Chapter 3. Techniques of measuring compressional wave properties.

A variety of techniques are available to measure the compressional wave properties of marine sediments. These all possess the same underlying principles, *i.e.* the emission of an acoustic wave from a source, the interaction of this acoustic wave with the sediment, detection by a receiver and subsequent processing to obtain compressional wave properties. Three general categories of acoustic techniques exist, namely remote methods laboratory methods and the use of *in situ* probes. While all techniques will generally measure group velocities the type of attenuation coefficient obtained varies between techniques, with remote methods and the use of in situ probes measuring effective attenuation while laboratory techniques typically measuring intrinsic attenuation.

As the aim of this project is to reliably determine the dependence of compressional wave properties on both frequency and geotechnical properties, the technique selected must enable reliable measurement of the compressional wave properties of a well-defined volume of sediment, from which sediment samples can be readily obtained.

3.1. Selection of optimum technique

Remote methods utilise a source and a suite of receivers, located within the water column to measure the acoustic waves reflected or refracted from the sediment column. Available sources include impulsive sources, which are typically used to examine deep sediment and crustal structures, and resonant sources, which are typically used to examine sediments lying less than 100 m below the seafloor. Resonant sources can be divided into those that possess very high frequencies (20 kHz to 1 MHz) and are used to examine the upper 5 m of the seafloor. Alternatively those with intermediate frequencies (100 Hz to 30 kHz) are used to examine sediment lying 5 to 100 m below the seafloor. Pulses emitted by resonant sources possess increased vertical resolutions, reduced penetrations and more repeatable natures than pulses emitted by impulsive sources (Verbeek and McGee, 1995).

In the case of impulsive sources the use of a number of receivers, towed at a range of distances from the source, enables a variety of processing techniques to be applied to both refraction and reflection data (Kearey and Brooks, 1991). However, uncertainty exists concerning the volume of sediment examined, with the vertical distance through which the acoustic waves have propagated computed from a modelled velocity for the sediment present. Higher frequency sources are generally used to directly classify surface sediment types rather than measure compressional wave properties. This is achieved through the comparison of either the intensity of the back-scattered signal (Pace and Gao, 1988) or alternative features of the first and second echoes from the seabed with ground-truthing samples. Sources at intermediate frequencies, *e.g.* chirp and boomer, have a broader range of processing techniques available, which have been comprehensively reviewed (Robb *et al.*, 2002). These techniques generally suffer from a lack of a published validation for remotely sensed acoustic data or the incorporation of a limiting or invalid assumption.

Though remote techniques present an efficient method for the surveying of large volumes of seafloor sediments, three major limitations exist. Firstly an intrinsic uncertainty exists in the volume of sediment through which the acoustic wave has propagated. Secondly no single processing technique exists which can reliably determine the compressional wave properties. Thirdly the collection of sediment samples from the sub surface sediments examined can be problematic.

Laboratory examinations of sediment samples provide an alternative way of measuring compressional wave properties. Intrinsic advantages include the manner in which the pressure and temperature of the samples can be controlled and the geotechnical properties of each sample can be easily measured. Techniques used to determine compressional wave properties from both resonant column experiments (Toksoz and Johnson, 1981) and standard wave propagation techniques (Courtney and Mayer, 1993b; Richardson and Briggs, 1993) have been thoroughly tested and validated.

The major limitation of laboratory techniques is the unknown disturbance of the samples under examination, arising from their collection, transportation, storage and preparation. A number of researchers aim to minimise this disturbance using the following approaches:

- The measurement of the properties of the sediment cores on board the research vessel within 24 hours of collection, in order to miminise the disturbance associated with transportation and storage (Courtney and Mayer, 1993a; Gorgas *et al.*, 2002; Sutton *et al.*, 1957).
- The collection of samples in the containers in which they are later analysed (Shumway, 1960).

- The collection of pressurised cores which enables the *in situ* hydrostatic pressure conditions to be maintained (Tuffin, 2001; Williams *et al.*, 2002).

The effects of storage on measured compressional wave properties has been examined. Variations in re-measured velocities vary from negligible differences over a storage period of seventy days (Sutton *et al.*, 1957) to considerable differences over a storage period of one year (Best *et al.*, 2001). Qualitative assessments of sediment disturbance have been undertaken. These produce a range of conclusions ranging from an attenuation coefficient which was “strongly affected by sediment disturbance which may occur during sampling and handling” (Richardson and Briggs, 1993) to the statement that “no coring disturbance was noted, but if present, is minimal and uniform throughout the samples examined” (Orsi and Dunn, 1990; Orsi and Dunn, 1991). The inconclusive nature of the above research highlights the variable effect sediment disturbance can have on compressional wave properties.

The limited size of the samples which can be collected places a lower boundary, of approximately 200 kHz, on the frequency of the acoustic wave which can be used. For frequencies less than this, a combination of diffraction effects and interference from reflected waves will disrupt the received acoustic signals. Some researchers manage to examine frequencies as low as 15 kHz in the laboratory (McLeroy and DeLoach, 1968; Wingham, 1985), through the construction of a large volume of sediment. Though these authors justify their actions through the use of preliminary investigations, which indicate that thorough mixing of the core samples and subsequent settling does not affect the measured sound field (McLeroy and DeLoach, 1968), it is highly unlikely that such reconstructed sediment truly represents *in situ* conditions. Discrepancies will arise due to the artificial fast depositional and compaction rates applicable to the reconstituted sediment, which will result in an artificial sediment structure (Laughton, 1957).

The use of transmission experiments which use *in situ* probes combines the advantages of a relatively simply geometry, and so relatively simple and reliable techniques of measuring geoacoustic properties, with the ability to make *in situ* measurements, *i.e.* those directly applicable to the seafloor sediments. Though some sediment disturbance will occur, this will be minimal with respect to that induced by sampling for laboratory techniques. As in the case of remote methods, there is no theoretical limitation on the frequencies that can be used, though the volume of sediment examined will decrease as the frequency used increases. Careful selection of fieldsites and probe positions will allow the examination of a well-defined volume of sediment, from which samples can be readily obtained. Hence transmission experiments which use *in situ* probes have been selected as the optimum experimental technique with which to investigate the aims of this project.

3.2. Transmission experiments using *in situ* probes

An ideal transmission experiment will incorporate the following elements:

1. Minimum sediment disturbance. This will depend on the manner in which the probes are inserted and the separation of the probes, with larger separations increasing the proportion of undisturbed sediment through which the acoustic pulse propagates.
2. A highly repeatable acoustic signal emitted by the source. This will depend on the repeatability of both the electronic signal sent to the source transducer and the coupling between the acoustic probes and the sediment. Theoretically the degree of repeatability increases as the dimensions of the active face of the transducer/receiver increases, owing to more points of contact between the sediment and the transducer.
3. A processing technique that does not require any limiting assumptions. Such assumptions may be invalid for marine sediments *e.g.* the assumption made by Log-Spectral-Ratio techniques that the attenuation coefficient is proportional to frequency (Robb *et al.*, 2002). The processing technique chosen should also incorporate the spreading losses and amplitude envelope of the acoustic pulse which are relevant to the sediment. In order to examine the effects of spreading losses and amplitude envelopes a common processing technique used to obtain compressional wave velocity and attenuation coefficient from transmission experiments will be discussed. This involves the comparison of signals that have been transmitted through sediment to calibration signals transmitted through the overlying water column.

Velocity v is calculated using

$$v = \frac{v_w}{\left(1 - \frac{\Delta t . v_w}{d}\right)} \qquad 3.1,$$

where v_w the velocity of the water (which is calculated from measured salinity and temperature using empirical relationships similar to those included in *Appendix A*), Δt is the difference in travel time taken for the emitted signal to travel between two probes in sediment and water and *d* is the probe separation. Velocities obtained using this method are group velocities

Attenuation coefficient α_n in nepers·m^{-1} is obtained from

$$\alpha_n = \frac{1}{d}\left(\ln\left(\frac{A_{w2}}{A_{w1}}\right) - \ln\left(\frac{A_{s2}}{A_{s1}}\right)\right) \qquad 3.2,$$

where A_{w1} and A_{w2} are the amplitudes of signals at probes 1 and 2 for propagation through the water, while A_{s1} and A_{s2} are the amplitudes of signals at probes 1 and 2 for propagation through the sediment. If the two probes considered are a source and receiver pair this technique will not account for changes in wave shape between the acoustic pulses transmitted through water and through the sediment. These are caused by two mechanisms. Firstly, the impedance mismatch between the transducer and the sediment, and the transducer and the water will differ, and the shape of the acoustic pulses emitted in each media will differ (Buckingham and Richardson, 2002). Secondly, water can be considered to be a non-attenuating and non-dispersive medium, while the sediment will possess a significant attenuation coefficient and may be dispersive (Stoll, 2001). This will result in higher frequency components being more strongly attenuated and travelling more quickly than lower frequency components, and will alter the shape of the received pulse. However if two receivers are considered wave shape changes arising from the impedance mismatch will be accounted for, while the degree to which the dissipation and dispersion of the acoustic pulse will be accounted for will depend on the separation of the receivers and compressional wave properties of the sediment.

One limitation of the above technique, irrespective of the probes selected, is the assumption that spreading losses in the sediment and water are the same. If these media possess different velocities this will not be the case, see *Section 4.3.3,* and the calculated attenuation coefficient will be incorrect.

4. A thorough analysis of the intrinsic errors induced by the device and processing technique should be incorporated.
5. A detailed analysis of the geotechnical properties of the sediments examined should be undertaken.
6. The ability to examine a range of frequencies and sediment types, in order to reliably examine the relationships between the geoacoustic properties measured and both the geotechnical properties of the sediments and frequency.

3.2.1. *In Situ* Research at frequencies of less than 1 kHz

Pre-1990 work at frequencies of less than 1 kHz utilised cross-hole surveys to obtain compressional wave attenuation coefficients. Cross-hole surveys involve the emission of an acoustic wave from a source which is placed in a borehole and the detection of the transmitted signal in adjacent boreholes. This includes the following work:

- Attenuation coefficients, that were obtained from 50 to 450 Hz, using spherical spreading and a direct comparison of the spectral amplitudes at each receiver used (McDonald *et al.*, 1958).
- Log-Spectral-ratio techniques, that were used to obtain attenuation coefficients at frequencies less than 125 Hz (Hauge, 1981).
- Modified spectral ratio technique, that incorporated spherical spreading losses, were used to examine frequencies from 50 to 400 Hz (Tullos and Reid, 1969).

The LSR technique applied by Hauge (1981) assumes that attenuation coefficient is proportional to frequency, the validity of which is still under debate (Kibblewhite, 1989; Stoll, 2001). The spherical spreading losses utilised by McDonal *et al* (1958) and Tullus and Reid (1969) are not validated in the literature and only Hauge (1958) offers an examination of the repeatability of the emitted pulse and the coupling of the geophones to the borehole wall. Though possible sources of error are identified, such as interference of intrabed multiples and unreliable geophone coupling to the borehole wall, only Tullos and Reid (1969) presents a quantitative error analysis. Probe separations between 3 and 165 m should ensure that an adequate proportion of the sediment through which the waves propagate is undisturbed. In addition, the measurement of corresponding geotechnical properties is either not presented, as in the case of McDonal *et al* (1958) and Hauge (1981), or limited to the percentage of sand sized particles, as in the case of Tullos and Reid (1969).

Post-1990 research in this low frequency range has used towed ocean bottom sledges, which can examine frequencies less than 35 Hz. This involved towing a source and suite of receivers close to the seafloor. Though this is strictly a remote technique the coupling of the device to the seabed permits its inclusion in this section. Typical sources include clusters of airguns (Ewing *et al.*, 1992; Stoll *et al.*, 1994) and a torsional shear wave generator *(Stoll and Bautista, 1998).* Standard refraction processing techniques

(Kearey and Brooks, 1991) were used to obtain compressional wave velocities. However, as stated in *Section 3.1,* the major limitation of such refraction techniques is the uncertainity in the volume of sediment through which the acoustic wave has travelled and to which the resulting velocities apply.

3.2.2. *In Situ* Research at discrete frequencies

The following three research projects utilise devices which can only examine a very limited number of discrete frequencies, and so provide no independent information about the frequency dependence of compressional wave properties.

A suite of devices were used by Hamilton to measure compressional wave velocity and attenuation coefficient at frequencies of 3.5, 7, 14, 25 and 100 kHz (Hamilton, 1963; Hamilton *et al.*, 1970; Hamilton *et al.*, 1956). The frequencies of 3.5, 7, 14 and 25 kHz were examined using the following apparatus; three hollow stainless steel rods attached to a fixed frame, with a source transducer attached to one rod and receiving transducers attached to the other two. Sediment depths between 30 and 60 cm and probe separations from 0.3 to 1 m could be examined. Compressional wave velocity and attenuation coefficient are calculated using a pair of receiving probes and *Equations 3.1* and *3.2* respectively. Resulting velocity errors of $\pm$ 5 $m \cdot s^{-1}$ were identified, with no errors stated for attenuation coefficient. The apparatus used for the 100 kHz measurements (Hamilton *et al.*, 1956) only possesses one source and one receiver, which could be deployed to a depth of 15.2 cm. Hence, the 100 kHz results do not account for alterations in pulse shape, while the results from lower frequencies do.

The apparatus was deployed using submersibles and "small boats" in order to examine a range of sediments (medium sands to silty clays) in a range of water depths (10 to 1100 m). For each site examined the porosity, percentage of sand sized particles and mean and median grain diameter were obtained from samples. The use of essentially the same technique and equipment over a wide range of frequencies, sediment types and water depths produces one of the most thorough of the early datasets concerning *in situ* compressional wave properties. Limitations include no published examination of the repeatability of both the acoustic waves emitted by the source and the coupling between deployments, the sparse spacing of frequencies within the range examined, the use of spreading losses applicable to water and the omission of an intrinsic error analysis for attenuation coefficients. Furthermore, the separation between the probes may vary in the water and sediment, due to lateral forces applied to the probes during insertion, which will increase the uncertainty in the velocities and attenuation coefficients obtained.

An alternative device is the profilometer, which used a nominal frequency of 200 kHz (Shirley and Hampton, 1972). This system was designed to be attached to the cutter of a corer to measure the *in situ* compressional wave velocity of sediments during the coring process, which can be directly related to the geotechnical properties of the sediment core collected. Though the latest research undertaken with the profilometer (Shirley and Anderson, 1975) also states that attenuation coefficient can be obtained, the methodology used is unclear and no published values are available to date. Analogue electronic circuitry is used to measure the velocity, and though the details of this process are also unclear, it is unlikely that the technique used accounts for pulse shape alterations. In addition, no error analysis was presented and the repeatability of both the emitted acoustic wave and the coupling of the probes to the sediment was not discussed. The limited surface area of the source transducer and receiver used (1.2 cm^2) indicate that coupling may be highly unrepeatable, while the limited Source-to-Receiver (S-R) separations examined (6 to 12 cm) imply that a large proportion of the sediment through which the acoustic wave propagates may be disturbed.

The most recent research in this category uses the *In Situ* Sediment Acoustic Measurement System (ISSAMS), which can measure the compressional wave velocity and attenuation coefficient at frequencies of 38 and 58 kHz. This employed four identical transceivers, with either one or two acting as a source and the remaining two or three acting as receivers (*Figure 3.1)* depending on the processing techniques used*.* The inner probe frame, displayed in (*Figure 3.1A)* is deployed within a platform with a height of 3 m and footprint of 2.5 m^2 *(Figure 3.1B)*. The compressional wave transducers can be placed at common depths of 10, 20 or 30 cm below the seafloor, with probe separations of 0.58 or 1 m used. To the authors knowledge no quantitative assessment of the repeatability of either the acoustic wave emitted by the source or the coupling of the transducers (which possess surface areas of 12.3 cm^2) is available in published literature.

The compressional wave velocity and attenuation coefficient were obtained using a source and receiver pair and *Equations 3.1* and *3.2*. Hence neither the effects of alterations in pulse shape nor discrepancies between spreading losses in water and the sediment are accounted for. Though the scatter in geoacoustic properties are discussed (Buckingham and Richardson, 2002) the intrinsic errors were not presented. The application of improved processing techniques to ISSAMS data collected during SAX99 is discussed in *Section 3.2.4.*

ISSAMS has been used to examine a range of sediments, including gassy muds in Eckernfőrde Bay, Germany, sands on the West Florida Sand Sheet, USA (Ricardson and Briggs, 1996) and carbonate sediments in the Lower Florida Keys, USA (Richardson *et al.*, 1997). In all cases, the porosity and mean grain diameter of the sediments were measured.

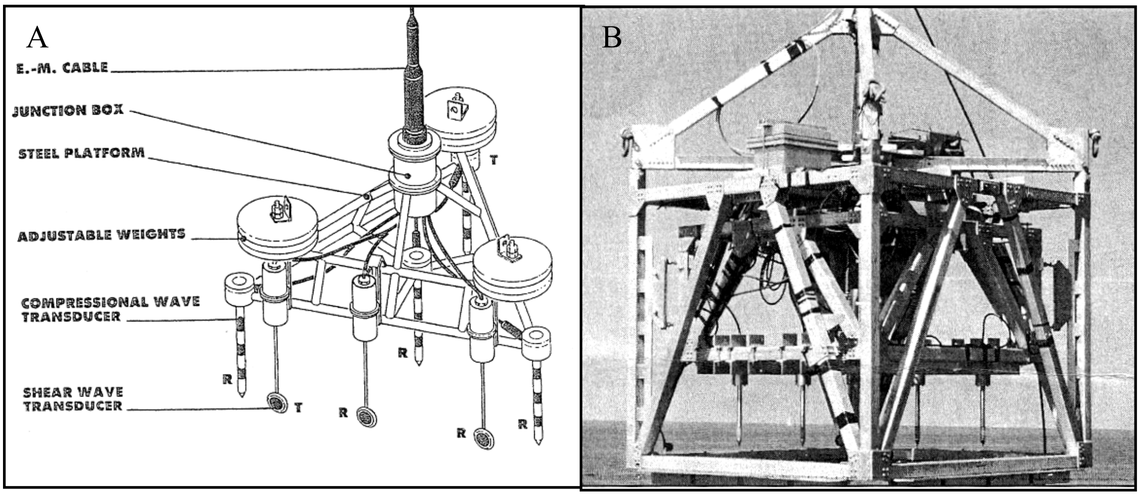

Figure 3.1. ISSAMS, displaying inner frame and probes (A), from (Richardson et al., 1997) and outer deployment frame (B), from (Griffin et al., 1996). Dimensions of outer deployment frame are a height of 3 m, width of 1.6 m and length of 1.6 m.

3.2.3. Probes which span a considerable frequency range

A number of experiments examine compressional wave velocity and attenuation coefficient over larger frequency ranges, while using the same device and methodology and hence allowing frequency-dependence to be reliably examined.

The earliest research in this field measured the compressional wave attenuation coefficient of inter-tidal muds in Emsworth Harbour, U.K (Wood and Weston, 1964). A frequency range of 4 to 48 kHz was examined, with measurements at 4, 8, 16, 32 and 48 kHz. The technique used the signals detected at S-R separations of 0.4 m to 60 m, which allowed subsequent processing to empirically account for spreading losses. It is likely that at the lower S-R separations used, a large proportion of the sediment through which the acoustic wave propagates is disturbed. Additional *in situ* velocity measurements were taken and specific gravity measurements were used to calculate porosity. However no error analysis is presented and the repeatability of both the acoustic wave emitted and the coupling of the probes to the sediment are not discussed.

A deep sea ocean probe (DSOP) was developed to examine sediment lying in water depths up to 1524 m (Lewis, 1971) and a frequency range of 5 to 50 kHz, in 5 kHz increments. The device consisted of four transducers located on the tips of the legs of a quad frame which could penetrate 1.52 m into the seafloor. The use of one of the transducers as a sparker source and the remaining three as receivers results in probe separations of 1.2 and 1.7 m. Though the acoustic wave emitted by the source is stated to be "quite repeatable" and adhere to spherical spreading losses, no data is displayed to justify these statements (Lewis, 1971). Velocity is simply calculated from the ratio of the distance travelled to the time taken, with errors of approximately $\pm$ 0.4 %. Frequency-dependent *in situ* velocities are not published, with all values reported applicable to the entire frequency range examined. Though attenuation coefficients were published for frequencies of 5 to 50 kHz in 5 kHz steps, these were only available for one location and errors are omitted. Coupling between transducers and sediments is not mentioned. Both the small size of the transducers used, *i.e.* 1.3 cm^2, and the comment that out of the six stations examined "three stations proved too granular for DOSP operations" (Lewis, 1971) imply that coupling reproducibility may be an important issue. One point of particular interest is the use of calibration water tests before and after deployment, which show that distortions of the DSOP frame on insertion to sediment may alter S-R separations by 4.8 mm. This distortion is not considered by any other workers who use a fixed rig. No geotechnical measurements are included in the literature.

The frequency range of 5 to 50 kHz was re-examined again in 5 kHz increments (McCann and McCann, 1985) using pipe transducers mounted in steel tubes. Environments examined included saturated sand and silt lying approximately up to 2 m deep in land and beach environments. Both velocity and attenuation coefficient were calculated using "gradient" techniques similar to those used within this project, *Section 5.2.1* and *5.3.1*, with intrinsic errors accurately incorporated. While the use of spherical spreading losses was justified, the examination of S-R separations from 0.5 to 2.5 m may not be sufficient to ensure a large proportion of undisturbed sediment (McCann, 1967).

The slightly lower frequency range of 1 to 30 kHz was examined, using frequency increments which varied from 500 Hz at low frequencies to 5 kHz at higher frequencies (Turgut and Yamamoto, 1990). The device consisted of two sources, a single tip sparker for frequencies less 1 kHz and a piezoceramic transducer for 1 to 30 kHz, and three receiving hydrophones. These were deployed at S-R separations from 1 to 3 m and depths up to 4 m using a hydraulic jet burial system which minimised sediment disturbance. Velocity was obtained using impulse response functions, while attenuation coefficient was calculated using a log-spectral-ratio approach and the assumption that spherical spreading is applicable, the validity of which was not proven. To span the required frequency range, two different sources and three different receivers were used, the dimensions of which are not available. The processing used does not account for different degrees of coupling to the sediment which may exist between the variety of devices used. Hence, the direct comparison of velocity and attenuation coefficient from 1 to 30 kHz, which was undertaken by the authors, is unreliable. In addition the relevant literature does not present an analysis of intrinsic errors, an examination of the repeatability of both the emitted acoustic wave and the coupling, while the only geotechnical property displayed was porosity.

The Acoustic Lance has been developed to examine the frequency range of 5 to 20 kHz (Fu *et al.*, 1996b). This can penetrate sediment to a depth of 3 m in water depths up to 6 km. The Acoustic Lance, *Figure 3.2,* consists of a source which is installed at the top of a corer, and a set of ten receivers which can be placed along the length of the core-barrel. This geometry suggests that the majority of the sediment through which the acoustic wave propagates is disturbed by the insertion of the Lance. Velocity is simply obtained from the ratio of the distance travelled to the time taken, with errors of $\pm$ 1 %. The inverse of the quality factor was obtained by accounting for spherical spreading and the application of a Bayesian inverse theory technique. As the justification of spherical spreading losses was not presented and the Bayesian technique applied assumes that attenuation coefficient is proportional to frequency, the validity of the processing applied is questionable. The resulting values of inverse quality factors range from 0 to 0.141, with errors from 3.7 to 92.9 % (Frazer and Fu, 1999). This device has been deployed in Mid-Atlantic ridge ponds

(Fu *et al.*, 1996b), gassy sediments in Kiel Bay, Germany (Fu *et al.*, 1996a), sandy sediments off Hawaii (Frazer and Fu, 1999) and silty sediments in Eel River, North California, (Frazer and Fu, 1999; Gorgas *et al.*, 2002). In all cases the mean grain diameter and porosity of the sediment were measured.

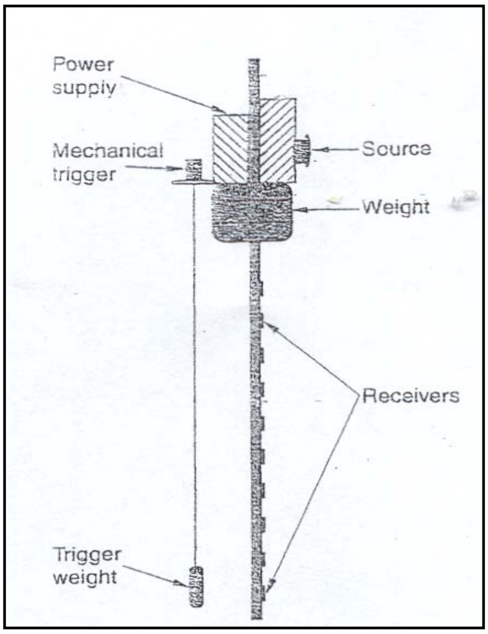

Figure 3.2. Acoustic Lance configuration, from (Fu et al., 1996a). The distance between mechanical trigger and bottom receiver is approximately 3 m.

The lowest range of frequencies examined by *in situ* probes use a broadband mini boomer source, which possesses a spectral content from 1 to 11 kHz (Best *et al.*, 2001). When combined with hydrophone receivers, which could be placed in or on the sediment, refraction experiments could be used to measure compressional wave velocity and attenuation coefficient. S-R separations of 1.1 to 18 m combined with the placement of the mini boomer source on the seafloor ensured that the majority of the sediment through which the acoustic waves propagate is undisturbed. Though a variety of processing techniques were considered, tests confirmed the stability of the filter-correlation technique (Best *et al.*, 2001). This technique has been applied to gassy muds in Southampton Water, U.K. (Tuffin, 2001) and silty muds in Lough Hyne, Ireland (Best *et al.*, 2001). A confirmation of the validity of the spherical spreading pattern used and the repeatability of the source signal has only been presented for the water column (Best *et al.*, 2001), and not in the sediment as required. The repeatability of the coupling was qualitatively examined, with results suggesting that "unrepeatable coupling is not a significant source of error" (Best *et al.*, 2001). A detailed error analysis is included, with resulting velocity errors of $\pm$ 50 to $\pm$ 300 m·s^{-1} and attenuation coefficient errors of $\pm$ 0.5 to $\pm$ 2.0 dB·m^{-1}.

3.2.4. SAX99

In 1999 a series of high-frequency sediment acoustic experiments, SAX99, were performed on sediments lying at a water depth of 18 to 19 m off the coast of Florida, USA. This deserves special mention as the aim of these experiments was to "quantify the interaction of high frequency acoustic fields, (mostly in the 10 to 300 kHz range) with seafloor sediments" (Thoros *et al.*, 2001). The geotechnical properties of the medium sand examined were measured using a large number of sediment samples and cores. In addition to scattering experiments, a variety of techniques incorporating *in situ* probes were used to measure compressional wave velocity and attenuation. In all cases only the scatter of measured values is presented and intrinsic errors are omitted from the published literature.

The experiments carried out in SAX99 which are most relevant to the present research are measurements of velocity and attenuation coefficient from 20 to 100 kHz, in increments of 5 kHz, made using ISSAMS (Buckingham and Richardson, 2002; Thoros *et al.*, 2001). The analysis of the transmission data obtained is by far the most thorough to date. A comprehensive examination of wave shape changes is included, which has been previously discussed in *Section 3.2.* In the case of ISSAMS, the electronic pulse transmitted to the source possessed a square envelope, *Figure 3.3*. When combined with the resonant mode in which the source transducer operated this resulted in major shape alterations between the electronic pulse transmitted to the source and the acoustic pulses emitted into water, *Figure 3.4,* and sediment, *Figure 3.5*. The effects of transducer ringing, which produce a tail effect, are most pronounced for propagation through water. For both propagation through water and sediment, the resulting pulse possessed a smoother envelope than the electronic pulse. Hence the authors conclude that techniques which use a comparison between the electronic pulse sent to the source transducer and a received pulse which has propagated though an acoustic medium, will incur significant systematic error (Buckingham and Richardson, 2002).

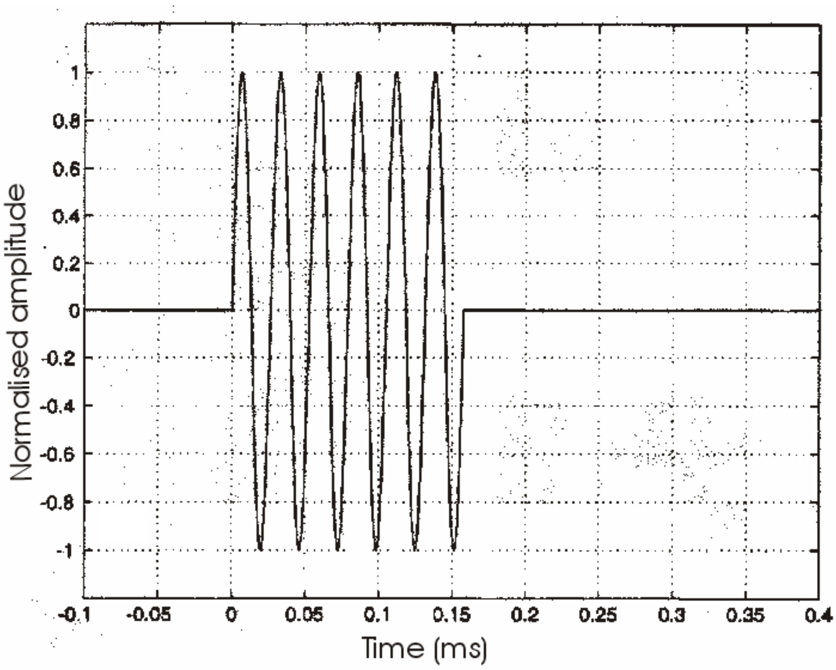

Figure 3.3. Electronic pulse transmitted to ISSAMS source transducer, from (Buckingham and Richardson, 2002).

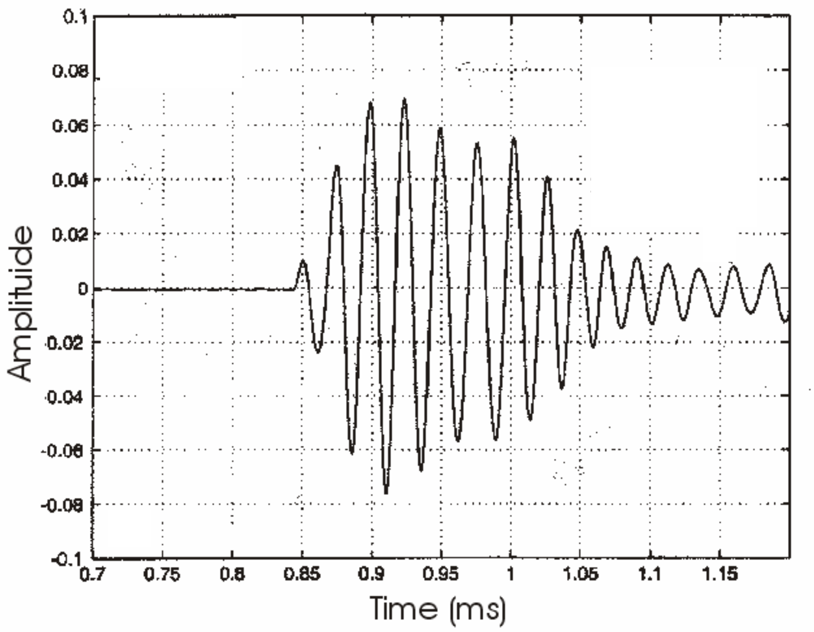

Figure 3.4. Pulse received by ISSAMS which has propagated through water with a S-R separation of 1.3 m, with "tail" added to pulse due to source transducer ringing effects. Amplitudes are plotted in arbitrary units. From (Buckingham and Richardson, 2002).

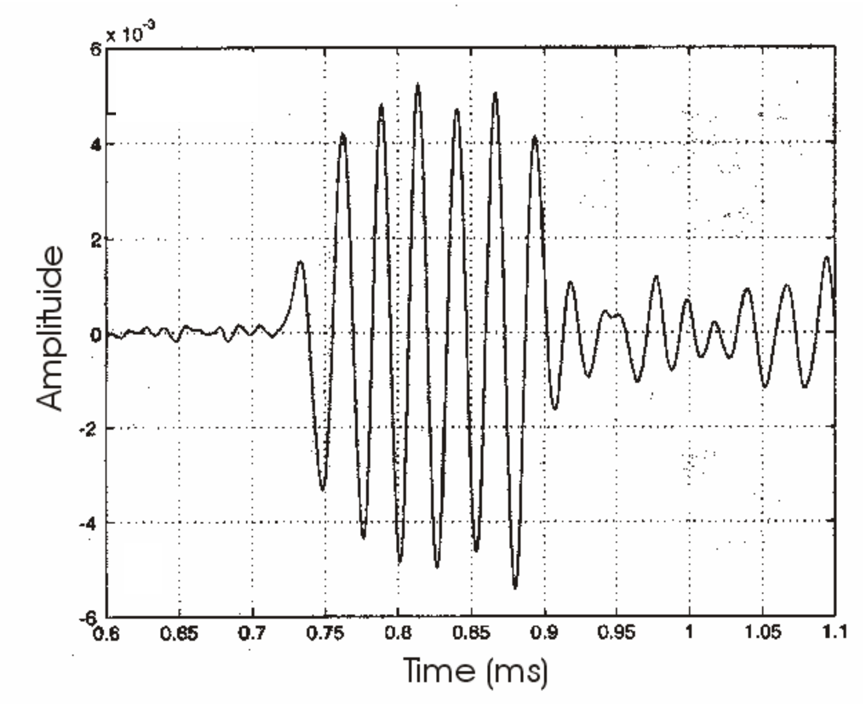

Figure 3.5. Pulse received by ISSAMS which has propagated through medium sand at the SAX99 site, using a S-R separation of 1.3 m. Amplitude is plotted in arbitrary units. From (Buckingham and Richardson, 2002).

The use of a source and receiver pair and a pair of receivers in the standard technique for calculating velocity discussed in *Section 3.2* were examined. The authors concluded that the use of a source and receiver pair results in a velocity which increases with S-R separation, while the use of a receiver pair produces velocities with no obvious systematic dependence, *Figure 3.6*. Therefore the authors use this second technique to calculate velocity, with errors of $\pm$ 9 m·s^{-1}. However the scatter in the velocities obtained from both techniques is considerable and reduces confidence in any trends observed. An alternative view is that velocities obtained at S-R separations less than 0.55 m and R-R separations less than 0.4 m are highly variable, owing to an increased proportion of the sediment under examination being disturbed. This would nullify any trends between velocity and probe separation for either technique.

Attenuation coefficient is calculated using comparison of peak temporal amplitude and transposition, *i.e.* the use of two receivers which lie between two sources and the transmission of pulse from each source in turn. Though this will account for mismatch between the receiver sensitivity, it will not account for unrepeatable coupling which results in a standard deviation of approximately $\pm$ 60 % in attenuation coefficient obtained

(Buckingham and Richardson, 2002). Only two locations were examined from 20 to 100 kHz, and though attenuation coefficient was "nearly linear" relating to frequency for both these sites the gradient of the slope varied by a factor of 2. This was attributed to the difference in the coupling of the transducers to the sediment

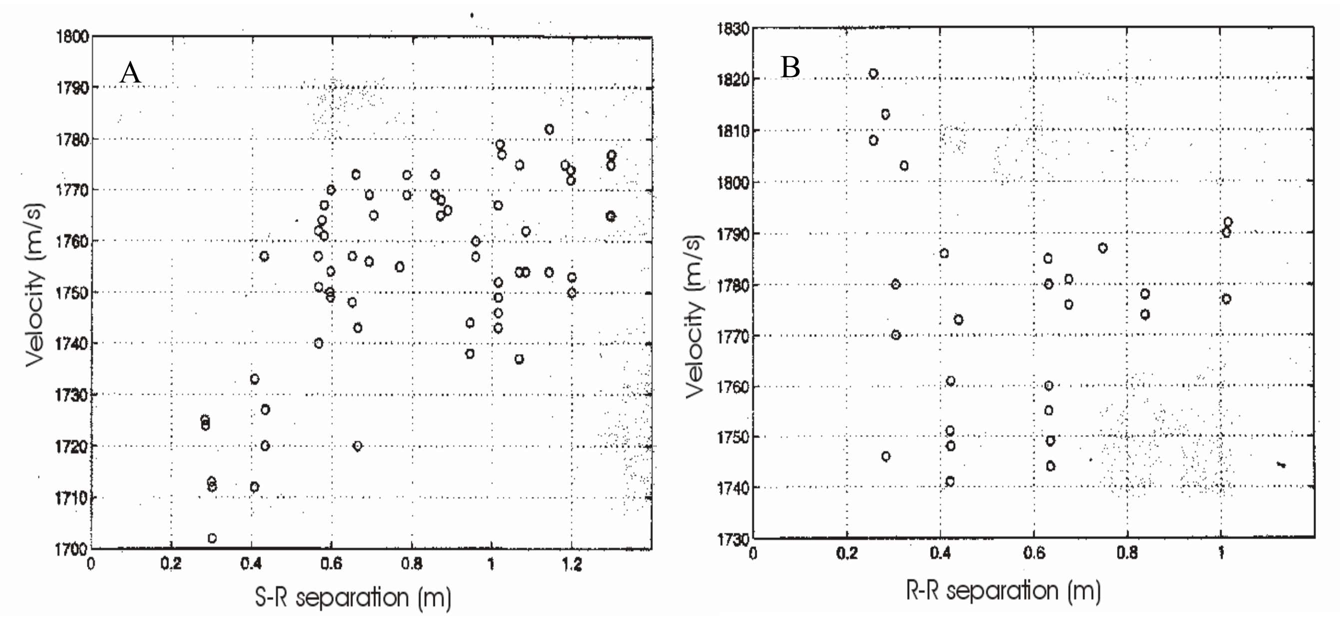

Figure 3.6. Compressional wave velocity versus probe separation using S-R separation (A) and receiver-to-receiver (R-R) separation (B). From (Buckingham and Richardson, 2002).

Additional techniques which use *in situ* probes to measure compressional wave velocity and attenuation during SAX99 include:

- At the lower frequencies of 125 and 400 Hz velocity was measured using bottom towed ocean sleds (Stoll, 2001; Williams *et al.*, 2002).
- A diver-portable geoacoustic tomographic system (Richardson *et al.*, 2001) was used to measure velocity at 150 kHz.
- Velocities and attenuation coefficients were obtained from 11 to 50 kHz using a source supported 5 m from the seafloor on a movable tower and a buried array of receivers (Williams *et al.*, 2002).
- Velocity was also measured from 100 to 200 kHz and attenuation coefficient from 100 to 260 kHz, in 20 kHz increments, using an attenuation array (Thoros *et al.*, 2001).

- Attenuation coefficient was measured at 170 kHz using an Acoustic Imager (Thoros *et al.*, 2001).

Though SAX99, and particularly ISSAMS, presents the most thorough *in situ* examination of compressional wave velocity and attenuation coefficient to date, its major limitation is its application to a single sediment type. This prevents any relationships being drawn between the geotechnical properties of the sediment and the compressional wave properties measured. The majority of techniques used within SAX99 assume that spreading losses are the same in water and sediment and neglect to discuss the repeatability of both the emitted acoustic wave and the coupling of the probes to the sedimentand source wave. Errors are predominantly calculated from the scatter in the results, with only a few cases citing intrinsic errors.

3.3. Summary

Transmission experiments using *in situ* probes have been identified as the optimum technique to perform the well-constrained experiment required with this project. The relatively simple geometry of transmission techniques allows both the volume of sediment through which the acoustic waves propagate to be well-defined and reliable processing techniques to be developed to obtain compressional wave velocity, attenuation and quality factor. The use of *in situ* probes acts to minimise sediment disturbance and allow *in situ* compressional wave properties to be measured.

However, the use of *in situ* probes to date possesses a number of limitations. The primary restraint is the lack of a series of experiments which use the same device and processing technique to examine a wide range of sediments and frequencies. This would produce results that were directly comparable and allow the relationships between geoacoustic properties and both the geophysical properties of the sediment and the frequency of the insonifying wave to be determined reliably. Compressional wave properties measured by *in situ* probes are generally limited to frequencies less than 50 kHz, with the notable exception of SAX99 which is limited to a single sediment type.

While the majority of the relevant research incorporates a methodology which minimises sediment disturbance and adequately measure the geotechnical properties of the sediment, published results suffer from at least one of the following omissions:

- The use of spreading losses which are invalid for the sediment under examination.

- The omission of a thorough analysis of intrinsic errors of the device used and processing techniques adopted.
- No examination of the repeatability of the acoustic wave emitted by the source.
- No examination of the coupling of the source transducer and receivers to the sediment.
- A processing technique which does not incorporate alterations to pulse shape.

The aim of the following two Chapters is to describe the development of a device, suite of experiments and processing techniques that will incorporate all the ideal requirements listed in *Section 3.2.*