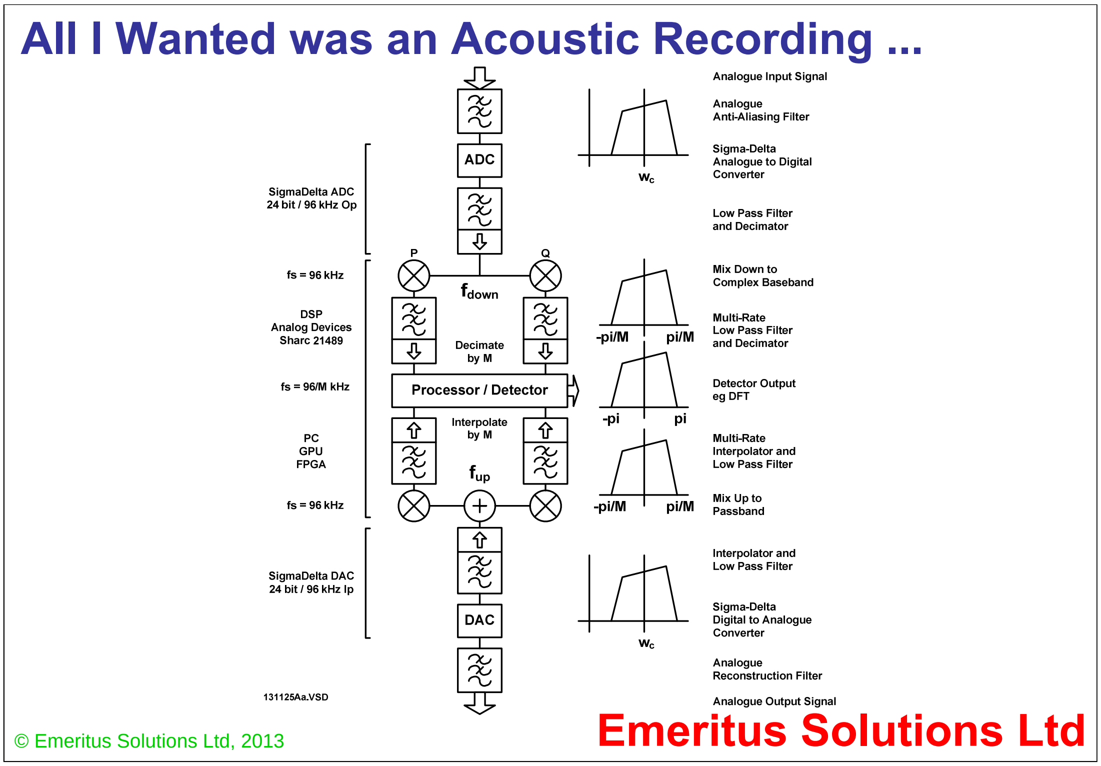


Abstract

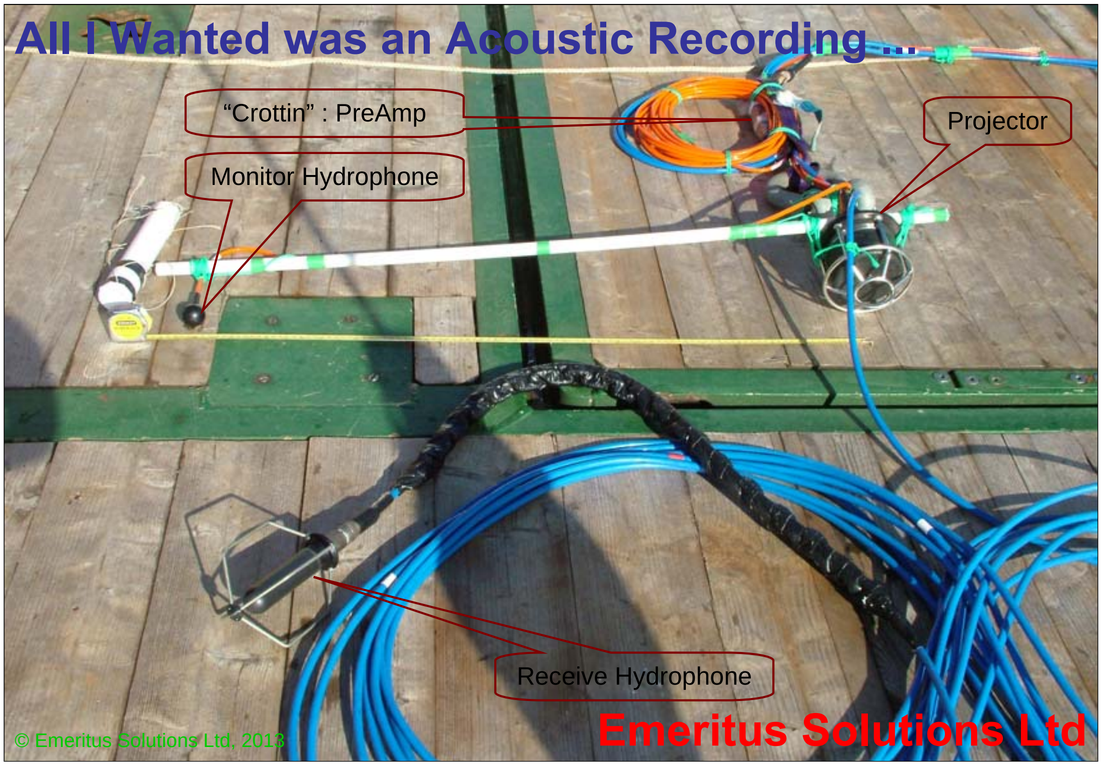
Hydrophones, used to receive acoustic signals, are probably the classic underwater sensor – what could be simpler ? However, when the signals click and the FFT spectrum surges, one might wish for something less troublesome than that simple ball hydrophone. This presentation will review the acoustic signal acquisition signal chain and comment on selected higher order design issues affecting the delivery of sweet signals from the receiver to the user. The technologies presented include ladder filters (1950's), gyrators (1970's), DSP, AOIP and 56 Henries of inductance in a PU moulding.

Biography – Eur Ing Dr Martin Bishop CEng FIEE

Eur Ing Dr Martin Bishop is a Technical Consultant and Director of Emeritus Solutions Ltd. His current interests include Digital Signal Processing, hard real time system implementation and remediation, positioning systems and algorithms, and acoustic sensor interfacing and recording. Martin's formative years were spent with the UK Ministry of Defence and latterly QinetiQ in the Portland area. While with MoD he was awarded a Personal Promotion to UG6 (Senior Principal) and while with QinetiQ was a QinetiQ Fellow. For the past ten years Martin has through Emeritus Solutions delivered ingenuity to the Defence and Oil and Gas sectors.

Digital Signal Processing

The usual destination of acoustic signals is a signal processing chain of the kind depicted on this VuGraph. The mechanisation can use a PC, DSP chip, GPU, FPGA or a bit of each. The algorithms can be time series or FFT based. Working on such systems and algorithms is Martin's day job.



A projector, monitor, receiver string is depicted rigged for deployment. Pre-amplification of the monitor and receive hydrophone signals are this presentation's focus.

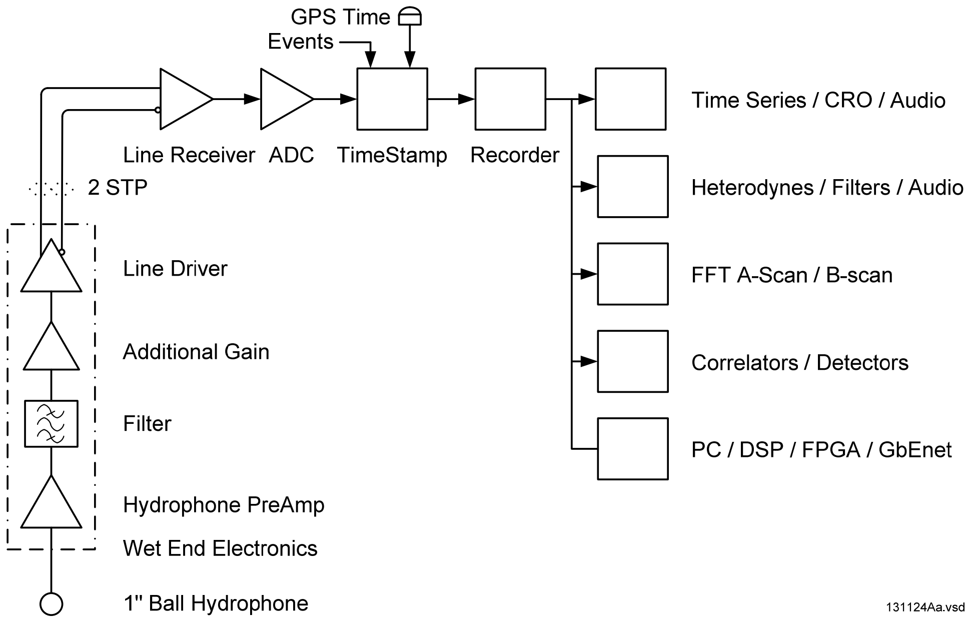
The receive hydrophone hangs below the projector, to provide a measure of acoustic isolation. The black parcelling conceals a meter of chain whipped onto the cable and employed as a sinker. The receiver's underwater cable is coiled in the traditional figure of eight flake. The receiver would typically be ~48 dB more sensitive than the Monitor hydrophone.

The presentation focuses on the 1" ball monitor hydrophone, which with additional gain could of course be employed as a receive hydrophone. The 1" ball is mounted 1 m from the projector.

The "Crottin" pre amplifier assembly is connected to the 1" ball by the orange, coaxial hydrophone cable. The Crottin contains a pre-amplifier card, with hydrophone (coax) and surface (2 STP) stub cables attached, and is named in honour of the black PU moulding which keeps the water out. The Crottin is connected to the main surface and hydrophone cables by underwater connectors.

The blue 2 STP surface cable is sunk by the shackle seen above the projector and is married to an 8 mm braid on three core hauling line.

Hydrophone Interfacing and Recording



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The signal processing, at the right of the diagram, is fed by the hydrophone via the conditioning, conversion, time stamping and recording elements at the top of the diagram.

The wet end electronics encapsulated in the crottin comprise the traditional receiver stages. First a high impedance, low noise input amplifier to optimise receiver noise performance. Next a mixture of gain and filtering is applied to condition the signal for transmission to the surface. The filter can be as simple as a single pole RC (AC) coupling stage; examples of this class of pre amp are considered in the sequel, however experience shows that they have restricted applicability. Finally, a line driver conditions the differential output signal for the 100+ m cable run to the surface receiver. Additionally, the pre amp implements rail splitting, low noise voltage regulation, reverse and overvoltage supply protection functions.

At the surface the line receiver buffers, optionally amplifies and differentially interfaces the analog signal to the ADC. Once in the digital domain (24 b x 96k / 192k sampling) the acoustic stream can be timestamped to < 1us resolution and marked with experimental events. Thereafter the record before processing paradigm is applied and sweet signals are available for processing.

“Crottin” Pre Amplifier

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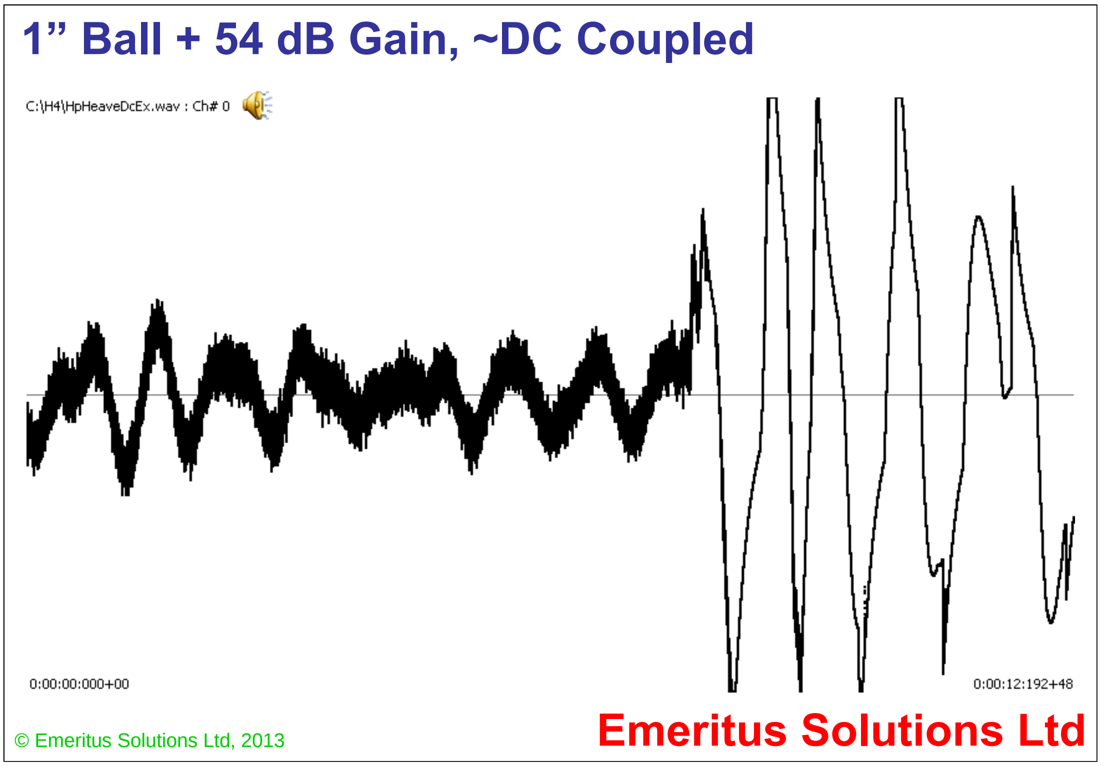
The assembly and encapsulation of a Crottin are depicted above.

At bottom left the “power conditioning” circuitry can be seen on the rear of the pre-amplifier PEC. The split rail supply is derived from DC passed down one half of the (blue) 2 STP cable.

The cable joint moulds used to form the PU encapsulation are shown, on the right, before and after pouring.

A significant advantage of “deep sixing” the pre amplifier is the benign EMC environment in which it operates. The surface power supply should be floating, dedicated and linear. Together with the use of low noise regulators in the wet end this provides “clean” power to the pre amplifier stages. Additionally, the salt water surrounding the Crottin and the separation from interferers generally eliminates the switched mode tonal artifacts present in most measurement settings.

Obviously, the differential signals received from the Crottin must be interfaced firstly to a differential receiver and then to the ADC using floating power supplies and appropriate galvanic isolation measures.



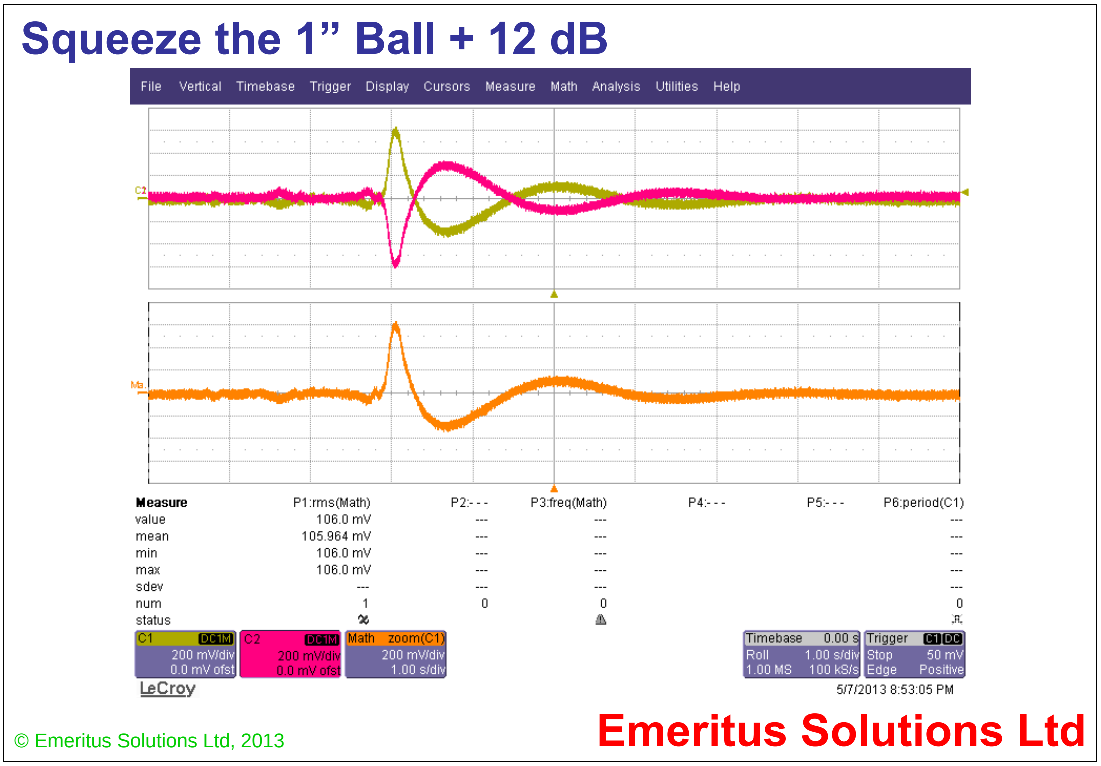
This is what happens when a lot of gain has a pressure signal applied to it. The right hand portion of the waveform depicts what a near DC coupled, high gain pre amplifier outputs when the 1” ball hydrophone is heaved up and down by a meter or so. The pressure signal dominates and the acoustic signal is swamped. All you can hear are clicks.

The situation is of course artificial. The 1” ball was veered and hauled vertically by a meter or so, appreciably more than platform motion would commonly effect. Benign platform motion exemplified by the cycles to the left of the plot is arguably “bad enough”.

The engineering problem is to understand the physics and to craft a solution which minimises the noise (by maximising the available gain), maximises the bandwidth, delivers uniform group delay, fits in a pre amplifier moulding, and has no undesirable second order characteristics.

The essence of the signal processing requirement is to remove the (potentially) large amplitude, low frequency pressure signals while passing the higher frequency, significantly lower amplitude acoustic signals; amplitude ratios of 60 .. 80 dBs (unwanted : desired) are quite possible.

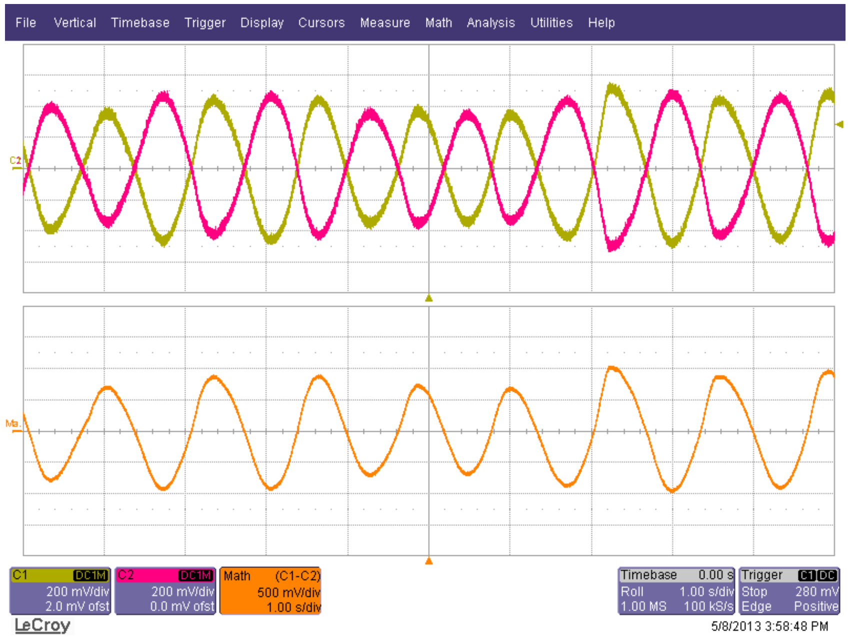
There has of course been research and development of depth / pressure insensitive hydrophones for a very long time. However, our standard hydrophones remain depth / pressure sensitive.



The pressure sensitivity of a 1” ball can be simply demonstrated by squeezing it. The traces depicted are for a 6 dB gain differential output pre amplifier. The positive, negative and differenced outputs are plotted against a 1 sec / div timebase.

The key takeaways are that the hydrophone / high impedance pre-amp combination is firstly dissipative and secondly that any mechanical resonance / damping is at a very low frequency – below a Hz.

1” Ball + 12dB : Up and Down ±200 mm



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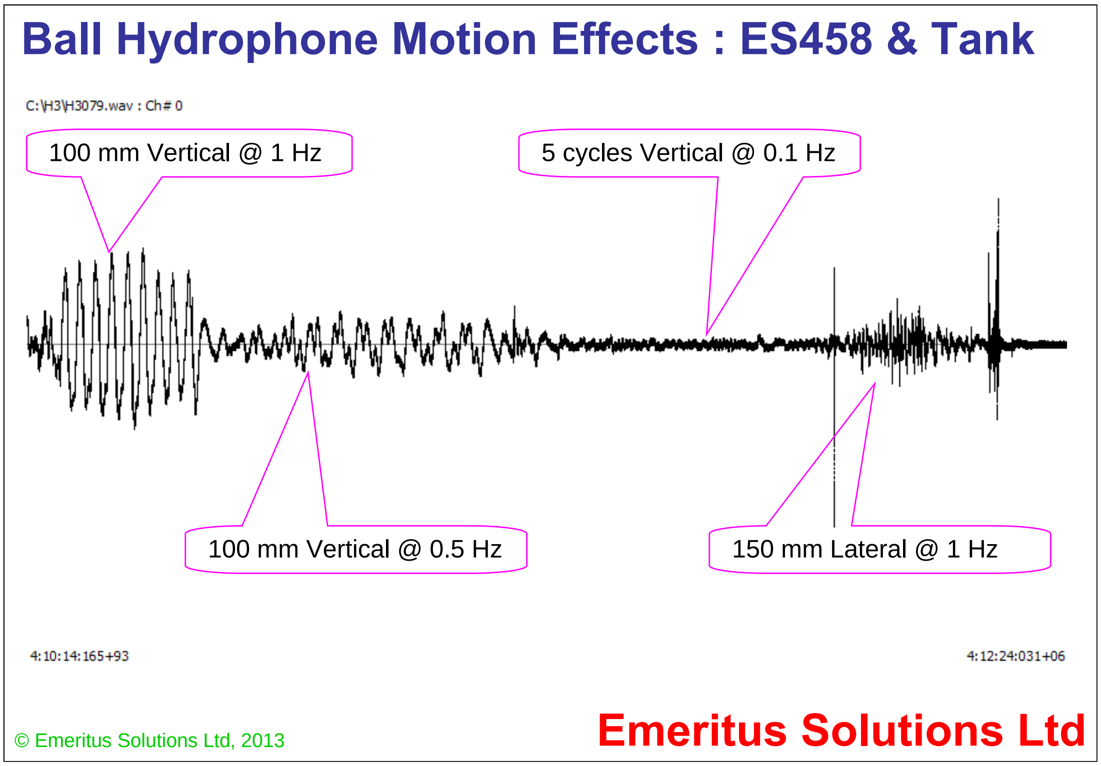
The significant amplitude of the pressure driven output of the same 1” ball, 6 dB differential pre amplifier configuration is plainly evident from this demonstration of the 1” ball being moved up / down in water by ±200 mm at about 1 Hz.

The differential receiver’s output voltage is almost 0 dBV. In even quite noisy acoustic conditions the acoustic field would only generate a signal at the -60 to -80 dBV level. The challenge, as ever, is to separate the wanted (acoustic) signal from the unwanted (pressure) signal. In principle a high pass filter should suffice.



Additional test tank experiments repeat and refine these observations. The hydrostatic pressure signal is observable at the hydrophone / preamplifier output. However, even with a near DC 0.16 Hz (10 uF / 1 MR) coupled pre amp some frequencies are too low – the pressure signal dissipating before it can be observed.

Experience at sea suggests that 10 to 50 Hz is a suitable transition band. Sonar equation calculations indicate that 48 dB of gain is a useful complement to a 1” ball, indicating that a stop band depth of > 50 dB is desirable.

Hydrophone Sensitivity

- 1" ball : M ≈ -202 dB re 1V/μPa = -22 dB re 1V/kPa
- 1 Bar = 100 kPa ≈ 10 meters sea water
- Output / hydrostatic pressure ≈ -2 dBV / m
  - e.g. ±0.1 m ≈ -22 dBV
- Output / sound pressure ≈ -202 dB re 1V/μPa
  - e.g. 120 dB SPL ≈ -82 dBV
- Acoustic signal is much smaller than pressure variation
  - PreAmp gain to raise level to 0 dBV is desirable
  - High Pass filter must precede gain
  - Filter attenuation must equal / exceed gain

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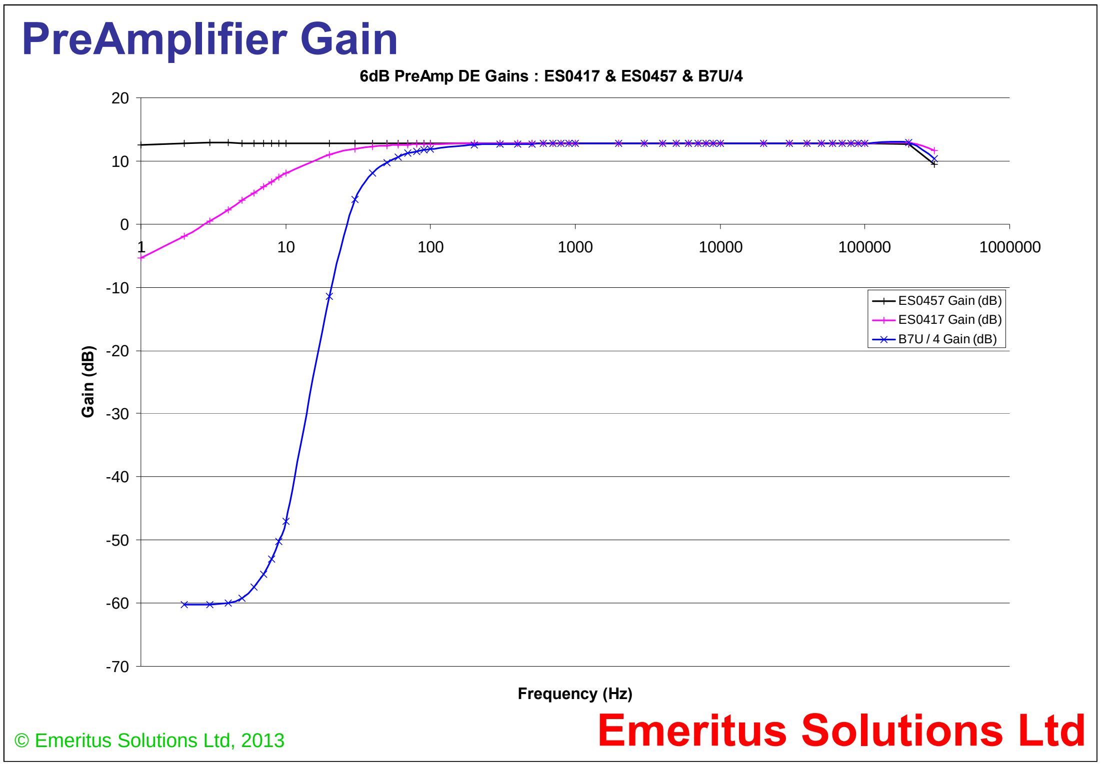
The hydrophone sensitivity M (Receive Response in American terminology) of a 1" ball hydrophone is approximately -202 dB re 1V/uPa.

Comparison of the output voltage due to 100 mm (rms) of motion and a fairly loud SPL of 120 dB identifies a marked disparity in output signal levels of 60 dB, in favour of the hydrostatic pressure variations. Simply put, if the pressure variation is not removed, it can, as we have seen, swamp the acoustic signal.

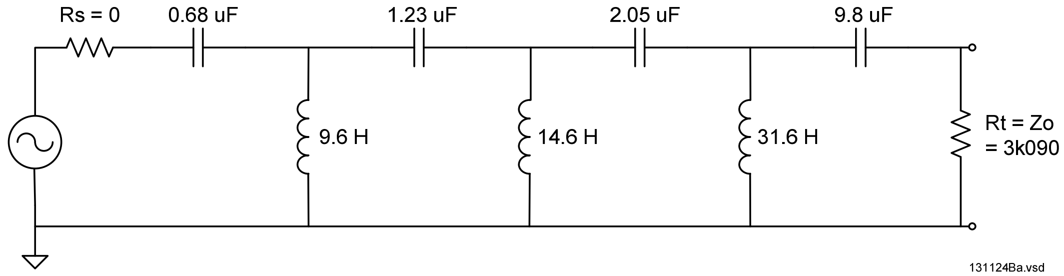
Consequently, a high pass filter is required prior to the pre amplifier's gain stages. While receiver design is usually optimised by a large gain in the initial stage in the extant circumstances the best option is to receive the signal, with modest gain, and to buffer it with much reduced impedance before passing it through a high pass filter to permit the application of the desired gain. Self evidently, the HP filter will have to be analog. Additionally, the filter will have to deliver a flat passband, uniform group delay, low sensitivity (esp. in the passband) to component values, low noise and low distortion. An easy task for a digital filter – but that's not an option.

Various factors drive the decision to use an analog HP filter. The facile reason is that we are filtering an analog signal. The central engineering reason is that we can "hopefully" obtain greater useful dynamic range and reduced intermodulation distortion by filtering out the large, unwanted pressure signal at the source and using the finite dynamic range on the uplink for the desired signal. The alternative of (digital) filtering at the top end would use more than half the dynamic range of both uplink and ADC to pass the unwanted pressure signal. Both the 1st Marquis of Montrose and our Canadian friends have apposite sayings for this sort of thing.



The three filter responses depicted encompass the approaches to interfacing a 1" ball hydrophone. The black trace, ES0457, is the near DC coupled pre amplifier used to evaluate the 1" balls pressure response. The magenta curve, ES0417, is a 10 Hz single pole (i.e. RC) AC coupled pre amplifier – suitable for removing OpAmp offsets and by no means an uncommon design. The blue trace is a 7th order Bessel filter with a -3 dB frequency of 50 Hz – it responds to the requirement of 50 dB down at 10 Hz. All three traces are bench measurements of pre amplifiers implemented on PCBs. The gain / loss floor of -60 dB is assessed as an instrumentation artifact; the RMS voltages were measured using an Agilent 34410A DVM which has a minimum range of 100 mV and is only specified for voltages > 1 mV rms.

Passive Ladder Filter



- **High Pass Filter : fc = 50 Hz, -60 dB @ 10 Hz**
- **7th Order Bessel Filter, for Linear Phase**
- **Singly terminated design has better performance**
- **Capacitors : ±5 .. 10 % tolerance and ...**
- **10 .. 32 H inductors are impractical**

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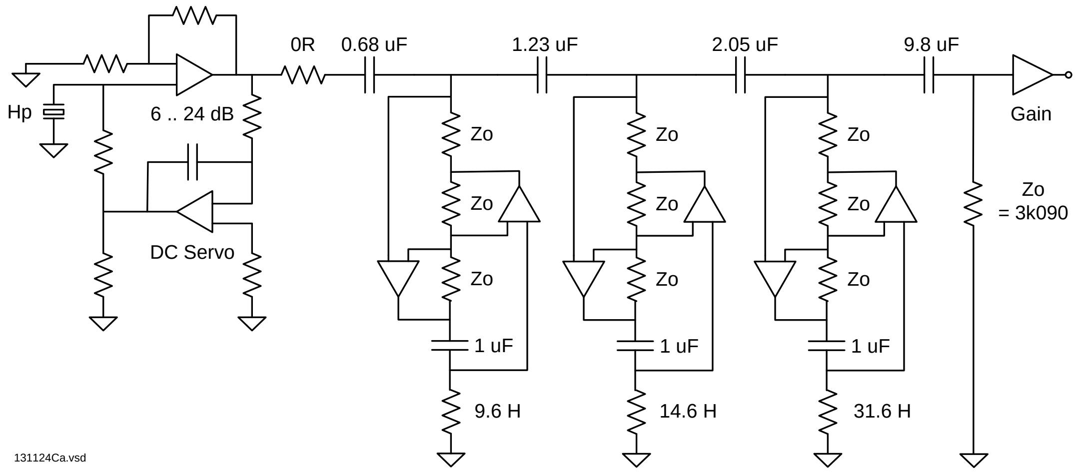
There are many classes of analog filter, which in contemporary practice generally utilise OpAmps as active elements. The filter depicted above is, of course, a passive ladder filter with many desirable attributes : it has low sensitivity (especially in the passband) to component errors, as a Bessel filter it has a constant group delay in the passband, etc.

However, the inductor values are unrealisable as passive components. Dissipation due to winding resistance would "detune" the design, and the coils might be a little large.

Nonetheless, this excellent fruit of 1940's / 50's network theory can, through the use of gyrators to realise the inductive limbs, be used as a prototype for a practical filter.

Ladder Filter Realisation using Gyrators



- **Inductors replaced by gyrators**
- **High impedance, low noise input amp + servo**
- **Gain / buffer to differential line driver**

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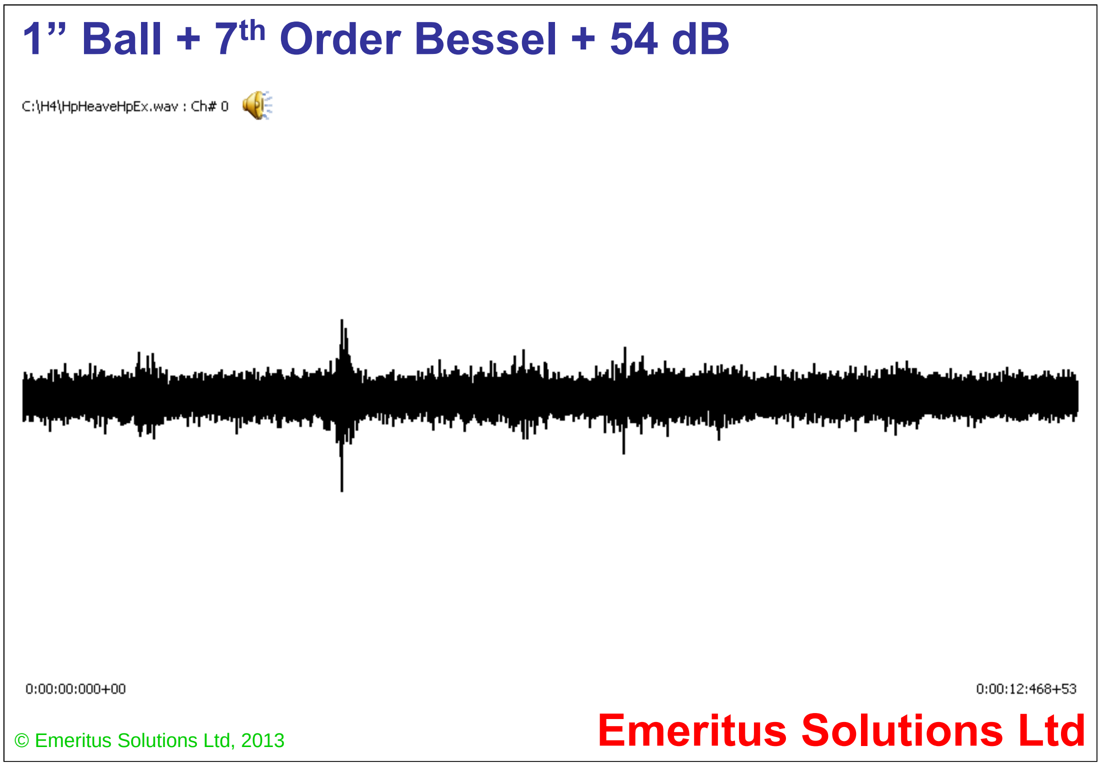
An implementation of the passive Bessel ladder filter using gyrators is depicted above. Gyrators are active circuits which invert their, 1 uF, capacitors to act as inductances; good filter references will explain. However, the secondary literature has its limitations, mostly omissions with a leavening of errors.

From a practical standpoint Zo is selected for medium impedance and to nudge the series capacitors towards values which can be realised by parallel combinations of standard capacitors : if the complete E6 range is available you are fortunate.

Zo can of course take any E96 value. The resistors (with inductance values) are then selected (again from E96 values) to set the gyrators effective inductance to the desired values. The adjustment of the design is thus fairly effectively performed by precise (0.1%) components – used for their resolution rather than accuracy.

The capacitors are of course a different story. Tolerances of 5% are excellent, with 10% more typical. And then there is the variation in capacitance due to temperature, age and DC bias (invariably it would seem a reduction). Nonetheless, the low sensitivity properties of the ladder prototypes deliver acceptable filter performance with 10 or even 20 per cent variations.

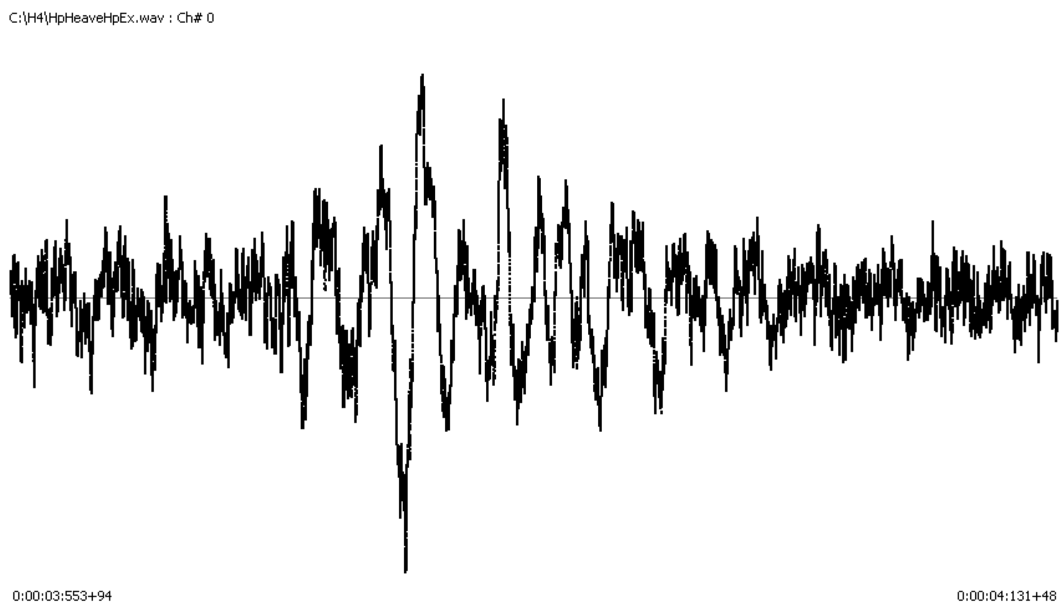
The use of a singly terminated prototype is intentional. While long denigrated in the literature, this (as opposed to the doubly terminated) prototype performs well in practice. The headroom required at the gyrators' internal nodes and the filter's component sensitivity are both (by analysis and measurement) lower for the singly terminated design. Additionally, the asymptotic passband gain of a singly terminated filter is 0 dB, for a doubly terminated prototype it would be determined by Rs / Rt.



As proof of the pudding a segment of data recorded through a 54 dB pre amplifier fitted with a 7th order Bessel filter is presented.

The transient events are the consequence of hauling and veering the hydrophone by a meter or so.

1” Ball + 7th Order Bessel + 54 dB - Zoom



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Zooming the time series, at the transient, shows the energy of the hydrophone displacement creeping through (perhaps unsurprisingly) at ~ 50 Hz, the high pass filter’s corner frequency.

The PEC in the background is the 54 dB Bessel filter fitted pre amplifier described in this presentation. The PEC only requires cable termination and potting to prepare it for use underwater. The surface mounted MLCC capacitors are of course an important enabling technology. The use of PU encapsulation requires all components to be suitable for use at ambient pressure.

Emeritus Solutions Ltd is a UK based Engineering Consultancy active in Underwater Acoustics, Navigation and all aspects of Digital Signal processing from algorithms to implementations. Our competencies include : Signal Processing and Navigation and Positioning, algorithms and analysis; Embedded and Processing System Design using FPGA SoCs, DSPs, GPUs, PCs, embedded processors and microcontrollers; Platform design using FPGAs, digital, analogue, PC and microcontroller hardware; System implementation using C / C++, Delphi / Pascal, assembler, and HDLs; System Remediation and Consultancy.

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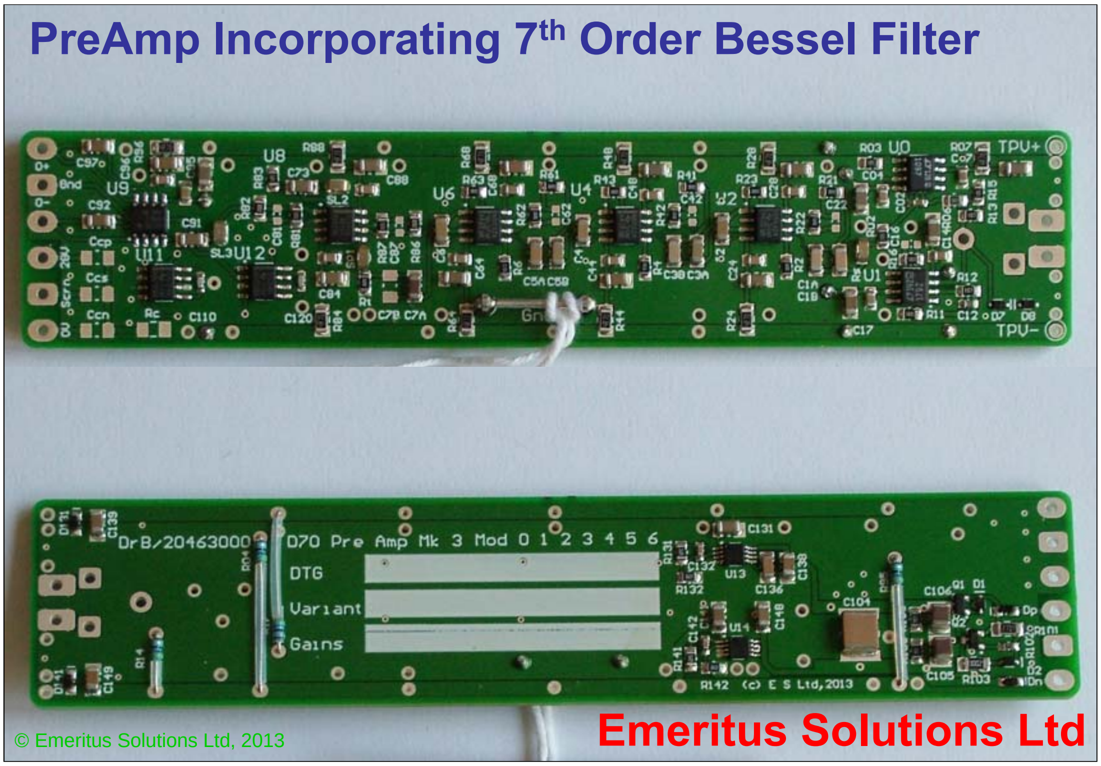
Perhaps the most important point regarding the bibliography is that many of the filter techniques employed are from several decades ago. Perhaps consequently, the contemporary filter literature often provides neither good nor on occasion accurate expositions of the techniques. Additionally, the development of “better” usually digital approaches to filtering caused many aspects of analog filter design to become less topical and eased them out of later editions of numerous standard works. Consequently, the optimal literature for analogue ladder filters and gyrators is in general from the end of their development eras. The references selected endeavour to provide some guidance in this regard.



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The PEC is double sided with the positive and negative supplies distributed on upper and lower edge tracks. Both top and bottom of the board are flooded with Gnd plane / fill which is beneficial both in terms of copper balance and electrically. The surface mount and through hole resistors terminated on the edge tracks connect the supply rails to the OpAmps. Other than signal routing links, for non standard configurations of the two post filter gain stages, the analog signal paths are tracked on the top of the board with ground plane below.