UNIVERSITY OF
Southampton
Institute of Sound and
Vibration Research

ISVR Technical Memorandum

# Mapping the Underworld Multi-Sensor Device Creation, Assessment,Protocols: Acoustic Technologies Advancement to Support Multi-Sensor Device
# An Assessment of the Use of a Scanning Laser to Measure Ground Vibration

J.M. Muggleton

ISVR Technical Memorandum No 986
January 2010

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INSTITUTE OF SOUND AND VIBRATION RESEARCH

DYNAMICS GROUP

**Mapping the Underworld**
**Multi-Sensor Device Creation, Assessment, Protocols: Acoustic Technologies**
**Advancement to Support Multi-Sensor Device**
**An Assessment of the Use of a Scanning Laser to Measure Ground Vibration**

by

**J.M. Muggleton**

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January 2010

Authorised for issue by
Professor Brian Mace
Group Chairman

## SUMMARY

This report concerns experimental work undertaken at ISVR under the EPSRC-funded 'Mapping the Underworld' programme, phase 2, EP/F065973/1. In the experimental work reported here, using a scanning laser is compared with using geophones for the measurement of ground vibration at low frequencies (typically <500Hz).

The performance of the sensors was compared on a number of different ground surfaces. For all the surfaces, there was general agreement between the laser data and the geophone data; the laser performed better on some surfaces than others, but the laser data was consistently of poorer quality than the geophone data. Surface velocity was found to be the key factor in determining data quality, rather than the surface texture itself; for most of the tests, the surface velocities were close to the laser system noise floor.

A number of ways to improve data quality were investigated including altering the surface texture, either by removal of surface dust/grit or by applying retroreflective tape, high pass filtering, signal averaging, both spatially and in the time/frequency domain, and using different types of input signal.

Finally, effects of the laser stand-off distance were assessed.

# CONTENTS

# 1. INTRODUCTION

This report concerns experimental work undertaken at ISVR under the EPSRC-funded 'Mapping the Underworld' programme, phase 2 [1], EP/F065973/1. Mapping the Underworld phase 2 aims to create a novel multi-sensor device that combines complementary technologies for remote buried utility service detection, location and, where possible, identification, without resorting to extensive excavations. An essential technology to be combined into the device is low-frequency acoustics, and suitable techniques for detecting buried infrastructure, in particular buried plastic water pipes, have been proposed. Initial investigations of these techniques were undertaken in phase 1 and further refinement is planned for phase 2.

Both proposed acoustic techniques rely on vibrational excitation of the ground or infrastructure as it comes up to the surface and subsequent measurement of the ground surface vibration in the vicinity. Up until now, geophones have been used for this ground surface measurement. The experimental work reported here focuses on using a scanning laser instead of geophones, the main perceived advantage being that a laser system would be non-contact. Here, data acquired using both geophones and a laser vibrometer are compared. In section 2 the sensors used and the basic experimental setup are described along with the measurement configurations used for all the tests. In section 3 a variety of ground surfaces are investigated along with other factors, such as signal level and stand-off distance, in order to determine the potential scope of a laser system for this application. Ways to improve data quality are then explored. In section 4, plans for future work under the Mapping the Underworld programme are outlined. Finally, some conclusions are drawn, underpinning the next phase of the experimental programme.

# 2. EXPERIMENTAL SETUP

## *2.1 Laser vibrometer*

The laser equipment used in these experiments was a Polytec PSV-400 3-D scanning laser Doppler vibrometer, on loan from the EPSRC engineering instrument loan pool. It has three independent scanning vibrometer sensor heads and controllers, allowing vibration velocity measurements to be made simultaneously from three different directions for each respective sample point. Once the laser heads have been aligned properly, the full three-dimensional vibration velocity at each point can then be calculated automatically. The 3D measurement configuration is shown in Figures 1(a) and 1(b).

(a)

(b)

Figure 1

PSV-400 3D scanning laser vibrometer

(a) vibration controllers and data management system; (b) scanning heads in 3D mode

Early tests revealed that, using the system in full 3D mode, the setting up procedure was complicated and rather lengthy, involving ensuring that the lasers were all pointing at the same location (2D alignment), camera focusing, laser focusing and then defining a 3D coordinate system relative to the object to be measured, in this case the ground surface (3D alignment). This would have to be repeated for each measurement area to be scanned. With the laser heads approximately 1.5m above the ground surface, the scanning area would be approximately one square metre. It was decided that measurement in this mode of operation would be impractical, both in the longer term as a component of the multi-sensor device, and in the short term for comparing the laser performance with that of a geophone. An alternative mode was possible, in which one sensor head was used alone, providing simple one-dimensional measurements. A minimal amount of setting up was required in this mode (camera focusing, laser focusing, and a 2D alignment to ensure the camera and the laser were pointing at the same spot- essential for defining the scan points). A laser head set up in this mode is shown in Figure 2.

Figure 2

Laser head in 1D mode

## 2.2 *Geophone*

The geophone used for comparison was an I/O SM-24 vertical geophone. Mounting on the ground surface is possible using either a ground spike, where surface penetration is possible and practical, or a tripod, where it is not. Measurements using both forms of mounting show that the spike and the tripod give almost identical results, so are therefore interchangeable. These measurements are reported in detail in Appendix I.

## 2.3 *Measurement configurations*

The laser system allows for a number of scan points to be defined before a measurement run is executed. Given that it was not possible to exactly collocate the geophone and a scan point, for each test run, ten scan points were defined around the geophone, as shown in Figure 3. The offsets were small compared to the wavelengths of interest (typically ~10m @ 10Hz down to ~0.25m @ 400Hz), but having a number of scan points allowed for the possibility of averaging the data to reduce the effects of both the offset (most noticeably slight differences in measured phase) and noise, or excluding extraneous measurements

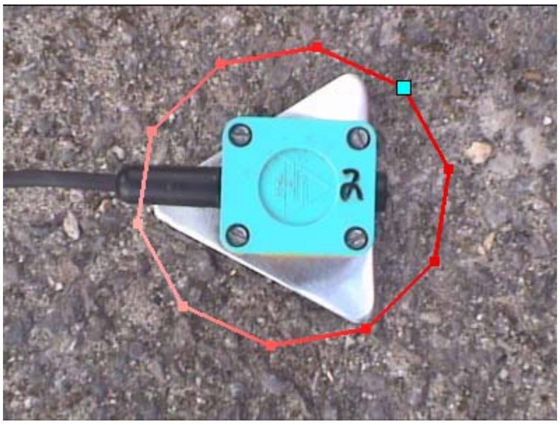


Figure 3

Geophone and laser scan points

# 3. MEASUREMENTS

For all the tests, the ground was excited with a Wilcoxon electrodynamic shaker placed on the ground. The geophone data was acquired through the laser system, as was the voltage input to the shaker, to be used as a reference. Early tests revealed that whilst the geophone measures positive velocity upwards, the laser measures positive velocity outwards (in this case downwards), so the phase of the laser measurements was reversed for all subsequent measurements. For all tests the topsoil (where present), typically down to a depth of 30-50cm, was a sandy silt, with the subsoil (extending down to ~2m or more) being similar, but with a higher clay content. This is typical of the soils found in the chalk river valleys of West Dorset.

## *3.1 Baseline measurements- coarse sand*

Initially measurements were made on ground where the surface layer was coarse sand. The shaker was excited with a periodic chirp from 1Hz-400Hz; the measurement frequency resolution was set at 1Hz. The time taken to acquire the data (set by the vibrometer software and determined by the frequency resolution) was approximately 1s per scan point, i.e. ~10s in total, provided that no scan points had to be remeasured (again determined by the vibrometer software, dependent on the quality of the data acquired). At this stage no averaging was employed. The laser stand-off (distance from the laser source to the ground) was set as close to 507mm as possible♣. For these measurements the tripod was used for mounting the geophone, as shown in Figure 4. The 10 scan points are also shown. The shaker was located on the ground approximately 0.5m from the measurement location in the direction of the arrow shown in the figure.

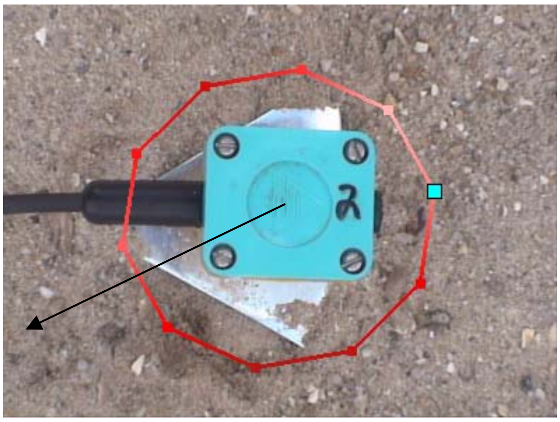


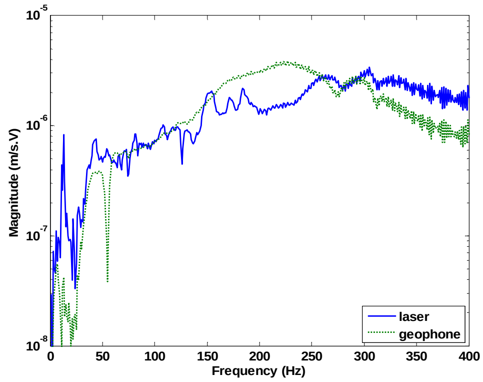
Figure 4

Geophone and laser scan points

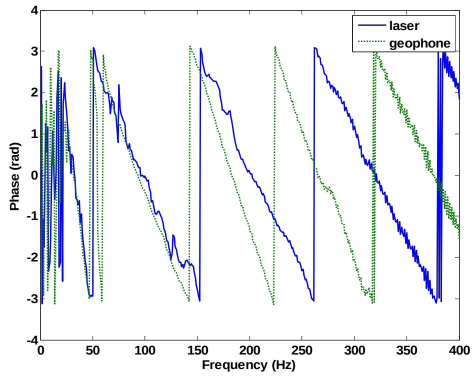
The highlighted point is scan point ‘1’; they are then numbered sequentially clockwise. The shaker is located approximately 0.5m from the geophone in the direction in which the arrow is pointing.

♣Optimal stand-off distances for the laser are 99 mm+204**n** mm where **n** is an integer. 507mm was the smallest stand-off distance that was possible using the supplied tripod.

For each measurement point, and for the geophone output, the cross power spectrum between the measured velocity and the voltage input to the shaker was determined. Figure 5 shows the magnitude and the phase for the laser data at scan point 1 and for the geophone data.




(a)




(b)

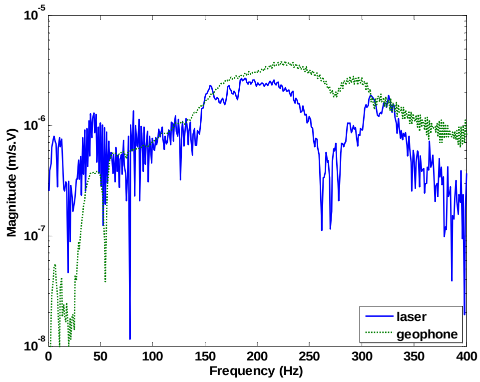
Figure 5

Comparison between laser (scan point 1) and geophone measurements – cross power spectrum

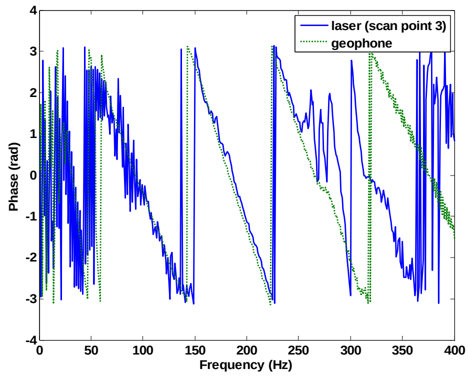
(a) magnitude; (b) phase.

Figure 5a shows that above approximately 30Hz, in general, there is good agreement in the magnitude information between the two sets of data. The geophone data exhibits a 50Hz spike, which is not uncommon in geophone measurements[♠]; this is not present in the laser data, as the laser is not directly coupled to the ground. Overall the laser data is noisier than the geophone data. This was found to be true of all the laser scan points, with scan point 1 being one of the least noisy. Scan point 3 was found to be the most noisy, and this is shown for comparison in Figure 6. Figure 5b shows that, at low frequencies, there is good agreement in the measured phase, but the laser data exhibits an increasing phase lag for higher frequencies. This is to be expected given that the geophone centre and the laser scan point are not collocated and the scan point is further from the source of vibration than the geophone. Estimating the offset in the direction of wave propagation to be approximately 5cm, and noticing that the phase lag is equal to pi at approximately 350Hz, this gives the surface wavespeed as around 35m/s, which is rather lower than expected (typically one might expect a wavespeed at least twice this value. Figure 7 shows the phase

[♠] Often, spikes at odd harmonics of 50Hz are also observed measured at scan point 6, the nearest to the excitation point. Here the laser data is in good agreement with the geophone data at all frequencies, and there is no significant phase difference. This rather suggests that the geophone was more in contact with the ground in the region of scan point 6 than scan point 1; if one then takes scan point 6 as the contact centre for the geophone, then the estimated surface wavespeed using the phase lag information from scan point 1 becomes 70m/s, which is much more plausible.




(a)




(b)

Figure 6

Comparison between laser (scan point 3) and geophone measurements – cross power spectrum

(a) magnitude; (b) phase

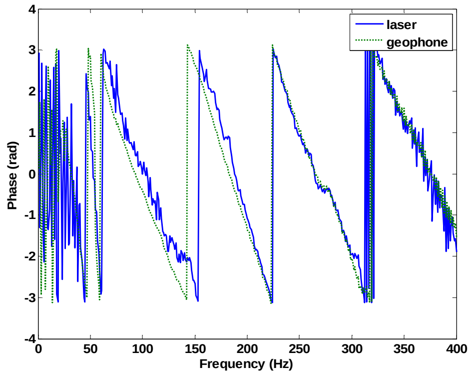
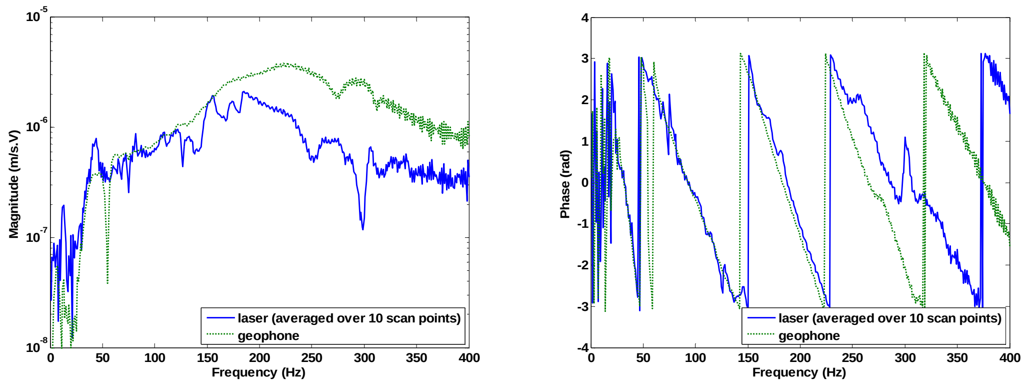



Figure 7

Comparison between laser (scan point 6) and geophone measurements – cross power spectrum

Figure 8 shows the magnitude and the unwrapped phase for the laser data, averaged over the ten scan points, and for the geophone data.




(a) (b)

Figure 8

Comparison between laser and geophone measurements – cross power spectrum

(a) magnitude; (b) phase.

The figures show that there is good agreement between the geophone data and the spatially averaged laser data at frequencies up to approximately 150Hz for the magnitude information, and up to approximately 250Hz for the phase. Above 250Hz, the laser data lags the geophone data; this is probably due to the contact centre of the geophone being not quite where anticipated. Again the 50Hz spike in the geophone data is evident in both plots. However, even for the spatially averaged data, with the exception of the 50Hz spikes, the laser data is of poorer quality than the geophone data.

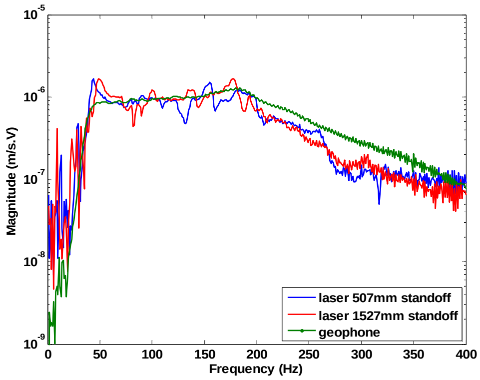
For reference purposes, the measured velocity magnitude measured with the geophone is shown in Figure 23 in section 3.3, where the velocities measured on different surfaces are compared. Velocities above 100Hz were found to be of the order of 10μm/s; this corresponds to surface displacements of between about 5 and 15nm at most of the frequencies.

## *3.2 Effect of stand-off distance*

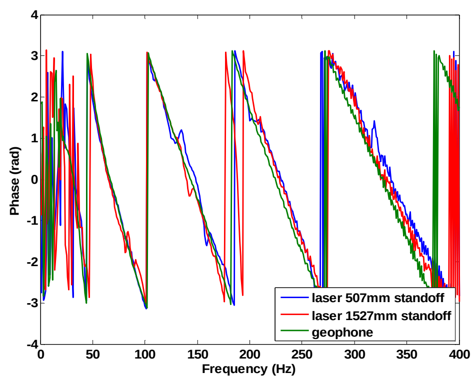
Optimal stand-off distances for the laser are 99 mm+204**n** mm where **n** is an integer. 507mm was the smallest stand-off distance that was possible using the supplied tripod, with 1527mm being the largest. Most of the measurements were carried out with the smallest stand-off distance. However, to examine the effect of stand-off, the following optimal stand-offs were tested: 507mm; 711mm; 915mm; 1119mm; 1323mm; and 1527mm. At each stand-off, camera focusing, laser focusing, and a 2D alignment was performed. The scan points were then redefined.

No significant difference was observed in the quality of the measured data at any of the stand-off distances, although there were small differences in the actual data due to the alignment points not being in exactly the same place for each run. This is not surprising given that using the laser system, measurement ranges of up to 100m are possible.

Figure 9 shows the laser data averaged over all ten scan points for the 507mm stand-off and the 1527mm stand-off (representing the stand-off extremes tested). As before, it can be seen that the spatially averaged laser data is noisier than the geophone data, but there is no noticeable difference between the two laser stand-offs. The one exception to this is a sudden dip in the phase in the 1527mm stand-off data at around 200Hz, but this was not thought to be significant as, if the phase data was unwrapped, the dip would all but disappear.




(a)




(b)

Figure 9

Effect of stand-off distance – cross power spectrum

(a) magnitude; (b) phase

For these tests the reference voltage used was that supplied to the shaker power amplifier.

## *3.3 Different ground surfaces*

Of particular importance in this project is the ability to make ground vibration measurements on a variety of different ground surfaces. The following six surfaces were tested, and the results from the laser compared with the geophone outputs: coarse sand (baseline – see section 3.1); concrete; tarmac, gravel; soil; and grass. Although this is not a comprehensive set, these surfaces were readily available at the test site and were considered to be representative of the surfaces likely to be encountered in practice. For all tests, the shaker was excited with a periodic chirp from 1Hz-400Hz, again with a measurement frequency resolution of 1Hz. The shaker was again placed approximately 0.5m from the measurement point for each test. For each measurement point, and for the geophone output, the cross power spectrum between the measured velocity and the voltage input to the shaker was again determined.

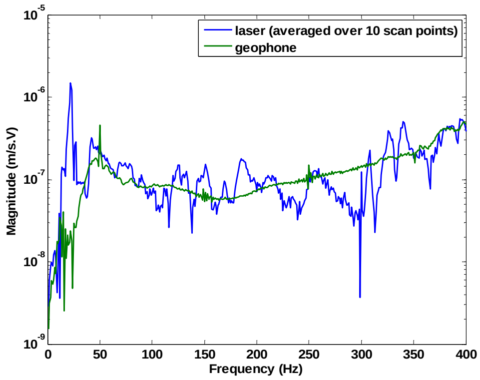
### *3.3.1 Concrete*

The concrete on the test site was that typically used as a floor screed. The measurement configuration with the scan points is shown in Figure 10. For this test, the tripod was used for the geophone. The data was classified as optimal, by the scanner software, for all the scan points, and no re-measurement was required.

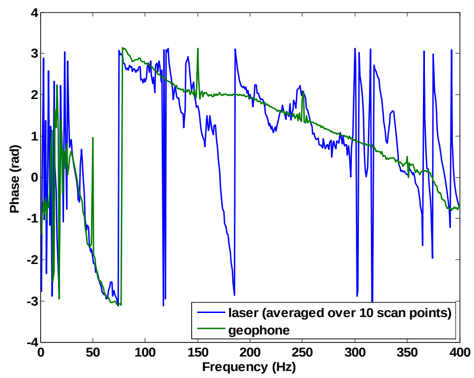
Figure 10

Geophone and laser scan points – concrete

Figure 11 shows the laser data averaged over all ten scan points compared with the geophone data. At all frequencies there is reasonable agreement in the magnitude data, but there is some variation around the smoother line of the geophone data. On average there is good agreement in the phase data, but again there are large variations. Unwrapping the phase data reduces the appearance of these variations as shown in Figure 12. Here it can be seen that the agreement is, in fact, good for frequencies between about 30Hz and 150Hz. With the exception of one scan point (point 9, which was in shadow at the top of the picture in Figure 10), the data from all the separate scan points are very similar. The data from scan point 9 (not shown) was noticeably more noisy.




(a)




(b)

Figure 11

Comparison between laser and geophone measurements for concrete – cross power spectrum

(a) magnitude; (b) phase.

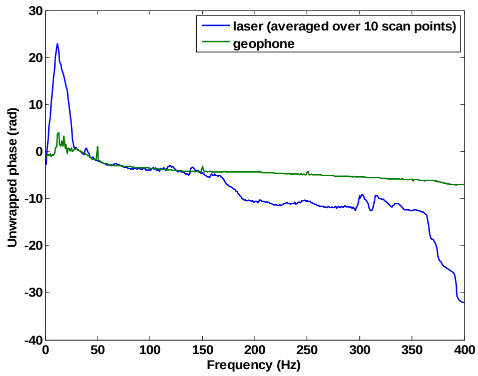



Figure 12

Comparison between laser and geophone measurements for concrete – cross power spectrum: unwrapped phase

The measured velocity magnitude measured with the geophone is shown in Figure 23 in section 3.3. Velocities were found to be of the order of 1μm/s at most frequencies; this corresponds to surface displacements of a between about 0.5 and 5nm at most of the frequencies.

### *3.3.2 Tarmac*

The tarmac on the test site was that used typically on domestic drives. The measurement configuration with the scan points is shown in Figure 13. For this test, the tripod was used for the geophone. The data was classified as optimal, by the scanner software, for all the scan points, and no re-measurement was required.

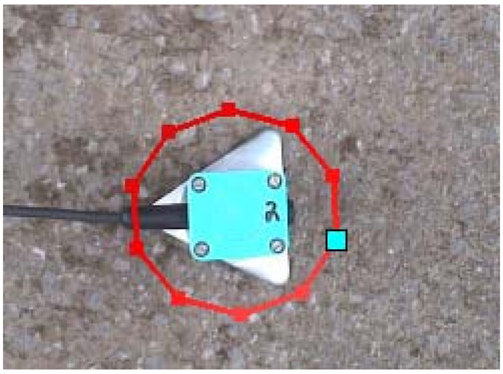
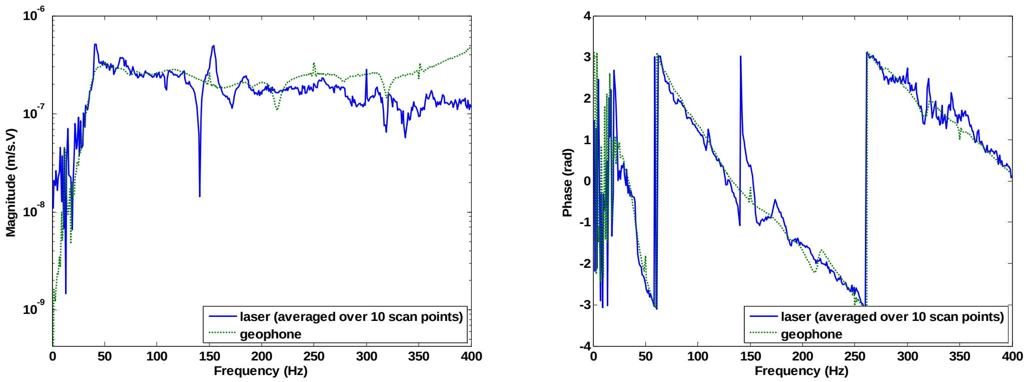


Figure 13

Geophone and laser scan points – tarmac

Figure 14 shows the laser data averaged over all ten scan points compared with the geophone data. There is reasonable agreement in the magnitude data between about 30Hz and 200Hz, with some variation around the smoother line of the geophone data. There is good agreement in the phase data above about 30Hz, with the exception of a spike in the laser data at around 150Hz. Unwrapping the phase data results in a phase jump at 150Hz, after which the gradients in the phase match again (not shown). At all frequencies, the laser data is noisier than the geophone data. The data from all the separate scan points are similar and not shown here.




(a) (b)

Figure 14

Comparison between laser and geophone measurements for tarmac – cross power spectrum

(a) magnitude; (b) phase.

The measured velocity magnitude measured with the geophone is shown in Figure 23 in section 3.3. Velocities were found to be of the order of 1μm/s above 50Hz; this corresponds to surface displacements of a between about 0.5 and 5nm at most of the frequencies.

### *3.3.3 Gravel*

The gravel on the test site was 20mm shingle. The measurement configuration with the scan points is shown in Figure 15. For this test, the tripod was used for the geophone. The data was classified as optimal, by the scanner software, for all the scan points, and no re-measurement was required.

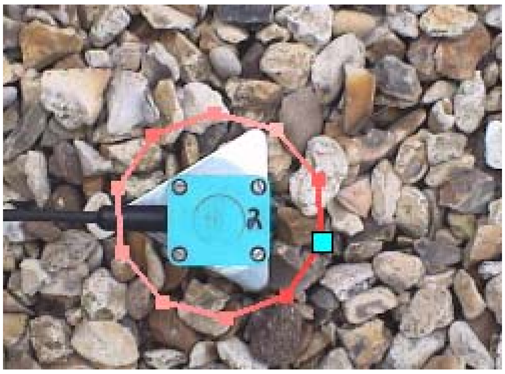
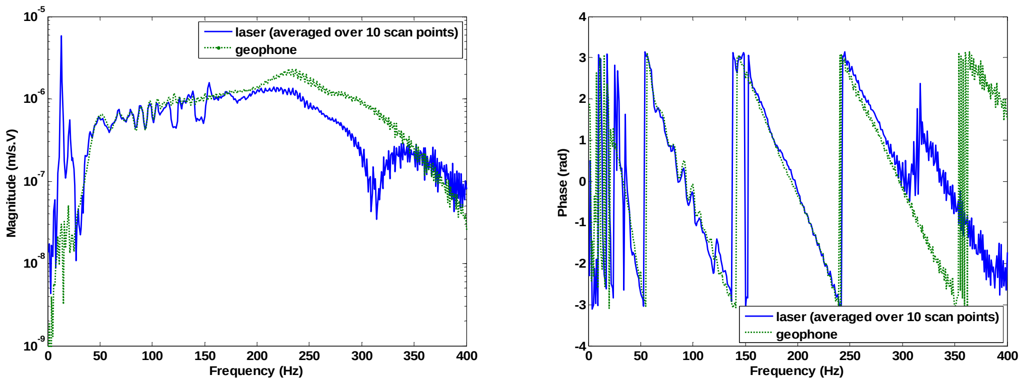


Figure 15

Geophone and laser scan points – gravel




(a) (b)

Figure 16

Comparison between laser and geophone measurements for gravel – cross power spectrum

(a) magnitude; (b) phase.

Figure 16 shows the laser data averaged over all ten scan points compared with the geophone data. There is reasonable agreement in the magnitude data, (a), between about 30Hz and 200Hz, with some variation around the smoother line of the geophone data. There is good agreement in the phase data between about 30Hz and 300Hz, with the exception of a spike in the laser data at around 150Hz. Unwrapping the phase data removes this spike (not shown).

The data from all the separate scan points are similar and not shown here.

The measured velocity magnitude measured with the geophone is shown in Figure 23 in section 3.3, where the velocities measured on different surfaces are compared. Velocities between 100Hz and 300Hz were found to be of the order of 10μm/s; this corresponds to surface displacements of between about 5 and 15nm.

### *3.3.4 Soil*

The soil on the test site was as described at the beginning of section 3. The measurement configuration with the scan points is shown in Figure 17. For this test, the spike was used for the geophone. The data was classified as optimal, by the scanner software, for all the scan points; some re-measurement was required, resulting in a total scan time of 16s (approximately 1.5 times the time required without re-measurement).

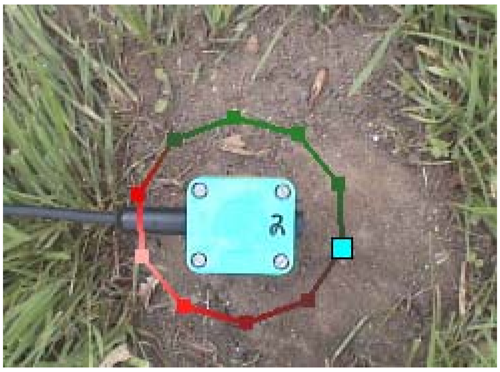
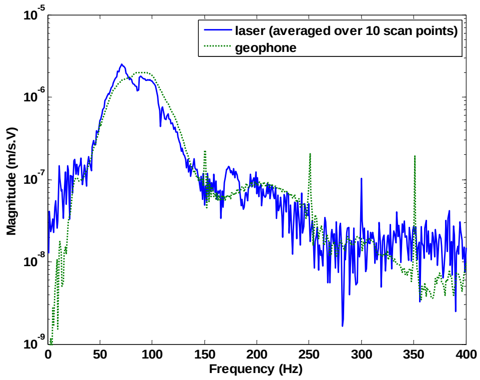


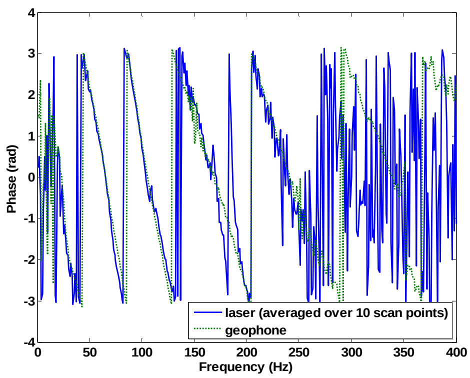
Figure 17

Geophone and laser scan points – soil

Figure 18 shows the laser data averaged over all ten scan points compared with the geophone data. There is reasonable agreement in both the magnitude and phase data, between about 30Hz and 300Hz, with some variation around the smoother line of the geophone data; the agreement is good up to about 15Hz. Above this frequency, the laser data becomes increasingly noisy.




(a)




(b)

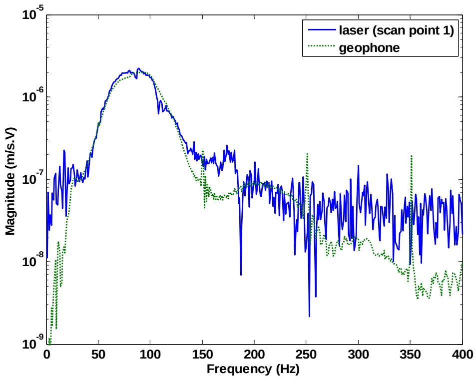
Figure 18

Comparison between laser and geophone measurements for soil – cross power spectrum

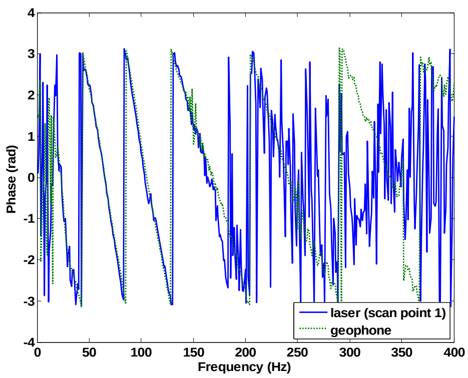
(a) magnitude; (b) phase.

Examining the data from the individual scan points, the data is markedly better for some points than for others.

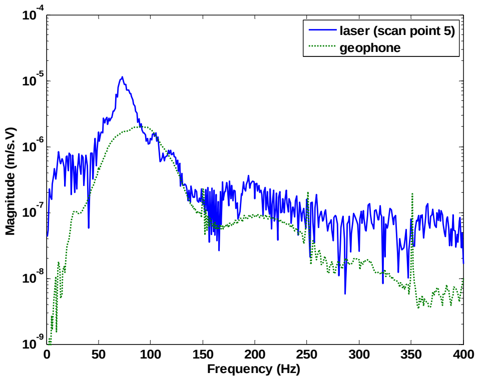
The plots in Figure 19 are representative of the best and worst cases. In the best case, (a) and (b), the magnitude data compare well from about 30Hz up to 130Hz, with the phase data matching well up to about 170Hz. In the worst case, (c) and (d), the agreement is not good in either the magnitude or the phase at any frequency.



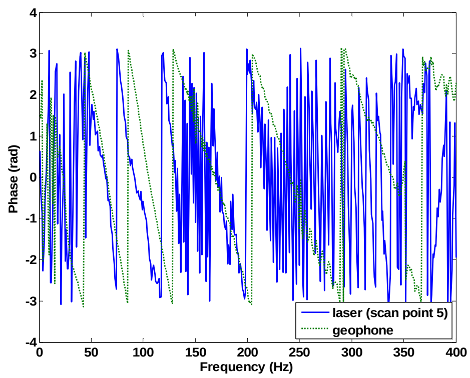

(a)




(b)




(c)




(d)

Figure 19

Comparison between laser and geophone measurements for soil, best & worst scan points– cross power spectrum

(a) best case magnitude; (b) best case phase; (c) worst case magnitude; (d) worst case phase

The measured velocity magnitude measured with the geophone is shown in Figure 23, in section 3.3. The velocity peaks at about 10µm/s at 100Hz and then drops to about 0.1µm/s/ by 300Hz. These velocities represent a peak surface displacement of approximately 15nm at 100Hz.

### *3.3.5 Grass*

The grass on the test site was rough grass, recently mown. The measurement configuration with the scan points is shown in Figure 20. For this test, the spike was used for the geophone. Of all the surfaces tested, it was anticipated that grass would be the least satisfactory. However, the data was classified as optimal, by the scanner software, for all the scan points. Some re-measurement of points was required, resulting in a total scan time of approximately 20s (i.e. double the time for the hard surfaces).

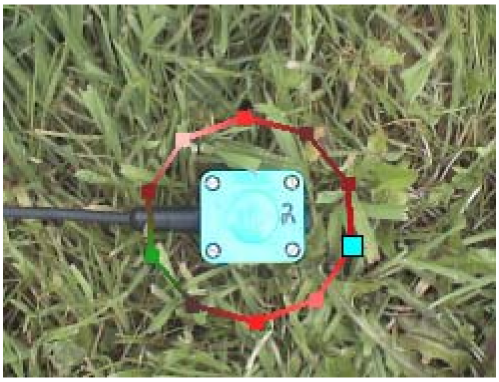
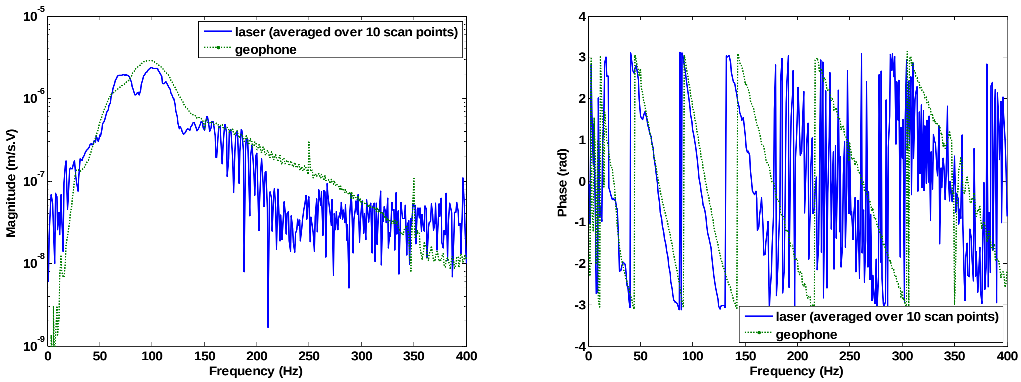


Figure 20

Geophone and laser scan points – grass

Figure 21 shows the laser data averaged over all ten scan points compared with the geophone data. Between about 30Hz and 100-150Hz there is good agreement between the geophone and spatially averaged laser data, with the laser data being only slightly noisier than the geophone data. At higher frequencies, the laser data becomes increasingly noisy and the magnitude and the phase information no longer compare well. That there is such good agreement at all over a reasonable frequency range is encouraging. At low frequencies, the ground/grass coupled system will behave as a base-excited single degree of freedom system for which (at low frequencies, well below the first resonance of the blade of grass) the velocity seen at the grass blade tip will equal that of the ground beneath. The shorter the grass, the higher that first resonant frequency, and so potentially the wider the useful frequency range.



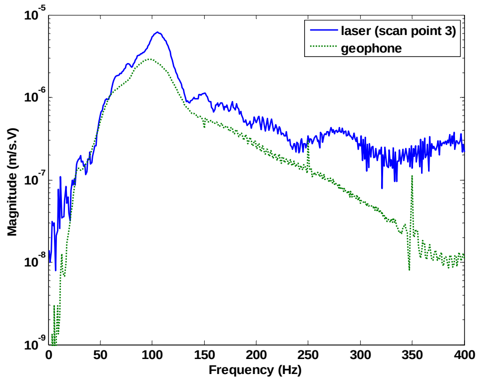

(a) (b)

Figure 21

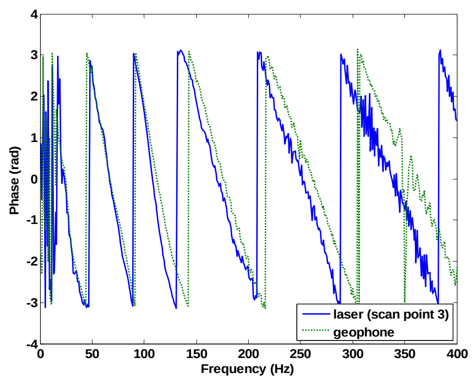
Comparison between laser and geophone measurements for grass – cross power spectrum

(a) magnitude; (b) phase.

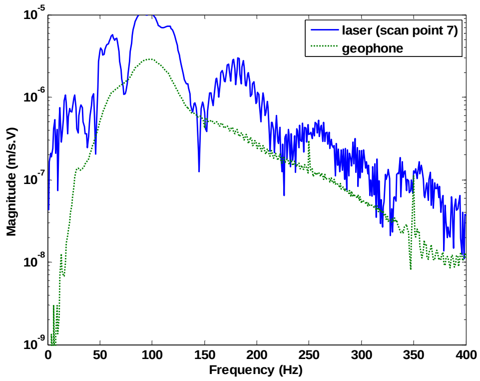
Examining the data from the individual scan points, the data is markedly better for some points than for others. Figures 22(a)-(d) are representative of the best and worst cases (note that the phase would not be expected to match up exactly due to the slight spatial offset). In the best case, (a) and (b), although the magnitudes do not match exactly, the phase as measured by the laser can be seen to be reliable for the whole frequency range above about 20Hz, with only a slight phase lead observed at the higher frequencies. In the worst case, (c) and (d), the agreement is not good in either the magnitude or the phase at any frequency.



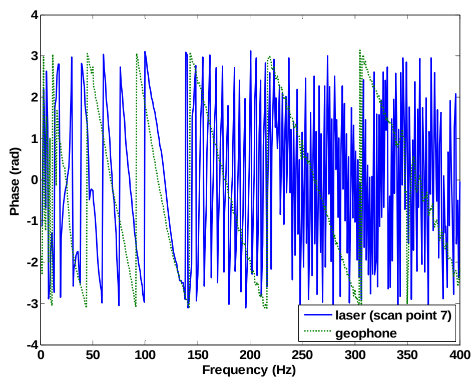

(a)




(b)




(c)




(d)

Figure 22

Comparison between laser and geophone measurements for grass, best & worst scan points– cross power spectrum

(a) best case magnitude; (b) best case phase; (c) worst case magnitude; (d) worst case phase

The measured velocity magnitude measured with the geophone is shown in Figure 23, in section 3.3. The velocity peaks at about 10μm/s at 100Hz and then drops to about

0.1μm/s/ at 400Hz. These velocities represent a peak surface displacement of approximately 15nm at 100Hz.

### *3.4 Velocity levels*

Figure 23 shows the velocity levels as measured by the geophone for all six surfaces. In each case, the voltage delivered to the shaker, and the distance between the shaker and the measurement point, were the same.

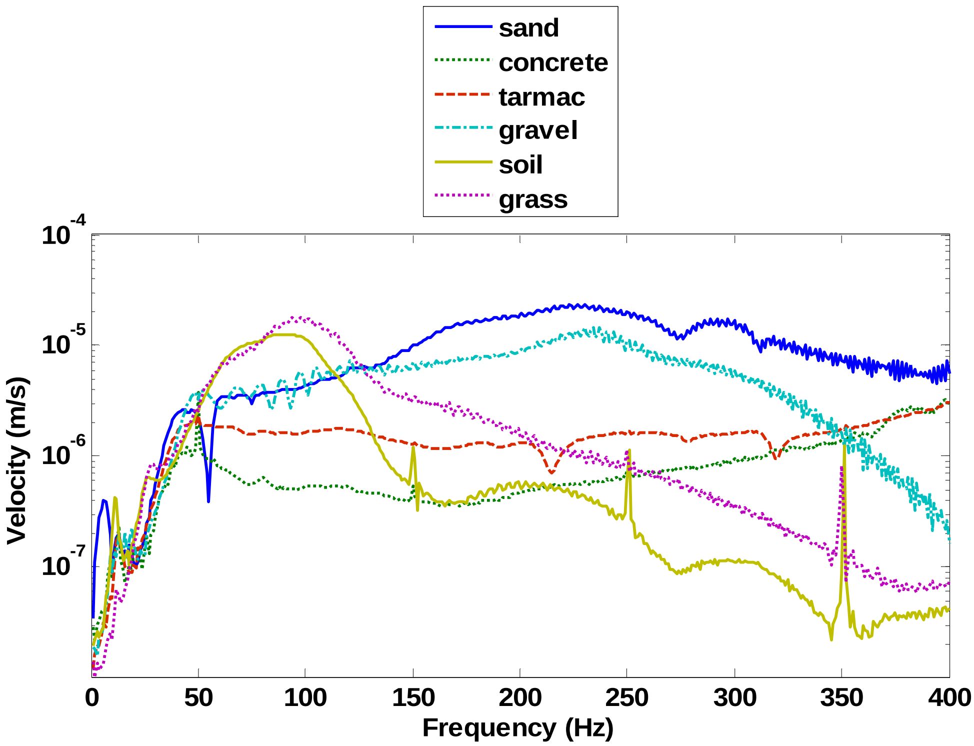



Figure 23

Magnitude of velocity for different ground surfaces

At low frequencies, below 50Hz, with the exception of peaks in the data for sand and soil, the velocities on all the surfaces are very similar. Above 50Hz, the levels diverge, but a few observations may be made. The velocities for the two hard, solid surfaces, tarmac and concrete, are similar, and do not vary much with frequency. The trends for soil and grass are similar, with the magnitudes matching up to about 100Hz. This is not surprising as the grass is on a soil base. Above 100Hz, the grass velocities exceed those of the soil underneath. The velocity peaks at about 100Hz, and then falls off rapidly with frequency. Spikes can be seen in the soil data at odd harmonics of mains frequency, 50Hz. Such spikes are only evident in the data for grass and not evident in the data for any of the other surfaces, suggesting that only the soil transmits the electromagnetic waves effectively. The data for sand and gravel are similar, with not much variation with frequency above 50Hz. The similarity is no surprise, given that both and gravel are granular materials and there was some gravel mixed in with the sand.

Considering the dataset as a whole, the largest velocities occur for soil/grass at around 100Hz and for sand/gravel between about 150Hz and 300Hz. The lowest velocities occur for concrete/tarmac between 50Hz and 200Hz, and for soil above 200Hz.

Comparing the laser data acquired for each surface (section 3.3) with the velocity magnitudes shown in Figure 23, it is clear that velocity magnitude has a significant effect on the quality of the laser data. The specifications for the laser indicate that the velocity resolution (or noise floor) between 10Hz and 5kHz (defined as the rms velocity amplitude at which the signal to noise ratio in a 1Hz spectral band is 0dB) is between 0.1 and 1μm/s, independent of the range setting on acquisition[♥]. It can be seen from the figure that, without signal averaging, for some of the surfaces the laser is operating close to its noise floor. The ability to measure velocities at these low magnitudes is important as they are similar to those measured on the previous test site (the Chilworth pipe rig site). Indeed, the velocities measured previously were, on occasion, as low as 0.1-1nm/s, i.e. around three orders of magnitude lower.

## *3.5 Improving data quality*

It is clear from the above discussions that for all the surfaces tested, the data acquired from the geophone were of greater quality than those acquired via the laser. A number of ways to improve the laser data were investigated and these are considered in the following sub-sections.

### *3.5.1 Increasing surface velocity*

From the above discussions, one of the most obvious ways to try to improve data quality is to increase the surface vibration velocity. Under many circumstances, this will be neither practical nor even possible; however, for the sake of completeness, the effect of increasing the surface velocity is considered briefly here. Tests were carried out on tarmac with two different shaker input voltages: for the first test, the velocity

[♥] At these frequencies, scanner noise is important as well as decoder noise levels were slightly above the lower end of the noise floor, and for the second test, the levels were close to the upper end of the noise floor, as shown in Figure 24.

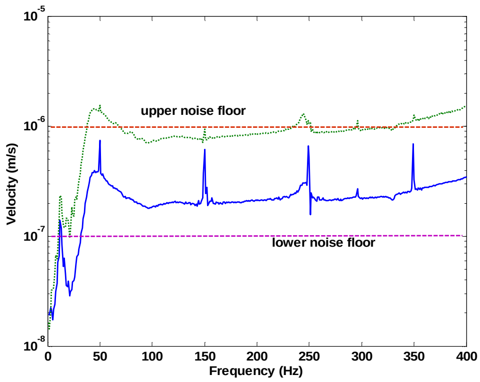
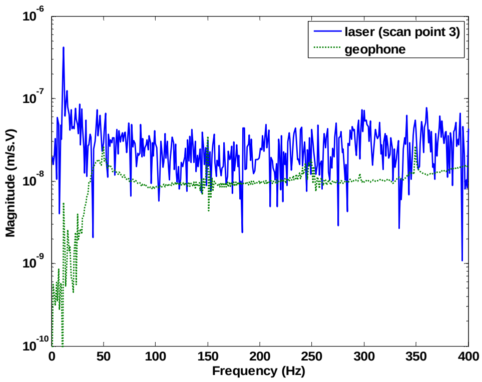


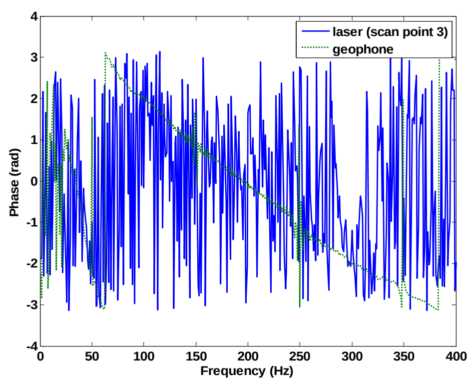

Figure 24

Magnitude of velocities for surface velocity tests

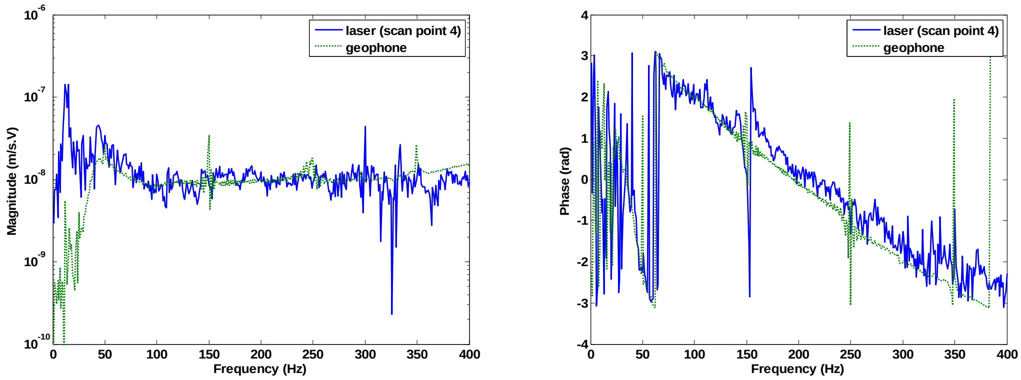
This represents a velocity change of slightly less than one order of magnitude, but at these levels the difference in the results was found to be significant. For the lower velocity case, the data is markedly better for some scan points than for others, whilst for the higher velocity case, there was much more consistency between scan points. The plots in figure 25 are representative of the best and worst cases for the lower velocity case. In the worst case, the magnitude of the cross spectrum as measured by the laser and the geophone differs by a factor of around three; furthermore, the classic saw-tooth phase pattern is barely visible. In the best case however, the magnitude data match reasonably well, and there is fair agreement in the phase data.




(a)




(b)

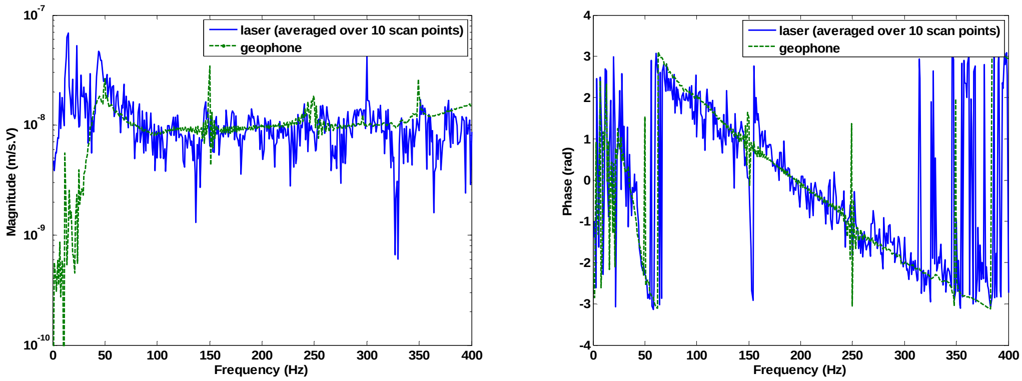



(c) (d)

Figure 25

Comparison between laser and geophone measurements for low velocity case, best & worst scan points– cross power spectrum

(a) best case magnitude; (b) best case phase; (c) worst case magnitude; (d) worst case phase



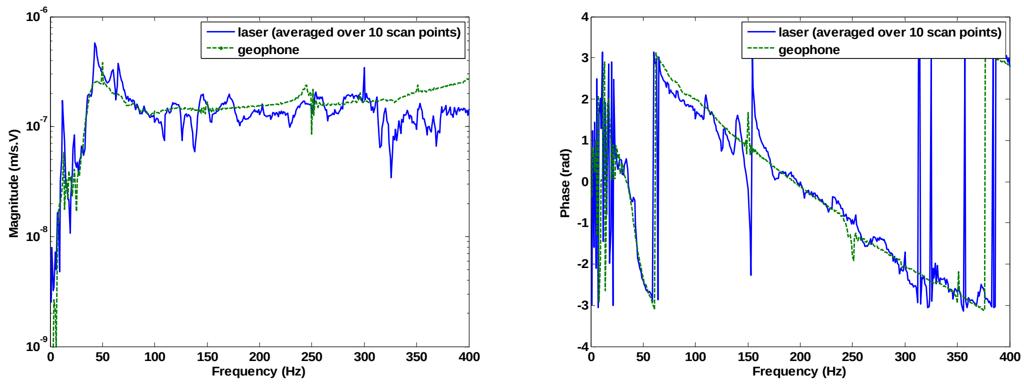

(a) (b)

Figure 26

Comparison between laser and geophone measurements for low velocity case,– cross power spectrum

(a) magnitude; (b) phase

Figures 26 and 27 show the cross power spectra for both velocity levels, averaged over all the scan points in each case. It can be seen that the laser data for the lower velocity case is much noisier than that for the higher velocity case, with the degree of matching between the laser and geophone data being greater for the latter. Tests with higher velocities were carried out, but the improvement was marginal. This suggests that, provided the surface velocities are above the noise floor, little improvement in data quality is to be had by increasing the velocities further.




(a) (b)

Figure 27

Comparison between laser and geophone measurements for high velocity case,– cross power spectrum

(a) magnitude; (b) phase

### *3.5.2 Increasing surface reflectivity*

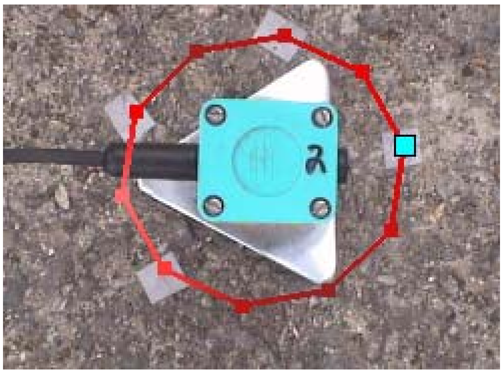


Figure 28

Test with 3M Scotchlite® reflective tape – tarmac

The velocity resolution figures provided in the laser specifications apply to a highly reflective surface, in particular 3M Scotchlite® tape. Although good signal levels were achieved on all surfaces tested, resulting in optimal data as defined by the laser software, it was thought that improvements in data quality might be realised by enhancing the reflectivity of the surfaces. With this in mind, a test was carried out in which four of the ten scan points were covered with 3M Scotchlite® self-adhesive tape. The surface used for the test was tarmac, as the tape was found to adhere easily and well to this surface. Figure 28 shows the measurement configuration along with the patches of tape.

Scan point 1 is the highlighted scan point, with the scan points numbered clockwise; here the tape is applied to scan points 1, 5, 7 and 9. As before, the shaker was excited with a periodic chirp from 1Hz-400Hz, with a frequency resolution of 1Hz. The shaker was again placed approximately 0.5m from the measurement point for each test. In this test, the voltage applied to the shaker was slightly lower than before – about half that used in the surface tests (section 3.3). The velocity as measured by the geophone is shown in Figure 29. At these lower velocities, the data is marginal, in that for some scan points, neither the magnitude nor the phase data match that acquired by the geophone, whilst for others, the data, although very noisy, compare reasonably well. It was thought that, under these circumstances, any improvement delivered by the tape would be easier to recognise.

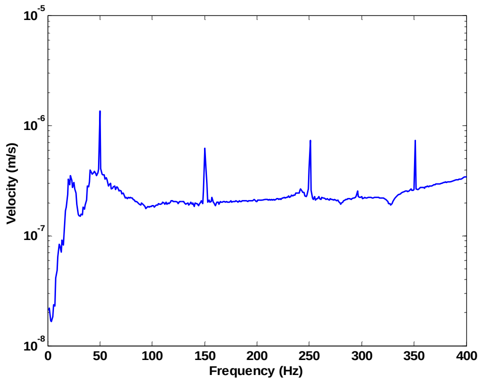
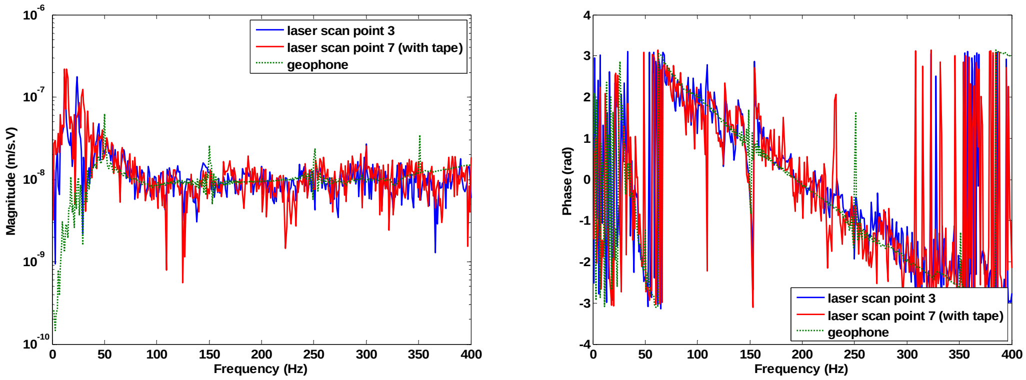



Figure 29

Magnitude of velocity for the 3M Scotchlite® reflective tape test - tarmac

No significant difference was found in the data for the scan points with or without reflective tape. For three scan points, no good data was acquired (one of these was a tape site); for three scan points, the phase matched that of the geophone data up to approximately 100Hz (two of these were tape sites); and for four scan points, the phase matched that of the geophone data up to 400Hz (one of these was a tape site). Figure 30 shows the cross power spectrum for the best cases with and without the tape. No improvement is seen for the with-tape case.




(a) (b)

Figure 30

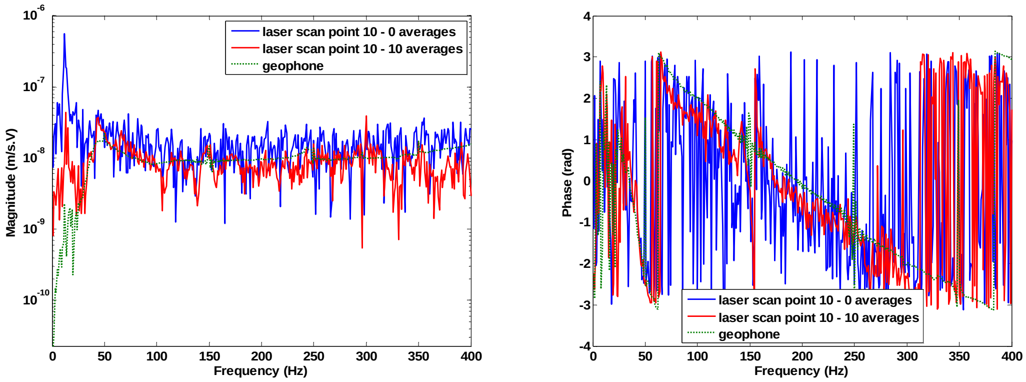
Comparison between scan points with and without 3M Scotchlite® reflective tape on tarmac – cross power spectrum

(a) magnitude; (b) phase.

That the reflective tape offers no improvement in data is a slightly surprising finding; however, the data was considered optimal by the scanner software for all the points (with and without tape), so the tarmac is evidently a ‘good enough’ reflector. The same can be said of all the surfaces tested; even grass and soil, for which some points had to be re-measured, ultimately generated optimal data points. Nonetheless, it should be remembered that all the tests were carried out at normal incidence; it may well be that the reflective tape would be more effective when making measurements at shallower angles. Another possible way to improve surface reflectivity might be to wet the surface (where possible and practical). Due to the failure of the tape to improve the data, this was not investigated during this series of tests.

### *3.5.3 Signal averaging*

Tests were carried out on tarmac to evaluate the effect of signal averaging on the laser data. Averaging obviously increases the time taken for data acquisition, with the total acquisition time being proportional to the number of averages. For this test the velocity levels were the same as shown in Figure 29, i.e. in the region of the laser system noise floor. Averaging was applied to both the laser data and the geophone data. Figure 31 shows the data for one scan point (the worst for the non-averaged data) with no averaging and with 10 averages. Significant improvement can be seen on using averaging, particularly for the phase data; the geophone data is still superior.



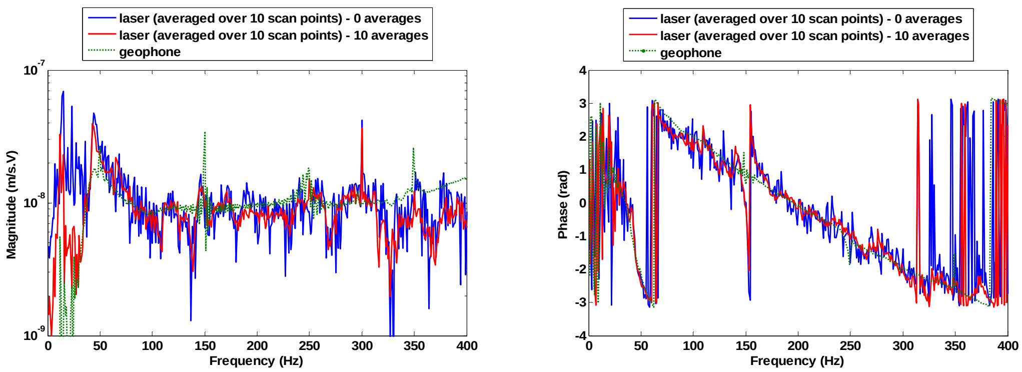

(a) (b)

Figure 31

Effect of signal averaging on single scan point – cross power spectrum

(a) magnitude; (b) phase.

Spatial averaging improves both sets of data as shown in Figure 32, with the signal averaging still having a significant effect. The geophone data is still superior, but for the phase data, the quality of the laser data is now approaching that of the geophone.




(a) (b)

Figure 32

Effect of signal averaging on spatially averaged data– cross power spectrum

(a) magnitude; (b) phase.

For higher velocity levels, averaging was found to offer some improvement, but less marked than that shown above.

### *3.5.4 Potential of filtering*

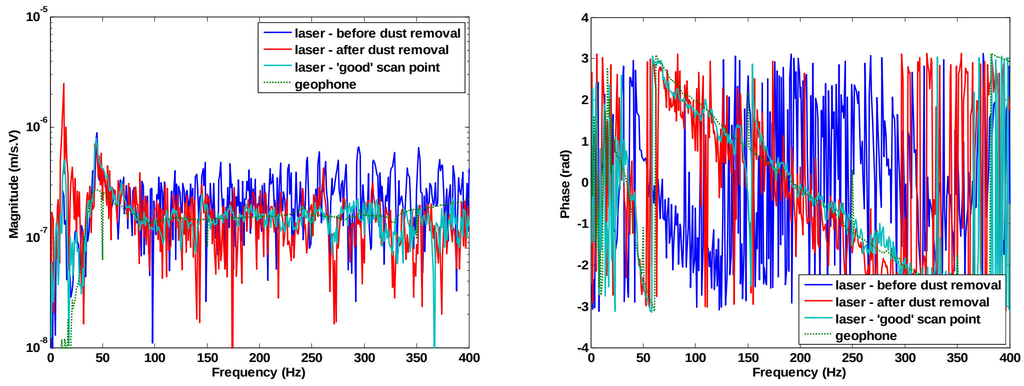
Frequently high pass filtering can be used as a means of improving the quality of ground vibration measurements and utilizing the entire dynamic range of the acquisition equipment, as there can often be high background noise levels at low frequencies. This was not the case for the measurements conducted here as the test site is an extremely quiet environment. The velocity curves in Figure 23 show that the signal levels below 50Hz are well below the peak values and mostly the lowest levels over the entire frequency range. Furthermore, the mains-associated spikes here do not present a problem, so notch filtering is not required. In more noisy environments, high pass filtering could be advantageous.

### *3.5.5 Input signal*

For most of the tests, a periodic chirp was used as the input signal to the shaker. A pseudo random signal was also tested for comparison. For both waveforms, sinusoidal signals of the same amplitude are emitted to all FFT lines at the same time within the desired frequency range (in this case 1Hz-400Hz). No difference could be seen in the measured results. Using a pseudo random signal could be more convenient in the long term, as then the problem of synchronising the data acquisition with the input signal does not occur, potentially a difficulty when re-measurement of a scan point is required.

### *3.5.6 Dust or grit removal*

For many of the tests carried out there was considerable variation in the quality of the laser data over the ten scan points. It was not readily apparent why this was so given that, for all the scan points, the data acquired was considered to be optimal by the scanner software. One possibility was that poor data was a consequence of freely vibrating particle(s) on top of the surface being measured (for example dust or grit in the case of the hard surfaces, tarmac and concrete). For one particularly poor scan point when measuring on tarmac, the run was repeated after the surface had been brushed to remove surface particles. The quality of the data was improved marginally, but was still inferior to the data acquired at the other scan points. The effect of the dust removal on one scan point is shown in Figure 33, along with the superior data for another scan point.




(a) (b)

Figure 33

Effect of dust/grit removal on poor data– cross power spectrum

(a) magnitude; (b) phase.

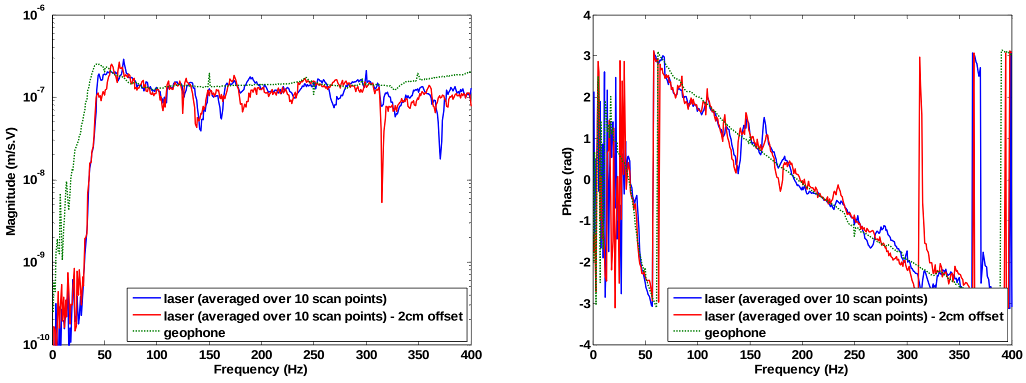
Anomalous data is relatively easy to spot, so the most prudent approach may be to simply alter the position of the scan point slightly and then repeat the measurement.

### *3.5.7 Alterations in background lighting*

Since carrying out this study, the author has been made aware that changes in background lighting can affect the signal quality, and hence improvements might be achievable via such means. This would need to be evaluated in the future.

## *3.6 Small variations in stand-off*

In the longer term, if making measurements along a road, for example, there are likely to be undulations which mean that the stand-off distance varies slightly between measurement points. It is not clear whether, under these circumstances, re-focusing of the laser beam would be required for every measurement point. Tests have been performed here to examine the effect of small variations in stand-off, in order to ascertain the importance of accurate focusing of the laser beam. Figure 34 shows the effect of altering the stand-off distance by 2cm, without refocusing of the laser. The spatially averaged data is shown.




(a) (b)

Figure 34

Effect of small stand-off variation– cross power spectrum

(a) magnitude; (b) phase.

Little difference can be seen between the two sets of data in either magnitude or phase, demonstrating that small variations in stand-off can be tolerated. The data with the 2cm offset is possibly of marginally poorer quality than the properly focused data, so for optimum quality data, refocusing for every measurement location would still be advantageous.

# 4. FUTURE WORK

A number of avenues have not yet been investigated and will be the subject of further work in the near future.

## *4.1 Non-normal incidence*

The main potential advantage of using the laser compared with using geophones is that it is non-contact so that, when making a number of measurements in different locations, lifting on and off the ground is not required. However, in all the tests performed here, the laser beam was aligned normal (or as close as possible) to the ground surface. In the longer term, for incorporation into the multi-sensor device, this would mean either having the instrument trolley directly over the surface to be measured for each measurement point, or having the laser fixed to a movable arm that would project various distances out in front of the trolley. If data could be acquired with the laser beam at an angle to the surface, then the potential exists for gathering data at longer ranges (the shallower the angle, the longer the range). Using a laser in this mode will be investigated in the next stage of the project.

## *4.2 Alternative laser vibrometers*

The laser vibrometer used in these tests was a 3D scanning vibrometer, not intended for mobile use, therefore large and somewhat cumbersome. The ability to measure in three dimensions is not essential, and whilst the scanning facility was useful for acquiring a number of data points in close proximity (allowing spatial averaging and potentially selection of the best data), the ultimate spatial resolution required in the multisensor device (10-20cm minimum) does not necessitate its use. Portable laser vibrometers are available and such a device would be more appropriate for this application.

One of the main limitations of the laser vibrometer used in these tests was the level of the noise floor (0.1-1μm/s). For the scanning device employed in these experiments the noise floor was mainly determined by the scanner noise; for a portable laser vibrometer, which does not scan, the noise floor would be somewhat lower (typically <0.01μm/s), indicating again that a portable device would be more suitable for this application.

# 5. CONCLUSIONS

Early tests revealed that using the system in full 3D mode would be impractical, both in the longer term as a component of the multi-sensor device, and in the short term for comparing the laser performance with that of a geophone. An alternative mode was possible, in which one sensor head was used alone, providing simple one-dimensional measurements, so this was used for all the tests.

For all the tests, the laser was aligned (as far as possible) normal to the ground surface, so it was expected that the laser and the geophone would be measuring the same quantity. Tests on all the ground surfaces revealed that this to be the case, particularly at the lower frequencies, although the geophone measured positive velocity upwards and the laser measured positive velocity outwards, so there was always a phase difference of $\pi$ to be accounted for.

The laser performed better on some surfaces than others but, with some remeasurement of scan points, optimal data was acquired for all tests. The variation in data quality between scan points was greater for the softer and unconsolidated surfaces (sand, soil and grass), with little difference between scan points for the harder ones (tarmac, concrete and gravel); this suggests that more data points might need to be acquired for the softer surfaces, to allow rejection of noisy data. However, surface velocity was found to be the key factor in determining data quality, rather than the surface texture itself; for most of the tests, the surface velocities were close to the laser system noise floor. It is likely that surface texture effects would become more significant for shallower incidence angles, but examination of this was beyond the scope of the present study. Notwithstanding the general agreement between the laser and the geophone, the laser data was, without exception, of poorer quality. One reason for this may be that the geophone data always undergoes some spatial averaging (either over the three tripod contact points, or along the length of the ground spike) whereas, for each scan point, the laser measures at a single point. One advantage of the laser data when compared with the geophone data was that it did not suffer from mains-associated spikes.

A number of ways to improve data quality were investigated. Little improvement was seen by altering the surface texture, either by removal of surface dust/grit or by applying retroreflective tape. This was probably because the surfaces were already ‘good’ enough for the laser system to judge the data as optimal (if after some remeasurement of points). The tape may prove more effective when considering non-normal incidence. High pass filtering, to enable higher gains to be used, was found not necessary for these tests but could be useful in more noisy environments. Signal averaging, both spatially and in the time/frequency domain significantly improved data quality, particularly for the lower surface velocity cases, although at a cost of increased acquisition time. No difference could be seen in the results between using a periodic chirp input or pseudo random. Using a pseudo random signal was found to be more convenient as then synchronising the data acquisition with the input signal is not necessary.

Finally, two effects of the laser stand-off distance were assessed. For small optimal stand-off distances (<2m), there was no variation in signal quality with stand-off. Small changes in stand-off distance (<2cm) without refocusing of the system resulted in no deterioration in data quality, although accurate focusing would be recommended.

These preliminary tests suggest that a laser system could be a viable alternative to geophones for measuring ground vibration. Measuring at non-normal incidence is a critical next phase the evaluation process, as it is a laser system's potential to measure at range that would deliver the main advantage over using geophones. Since carrying out this study, a portable laser vibrometer has been purchased; after initial evaluation, this instrument will be used for all subsequent tests.

## 6. REFERENCE


1. www.mappingtheunderworld.ac.uk

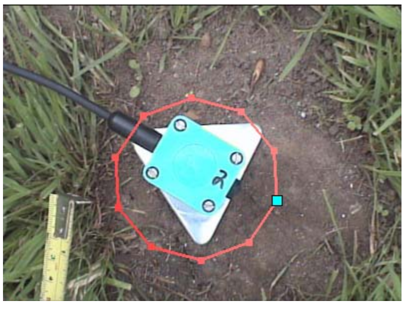

## APPENDIX I

## COMPARISON OF GEOPHONE MOUNTING METHODS

In all previous experiments, mounting the geophone on the ground surface has been achieved via a ground spike. This results in good coupling with the ground, but is clearly impractical for hard surfaces such as concrete and tarmac; here an alternative mount – a tripod consisting of a small curved triangular metal plate – is tested, and compared with the spike mounting. Both configurations are shown in Figure A1.

(a)

(b)



(c)

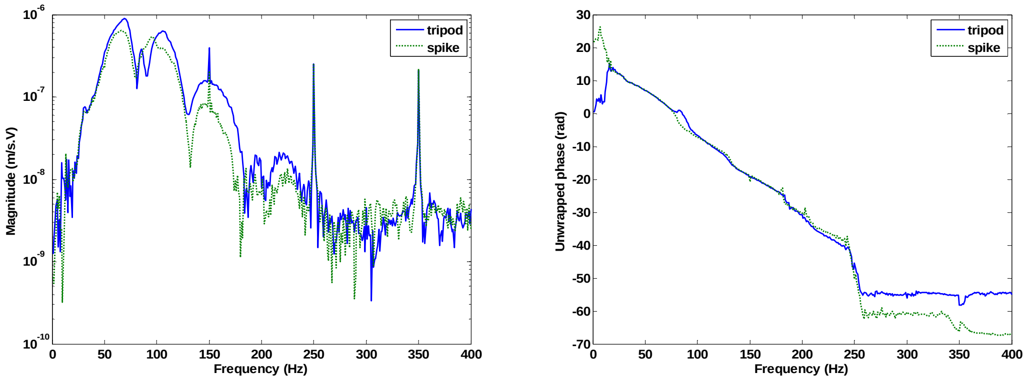
Figure A1

Geophone mountings

(a) with spike; (b) with metal tripod; (c) with tripod in situ, on soil surface (laser scan points are also shown here).

Testing was carried out on soil as the medium easily allows for the insertion of the ground spike as well as using the tripod. Tests were carried out sequentially on the same soil spot for each configuration. As for all the laser tests, excitation was provided by a Wilcoxon inertial shaker mounted directly on the ground surface, in this case approximately 1m away from the geophone position. A period chirp input from 1Hz – 400Hz was used.

For each test the cross power spectrum between the geophone output and the voltage input to the shaker was determined. Figure A1 shows the magnitude and unwrapped phase for each geophone configuration.




(a) (b)

Figure A2

Comparison between geophone mountings – cross spectrum measurements

(a) magnitude; (b) unwrapped phase.

Good agreement is observed in both the magnitude and unwrapped phase, for frequencies between approximately 20Hz and 250Hz. Both sets of data exhibit spikes at odd harmonics of 50Hz. Above 250Hz phase unwrapping is no longer viable, evidenced by the flattening of the unwrapped phase. The first resonance of the geophone occurs at around 240Hz, so good data can be expected up to this frequency. The agreement is better for the phase information than for the magnitude; this is as expected given that unwrapped phase is more robust in the presence of noise. The small differences can be attributed to two main factors: the more important one is probably that the measurements are derived from two separate runs; however, in addition, the tripod will measure the vibration at the ground surface averaged over the three contact points, whilst the spike will measure the vibration at one surface location, but averaged over the length of the spike. At the frequencies of interest, very little difference would be anticipated.

The results show that vibration coupling between the geophone and the ground is as good using the tripod as it is using the spike. For reference purposes, the measured velocity magnitudes are shown in Figure A3. These velocities represent surface displacements of a few nanometres at frequencies up to 150Hz, and less than one nanometre at higher frequencies.

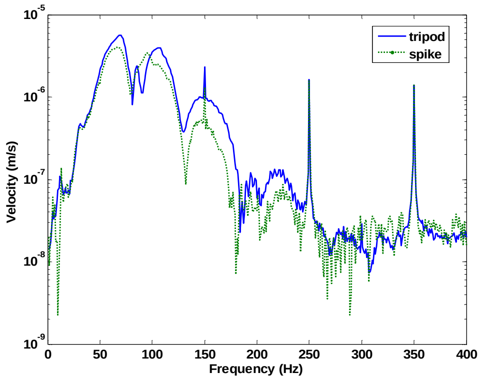



Figure A3

Comparison between geophone mountings – velocity measurements