other testing has been completed.

CONCLUSIONS

The auto-orienting geophone concept is valid and has been shown to work in a laboratory setting. Between the physical stops internally the auto-levelling method keeps the elements within angular design limits.

The use of this geophone in a seismic survey using a single geophone at each trace location will deliver superior trace to trace consistency in amplitude response over a standard geophone because of better vertical alignment of the elements. The simplified planting logistics particularly in the case of 3 component geophones would increase crew efficiency, thereby improving productivity.

Coupling between the outer case and the inner sphere appears to be very good, with no measurable phase lag or amplitude change apparent over the seismic frequency range. Isolation between orthogonal elements in the 3 component geophone is comparable to that in a standard 3 component geophone

Pendulum motion does occur with a low viscosity fluid (e.g. water) but the resonant frequency is too low to be a problem. At higher frequencies the amplitude of pendulum oscillation is too low to be measurable with the current test setup. Most commercial geophone manufacturers do not seem to feel that pendulum motion is a major problem.

FUTURE WORK

A natural extension of this design is to the marine case. We envisage a 4-component instrument (3-C geophone and hydrophone) that would be encased in a cylindrical mold to lie in the sea floor . Figure 20 shows the prototype for this application, with the cylindrical outer case designed to lie horizontally on the sea floor.

Another design issue to tackle is connecting the geophone elements to an external recording unit through a method other than the current connecting wires (the problem with wire stiffness has been covered in this report). Brushes, other contacts or inductive connectors could be used, or a more active method involving radio, ultrasonics or optical signal transfer might be possible.

Field testing of the auto orienting geophones will be undertaken in the next few months to compare them with a standard geophone.

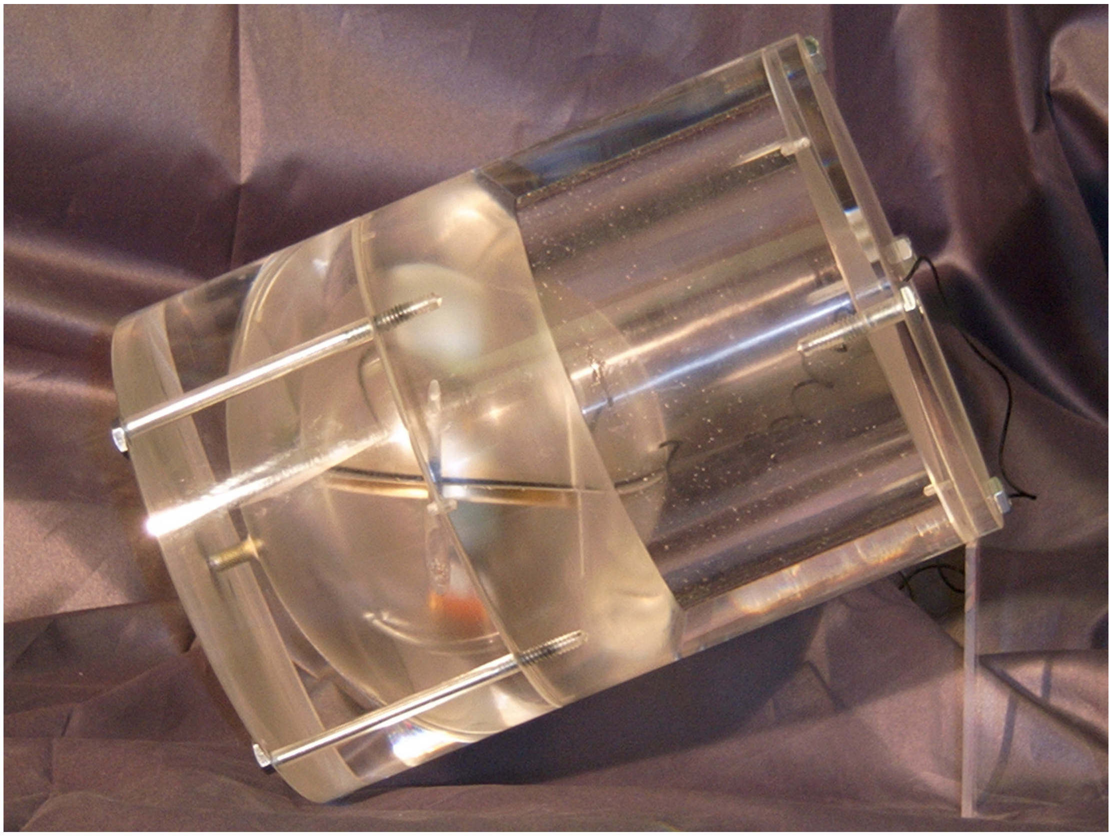

Figure 20. The prototype OBC (Ocean Bottom Cable) device.

ACKNOWLEDGEMENTS

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