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DEVELOPMENT OF A PULSED ACOUSTIC TELEMETRY SYSTEM FOR PENETRATORS

C.G. Flewellen

NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE OF OCEANOGRAPHIC SCIENCES

INSTITUTE OF OCEANOGRAPHIC SCIENCES

Wormley, Godalming,
Surrey GU8 5UB
(042-879-4141)

(Director: Dr. A. S. Laughton, FRS)

Bidston Observatory,
Birkenhead,
Merseyside L43 7RA
(051-653-8633)

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Institute of Oceanographic Sciences
Deacon Laboratory
Wormley, Godalming
Surrey GU8 5UB

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FLEWELLEN, C.G.

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ISSUING ORGANISATION

Institute of Oceanographic Sciences
Deacon Laboratory
Wormley, Godalming
Surrey GU8 5UB. UK.

Director: Dr A S Laughton FRS

TELEPHONE
0428 79 4141

TELEX
858833 OCEANS G

TELEFAX
0428 79 3066

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DEPARTMENT OF THE ENVIRONMENT
RADIOACTIVE WASTE MANAGEMENT RESEARCH PROGRAMME

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Author/Affiliation: C.G. Flewellen, Institute of Oceanographic Sciences, Deacon Laboratory, Wormley, Godalming, Surrey, UK

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A computer based data logging and acoustic transmission system was designed for mounting in the tail of a model penetrator. A frequency of 3.5 kHz was chosen to minimise the attenuation of signals transmitted through tens of metres of sediment and five kilometres of water in the deep ocean. Provision was made to sample up to eight sensors for measuring acceleration, tilt, temperature and pore-pressure during the descent of the penetrator through the water column and the sediment. Software was written, first in machine code and later in FORTH, to sample at 10 Hz during the descent through the water column, and at 500 Hz during the deceleration through the sediment and to transmit this data using pulse interval telemetry. The equipment developed consisted of a pressure case carrying the 3.5 kHz transducer at one end, underwater connectors to a separate sensor housing at the other end; it contained a battery pack and board of electronics. Early trials produced a number of failures due, it was assumed, to high static and dynamic pressures but after a number of modifications were made the success rate improved. After twelve deployments in both deep and shallow water the overall success rate was 50%, the last three trials being completely successful.

Keywords

94 Ocean disposal, 124 Borehole studies, 132 Marine emplacement studies, 199 Instrumentation.

CONTENTS

1. INTRODUCTION

The Deep Ocean Model Penetrator (ref. 1) is a 2 tonne projectile used to assess the mechanical properties of ocean sediments and to determine the depth to which high level radioactive wastes could be buried. The penetrator is allowed to free-fall through the water to embed itself in the underlying sediment. Penetrators have been successfully instrumented with continuous acoustic transmitters; the doppler shift in the frequency of this signal providing the shipboard receiver with a measure of the penetrator's velocity. This can be differentiated to yield the deceleration of the penetrator and integrated to provide the depth of penetration. Using a suitable soil model, these data can be used to estimate the variation of sediment strength with depth (ref. 2).

Differentiation accentuates any noise on the raw velocity signal and it was desired therefore to measure directly the deceleration of the centre of mass as well as log data from a range of other sensors during the descent through the water-column, during deceleration and after the penetrator had come to rest. The sensors were to include tilt meters, accelerometers, a temperature sensor and differential pore-pressure gauges. It was hoped that pore-pressure measurements would determine whether hole-closure occurred immediately. A more sophisticated system was required to log these data and transmit them through the sediment after embedment and would have at least two advantages over a doppler system:-

(i) The information would not be transmitted through the noisy wake of the penetrator.

(ii) Deceleration could be sampled faster than the information bandwidth of a doppler system would allow.

Special consideration was given to the fact that the system might ultimately be used with full scale penetrators that would penetrate deeper and result in a greater acoustic attenuation than the model penetrators used in these experiments.

PATSY (Pulsed Acoustic Telemetry SYstem) was developed to meet these requirements. The system described in this report was designed around a 3.5 kHz acoustic transducer capable of transmitting high power pulses and receiving weak interrogation signals from a transmitter at the sea surface. A microprocessor is used to log the data from the sensors and then encode and transmit them. PATSY is capable of transponding, that is echoing back a pulse on receiving one from the ship, making it possible to locate the instrument relative to the ship's known position. Because of its ability to transpond the system was known initially as LFTS (Low Frequency Transponder System).

2. OBJECTIVES

(i) To develop a technique for transmission, acoustically, of information about the depth of penetration and attitude of a penetrator.

(ii) To develop the system to detect hole-closure.

(iii) To transfer the manufacture of the telemetry system to an industrial organisation.

3. THEORY

3.1 System Constraints

There are some bounds set by the laws of physics which can be used to define the optimum performance to be aimed for. There are other soft limits imposed by the cost of the system and ship's time, the volume available in the penetrator for instrumentation and batteries and the quality and quantity of the data that is to be transmitted. There are trade-offs and compromises that can be made in the latter case.

Signal to noise ratio

The signal level received by the ship from the penetrator transmitter, in 30 to 40 metres of sediment and 6000 metres of water, should be higher than the noise in poor weather conditions, i.e. a signal to noise ratio better than 0 dB must be achieved. When transponding is to be used to fix the position of the penetrator the signal to noise level at the instrument must be even better. The listening conditions there, however, are considerably better, as deep in the sediment there will be a lower noise background than at the ship where also more power is available for transmission to the transponder.

Operating frequency

In deep water the noise from a variety of sources reaches a minimum in the range 1 to 20 kHz. The actual noise levels are very dependent on the weather conditions, local shipping and particularly self noise from the research ship's main engines and thruster as well as auxiliary equipment. The main source of loss in the acoustic signal path is due to inverse square-law spreading and is frequency independent and inevitable. However, attenuation is frequency dependent, being an exponential function of frequency in both water and sediment and very much higher in the latter. It is therefore desirable to use the lowest frequency possible to get a signal through the sediment. Although noise levels will rise with reducing frequency the strongest constraint is set by the physical dimensions of the transducer since as its maximum dimension becomes smaller than a wave-length in water its radiation resistance becomes high and its beam-angle wide. The high radiation resistance, due to poor coupling into the water, means that the transducer can be over stressed either electrically or mechanically before the desired power level can be reached. The wide beam-angle wastes power in directions other than near the vertical.

Data encoding

The encoding techniques available for acoustic telemetry of data include modulation of the phase, frequency or amplitude of a carrier, and modulation of the time interval between pulses.

Amplitude and phase modulation of a carrier are impractical in deep water for at least three reasons:-

(1) Signal to noise ratios better than 20 dB are rarely achieved so there would be very limited dynamic range.

(2) Acoustic signals do not travel by simple "line-of-sight" paths but by multiple paths differing by only fractions of a wave-length due to small angle scattering and turbulence. The combination of signals produces randomly varying amplitude and phase distortions at the receiving hydrophone.

(3) Reverberation from layers within the sediment and from the water surface interfere with the direct signal, although the effect can in theory be removed if the pattern of echoes is constant or only changing slowly.

Frequency modulation suffers like phase modulation unless frequency shifting is employed, which uses available bandwidth and energy less efficiently than other techniques.

Time modulation, using the time delay between two short pulses to carry the information, can be very efficient and can have a large dynamic range. Its disadvantage is that it is slow, though signals can be multiplexed to increase the effective data rate.

Transmission pulse length

The shortest length possible is controlled by the bandwidth of the transducer, being approximately equal to the reciprocal of the bandwidth. However, the longer the pulse the better, as it will contain proportionally more energy. If the coding scheme requires pulses to be transmitted in rapid succession then a long pulse would be a limitation, especially as additional time must be allowed after each pulse for power amplifier capacitors to recharge. A range of between 2 and 20msec seems sensible.

Total energy for transmission

This is essentially limited by the volume in the package that can be allocated to batteries. Lithium cells having about twice the energy-density of alkaline cells would make available several megajoules. Note: the kinetic energy of a 1800 kg penetrator at its terminal velocity is of the same order. It has been estimated that AAA alkaline cells would allow up to 1 megabit of information to be sent using pulse interval telemetry.

Listening time

Several hours would be reasonable, but much longer would become expensive in ship's time and increase the risk of losing data due to a worsening of the weather or because the ship has drifted too far off station and must make noise manoeuvring back again.

Resolution

Digital coding, using frequency shift keying, for example, could have unlimited resolution by merely extending the number of bits in a sequence, but is very expensive in energy. Pulse interval telemetry (P.I.T.) uses only one pulse per data word (plus one reference pulse) and the resolution is limited only by the maximum time that can be allowed to elapse between the pulses. P.I.T. is, however, a form of analogue modulation and will suffer from timing noise. This will arise from amplitude noise riding on the signal and variations in path-length as the receiving "fish" heaves up and down with the swell.

The approximate bit resolution of P.I.T. can be calculated as follows. The rise time t_r of each pulse will be less than half the pulse length, the exact fraction being dependent upon the type and order of the band defining filters used. If the signal pulse voltage into the detector is v_s, the leading edge is rising at v_s/t_r volts per second. In the presence of added noise, v_n rms, the threshold detector time jitter will therefore be $\Delta t = (v_n/v_s)t_r$ (rms), assuming that $v_s > 2v_n$ i.e. a signal to noise ratio greater than 6 db. In general this jitter will be present at both reference and signal channel pulses, though uncorrelated, so the time interval jitter will be $\sqrt{2}t_r\ (v_n/v_s)$. If the maximum, or full scale, time interval is t_o, the time interval resolution of the channel is therefore 1 part in $2^{-\frac{1}{2}}(t_o/t_r)(v_s/v_n)$. For the parameters used here, t_o = 2 secs, t_r = 2 msec, $v_s/v_n > 2$, so the resolution is better than 1 in 1414, i.e. between 10 and 11 bits. The bit rate is thus around 5 bits/sec for a single channel. However increasing the number of channels from 1 to N is straightforward, the only decision required concerns whether the pulse intervals for different channels will be allowed to overlap, in which case for (N+1) pulses transmitted 10N bits equivalent are communicated. In previous underwater applications of P.I.T. overlapping intervals have been allowed and not found to cause undue confusion using a form of direct line scan recorder display. However, this feature clearly relies on the recognition of which pulse belongs to which channel at every new frame of pulses.

If the shipborne receiving transducer is heaving at a rate V m/s between the arrival of reference and signal channel pulse, the timing error introduced in addition to the random noise component above is given by (V/C) td where C is the sound speed (~1500 m/s) and td the signal delay. Generally V will be less than 1.5 m/s, in which case the error amounts to less than .1% of the signal.

Singing round

This can occur during transponding if the transponder responds to the echo of one of its earlier transmissions. In certain critical water depths, when the round trip time for the echo is a multiple of the repetition period, a permanent oscillation can be set up. This problem can usually be avoided by making the transponder receiver not sufficiently sensitive to hear its own echoes and by arranging that it listens in the narrow time window surrounding the expected interrogation pulse arrival time.

Two or more transponders in the area could interfere with each other in a more complex way.

Pulse repetition rate

If pulse interval telemetry is used then the desired resolution sets the fastest rate and there seems to be no good reason for using a slower rate as it would increase the time taken to receive all the data.

Timing of sampling

Certain sensors, particularly accelerometers, are likely to be affected by acoustic pick-up during transmissions. There is also the probability of electrical interference to sensitive sensor processing circuitry at the same time. Sampling must either be synchronised with the quiet periods during a transmission sequence or performed in a different phase and logged for later transmission.

3.2 The Selected Parameters

Pulse interval telemetry was the technique adopted for transmitting data from penetrators. 3.5 kHz was selected for the operating frequency, being the lowest frequency for which a practical transducer could be designed and also the frequency already used by IOS for sub-bottom profiling. The transducer designed for this job had a bandwidth of about 400 Hz. Allowing for the spread between different units, the choice of 200 Hz as the design bandwidth seemed reasonable. This sets the minimum pulse length to 5 ms and this was adopted.

In early tests transponding was used as a means of transmitting data, i.e. in response to regular interrogation pulses from the ship PATSY echoed the pulse and followed it by a number of pulses at variable time delays to carry the information. Reverberation between sediment layers caused trigger jitter and loss of synchronisation. It was thus decided to use free-pinging pulse interval telemetry, the transmission rate being controlled by a local crystal oscillator.

The ability to transpond was, however, retained to provide a means of locating the transponder relative to the ship. In principle the penetration depth can be measured provided the rate of drift of the ship from the launch site is accurately known.

The receiver was designed with a bandwidth of 200 Hz and automatic gain control so that the triggering threshold would adjust itself to suit the received signal level while remaining too insensitive to sing-round.

The power amplifier was built to provide 100 watts of acoustic power while consuming about 200 watts from batteries. The energy required to produce a 5 ms pulse is therefore 1 joule.

It was decided to use a 2 second repetition rate and multiplex a number of data channels by scaling and offsetting each one individually. Thus it would be possible in say an hour to transmit 1800 samples in each of 5 channels with a resolution of 10 bits.

3.3 Sonar Calculations

Assuming:-

Operating frequency	= 3.5 kHz
Water depth	= 6000 m
Penetration depth	= 35 m
Attenuation in sediment	= 0.1 dB/m/kHz
	= 12 dB one way
Power of ship's system	= 2 Kw
with directivity index	= 10 dB
Power of telemetry system	= 100 W
with directivity index	= 5 dB
and with 5 msec pulse, bandwidth	= 200 Hz
Sea-state 6 noise in 200 Hz bandwidth	= -42 dB re 1 Pa

(1) Sound pressure level at transducer	
Transceiver source level	= 33 dB re 1 watt
+ 50.8 dB re 1 Pa/watt @ 1 metre	= 83.8
+ 10 dB directivity index	= 94 dB re 1 Pa
Losses:	
Spreading loss over 6000 m	= 75.6 dB
Water attenuation (@ 0.25 dB/km)	= 1.5 dB
Scattering loss	= 3.0 dB
Loss due to acoustic impedance mismatch at the bottom	= 1.0 dB
Attenuation through sediment	= 12 dB
Total	= 93 dB
Thus sound pressure level at transducer	= 1 dB re 1 Pa

(2) Sound pressure level at the ship	
Transducer source level	= 20 dB re 1 watt
+ 50.8 dB re 1 Pa/watt @ 1 metre	= 70.8
+ 5 dB directivity index	= 76 dB
With the same losses the level at the surface will be	= -17 dB re 1 Pa

This is about the same level as the profiler's bottom echo assuming 30% reflectance.

(3) Sing-round level at transponder	
The total losses will be greater by 6 dB because of the double path plus the remaining losses repeated, i.e.	= 93 dB
Extra distance	+6
Other water losses	+5.5
Sediment attenuation	+12
Total	= 116.5 dB re 1 Pa

With a transponder source level of 76 dB re 1 Pa the sound pressure level back at the transponder will be = -40.5 dB re 1 Pa

This is about 40 dB below the expected level from the ship. This assumes 100% reflection at the surface.

(4) Noise level at transducer

The level near the surface will be about -42 dB re 1 Pa and there will be a few dBs drop in the water-column due to attenuation, scattering and refraction. It is expected that the noise will receive a similar attenuation in the sediment, as the signal. Allowing 15 dB for these losses

Noise level at transducer = -57 dB re 1 Pa

Ship's noise could, however, add considerably to this.

(5) Transducer receiving sensitivity -95 db re 1V/Pa

4. SYSTEM DESCRIPTION

4.1 Hardware

4.1.1 The transducer

This is a commercially produced item using a piezo-electric ring mounted off from a base-plate and surrounded by a rubber boot filled with oil. The base-plate carries a thread and 'O' ring seal compatible with an IOS designed pressure case.

One of the disadvantages of a ring transducer is that the electro-acoustic coupling is poor and this both raises the impedance seen into the electrical terminals and narrows the bandwidth. Limits are thus imposed on the maximum power that can be transmitted and the form of modulation that can be used.

4.1.2 The pressure case (see Fig. 1)

Earlier plans to use the penetrator as a pressure case were discarded due to the difficulty of machining a heavy penetrator to the necessary precision. A standard 6 inch outside diameter, 30 inch long tube takes the transducer at one end, and an end cap with 16 electrical connections for underwater plugs at the other.

4.1.3 The optical switch

An optical device, adapted from an IOS design to fit into the nose of the penetrator, detects the moment of impact with the seabed. In operation, infrared pulses are transmitted across a small gap to a light sensitive transistor until blocked by sediment.

4.1.4 The circuitry (see details in Annex and Fig. 2)

One long printed circuit board carries a low power microprocessor, support chips, memory and analogue circuitry. The analogue and digital elements of the board are deliberately separated to reduce mutual interference.

The analogue part comprises:-

(i) The transmitter. Essentially this is two power transistors driven through a buffer from the microprocessor and coupled through an output transformer to the transducer via a tuning choke.

(ii) The receiver. A signal from the transducer is extracted by a tertiary winding on the output transformer through a matched pad. The matched pad prevents the transmitter being loaded down by the receiver during transmission but ensures that maximum power is absorbed from the transducer on reception. The signal is amplified up by a low-noise first stage and two band-pass filter stages with an automatic gain controlled stage between them. Detection is approximately square-law in the region of 50 mV, the switching point of the following comparator. The output from this is sharpened up to provide a negative logic signal to interrupt the microprocessor.

(iii) The analogue to digital converter. One of 8 (expandable to 16) analogue signals between +5 and -5 volts is selected by a multiplexer for digitising. During conversion the signal is held steady by the sample and hold circuit. 12 bits are converted in about 60 microseconds.

(iv) The supply switch. Transistors are used to control the +12 and -12 volt supplies to off-board sensor conditioning circuitry, to allow them to be switched off to conserve power between samples at low sampling rates.

The digital part of the board consists of an HD6303 microprocessor that can address 16K of read-only-memory (ROM) and up to 40K of static random-access-memory (SRAM) (Fig. 3). The processor controls the analogue to digital converter and generates pulses to drive the transmitter.

4.2 **Software** (see details in Annex and Fig. 3)

In the early stages the logging and transmission program was written in machine code but this proved to be difficult to develop and debug. All later code was compiled by a "tuned" version of FORTH resident in ROM.

FORTH plus the compiled code can be viewed as a dictionary of procedures or 'words' on to the end of which additional words may be compiled at any time. This allows the user, through a standard terminal and interfacing box, to create test routines at the last minute to, for instance, check the calibration and correct functioning of sensors and test the memory used for data storage. It is even possible in an emergency to recompile a new version of the main program without the use of a development system and produce code that will execute immediately and at full operational speed.

4.3 Sampling and Data Transmission Sequence

This is the description of a typical sequence (see Fig. 4).

4.3.1 Preparation

After test and diagnostics have been run the user can preset a number of parameters such as the number of cycles of sampling or transmission of different data sets and the scaling to be applied to each channel for transmission. To reduce the work-load these parameters can be given default values by executing SETUP and then only alterations need be made. The main program can then be executed triggering a series of pings at one a minute. The terminal can now be disconnected and the electronics sealed into its pressure case.

The optical switch is used to sense the instant of contact with the sediment, and can also be used to inform the computer of the instant of launch by the removal of a shutter blocking the optical path. Ten seconds after the shutter is initially introduced this is acknowledged by the ping rate changing to once every ten seconds. (Because the telemetry system and sensor package must be connected to each other before the optical switch can be connected, a shorting plug must be substituted for the optical switch, i.e. the unconnected optical switch is equivalent to a connected but blocked switch. The exchange of the lead from shorting plug to optical switch must then be performed within 10 seconds).

Later on in the experimental programme, the optical switch was used to provide a 2400 baud serial link to the terminal so that it was no longer necessary to start the program until after the pressure case had been assembled into the penetrator and various diagnostic tests made. In addition 2-second long break periods were introduced between logging and transmission sequences, during which time, if the serial interface was connected and sending characters, the program could be aborted. The time after the shutter was introduced to the optical switch before the program entered the armed state was increased to 30 seconds.

4.3.2 Descent through the water-column

As the penetrator is released and the optical switch unblocked PHASE1 sampling starts. Sampling of tilt, temperature and acceleration proceeds at 10 Hz interleaved with pinging at the same frequency. (This pinging was later cut out of the program). These medium sampled data values are stored for later transmission. Meanwhile two accelerometers are sampled at 500 Hz and stored in a rolling-buffer. One minute into the fall the optical switch is enabled to interrupt on contact with the sediment.

4.3.3 Deceleration through the sediment

This, PHASE2, of the sampling is instigated by an interrupt from the optical switch or, as a backup, by the deceleration signals exceeding a threshold of 3g. PHASE2 is similar to PHASE1 except that it times-out after 2 seconds and no pings are transmitted.

4.3.4 Transmission of resting attitude

This is a live transmission, using free-running pinging at 1/2 Hz repetition rate, of tilt and accelerometer signals.

4.3.5 First transponding session

Ten minutes of transponding at this time, before the ship has had a chance to drift away, allows the penetration depth of the transducer to be determined acoustically.

4.3.6 Logged data transmissions

The fast rate (500 Hz) data that has been sampled into rolling-buffers during PHASE1 and PHASE2 is backed up to a point 1/2 second before deceleration commenced and is copied into other buffers before being transmitted by free running P.I.T. The medium rate (10 Hz) data sampled through the water-column follows similarly encoded. This sequence is not in the correct temporal order but it is considered desirable to transmit the more important fast rate data first before anything can go wrong. It might help the immediate interpretation of the logged data if the samples in each batch were transmitted in reverse order.

4.3.7 Second transponding session

By the time the complete logged data set has been sent 1 to 2 hours will have passed during which the ship can have drifted several miles from the launch site. A suitable period of transponding at this stage will allow the penetrator's position to be fixed and for the ship to manoeuvre back to a point overhead.

4.3.8 Second session of live pinging

This is a good opportunity, for 5 to 10 minutes, to find out whether the attitude of the penetrator has changed and to get a stable temperature measurement in case temperature compensation needs to be applied to any of the data.

4.3.9 The end

Rather than simply stopping the program it might as well repeat itself indefinitely by looping back to transmit the fast data again (Section 4.3.5).

In future, it may be required that after several repetitions of the logged data the telemetry system should reduce power consumption to a minimum, and sample and log data at a slow rate over months or years and come fully awake to transmit that data on demand.

5. TEST PROGRAMME

5.1 Discovery, November 1983

Three wire tests were performed in water depths from 4600 to 5400 m using transponding to transmit the data. During the first test the transponder replied to the 3.5 kHz profiler down to 2 watts of transmitted power but continued to transpond erratically on noise. Before the later two tests the noise performance of the receiver was greatly improved to increase the triggering stability.

The program for these tests was written in machine code for the Motorola MC146805 and was rather inflexible. A temperature sensor and a signal derived from the receiver detector were used to simulate real sensors and sampled live and transponded back immediately. A high degree of rejection of unwanted pulses, which would have caused mistriggering, was achieved by only enabling receiver interrupts for 1% of the time bracketing the expected arrival time of the interrogation pulse (i.e. 2 seconds from the last successful trigger). If ten pulses were missed consecutively the micro-processor powered down to be "awoken" by the next interrupt.

The penetrator was launched at 1136Z on 9th November but was never heard from again. A tape recording of the signal from the 3.5 kHz fish was later replayed and the penetrator was heard to whistle all the way to the bottom suggesting that the transducer might have been damaged or torn out of the penetrator by drag forces to leave a cavity. The double doppler shift between this and its bottom echo allowed the terminal velocity to be estimated at 55 m/s ± 2 m/s. This was somewhat higher than the travel time indicated (52 m/s).

5.2 **M.S. Tyro, March 1984**

A temporary cowling of steel was made in an attempt to remove the drag forces from the rubber boot of the transducer.

The electronics and software were essentially the same as on the Discovery cruise. One alteration was, however, that in response to a number of pings received at a 2.5 (rather than 2) second rate, the transponder would enter a command mode which in the future would allow, with coded pulse sequences, some user control over sampling and transmitting. On the Tyro the one command mode present was entered automatically and triggered a session of 20 minutes of pinging at 2 Hz.

Two instrumented penetrators were to be launched on this cruise, though no wire tests could be performed as the winch operating team were not on this leg.

The first drop

During preparations for launch the transponder was triggered on deck by ship's machinery noise picked up through the deck. It must have heard pulses 2.5 seconds apart as it entered its command mode and started pinging. It was only discovered later that the duration of this pinging having been increased to 50 minutes for test purposes had not been changed back.

The penetrator was launched tail-first and after initial turbulent noise had died away the 2 Hz pings could be heard.

The transponder continued to ping for about 50 minutes and although interrogated at a 2 second rate it would not transpond but returned to the command mode and began a further pinging sequence. Eventually, with the transmission rate now at 1 pulse per second, transponding started. By this time the ship had drifted more than 1.5 km from the dropping site. There was no sign of any modulation, temperature and received signal level, on the telemetry signal.

To judge the range of the transponder the ship steamed off at 5 kts for half an hour. As soon as the engines were started the transponder quit its transponding mode and started free pinging again. However, the pings could still be seen through the ship's noise out to about 6 km horizontal range. When the ship had returned to the site and stopped engines, the pings were seen again but drifting erratically. It was two pinging sequences later before transponding started again.

The second drop

Experience from the first drop indicated that the free pinging was a nuisance so this was written out of the software. The receiver sensitivity was reduced by 12 dB as the first transponder had been too sensitive while there was 12 dB more power available from the 3.5 kHz transceiver.

The penetrator was launched but there was no sign of the transponder. During the fall there was the same high level of 'hooting' as had been recorded on Discovery so it is possible that the fate of the transponder was the same.

5.3 **Discovery, October 1984**

As the penetrators were not loaded for this cruise wire-tests were performed to test the new version of the telemetry system - PATSY (Penetrator Acoustic Telemetry SYstem). The various developments were:-

(i) A faster low power microprocessor capable of addressing 64K of memory was used. The earlier one was limited to 8K.

(ii) The software was written in FORTH.

(iii) Analogue to digital conversion was performed by a single chip. Before, a software routine had been necessary to do the successive approximation.

(iv) Series rather than parallel tuning of the transducer was adopted.

First wire-test

The telemetry system was fitted into a pressure case, which was bolted and wired up to a sensor package provided by the Building Research Establishment. The connections were altered to provide a spare connector at the end of the PATSY pressure case for use as a water switch. Software had been written to test for a low resistance across this connector and thus trigger sampling and pinging at 1/2 Hz. After a preset number of these cycles the program moved on to do 1 to 2 seconds of fast sampling at 500 Hz while pinging at 10 Hz. This action would, in a penetrator, have been triggered by contact with the bottom.

In the water-column 2 accelerometers, 2 orthogonal tilt sensors and a temperature sensor were to be sampled. Only the accelerometers were sampled in the fast phase.

The descent took longer than estimated so the medium sampling terminated some 2000 metres from the bottom; the fast sampling followed immediately and the system went into its transponding mode to transmit portions of the logged data.

The transponding was extremely erratic, very rarely locking on to the interrogation pulse from the surface and quickly losing lock again. This was blamed on the receiver being too sensitive (the extra attenuation through sediment had been allowed for) and the fact that the automatic gain control (AGC) was peak sensing and was adjusting its gain according to the strongest signals received - the transponder's own bottom echoes.

During hauling all signals disappeared, and after recovery it was found that a stack had overflowed. This was a simple software bug and easily eliminated.

Second wire-test

For this test the receiver gain was reduced by 6 dB, the AGC changed to RMS sensing and the duration of water-column sampling increased. This time the descent was quicker and it was necessary to wait at the bottom for medium sampling to end. Erratic transponding started but in worsening weather quickly faded out to restart again during hauling when there was 3000 m of wire out. However, the transponder refused to lock onto the interrogation pulse. After recovery data in memory were played onto a dry paper recorder showing that the sensors were working correctly, the only flaw being that one tilt sensor and one accelerometer were appearing at the same position on the record.

Third wire-test

This was an unexpected bonus and although nothing new was tried it served as a test of a further sensor package. The signal strength was good but transponding performance bad.

Fourth wire-test

Many of the problems with transponding were admittedly due to the nature of wire-testing, the transponder being 200 m above the bottom rather than say 30 m below it. In the former case there would be a high level of echoes from the transponder's transmissions and with up to 6 pulses continually changing their timing relationships, as the data modulates them, a very complex pattern emerges. Below the bottom, echoes from any distant reflector will have a high attenuation and surface reflections are too feeble after 2 passes through the sediment to be detected.

It was decided to try free running pinging for this test and the results were so good that it was decided to adopt this permanently. The disadvantage of not being able to range on the transducer would not be serious because an extra phase of transponding only, i.e. a single pulse being transmitted in response to an interrogation pulse, could be slotted into the sequence.

This system received a hard knock against the side of the ship during recovery and stopped working. Apparently a connection through the board via a socket pin had broken. Later boards were to be made with plated through holes.

5.4 Loch Linnhe, February 1985

At the Underwater Trials Ltd facility a pontoon with a winch and gantry was used to launch penetrators chained to a lifting cable. The 3.5 kHz systems were not tested in the deepest water available so terminal velocities were not reached. A program was written to wait for the closure of the water contact switch then sample at a medium rate for up to 20 seconds or until the bottom was detected. One second of fast sampling was then followed by transmission of this data by P.I.T.

Test 1

The penetrator was lowered into the water to stabilise it before release but unfortunately this triggered the water switch too early. It was therefore not launched. During recovery the electronics package was jarred and pinging stopped. A power supply limiting resistor was found to be burnt out though the cause was not identified at the time.

Test 2

While preparing a second system for another launch dampness in the water switch caused triggering as soon as it was connected. As the electronics were being removed the limiting resistor burnt out again.

Test 3

This time the water switch operated correctly but pinging stopped before the bottom was reached. The cowling protecting the transducer was found to be dented, presumably by the lifting chains banging into it. There was no damage to the transducer, however. The cause of the sudden failures was now obvious - an integrated circuit (a ROM in fact) seemed tight enough in its socket but was able to walk out of its socket if the board was tapped on the side.

Test 4

With all socketed chips tied in with lacing cord and the water switch dried out with a water repellent lubricant, a launch was attempted. However, the water switch could not be wetted even when the penetrator was lowered deeper so this test was aborted.

Test 5

Everything worked this time and a lot of the logged data were tape recorded (see Fig. 5). It was decided to reset the program and immediately do another launch but unfortunately sand trapped around the electronic pressure cases prevented their removal and the test series had to be terminated.

The data were only slightly marred by a few timing jumps and the odd missing or displaced pulses. The causes were subtle but the solutions easy.

5.5 **Marion Dufresne, June 1985**

Six telemetry systems were set up and tested in the laboratory but only four penetrators were ready in time. Five of the six systems were used either for wire tests or deployments, the first having one wire test before launching and three having two pre-launch wire tests. The electronics boards were numbered from 1 to 6, the first three having been made in-house and the others contracted out. There were 14 wire tests, launches and attempted launches.

(1) Board 1

This board did not work immediately having probably suffered electrostatic damage while in transit. After repairs it was mounted on a frame with a sensor package and optical switch and clamped about 50 m up the wire from the RGD pore-water sampler. The intention was to use it as an echo-sounder so that by hauling or veering some slack could be kept in the cable while the sampler was operating.

Instead of a water switch, the optical switch was used as a means of triggering the start of water-column sampling. The switch was blocked before launch and this shutter removed at launch.

The plywood shutter did not come out cleanly at launch and although 1 minute had been allowed between launch and the enabling of the optical switch to detect the mud contact, the plywood was fluttering in the optical path when this time ran out. All the sampling was completed at the surface but the test was continued as the bottom echoes from data transmission would still provide the information required.

The signal to noise ratio was poor and worsened during pay-out so that it became impossible to receive a direct signal let alone a bottom echo. The cause was the ship's variable pitch propeller and bow thruster, the main engine having to be kept running, and this noise was particularly bad at 3.5 kHz.

(2) Board 3 (penetrator deployment)

The system was prepared and set running, pinging once per minute, and connected to the sensor package. As soon as this was done, however, the program moved on to its ready-to-be-triggered state as though the optical switch was already connected but blocked. Triggering the start of sampling was avoided by blocking the optical switch before connecting it.

The launch was satisfactory, the fast pinging starting when the optical switch was unblocked just before release, but within a few seconds it stopped though the noise of the penetrator's wake could still be heard. There was no sign of any pinging or transponding.

(3) Board 6

The frame used for the previous wire test was welded to a metal pipe and threaded onto a steel cable. With a weight on the end of the cable and sections of rubber tube threaded on above it, 660 m of cable were paid out. The instrument package was then released to slide down the cable at about 4 m/s. Although, of course, the optical switch was not triggered by any sediment contact the deceleration threshold was exceeded and the instrument duly logged at a fast sampling rate. These data were later read out of memory onto a dry-paper recorder in the shipboard laboratory.

This was a confidence boosting experiment especially as the open pressure case had been left on deck in the sun and high humidity all afternoon, while preparations were being made, and then had to suffer a few knocks and then the vibration of the descent.

(4) Board 6

At this stage, it occurred to the author that it was possible for the power amplifier to be destroyed by the high level of turbulence-induced noise close to the transducer and that this might be an explanation for the failure of the first penetrator experiment. The mechanism suggested was that low frequency currents of quite modest amplitude flowing through the output transformer would cause it to saturate leaving the power transistors with practically a short circuit load. Sustained operation at a high pulse rate into this load would cause over-dissipation and the destruction of the transistors.

A test in the laboratory proved that this was possible; so from now on the fast (10 Hz) pinging during water-column sampling was removed from the program.

For this wire-test the instrument was mounted with the optical switch to act as the trigger weight for a box-core. The optical switch shutter had to be removed sometime prior to the start of paying-out and somewhat later a bang against the side of the ship exceeded the deceleration threshold and triggered the fast sampling phase. The coring station was continued and the direct arrival from the transducer was seen throughout the water-column though there was no sign of a bottom echo.

(5) Board 6

It was with considerable difficulty that this was finally fixed into the penetrator due to a misalignment somewhere. Unfortunately the optical switch shutter fell out too early and the launch was aborted when the system started to transmit data while suspended from the crane.

(6) Board 5

The instrument assembly was mounted onto the head weight of the Institut Francais du Petrole STACOR coring system with a shutter in the optical switch to be released when the core was triggered. Pinging at the 10 second rate continued throughout the coring station as the string to the shutter broke. Had the data been sampled they would have been particularly interesting as the core barrel came up with a 30 degree bend in it.

(7) Board 6 *(penetrator deployment)*

The system was assembled into a penetrator well in advance of launch. The launch was perfect and the descent was made in silence as intended. There was no sign of a signal from the bottom until, by making adjustments of the receiver gain controls, signals were displayed and tape recorded and plenty of useful data was obtained. The accelerometer traces were very detailed and included three spikes where the deceleration plus gravity had exceeded 10 g. These spikes were clipped because they were above the full scale limit of the sampling system.

The temperature trace was not sensible as it was constant at a level corresponding to zero volts sampled indicating a steady 15 degrees. About 2 hours later during a live transmission this trace was oscillating erratically at about the same level, though the whole package should have reached 2 degrees by this time.

The tilt signals during the descent were not of much value as the sensitivity was too high (9 degrees full scale) and the damped pendulum sensors were not intended for dynamic measurements. The tilt during the live transmission was measured as 3.5 degrees from the vertical.

(8) Board 1

This was a repeat of the previous test performed with STACOR, and this time the optical switch worked but the quality of the data suggested that there was a sampling problem.

(9) Board 1

The result of this experiment was the same as for the first STACOR test - the string broke!

(10) Board 5

The experimental set-up was the same as for previous STACOR wire tests but with a new design of optical switch built by BRE. At about 4000 m depth the optical switch started leaking and this was interpreted as a trigger so that sampling was performed before the bottom was reached. However, a live transmission length of 2 hours had been programmed in and this provided tilt information before core triggering and during pull-out.

(11) Board 1 (penetrator deployment)

The system was prepared 5 hours before this penetrator launch but no signals could be detected after the penetrator had landed.

(12) Board 5

This was the final wire test using STACOR and it was decided to try the optical switch triggering just once more. However, this time it worked perfectly and medium sampling was performed during the coring operation. After the tilt sensors had settled the attitude of the core could be measured.

(13) Board 5 (penetrator deployment)

This last penetrator was successfully launched and although listening was continued for an hour after launch no signals were received.

(14) Board 2

This board had suffered an accident early on in the cruise and it had been decided not to use it; but as the repairs seemed to be satisfactory it was deployed on a prototype shear vane mechanism built by BRE. The purpose of this exercise was to see how deep the mechanism penetrated the bottom and at the same time to test another of the new design of optical switch.

The system was triggered correctly at the surface but although the optical switch was later found to be packed with mud the sampling was not performed at the bottom. The memory was found to be faulty after recovery.

5.6 **Thornton Shaft (Kirkaldy), March 1986**

This flooded mine-shaft which is operated by Underwater Trials Ltd was used in a further sliding wire test in the hope of generating a failure in the electronics or transducer while still being able to recover the instrument. After the streamlined sledge and its braking system had been tested a PATSY package was mounted in it. After launch the system was found to be operating correctly; that is signals from a hydrophone were observed on an oscilloscope. After a further launch pinging became erratic and it was latter discovered that water had leaked into the transducer. A modification to the mounting of the rubber boot was already in the pipe-line so it was hoped that future transducers would not leak.

5.7 **Castor 02, April 1986**

During previous tests no tangible evidence could be extracted from the failed experiments. A buoyant package was devised to carry the telemetry system down in a penetrator to terminal velocity and then release it at a preset depth. The only sensor sampled was an absolute pressure gauge to be used to calibrate the release mechanism.

The package was successfully released on the first trial and was still pinging every ten seconds as required, though there had been a small leak.

For the second test the trigger pressure for release was increased but this time there was no release and the telemetry system was later heard to be pinging through the sediment. As these tests were performed in shallow water (ca. 400 m) it was suggested that though the penetrator may have reached its release depth before the bottom was reached there was not enough time for the mechanism to operate.

5.8 **Tyro, October 1986**

Five commercially made boards were tested soon after the ship left Madeira and all functioned perfectly. Several planned modifications were made to improve the transponding performance.

Prior to two penetrator drops some experiments were performed with a vehicle built by the Joint Research Centre (JRC) and designed to slide down a plastic coated wire to a set of discs providing dynamic braking. It was hoped to simulate the damaging conditions experienced during a penetrator launch while being able to recover the equipment to identify design problems.

Test 1

No transmissions were detected from PATSY after launch but a few minutes after leads had been disconnected on recovery, data transmission started. It was found that an underwater connecting lead had been sliced into at launch, imposing a short-circuit that had stopped the computer. Once the cable had been disconnected the program continued to execute from the point at which it had halted.

Test 2

As the sensor package had to be mounted upside down the sign of the deceleration threshold was changed in the software for this test. Data were transmitted after launch but did not correspond to those expected. A regularly used rechargeable battery pack was found to have a broken connection.

Though faults occurred during these tests they were not in the PATSY hardware or software. The estimated terminal velocities of between 10 and 15 m/s would not have been expected to create the degree of drag and turbulence that might be damaging the transducer or electronics in a free falling penetrator.

JRC penetrator launch

For these trials the infra-red beam of the optical switch was intercepted by a specially designed optical coupler to provide a 2400 baud serial communications link between PATSY and a remote terminal.

The same telemetry system that had been through the previous tests was assembled into the penetrator and then thoroughly tested in situ using the new communications technique. The penetrator was launched horizontally hung from a strop and although this broke before it could be guillotined the launch was satisfactory. No transmissions from PATSY were detected even after 53 minutes when, had there been no bottom trigger, the sampling routine would have timed-out and live data transmissions begun.

BRE Penetrator launch

The penetrator had been modified to take two differential pore-pressure sensors - one measuring pressure at the nose and the other the pressure half way down the shaft of penetrator. The reference pressure for these gauges was that in the cavity inside the penetrator, sealed except for a plastic pipe leading from the tail.

Modifications were made to the software to provide a relay drive signal to select the pressure sensors which shared common conditioning circuitry.

When launch took place only a couple of hours of ship time remained. Data transmissions were soon detected though seemingly unsynchronised with the two second sweep of the line-scan recorder. After a very satisfactory 5 minutes of transponding about 100 minutes of logged data were received before the ship, which had now drifted 4.3 km, had to leave for Holland.

It was evident from the medium rate data that triggering had occurred in the water column - in fact one of the accelerometers had been damaged at launch and was therefore generating a false signal. In addition it was discovered that one pressure sensor was being consistently deleted from the display due to the hurried software alterations and that the repetition period of the live data was 50 msec longer than it should have been (see Fig. 6).

5.9 Castor 02, November 1986

Although wind tunnel measurements on a scaled penetrator had indicated there would be negligible pressure fluctuation above about 8 Hz, the author wondered whether the tail fins might not have a resonant mode in the vicinity of 3.5 kHz that might be damaging the transducer and power amplifier.

Prior to launch in say 5400 m of water, an 1850 kg penetrator has about 100 MJ of potential energy. However, it reaches the sediment at about 50 m/sec with only 2 MJ of kinetic energy, so most of the potential energy is lost during flight at the rate of about 1 MW. If only a small percentage of this power was being extracted by a bending mode of the tail fins, excited by vortex shedding, large and possibly damaging pressures could be generated near the transducer at its resonant frequency.

It was thus decided to trim about 100 mm off the trailing edges of the tail fins and add voltage limiting resistors across the transducer terminals.

Two instrumented penetrators were dropped in about 250 m of water off Cap d'Antibes. The first launch had to be abandoned when the system triggered itself just before it was due to be released. The penetrator was safely returned to the deck. It transpired that a timing component in the optical switch drive circuitry had been incorrectly changed during testing.

First pore-pressure penetrator

With an expected water column transit time of 10 seconds, it was necessary to hold up release of the penetrator for at least one minute after triggering to ensure bottom triggering had been enabled. After the minute was up, the penetrator was held a little longer to check for a pre-trigger then the penetrator was released.

Live data transmission started as soon as the penetrator had come to rest at an inclination of about 5 degrees. Though the pore-pressure sensors showed small changes in the first five minutes they soon ran into saturation at 6.5 to 7 bar and were still saturated after more than four hours.

It soon became apparent that the optical switch had triggered fast-sampling about 5 seconds after launch when the data indicated that the penetrator was still accelerating towards terminal velocity.

Second pore-pressure penetrator

Because of the erratic behaviour of the optical switch it was decided to alter the software so that only a deceleration exceeding 3 g would provide the bottom trigger. The optical switch was, however, still used to provide the on-deck communications link.

The launch proceeded perfectly and the transmitted data soon indicated that correct triggering had occurred (see Fig. 7). The first live data showed a tilt of about 6.5 degrees from the vertical and changes in pore-pressure similar to the previous results (see Fig. 8).

The fast sampled accelerometer data indicated a peak deceleration of 13 g. This was digitised (see Fig. 9) then integrated once to provide the velocity profile (see Fig. 10) and then again to yield the penetration (see Fig. 11).

During these two trials the transponding performance was initially good but became degraded after a few hours and the transponder stopped replying. It was as if the receiver power-supply was being run down rapidly though it should have lasted for at least six months.

6. DISCUSSION

During the early deployments there were a number of total failures - that is no 3.5 kHz signals were received after launch (see Table 1). It was thus difficult to determine what component might be failing. Two small items of evidence were, however, obtained. After one launch - when the system was pinging at 10 Hz - the pinging ceased about 5 seconds later. Secondly during most of the deployments a high level of hooting was heard near 3.5 kHz. It was first assumed that the drag on the tail acting directly on the transducer was tearing its rubber boot off even before the penetrator had reached terminal velocity. A cowling first of steel then of aluminium was designed to protect the transducer. When four out of six systems thus protected failed to perform more attention was given to the "hooting". In case high levels of noise picked up by the transducer were causing saturation of the tuning choke and transformer it was decided not to have the system pinging during descent. This produced an immediate success but the next two deployments failed. Later, the possibility that the tail fins were being excited to vibrate at a frequency close to 3.5 kHz was considered. By trimming the tail fins and protecting the transducer from excessive voltages it was hoped to reduce this problem and indeed the last two trials were successful. However, it may have been because these penetrators carried pore-pressure sensors and were sealed and flooded with water before launch.

7. CONCLUSIONS

The research programme has clearly demonstrated the feasibility of transmitting data acoustically from penetrators buried in tens of metres of sediment in water depths of 5 km and more. However the poor reliability of the early units resulted in the research programme being directed towards improving the system collected from instrumented penetrator tests. The exact cause of the early failures remains a mystery, although the progressive improvement in reliability during the experimental programme suggests that the remedial actions taken were at least partially effective.

Despite the reliability problems, the experiments have confirmed that PATSY is a sophisticated and versatile instrumentation system, capable of collecting and transmitting data from a number of sensors at data capture rates of up to 500 Hz. Furthermore, PATSY offers the potential of being able to monitor long term in situ experiments and is limited only by the longevity of battery power supplies; such experiments are likely to be essential if research into deep ocean disposal of radioactive waste continues.

The detailed conclusions that can be drawn from the experiments with PATSY are:-

(1) 100 watt pulses at 3.5 kHz adequately penetrate 30 m of sediment.

(2) Data transmission by free pinging was preferable to the use of transponding.

(3) The software, written in FORTH, had been reliable and easy to modify and test.

(4) Large amounts of data can be transmitted. During the final trial about 760 Kbits of data were received at an average baud-rate of 13.6.

(5) Though slow, pulse interval telemetry is efficient in its use of available battery energy, about 6.5 bits being transmitted per joule.

(6) Ship drift from the launch site during data gathering resulted in a gradual deterioration of the received signal strength.

8. ACKNOWLEDGEMENTS

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Marion Dufresne - Dr A. Barbreau (Chef de Mission) of Commissariat a l'Energie Atomique (CEA), Dr R.T.E. Schuttenhelm (Scientific Coordinator) of RGD, Mr Y. Balut (Operations Manager) of Terres Australes et Antarctiques Francaises and other members of the ESOPE scientific party;

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(S.P. 1.07.C2.86.05).

Summary of Penetrator Tests

No.			Prog.	Sensors	Press. case	Cowl	Fins trimmed	Sealed and filled	Wire test	Ship
1	D	T	M/C	TM/TILT	NO	NO	NO	NO	YES	Disco
(2)	D	T	M/C	TEMP	NO	YES	NO	NO	NO	Tyro
3	D	T	M/C	TEMP	NO	YES	NO	NO	NO	Tyro
4	D	P	Forth	2A 2T TM	YES	YES	NO	NO	NO	M duf.
(5)	D	P	Forth	2A 2T TM	YES	YES	NO	NO	YES	M duf.
6	D	P	Forth	2A 2T TM	YES	YES	NO	NO	YES	M duf.
7	D	P	Forth	2A 2T TM	YES	YES	NO	NO	YES	M duf.
(8)	S	P	Forth	Abs press	YES	YES	NO	NO	NO	Castor
9	D	P	Forth	2A 2T TM	YES	YES	NO	NO	YES	Tyro
(10)	D	P	Forth	2A 2T 2P	YES	YES	NO	YES	NO	Tyro
(11)	S	P	Forth	2A 2T 2P	YES	YES	YES	YES	NO	Castor
(12)	S	P	Forth	2A 2T 2P	YES	YES	YES	YES	NO	Castor

KEY

○	System transmitted through the sediment
S/D	Shallow/Deep water
P/T	Operating as Pinger or Transponder
M/C	Machine Code
A	Accelerometer
T	single axis Tilt sensor
TM	Temperature sensor
P	Pore Pressure sensor

TABLE I

TELEMETRY SYSTEM OUTLINE

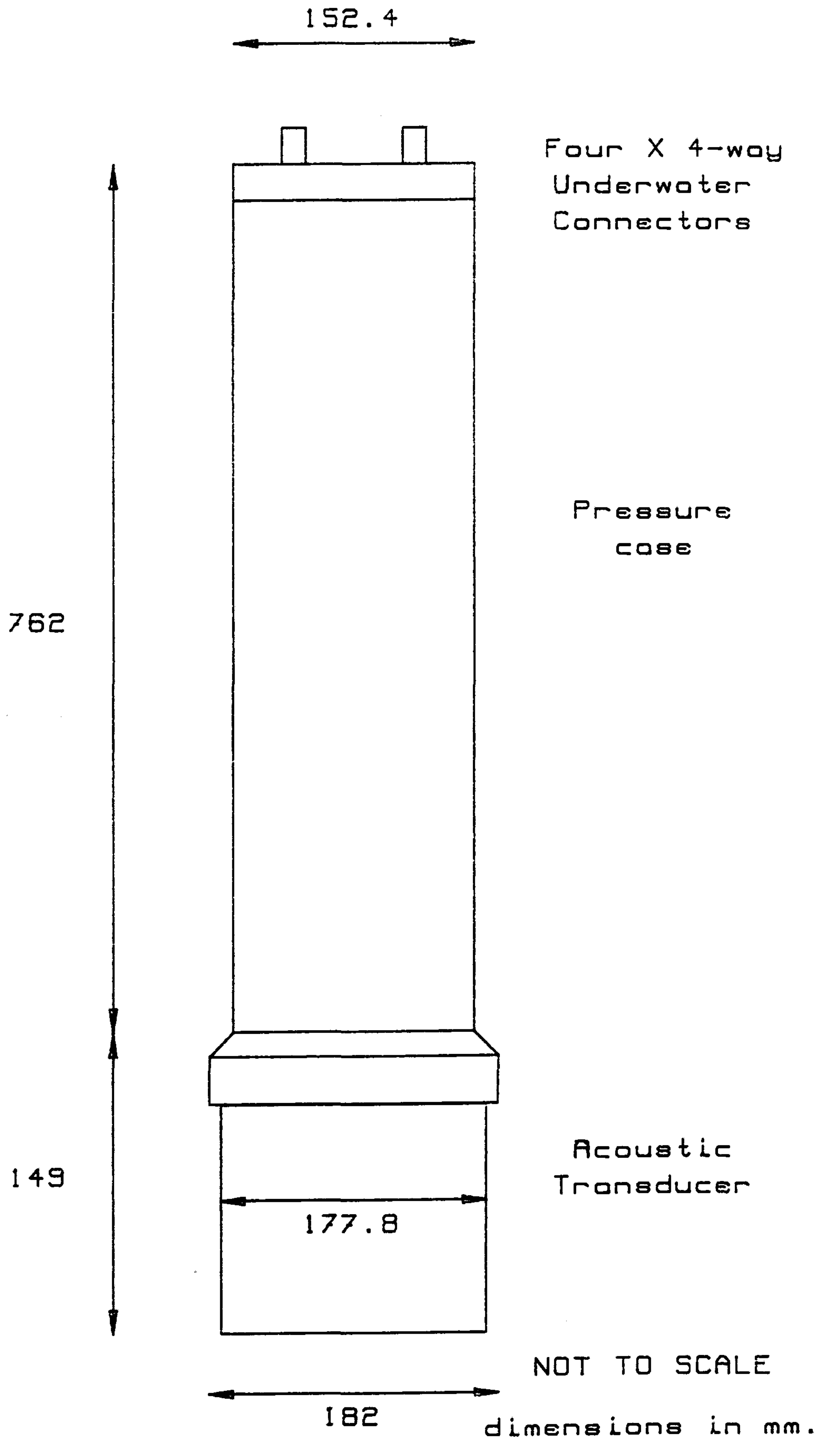

Fig. 1

SYSTEM FLOW CHART

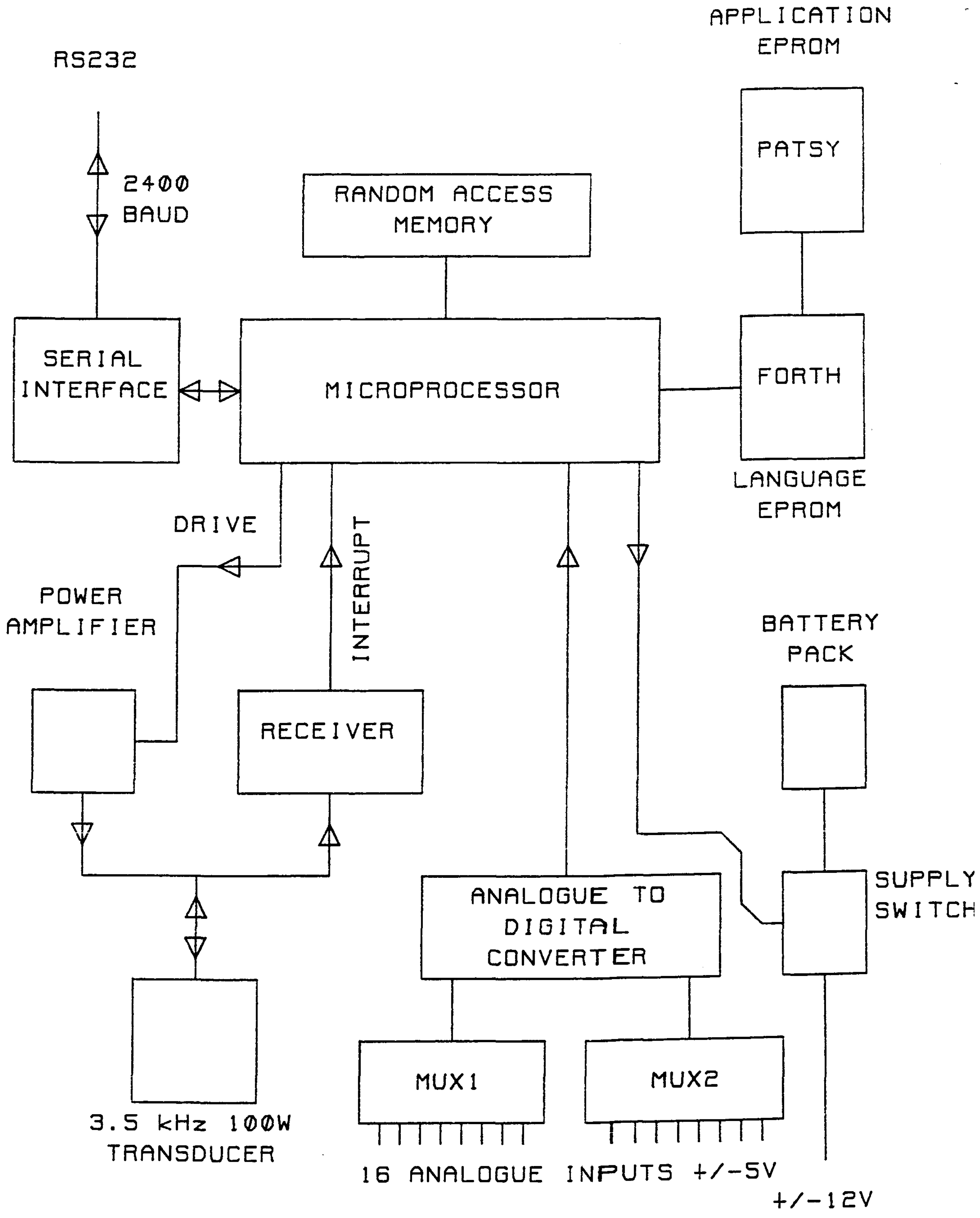

Fig. 2

MEMORY MAP

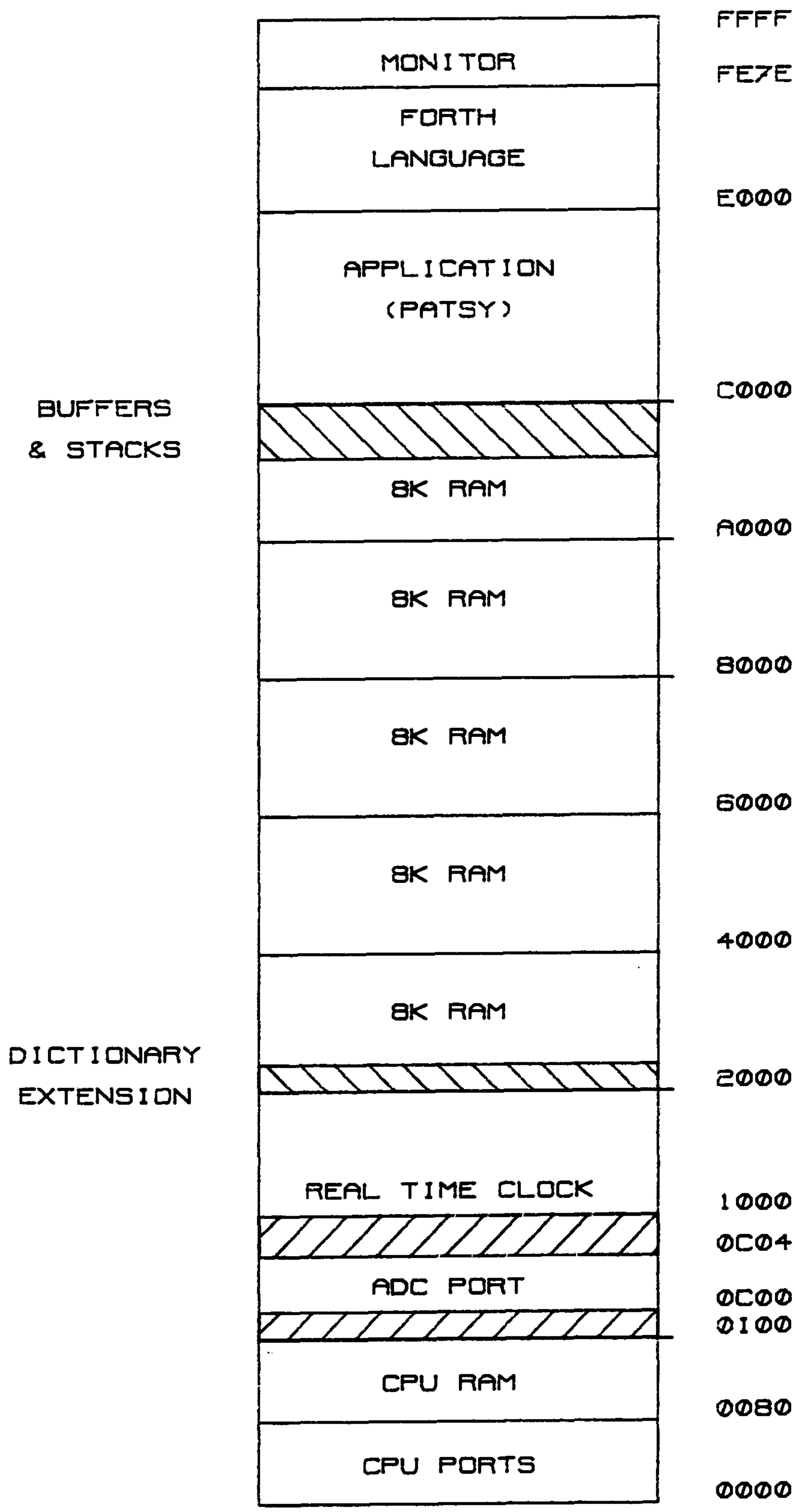

Fig. 3

LAUNCH, SAMPLING AND TRANSMISSION SEQUENCE

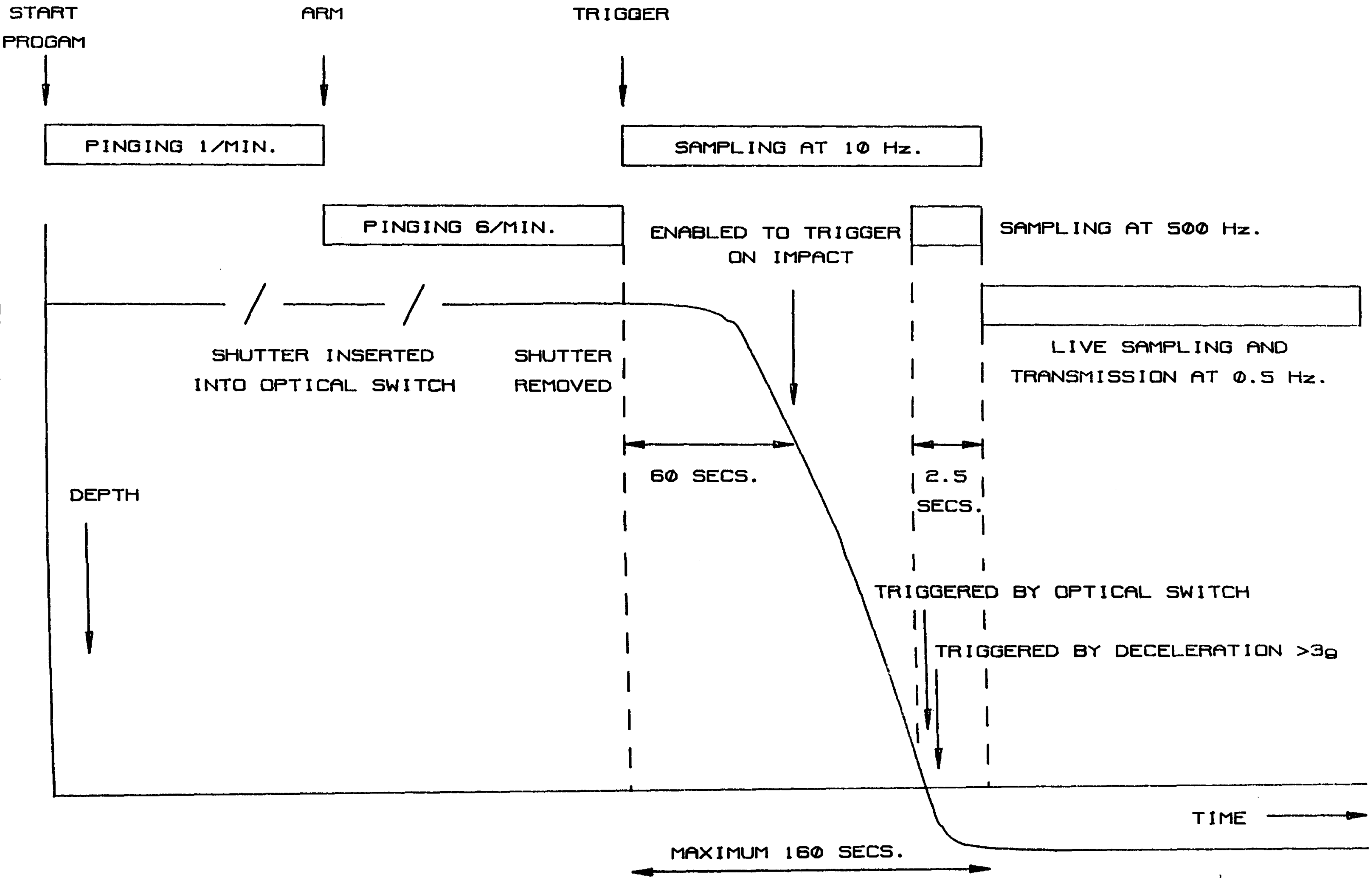

Fig. 4

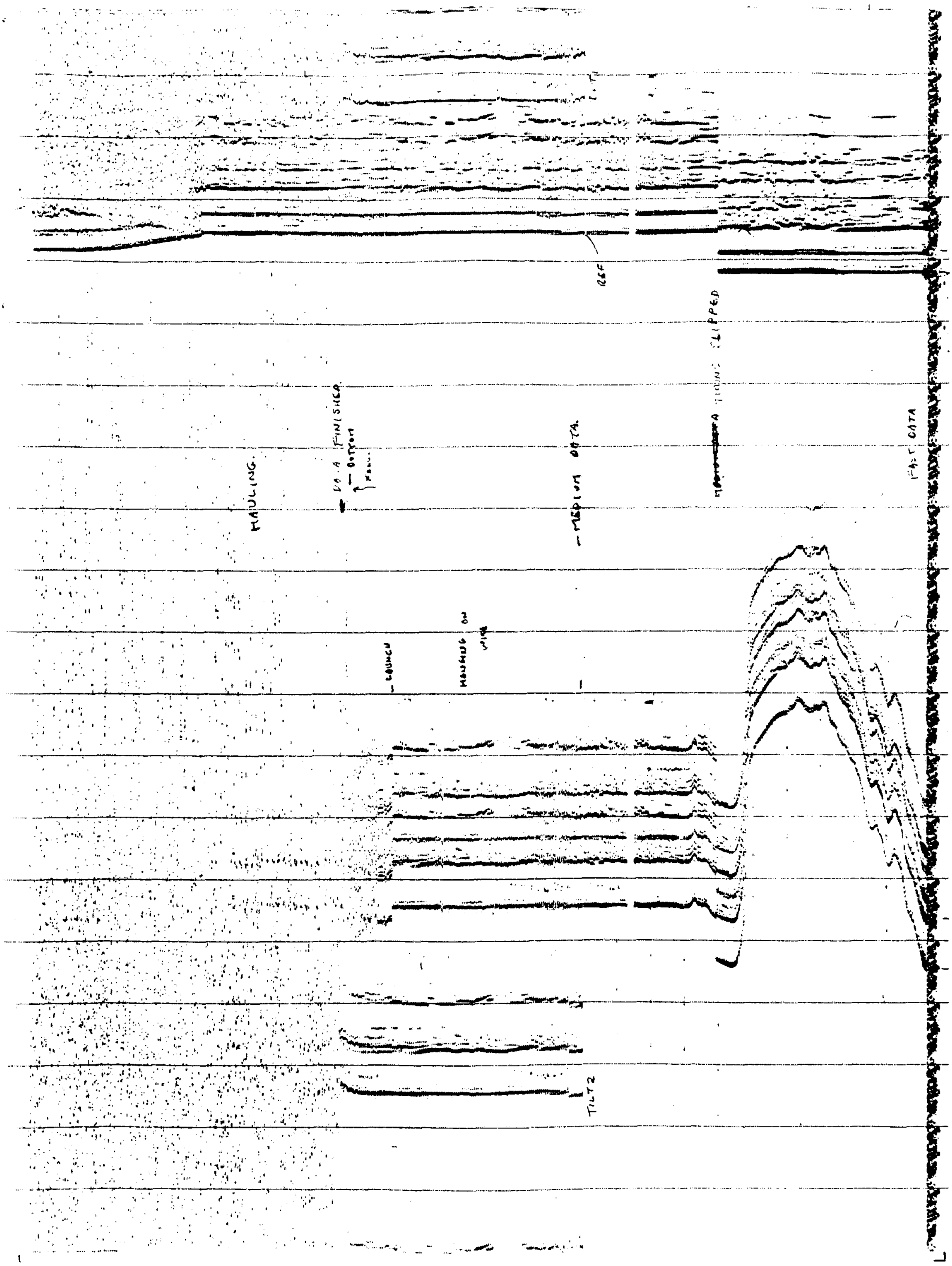

Figure 5 Line scan recorder display of Loch Linnhe data

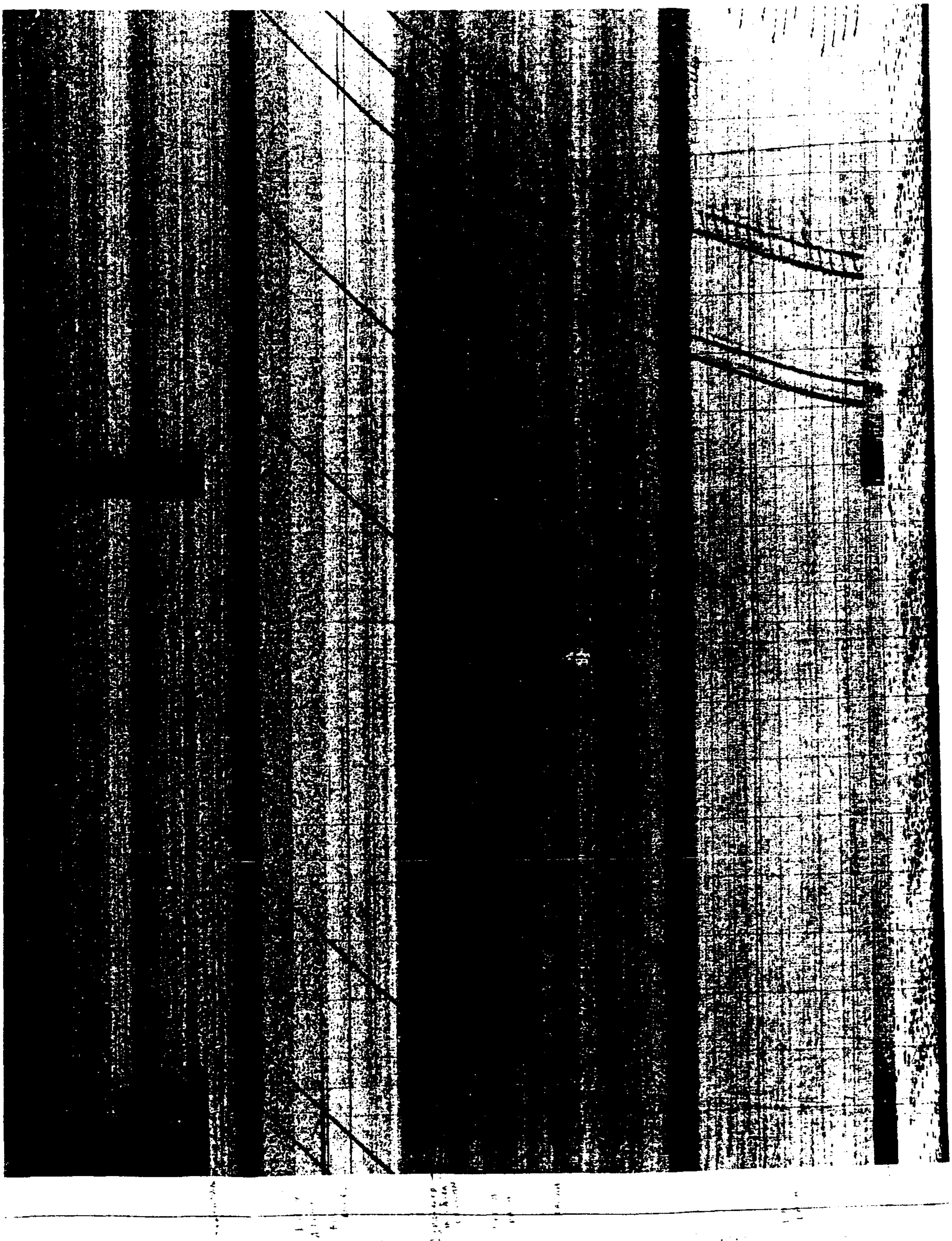

Figure 6   Tyro, October 1986.   Trace curvature due to ship drift

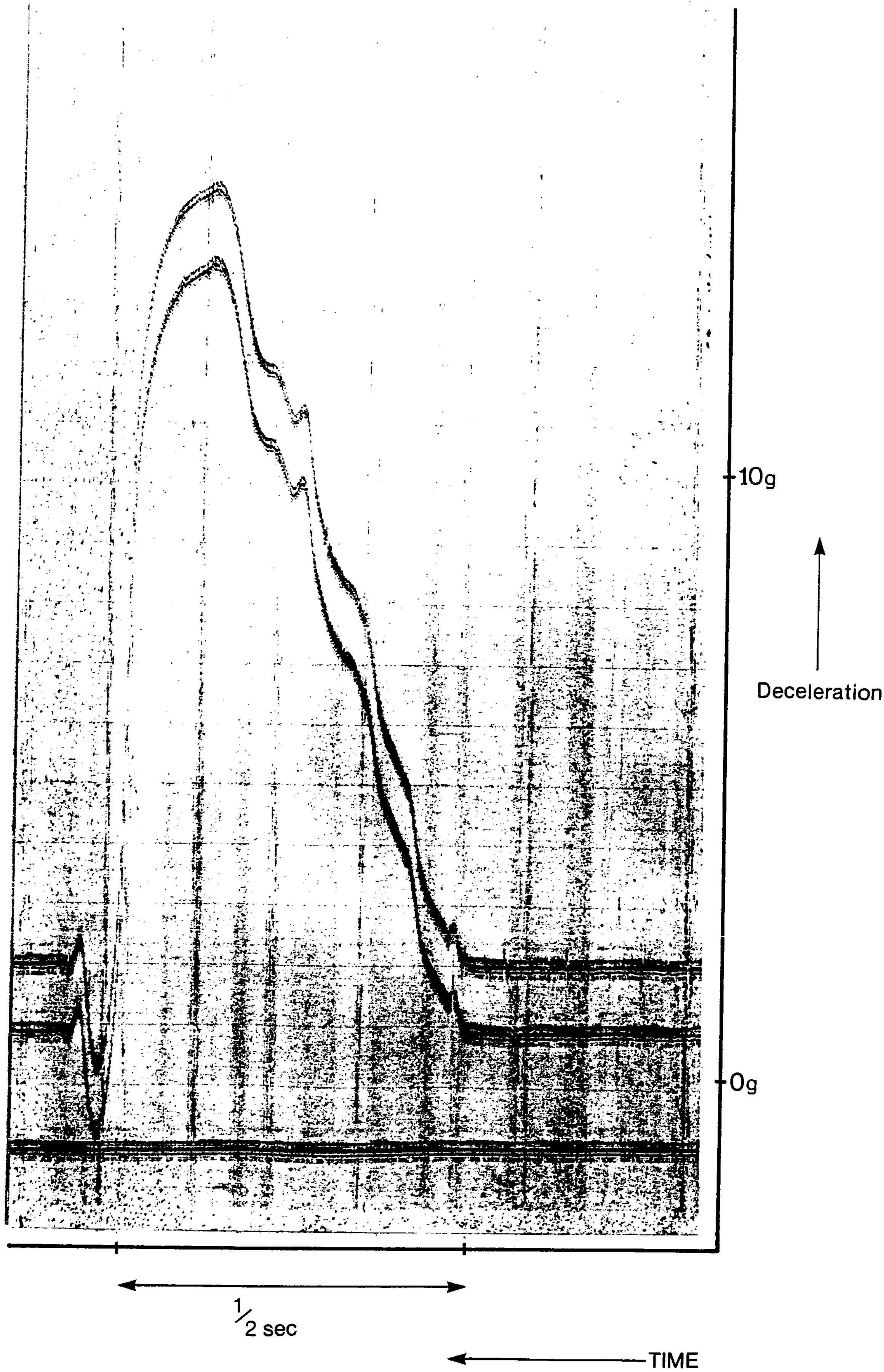

Figure 7 Fast sampled accelerometer data. Castor 02, November 1986.

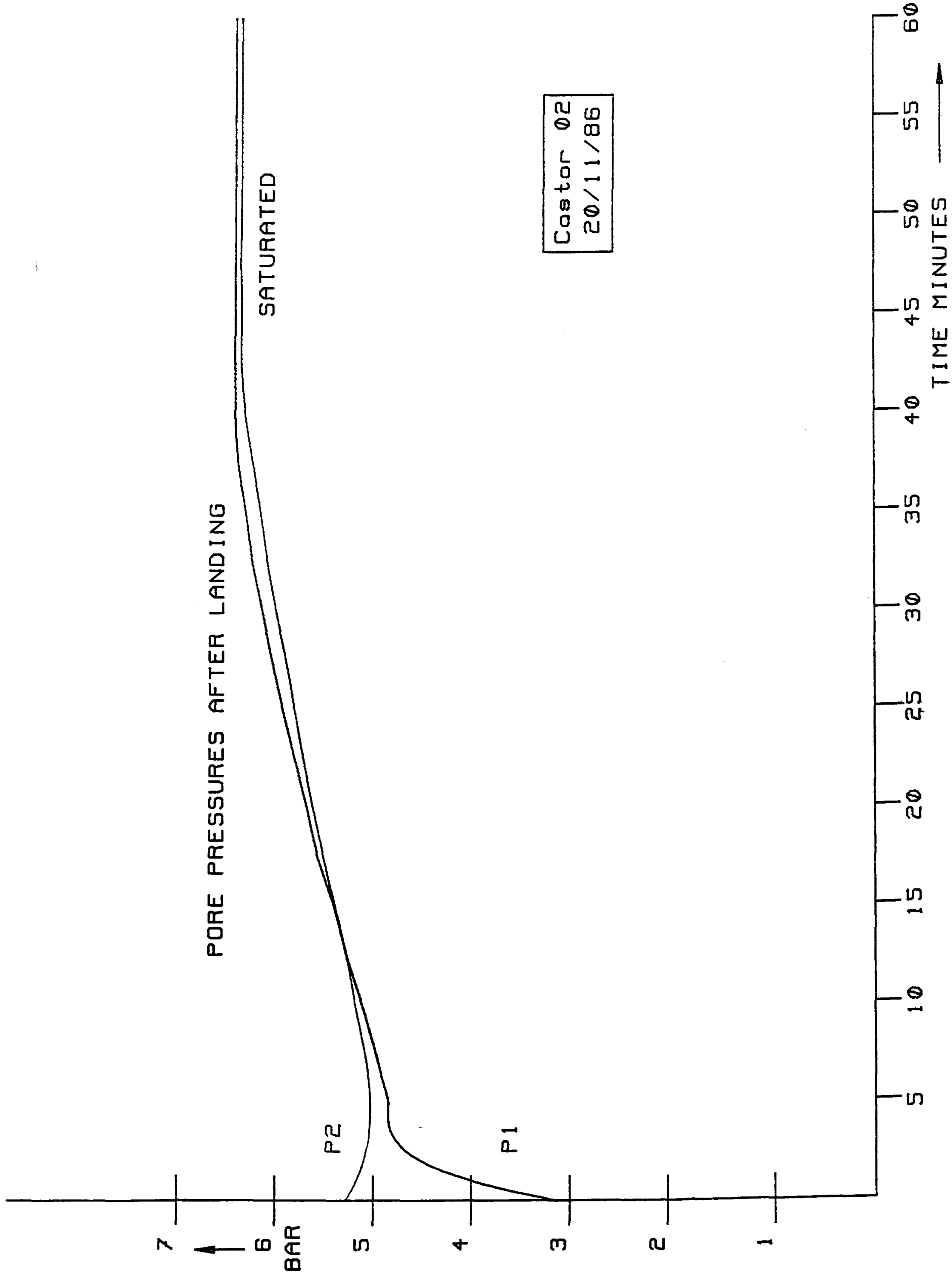

Figure 8 Pore pressures immediately after impact

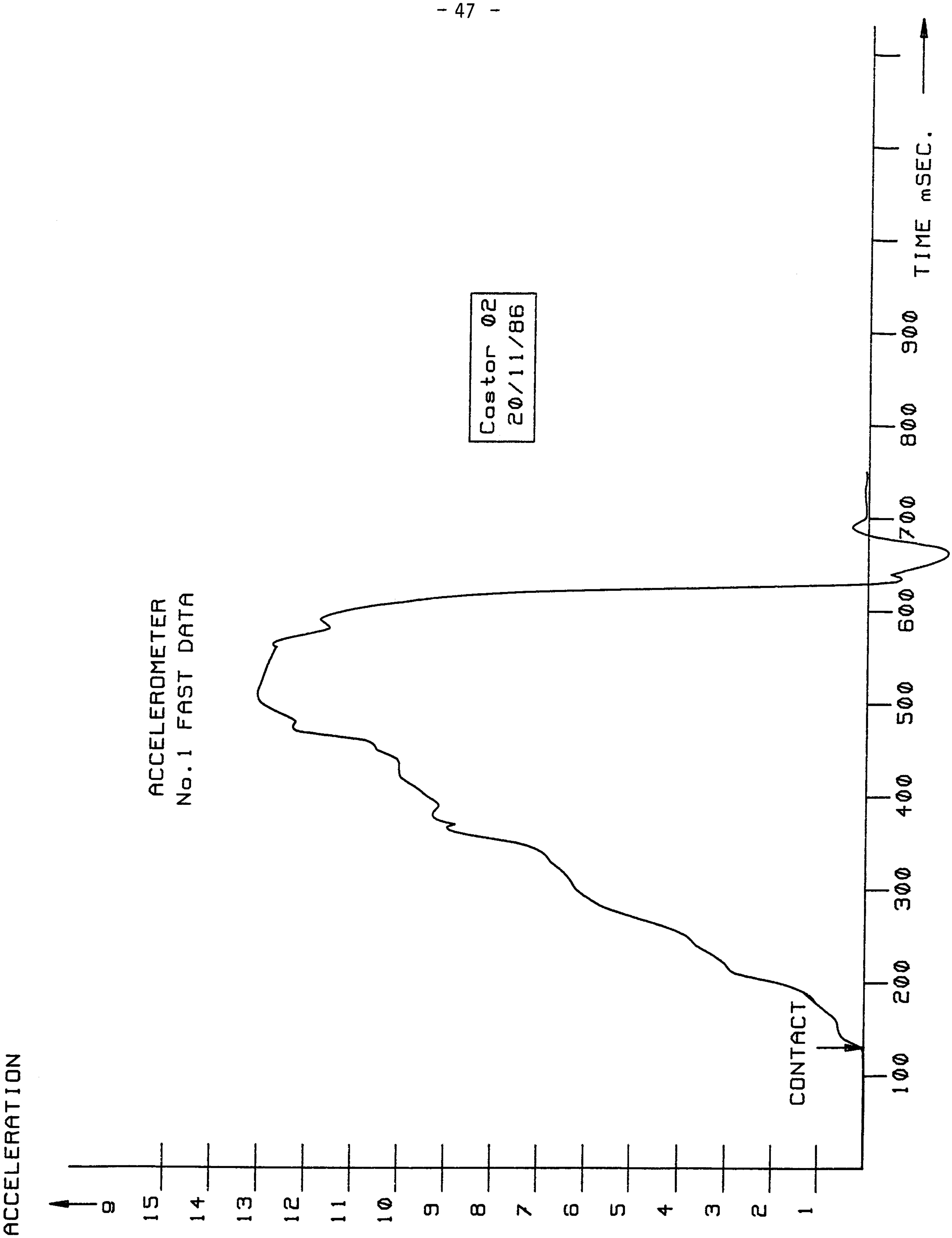

Figure 9 Digitised accelerometer data, Castor 02, November 1986

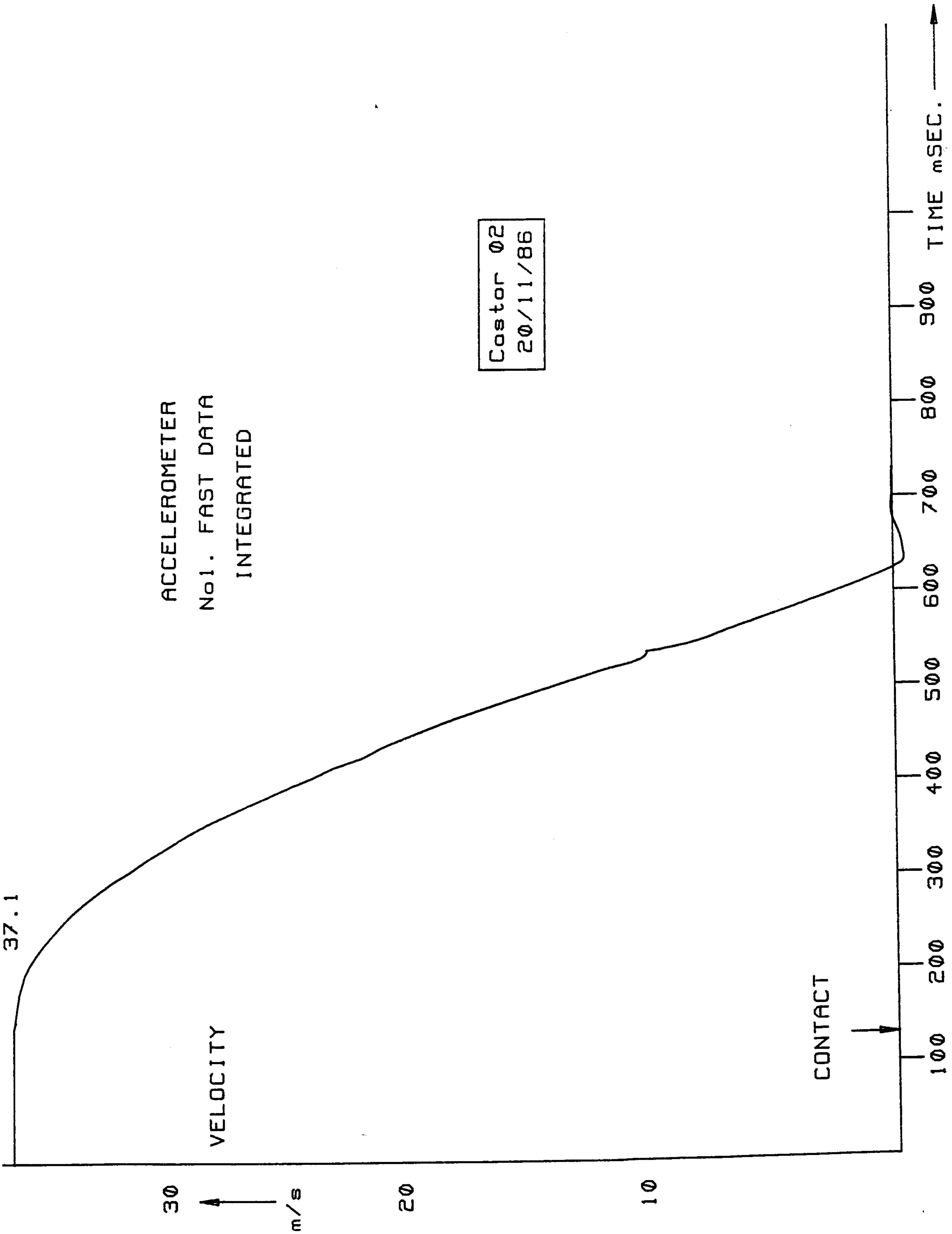

Figure 10 Penetrator velocity as a function of time

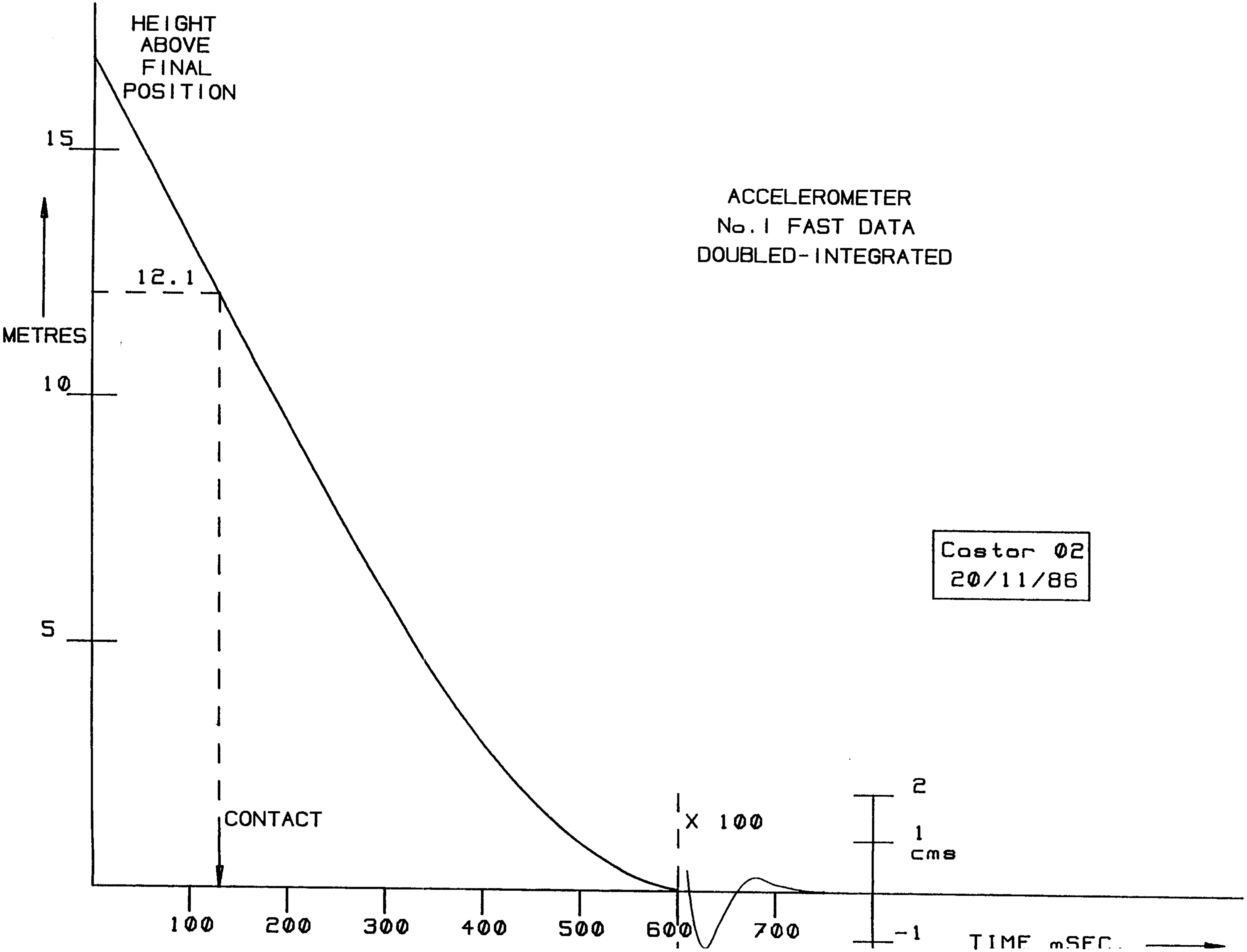

Figure 11 Penetrator displacement as a function of time