CALIBRATING LOW FREQUENCY DIGITAL HYDROPHONES

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Abstract: *Ocean Networks Canada initiated a project to evaluate the performance of a low frequency, smart hydrophone for cabled ocean observatories. A suitable independent calibration facility could not be found that was capable of calibrating a) digital hydrophones or b) down to 0.01 Hz. The lack of an end to end calibration capability for digital hydrophone systems is a potential source of errors, and the lack of a standard for digital hydrophone calibrations invites the use of multiple metrics such as dB re µPa^2@FS or dB re counts^2/µPa^2. The lack of an existing end to end calibration system necessitated the design of a low frequency, digital, hydrophone calibration system for the ocean observatory. This paper describes the design, operating challenges and performance of the new calibration system. The system is driven by a piston that sinusoidally pressurizes a small, constrained volume of water in which a reference pressure sensor and the unit under test are immersed. The calibration assembly is immersed in a water bath for thermal damping and the bath is enclosed for vibration isolation.*

Keywords: *acoustic, calibration, hydrophone, low frequency*

1. MOTIVATION

Ocean Networks Canada (ONC) operates the VENUS and NEPTUNE Canada cabled underwater observatory networks. Hydrophone data is one of the core data sets that ONC provides free of charge to researchers around the world. In response to pressure from a number of stakeholders ONC initiated a project to improve the reliability, maintainability and acoustic quality of the hydrophone data.

Systematic issues with ONC's previous two digital Ethernet hydrophone implementations (custom built hydrophone arrays and single element hydrophones purchased from a hydrophone manufacturer) could have been discovered had a full end to end (acoustic pressure to counts) calibration been carried out.

To improve ONC’s hydrophone data the specifications of a number of technologies were assessed and the Ocean Sonics icListen Smart Hydrophones were chosen for a series of technology demonstration projects. The first project focused on the icListen LF hydrophone. This meant verifying the dynamic range, long term reliability and sensitivity over the frequency range of 0.01 Hz to 1600 Hz.

Hydrophone calibration techniques are well understood (Bobber, 1989). Although open water and large tank facilities are readily available, facilities willing to calibrate digital hydrophones could not be found. Calibration facilities down to 20 Hz, using air, are also available but only for analog sensors. Below 20 Hz, neither analog nor digital calibration facilities could be found. Therefore it was decided to construct the 0.01 Hz capability in house. This paper describes the low frequency prototype system and its results.

2. VERY LOW FREQUENCY PROTOTYPE DESIGN

For a comparison calibration it is necessary to expose both the reference and the hydrophone under test to the same acoustic pressure. The reference will allow the calculation of the acoustic pressure and the test hydrophone’s output at that pressure which can then be used to compute the sensitivity. The concept is shown in Figure 1. This measurement is performed at multiple frequencies spanning the test hydrophone’s operating range to produce a sensitivity plot.

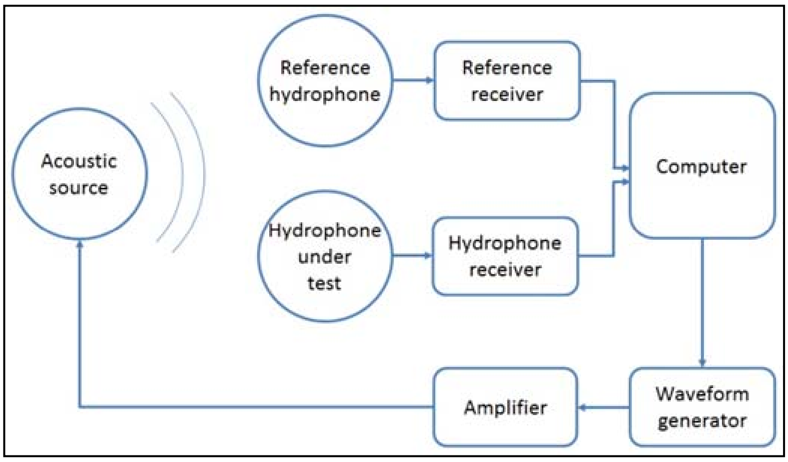


Fig.1: Traditional comparison calibration

During the design phase it was decided to calibrate frequencies at and above 100 Hz using a traditional reference hydrophone comparison calibration technique in open water. Below 100 Hz a new calibration system would be designed. In order to provide some spectral overlap the low frequency calibration system was originally designed to operate up to a maximum frequency of $f_{max} = 500$ Hz.

To provide spectral overlap with the observatory's seismometers it was desirable to extend the icListen LF hydrophone calibrations down to a minimum frequency of $f_{min} = 0.001$ Hz.

Calibrating a hydrophone in the far field in this frequency range is impractical due to the long wavelengths involved. Therefore to minimize diffraction issues the calibration system was designed to operate as a hydrostatic pressure system. To achieve this, the longest dimension of the pressurized volume was constrained to < $1/20^{th}$ of a wavelength (λ) at the highest frequency of operation. At $\lambda/20$ the maximum differential pressure ratio (dP_{rel}) of any point in the chamber relative to the midpoint of the longest internal dimension at $\pi/2$ phase in the sinusoidal pressure is $dP_{rel} = \sin(\pi/2-\pi/20)) = 0.988$. In dB this equates to a maximum pressure error of $E_{dB} = 20*\log_{10}(dP_{rel}) = 0.1$ dB . In water with a sound speed of $c = 1485$m/s, this equates to a maximum internal dimension of $D_{max} = c/(20*f_{max}) = 15$cm. The longest internal dimension in the prototype calibration system is the water path from the reference pressure sensor to the vent ball valve as depicted in Figure 2.

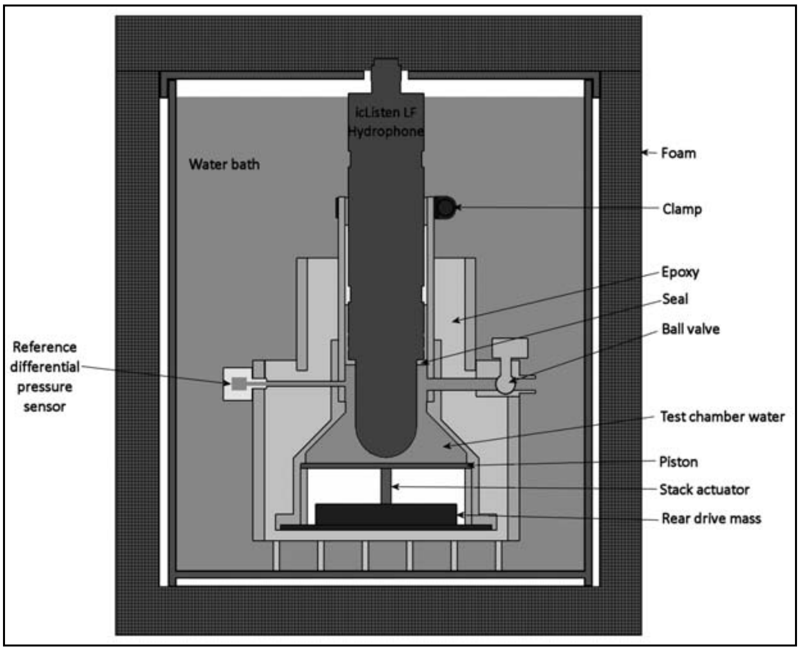


Figure 2 – Cross section of the VLF calibration system prototype

Since reference hydrophones were not available for the frequency range desired a pressure sensor was chosen as the reference. The icListen LF hydrophone being tested had a full scale acoustic specification of 168 dB re $1\mu Pa^2$ (355 Pa peak) on the flat portion of the manufacturer's plots. To allow for some thermal variations of pressure in the constrained water volume the pressure range requirement was doubled. The most appropriate sensor found was a silicon wafer strain gauge differential pressure sensor with a full scale range of ±500 Pa and response time of 1 ms. To improve the accuracy and verify the linearity the pressure sensor was re-calibrated as shown in Figure 3. The standard deviation of the calibration was 0.08%FS.

The calibration setup is shown in figure 4. A digital oscilloscope was used to capture the data from the reference pressure sensor. The oscilloscope, waveform generator and hydrophone under test were automatically controlled during the calibration using a MATLAB script so that the reference pressure data could be synchronized with the hydrophone data. The hydrophone was connected to the Ethernet port of the computer while the oscilloscope and waveform generator were connected to USB ports.

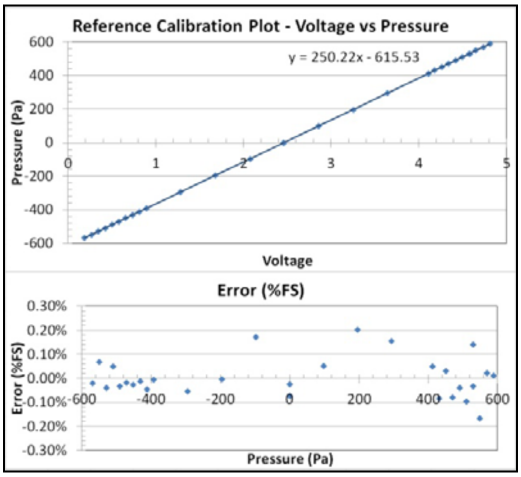


Figure 3 – Reference calibration

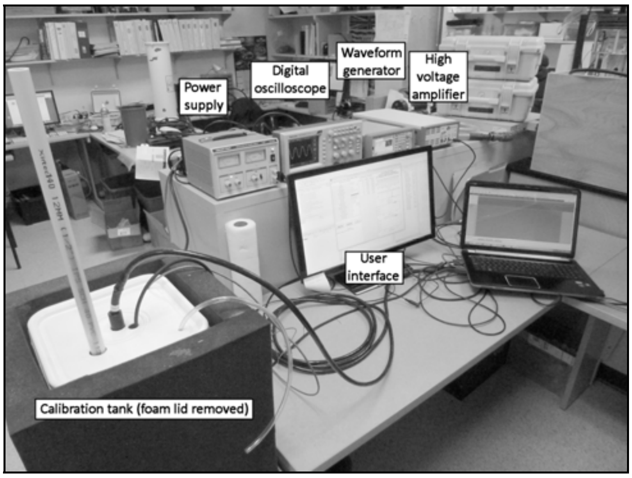
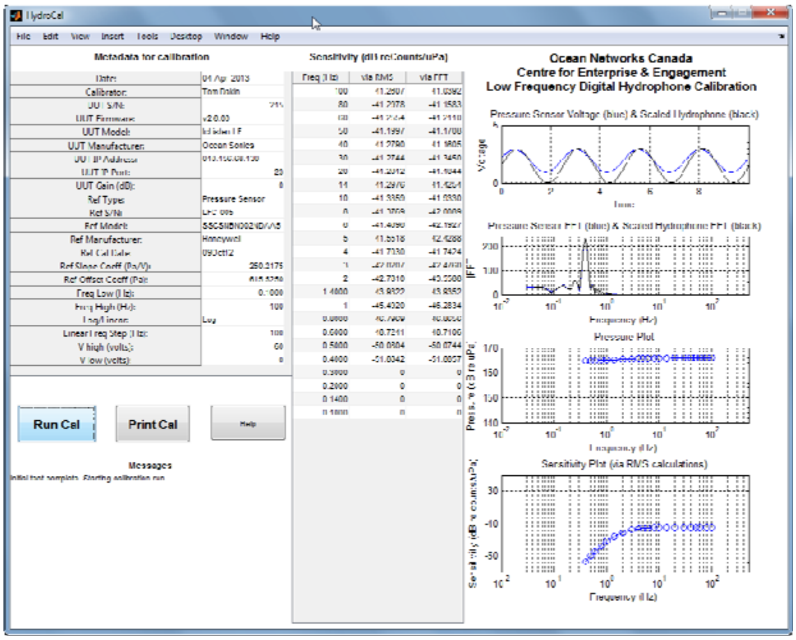


Figure 4 – Prototype system setup

3. RESULTS

Data from the calibration results are provided in two forms; an immediate graphical interface as well as a detailed matrix report log. The interface allows the users to set parameters such as frequency range, hydrophone gain, reference coefficients and the sound pressure level. It also stores metadata such as the hydrophone serial number, IP address, calibration operator and the reference sensor information.



Metadata for calibration

Date:	04 Apr 2013
Calibrator:	Tom Dakin
UUT S/N:	[illegible]
UUT Firmware:	v2.0.03
UUT Model:	[illegible]
UUT Manufacturer:	Ocean Sonics
UUT IP Address:	[illegible]
UUT IP Port:	20
UUT Gain (dB):	0
Ref Type:	Pressure Sensor
Ref S/N:	[illegible]
Ref Model:	[illegible]
Ref Manufacturer:	Honeywell
Ref Cal Date:	09Oct12
Ref Slope Coeff (Pa/V):	250.2175
Ref Offset Coeff (Pa):	[illegible]
Freq Low (Hz):	[illegible]
Freq High (Hz):	100
Log/Linear:	Log
Linear Freq Step (Hz):	100
V high (volts):	60
V low (volts):	0

Messages

Initial test complete. Starting calibration run

Sensitivity (dB re Counts/uPa)

Freq (Hz)	via RMS	via FFT
100	[illegible]	[illegible]
80	-41.2078	-41.1583
60	[illegible]	[illegible]
50	-41.1997	[illegible]
40	[illegible]	[illegible]
30	-41.2744	[illegible]
20	-41.2012	[illegible]
14	[illegible]	[illegible]
10	[illegible]	[illegible]
8	[illegible]	[illegible]
6	-41.4090	[illegible]
5	[illegible]	[illegible]
4	-41.7130	-41.7424
3	[illegible]	[illegible]
2	-42.7310	[illegible]
1.4000	[illegible]	[illegible]
1	-45.4020	-46.2834
0.8000	[illegible]	[illegible]
0.6000	[illegible]	[illegible]
0.5000	[illegible]	[illegible]
0.4000	-51.0342	[illegible]
0.3000	0	0
0.2000	0	0
0.1400	0	0
0.1000	0	0

Figure 5 – User interface of Calibration in Progress

The system is capable of producing very stable results with respect to hydrophone sensitivity, as shown in figure 6. Collections of calibration results, in this case using an icListen LF with at 2 pole front end filter, were combined to determine the repeatability of the system. The majority of the operable frequency range maintains a standard deviation below 0.05 dB re counts^2/µPa^2, faltering at the very low frequencies where a combination of loss in hydrophone sensitivity and environmental noise affect the accuracy.

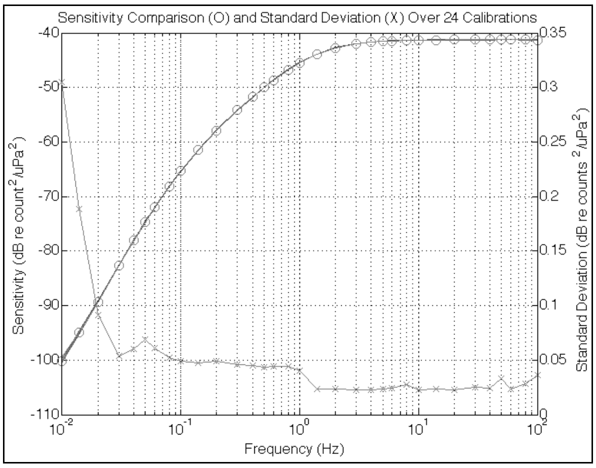


Figure 6 – Repeatability of Calibrations
24 runs of 2 pole filter icListen LF

The automated nature of the calibration system and the ability to set various sound pressure levels in the chamber allows the hydrophone sensitivity to be mapped over a wide range of sound pressure levels. This characterises the hydrophone's non-linearity. As shown in figure 7, the icListen LF has been designed to reduce clipping at high sound pressure levels (SPL) by reducing the sensitivity. The sensitivities are flat for all frequencies up to a frequency dependent maximum. Since the majority of the data collected will be in the flat portion of the sensitivity versus SPL plot, the flat sensitivity magnitude should be plotted in the traditional sensitivity versus frequency plot. A more complete analysis is shown by plotting the sensitivities at various SPLs, as shown in figure 8. However this is likely too complex to be implemented in computations of high intensity measurements.

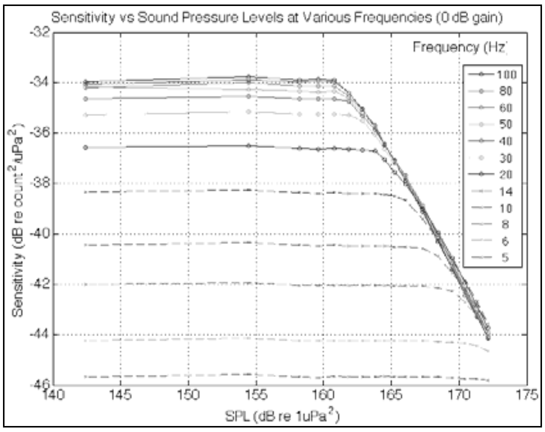


Figure 7 – High SPL Sensitivity Roll-off
1 pole filter icListen LF

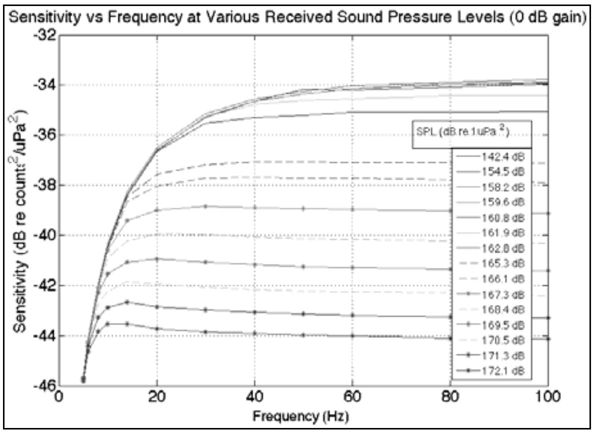


Figure 8 – Sensitivity plots at various SPLs
1 pole filter icListen LF

4. OPERATING CHALLENGES

Several expected challenges arose during operation of the calibration system. Bubbles cause a resonance peak and trough in the pressure plot (which should be a straight line as shown in the pressure plot of figure 5), necessitating the hydrophone removal to remove the bubbles. Electrical noise will show up in the voltage plot of figure 5 and can be minimized by turning surrounding systems off. Air pressure and acoustic noise also show up as spikes in the sensitivity plot and a recalibration will prove if the spikes are repeatable or due to noise. Thermal variations with time over-range the reference pressure sensor. A wider range reference sensor, faster thermal equalization (metal chamber) and automated pressure equalization between data points will resolve this issue.

Several unforeseen challenges arose. The ball valve displaced water when closing and over-ranged the differential pressure sensor. This was resolved by equalizing the back side pressure on the reference sensor (water filled tube). Compliant tank walls reduced the achievable SPL. Thickening the walls with 2.5 cm of cast epoxy nearly doubled the SPL. The next version of the calibration system will use a metal casing. The dual compression pipe seal around the hydrophone was compliant and difficult to successfully install and remove. The next version will utilize stiff o-ring seals which will reduce the setup and tear down time dramatically. The ‘analog’ reference pressure sensor turned out to be a digital sensor with a digital to analog converter operating at 1 kHz. This generated stepped sinusoids at high frequencies and reduced the effective upper frequency of the system to 100 Hz. The next system will utilize a silicon Wheatstone bridge strain gauge that will have a 1 kHz range.

Another unexpected challenge arose when discussing the sensitivity results with several hydrophone manufacturers. One manufacturer wished to use dB re μPa^2@FS while another used dB re $counts^2/mPa^2$. The author’s preference is dB re $counts^2/\mu Pa^2$ within the linear portion of the hydrophone sensitivity as discussed above.

5. CONCLUSIONS

Hydrophone calibration facilities have not yet embraced the digital age.

The prototype VLF calibration system allowed ONC to successfully analyse the low frequency sensitivity of the icListen smart hydrophones. The system took advantage of the digital nature of the hydrophone to allow automation of the calibration process. This allowed the non-linear response of the hydrophone with respect to SPL to be characterized. The non-linear response shows the need to specify the sensitivity in the flat low SPL operating regime rather than referenced to full scale output which in this case was attenuated in sensitivity.

The prototype issues with compliance and ease of use can be addressed with a new system design. A fully analog reference will extend the upper frequency range and a new hydrophone seal will reduce the set up time.

REFERENCES

[1] **R.J. BOBBER**, *Underwater Electroacoustic Measurements*. USA, Peninsula Press, (2nd edition), 1989.